Seasonal Weight Restriction Decision Making based on Understanding and Monitoring of Frost Susceptibility of Pavement Structures

Final Report

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16. Abstract
Seasonal Weight Restrictions (SWR) are implemented to protect pavements during spring thaw when freeze–thaw processes significantly reduce road bearing capacity. In Wisconsin, current SWR practices rely primarily on fixed dates, field observations, and simplified temperature-based indices, which do not fully account for site-specific pavement behavior or use available monitoring data. This project develops an integrated framework for SWR decision-making that combines field monitoring, physics-based modeling, data-driven analysis, and decision support implementation. Eight monitoring stations were deployed across Wisconsin to collect temperature, moisture, and vibration data, supported by Ground Penetrating Radar (GPR) and Falling Weight Deflectometer (FWD) testing for structural characterization and validation. A three-stage constitutive model was developed to estimate pavement resilient modulus under freeze–thaw conditions, capturing unfrozen behavior, frozen stiffness enhancement, and thaw-induced weakening and recovery. The model was validated against FWD measurements and WisDOT decision dates; the composite pavement modulus rises to about 2.8 to 4.8 times the summer baseline under frozen conditions and falls 30 to 40 percent below that baseline during spring thaw. A complementary data-driven model (Vib-Net) enables real-time stiffness estimation using a single accelerometer with high predictive accuracy. These developments were integrated into a web-based decision support system (WiSWR), which uses real-time data from 81 Road Weather Information System (RWIS) stations to provide zone-based SWR recommendations. The results demonstrate that integrating field data, modeling, and decision support tools can significantly improve the accuracy and practicality of SWR decision-making in Wisconsin.

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Executive Summary

Background

Seasonal Weight Restrictions (SWR) are essential for protecting pavement infrastructure in cold regions during spring thaw periods. During winter, frozen moisture increases pavement stiffness and load-bearing capacity. In spring, thawing leads to elevated moisture and reduced drainage, plus potentially larger voids due to expansion during freezing and contraction during thawing, causing a temporary loss of strength and stiffness in pavement and subgrade layers. Under these conditions, pavements can lose more than 50% of their bearing capacity and more than 40% of the stiffness, making them highly vulnerable to damage from heavy vehicle loads.

In Wisconsin, SWR affects approximately 12% of the state highway system and a larger portion of local roads. The timing of SWR is therefore critical. Early implementation can impose unnecessary economic burdens on freight movement, while delayed implementation can result in pavement damage and increased maintenance costs.

Current SWR practices are based on fixed dates, field observations, or simplified indices derived from temperature data. While these approaches are practical, they often lack accuracy, fail to reflect local pavement conditions, and do not fully use available data from monitoring systems such as the Road Weather Information System (RWIS).

Objectives

The objective of this project was to develop a data-driven and implementable framework for SWR decision-making in Wisconsin. The project focused on

1. Improving the understanding of seasonal variations in pavement temperature, moisture, and stiffness,
2. Developing methods to estimate pavement structural performance under freeze–thaw conditions,
3. Integrating field data and modeling into a practical decision-making framework,
4. Delivering a system that supports real-time SWR decisions.

Approach

The project combined field monitoring, modeling, and system development into a unified framework.

Field Monitoring

Eight monitoring stations were deployed across Wisconsin to capture regional variations in pavement behavior. Five of them (Iron, Florence, Oneida, Trempealeau, and Dodge), spanning the four instrumented freeze–thaw zones (Zones 1 through 4), returned complete winter records and form the analyzed dataset. Each site was instrumented with temperature and moisture sensors, and selected sites included accelerometers for vibration monitoring. These systems were integrated with existing RWIS infrastructure to enable continuous data collection.

Field characterization was conducted using Ground Penetrating Radar (GPR) to determine pavement layer structure and Falling Weight Deflectometer (FWD) testing to measure pavement stiffness. These measurements provided a basis for model calibration and validation.

Physics-Based Modeling

A three-stage constitutive modeling framework was developed to estimate pavement resilient modulus under freeze–thaw conditions:
Stage 1: Unfrozen behavior based on stress-dependent relationships with moisture correction
Stage 2: Frozen behavior representing stiffness increase due to ice bonding
Stage 3: Thaw weakening and recovery

The model was calibrated with field FWD measurements and validated against WisDOT SWR and Frozen Roads Declaration dates. Results indicate that the composite pavement modulus rises to about 2.8 to 4.8 times the summer baseline during frozen conditions and falls 30 to 40 percent below that baseline during spring thaw, with the subgrade modulus at the 2.0 ft sensing depth dropping to about 40 percent of its summer value.

Data-Driven Modeling

A data-driven model (Vib-Net) was developed to estimate pavement stiffness using vibration

signals from a single accelerometer combined with temperature data. This approach enables continuous and scalable monitoring without the need for frequent field testing. The model achieved strong predictive performance with high correlation to field-based stiffness estimates.

Decision Support System

The research outcomes were integrated into a web-based decision support system, WiSWR (the Wisconsin Smart Weight Restriction website, wiswr.org). The system uses real-time data from 81 RWIS stations and provides:

- Zone-based SWR recommendations across WisDOT's five administrative climate zones (anchored by field stations in the four instrumented zones: Zone 1 Iron/Florence, Zone 2 Oneida, Zone 3 Trempealeau, and Zone 4 Dodge),
- Current and historical weather information (RWIS),
- Pavement stiffness (resilient modulus) variations,
- Road condition forecast including road weather conditions and SWR actions,
- Information and data about field instrumentation.
- A Large Language Model (LLM) agent is deployed on every web page (service) to assist with the use of the tool.

The system is designed to support transportation engineers and decision-makers in implementing SWR more effectively.

Key Findings

The following are the key findings.

- Pavement stiffness varies significantly during freeze–thaw cycles, with substantial reductions during spring thaw.
- Field monitoring combined with modeling provides a reliable basis for estimating these variations.
- The developed constitutive model captures seasonal pavement behavior and aligns with observed SWR decisions.
- Data-driven methods can provide scalable, real-time estimation of pavement conditions.

- Integration of monitoring data and models into a decision support system enables more convenient and reliable data use for guiding field practices.

Conclusions and Implementation

This project demonstrates that SWR decision-making can be significantly improved through the integration of field monitoring, physics-based modeling, and data-driven analysis. The developed framework provides a practical pathway for transitioning from calendar-based or inspection-based approaches to more automated model-based and data-driven methods.

The WiSWR system offers an immediately usable tool for implementing these advances, providing real-time, zone-based recommendations that can support more accurate and consistent SWR decisions across Wisconsin.

Recommendations

The following are recommendations for future research:

- Expand monitoring to additional locations to improve spatial coverage,
- Integrate the framework with existing WisDOT operational systems,
- Continue validation across multiple seasons,
- Further develop data-driven models for enhanced prediction capability.

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Chapter 1 Introduction

1.1 Background

Seasonal Weight Restrictions (SWR), also referred to as Spring Load Restrictions (SLR), are widely implemented in cold regions to protect pavement infrastructure during freeze–thaw cycles. The mechanical response of pavement systems is strongly influenced by temperature-dependent phase changes of pore water in pavement layers and subgrade soils. During winter, freezing of pore water and ice bonding between soil particles increases stiffness and bearing capacity (Baïz et al., 2008; Konrad and Morgenstern, 1982; Liu and Yu, 2011). In contrast, during the spring thaw, melting ice leads to elevated water content and reduced drainage, which results in a temporary loss of strength and stiffness in the pavement system (Simonsen and Isacsson, 1999; Shoop et al., 2008).

A key mechanism during thaw is the formation of a saturated layer above still-frozen soil. Because the underlying frozen layer remains relatively impermeable, meltwater is trapped within the thawed zone. As a result, pore water pressure increases and soil shear strength decreases under traffic loading. This process, commonly referred to as thaw weakening, can significantly reduce pavement support capacity and increase susceptibility to rutting, cracking, and long-term structural damage (Doré, 2004; Janoo and Shoop, 2004). Pavements can lose more than 50% of their bearing capacity and more than 40% of the stiffness during this period, with even larger reductions observed in gravel roads and thin pavement structures (Isotalo, 1993; Marquis, 2008). The impact of freeze–thaw cycles on pavement performance is substantial. It has been reported that approximately 60% of annual pavement distress occurs during the spring thaw period, despite accounting for a smaller portion of annual traffic loading (White and Coree, 1990). These effects translate into significant economic costs associated with maintenance, rehabilitation, and operational disruptions.

To mitigate these impacts, transportation agencies implement SWR policies that temporarily reduce individual axle loads and the total gross vehicle weight during periods of reduced pavement capacity. The effectiveness of SWR depends critically on accurately identifying both the onset and duration of the thaw-weakened period. When a winter premium or an increased allowable axle

load is intended, the dates of the frozen period also need to be accurately determined. Premature restrictions can impose unnecessary economic burdens on freight movement, whereas delayed restrictions can lead to irreversible pavement damage (Levinson et al., 2005).

In Wisconsin, SWR is applied to approximately 12% of the state highway system and a larger portion of local roads. SWR is typically implemented between early March and May, although the exact timing varies from year to year depending on weather conditions. The need to balance infrastructure protection with economic activity makes SWR decision-making a critical operational issue for the Wisconsin Department of Transportation (WisDOT).

1.2 Current Practice

SWR practices have evolved over decades and are widely used across the United States, Canada, and other cold-region countries. These practices can generally be categorized into three groups: (1) fixed-date approaches, (2) observational methods, and (3) quantitative methods.

Fixed-date approaches rely on historical averages and predetermined schedules to impose and remove restrictions. While simple and easy to implement, these methods do not account for year-to-year variability in weather conditions.

Observational methods are based on field indicators such as water seeping from pavement cracks, rutting, or general visual assessment of pavement conditions. Although these methods reflect actual field conditions, they are labor-intensive, subjective, and often reactive rather than predictive.

Quantitative methods incorporate measurements and models to estimate pavement conditions more systematically. These include frost depth monitoring (for example, frost tubes, which are widely used in Wisconsin to measure frost penetration depth), temperature measurements, moisture sensing, deflection-based testing using Falling Weight Deflectometer (FWD), freezing/thawing indices, and mechanistic pavement models (Kestler et al., 2007; Bao et al., 2019; Bao et al., 2021).

These categories are illustrated conceptually in **Figure 1-1**.

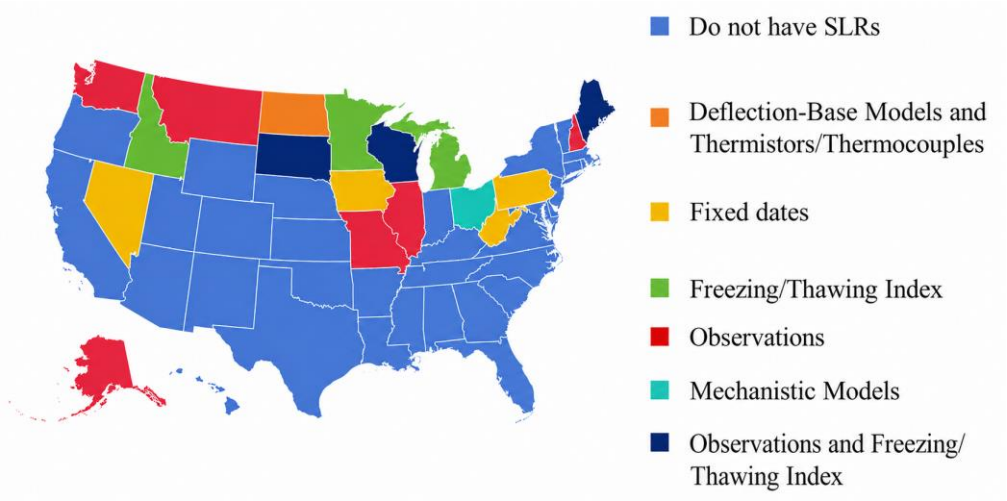


Figure 1-1 Seasonal weight restriction practices in the U.S.

In practice, many transportation agencies still rely on fixed dates and observational approaches. A survey of state Departments of Transportation (DOTs) showed that a majority of agencies use labor-intensive inspections or calendar-based methods, with fewer agencies adopting fully quantitative approaches (Kestler et al., 1998; Kestler et al., 2007).

Recent efforts have introduced more advanced, data-driven approaches. These include models developed by FHWA-WSDOT, MnDOT (Van Deusen et al., 1998), and other agencies that incorporate temperature indices and field measurements. More recent systems integrate real-time data and web-based platforms to support decision-making.

Recent state-level deployments also include the Michigan Department of Transportation temperature-based model, which was operationalized as an in-service tool in 2021 to time SLR posting and lifting decisions across the Michigan trunk-line network (MDOT, 2021). The Michigan effort and similar real-time, web-based state systems are reviewed in the recent literature on seasonal load restriction practice and provide precedent for the integrated approach pursued in this study.

Table 1-1 Comparison of models based on the freezing/thawing index

Model	Key Feature	Calculation Basis	Advantages	Disadvantages
FHWA-WSDOT	Quantitative SLR decision based on freezing/thawing indices	Air temperature	Straightforward, uses widely available air temperature data	Limited by availability of deflection measurement equipment
MnDOT	Adapts reference temperature to current weather conditions	Actual and forecasted air temperature with dynamic reference temperature	More accurate start dates for SLR, accounts for solar gain	Fixed duration of SLR may not be suitable for all conditions
MDOT	Web-based tool, operational statewide since 2021, that times SLR posting and lifting	Indices computed from RWIS data to obtain freezing and thawing depths for decision support	Real-time, automated, statewide deployment; validated against field frost observations	Requires a statewide sensing network (RWIS, frost tubes)
MIT	National model in Canada, adapts to climate change	Pavement strength with FWD correlated with CTI	Considers changing climate, uses FWD for pavement strength	Requires FWD for pavement strength assessment
SDDOT	Simple model based on min and max air temperatures	Minimum and maximum air temperatures	Effective for identifying thaw periods, simple to use	May not be as accurate without calibration

USDA-NHDOT	Estimates pavement temperature from air temperature using Summer and Winter n-factors	Air temperature with sinusoidal adjustments	Accurate for determining SLR start dates, includes sinusoidal temperature adjustments	Modified Berggren equation may be less accurate than other models for SLR removal

1.3 Limitations of Current Practices

Despite these advancements, current SWR practices still face several important limitations.

First, pavement structure and material behavior are not adequately considered. Many methods rely on simplified indicators such as thaw depth or air temperature without explicitly considering the mechanical response of pavement systems. In particular, the variation of stiffness and strength within pavement layers is not directly captured.

Second, local adaptation is often limited. Many models are developed for specific regions and applied elsewhere without sufficient calibration. Differences in climate, soil type, pavement structure, and drainage conditions can lead to significant discrepancies in predicted versus actual pavement behavior.

Third, available data are not fully utilized. State DOTs have developed extensive monitoring infrastructure, including Road Weather Information Systems (RWIS), but SWR decisions often rely primarily on the air temperature or limited field observations rather than integrating multiple data sources.

Fourth, there is a lack of representative subsurface measurements. Many measurements are collected at locations that do not accurately represent pavement conditions, such as off-road temperature sensors or shallow measurements that do not capture the full pavement structure.

Finally, monitoring, modeling, and decision-making are often not integrated into a unified framework. While each component has advanced individually, the lack of integration limits their effectiveness in operational decision-making.

1.4 Research Needs

Beyond the five needs above, two additional needs identified during this project should inform future work.

- Use of low-cost vibration sensing as a network-extension layer for stiffness estimation, so that the small set of FWD-anchored sites can be extended to a much larger network without commissioning new FWD campaigns at every location.
- A single web-based interface that lets the regional engineer reach the stiffness-based view, the Frozen Road Declaration (FRD), Seasonal Weight Restriction (SWR), and Normal Operations (NRM) categories, and the underlying RWIS data through one channel rather than separate spreadsheets, file shares, and email threads.

The limitations described above highlight the need for a more comprehensive approach to SWR decision-making. Such an approach should integrate field measurements, mechanistic understanding, and data analysis to provide accurate, site-specific, and actionable information.

Key research needs include the following:

1. Direct measurement of pavement and subgrade conditions, including temperature and moisture variations with depth, for roads that need/represent SWR practice,
2. Translation of field measurements into engineering parameters such as pavement stiffness and bearing capacity,
3. Consideration of site-specific conditions and regional variability,
4. Use of available data infrastructure such as RWIS for more robust and reliable SWR decision support tool deployment,
5. Integration of monitoring, modeling, and decision-making into a unified framework.

Advances in sensing technologies, data analytics, and computational modeling provide opportunities to address the above needs. Low-cost sensors enable continuous monitoring, while physics-based and data-driven models allow interpretation of these data. Also, web-based systems provide a pathway for implementation in real-world operations.

1.5 Overview of This Study and Report Organization

This project addresses the identified needs by developing an integrated framework for SWR decision-making in Wisconsin. The framework combines field monitoring, physics-based modeling, data-driven analysis, and decision support implementation.

The overall workflow of the study is illustrated in **Figure 1-2**. As shown, the key components of the framework include

- Field monitoring systems to collect temperature, moisture, and vibration data,
- Physics-based models to estimate pavement stiffness under freeze–thaw conditions,
- Data-driven models to enable scalable and real-time estimation,
- A web-based decision support system to provide actionable information.

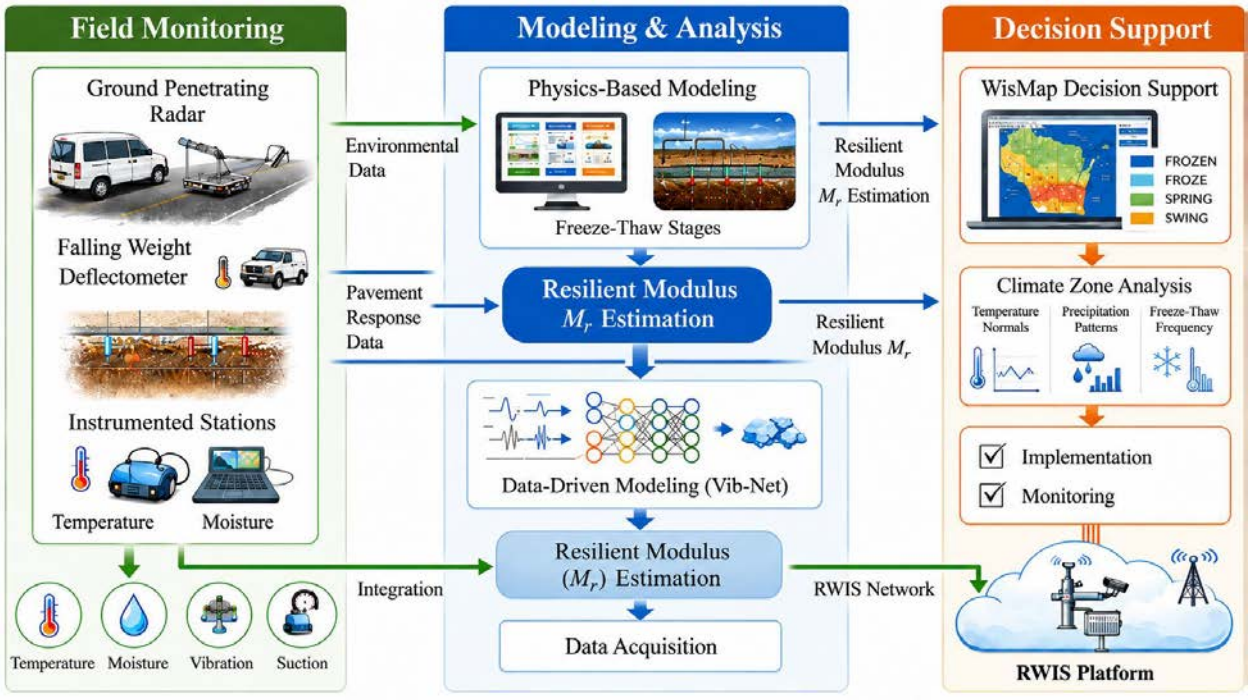


Figure 1-2 Overall framework of the study

These components have been integrated in this project to translate raw field data into SWR recommendations that can be used in practice.

The remainder of this project report is organized as follows.

- Chapter 2 introduces the field monitoring program and data collection.
- Chapter 3 presents the physics-based modeling framework and validation.
- Chapter 4 summarizes the data-driven modeling approach.
- Chapter 5 delivers the WiSWR decision support system.
- Chapter 6 shares conclusions and recommendations for implementation.

Chapter 2 Field Monitoring Program and Data Collection

2.1 Overview

A comprehensive field monitoring program was established to characterize seasonal variations in pavement conditions across Wisconsin. The primary objective was to directly measure temperature, moisture, and mechanical response within pavement structures and subgrade soils, and to provide high-quality data for model development and validation.

A total of eight monitoring stations were deployed across Wisconsin to capture regional variability in climate, soil conditions, and pavement structures. These sites were selected to represent different geographic regions, environmental conditions, and road types relevant to SWR decision-making. Among these, the Theresa site in Dodge County is presented as a representative example for detailed discussion in this report.

The eight stations were installed over a two-week field campaign, with traffic control in place at each roadside site to protect the crew and the traveling public. The network was designed to operate for at least two years so that it would span several full freeze–thaw cycles under a range of winter conditions. **Figure 2-1** maps the network, and **Table 2-1** lists every site with its county, WisDOT Transportation Region, and Frozen-Road zone. The sites cover three WisDOT Transportation Regions (North Central, Northwest, and Southwest) and four of the five Frozen-Road zones used in the state's seasonal weight-restriction program; the far-southern Zone 5 has no instrumented site. Five of the eight stations (Iron, Oneida, Trempealeau, Dodge, and Florence) returned continuous records through the 2024–2025 winter and form the basis of the analyses that follow, while the loggers at Price, Barron, and Wood did not return usable data.

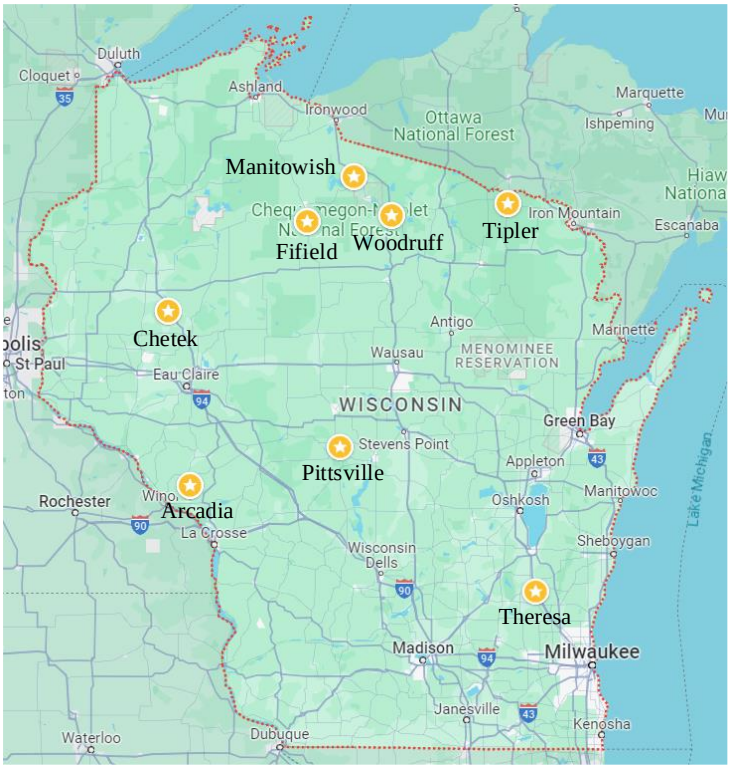


Figure 2-1 Field instrumentation sites across Wisconsin

Table 2-1 Station information for the eight field instrumentation sites: city, county, WisDOT Transportation Region, and Frozen-Road zone.

Site	City / township	County	WisDOT Region	Frozen-Road zone
1	Manitowish	Iron	North Central	Zone 1 (Northern)
2	Woodruff	Oneida	North Central	Zone 2 (North Central)
3	Fifield	Price	North Central	Zone 1 (Northern)
4	Chetek	Barron	Northwest	Zone 2 (North Central)
5	Arcadia	Trempealeau	Northwest	Zone 3 (Central)
6	Pittsville	Wood	North Central	Zone 3 (Central)
7	Theresa	Dodge	Southwest	Zone 4 (South Central)
8	Tipler	Florence	North Central	Zone 1 (Northern)

The monitoring program was designed to address key limitations identified in current SWR practices, particularly the lack of subsurface data and the limited ability to relate environmental conditions to pavement structural performance.

2.2 Site Characterization

Each monitoring site was characterized using a combination of non-destructive testing and field measurements to establish baseline pavement structure and material properties as illustrated in **Figure 2-2**.



Figure 2-2 Field truck configured for pavement testing: (a) air-coupled GPR on the front and FWD on the rear, (b) front-mounted air-coupled GPR system with orange horn antenna used for continuous asphalt-layer thickness mapping, (c) rear view showing the FWD mounting and sensor beam, (d) close-up of the FWD geophone beam and load-plate assembly used to capture deflection basins.

As shown in **Figure 2-3**, at the Theresa site, Ground Penetrating Radar (GPR) testing was conducted to determine pavement layer thicknesses and structural interfaces. The results identified a two-layer system consisting of a Hot Mix Asphalt (HMA) surface layer over an aggregate base, with clear reflection interfaces at approximately 3.9 inches and 13.0 inches depth.

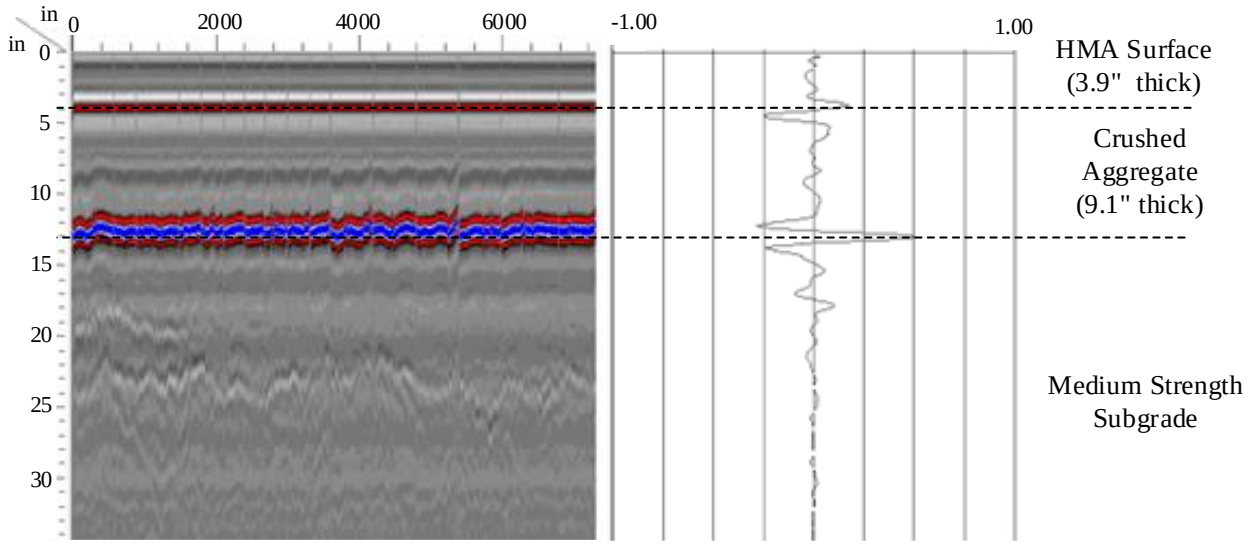
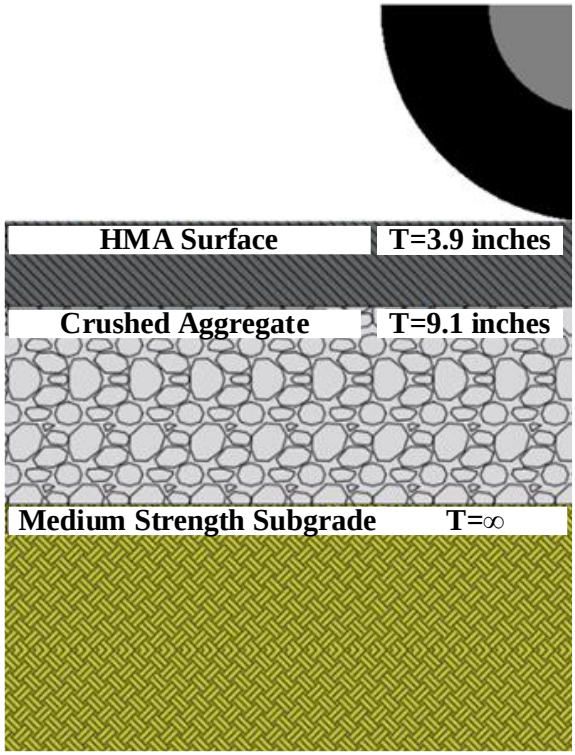


Figure 2-3 GPR profile showing two-layer pavement structure with reflection interfaces at 3.9" and 13.0" depth

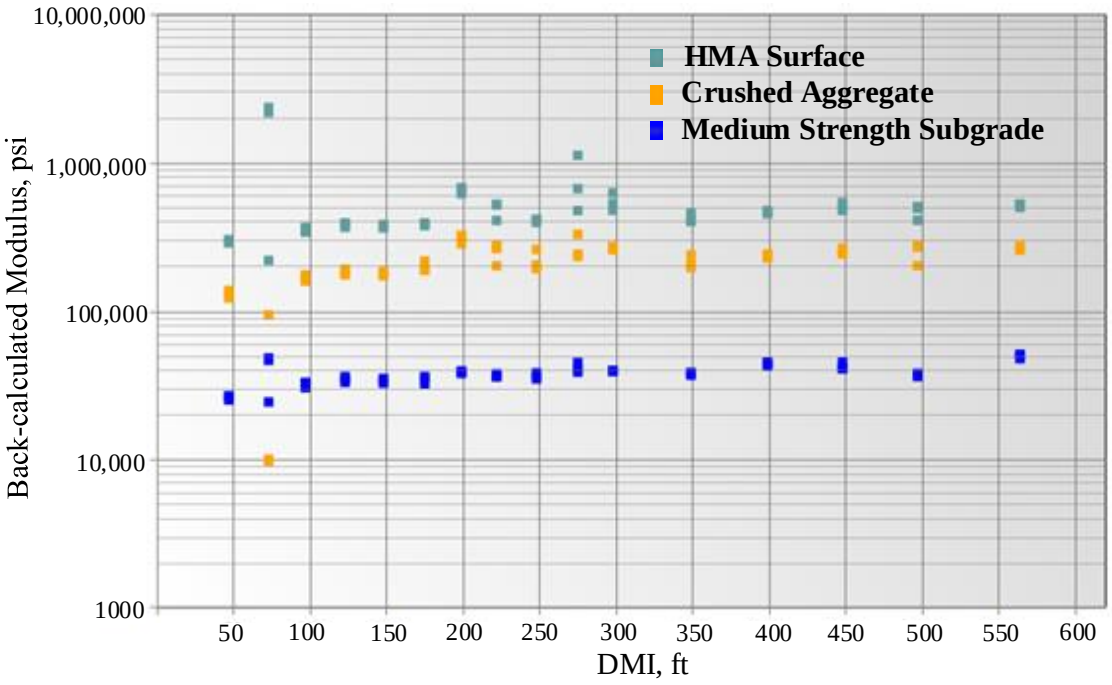
FWD testing was performed to evaluate pavement structural capacity. The FWD data, combined with GPR-derived layer thicknesses, were used for backcalculation of layer moduli with the ELMOD program (Dynatest) and for calibration of the modeling framework.

Testing was conducted using multiple load levels, and surface deflections were recorded using geophones positioned at varying radial distances from the load plate. Specifically, deflection sensors D1 through D6 were spaced at offsets of 12, 24, 36, 48, 60, and 72 inches from the center of the loading plate (behind), respectively, while deflection sensors D7 and D8 were positioned on the other two sides (left and front), both at a distance of 12 inches from the center of the plate. The drops closest to the standard 9,000 lbf target load were used for the backcalculation.

These field characterization efforts provided essential inputs for both physics-based modeling and validation of monitoring-based predictions as presented in **Figure 2-4** and **Table 2-2**.



(a)



(b)

Figure 2-4 FWD results: (a) calculation profile and (b) back-calculated (elastic) layer moduli

Table 2-2 Layer modulus results from FWD

Layer	Material Type	Back-calculated Modulus (psi)	Back-calculated Modulus (MPa)	Poisson's Ratio	Thickness (in)	Thickness (ft)
1	HMA Surface	536,826	3,702	0.35	3.90	0.325
2	Crushed Aggregate	214,301	1,477	0.35	9.10	0.758
3	Medium Strength Subgrade	37,897	261	0.44	∞	∞

2.3 Instrumentation and Sensor Deployment

Each monitoring station was instrumented to capture continuous measurements of temperature and moisture within the pavement structure and subgrade. The system was installed in a drilled borehole 10 ft deep and 4 in in diameter, backfilled after installation to restore near in-situ conditions. It comprised 13 temperature sensors distributed vertically to capture thermal gradients and freeze-front propagation, and 3 TEROS 11 sensors measuring soil moisture and temperature at key depths. Accelerometers (MPU 6050) and suction sensors (TEROS 21) were also deployed.

Temperature sensors (DS18B20, 1-wire digital temperature sensor) were installed at multiple depths within the pavement and subgrade to capture thermal gradients and freeze–thaw progression. At each selected site, a total of 13 temperature sensors were deployed along a vertical profile extending through the pavement layers and into the subgrade. They are installed starting 6 inches below the ground surface with a spacing of 6 inches between neighboring sensors. These sensors provided continuous measurements of temperature variation with depth, enabling identification of freezing and thawing fronts over time.

Figure 2-5 presents the monitored subsurface temperature and volumetric water content at 0.5, 2.0, and 5.0 ft for the instrumented station-winters. The temperature records show the same seasonal pattern at every site: the 0.5 ft trace crosses the freezing point in December or January, stays near or below 0 °C through late February, and rebounds in late March, while the 5.0 ft trace lags the shallower depths and rarely freezes. The water-content records mirror this thermal signal.

Where a sensing depth freezes, the apparent liquid water content drops sharply because pore water turns to ice, and it recovers just as sharply when the thaw front passes. The northern sites (Sites 1, 2, and 8) show the deepest and longest-lasting freeze signatures, and the southernmost site (Site 7) shows the shortest, which is consistent with the WisDOT zone structure used in Chapter 5. **Figure 2-6** tracks this freeze-thaw progression at each site, showing the frost-penetration and thaw fronts together with the WisDOT Frozen-road and Class-II windows.

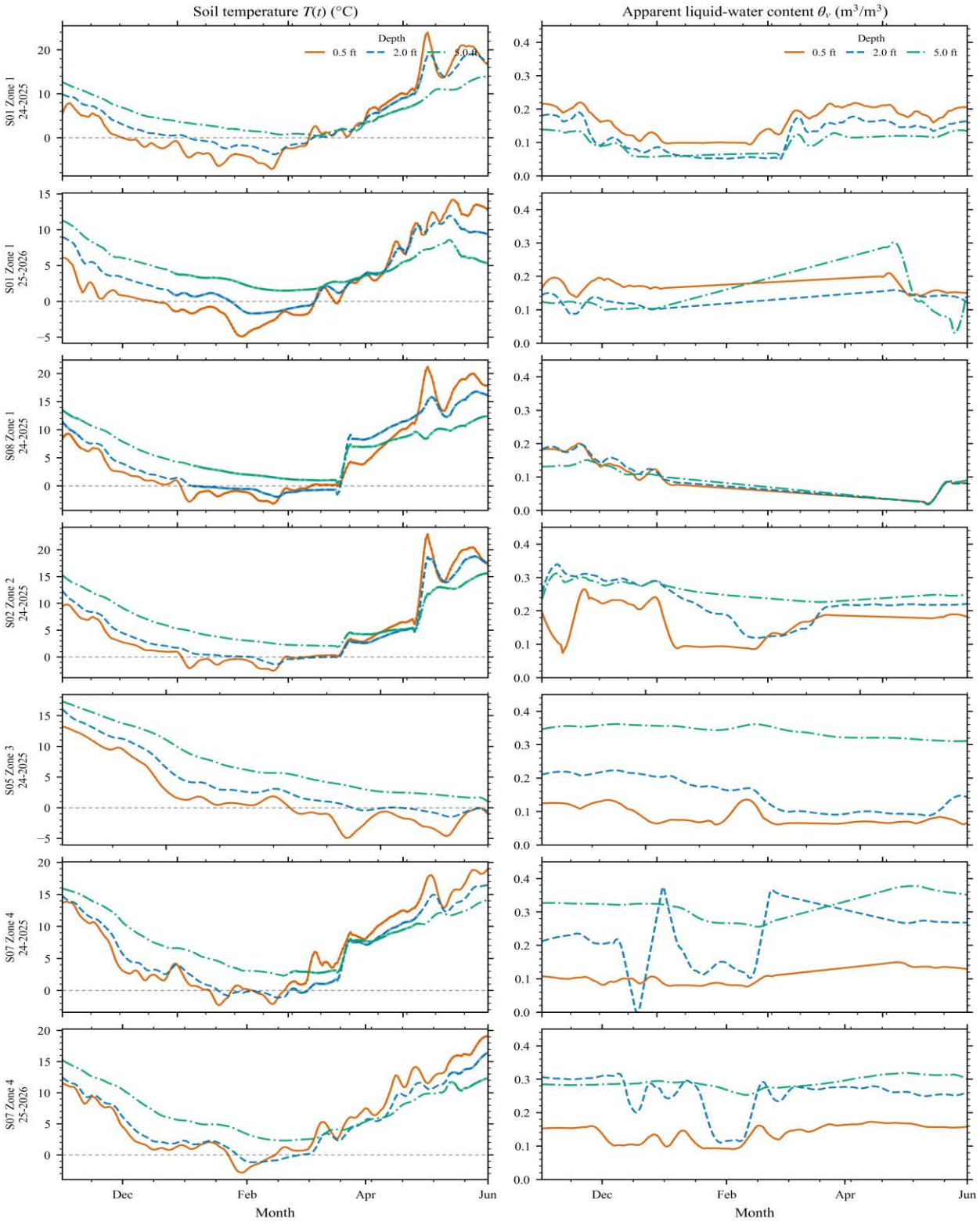


Figure 2-5 Monitored subsurface temperature (left) and volumetric water content (right) at 0.5, 2.0, and 5.0 ft for the instrumented station-winters

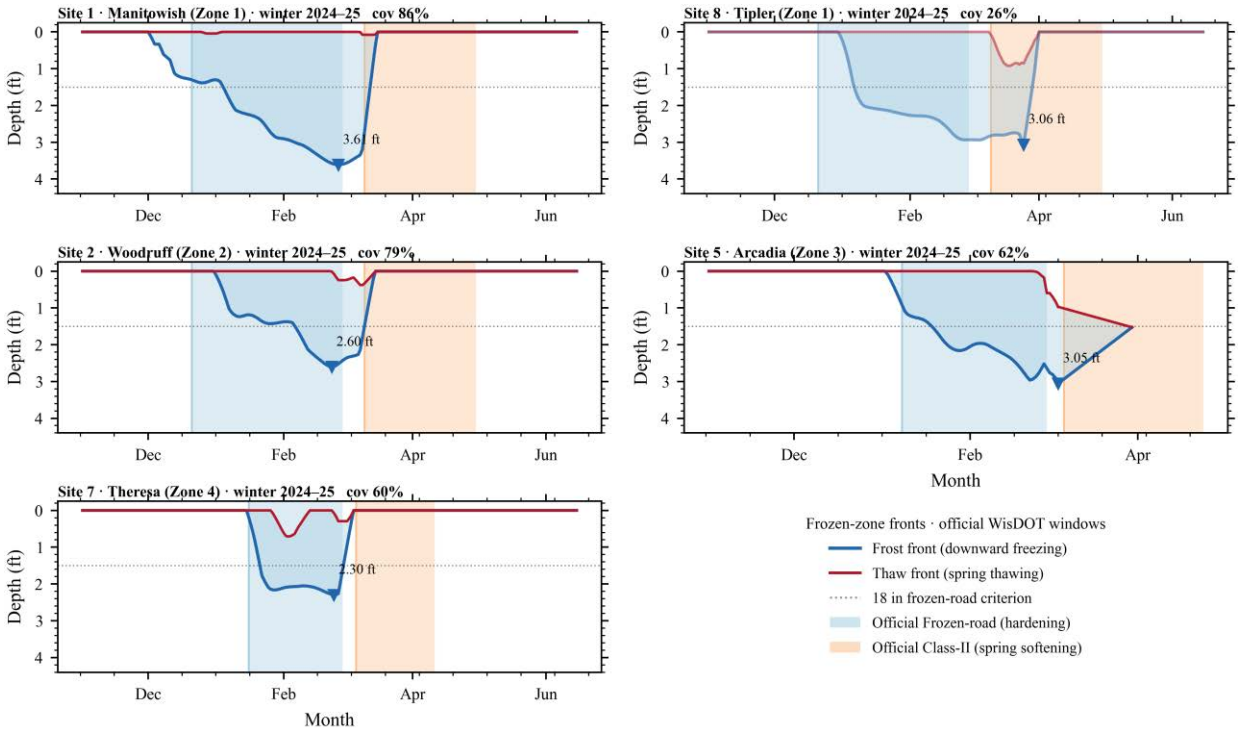


Figure 2-6 Subsurface freeze–thaw progression at the instrumented sites (Zones 1–4): the frost-penetration and thaw fronts from the multi-depth temperature profiles, with the WisDOT Frozen-road and Class-II windows

Soil moisture conditions were monitored using capacitive sensors installed at selected depths. Three moisture sensors were deployed within the subgrade to capture variations in volumetric water content associated with freeze–thaw cycles. Typical monitored soil moisture variations, together with the corresponding matric suction, are shown in **Figure 2-7**. These measurements are critical for understanding thaw weakening, as moisture accumulation and drainage conditions directly influence soil strength and pavement support. Matric suction is the tension that holds water in the soil pores: it is high when the subgrade is dry or frozen and the water is held tightly, and it drops sharply when spring meltwater saturates the soil. Because the soil loses strength as this tension collapses, the suction record marks the thaw-weakening period directly and complements the water-content measurements.

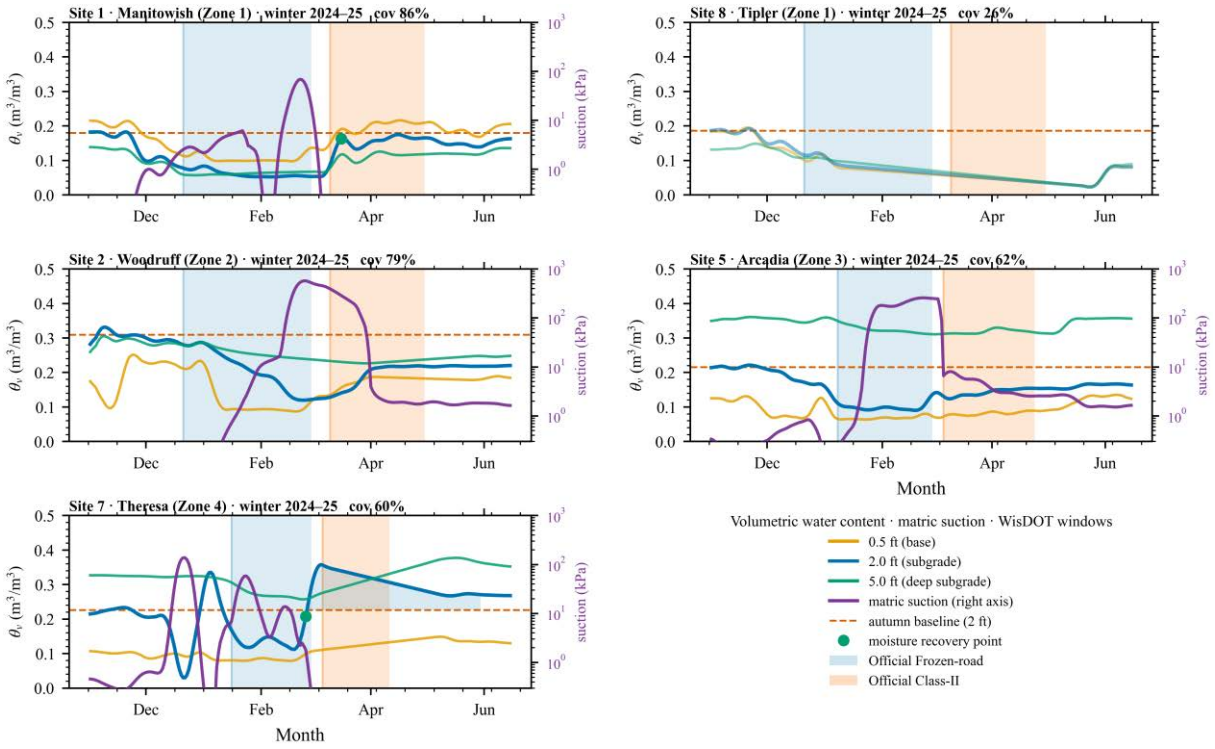


Figure 2-7 Volumetric water content at 0.5, 2.0, and 5.0 ft and matric suction (log scale, right axis) at the instrumented sites (Zones 1–4), with the official WisDOT windows. Spring meltwater raises the water content above the autumn baseline before recovery

Vibration Measurement

At the eight selected monitoring sites, accelerometers (MPU 6050) were installed on the pavement surface to measure vibration responses induced by passing vehicles. These data were used to support the development of data-driven models for estimating pavement stiffness. **Figure 2-8** presents typical acceleration data in both the time and frequency domain.

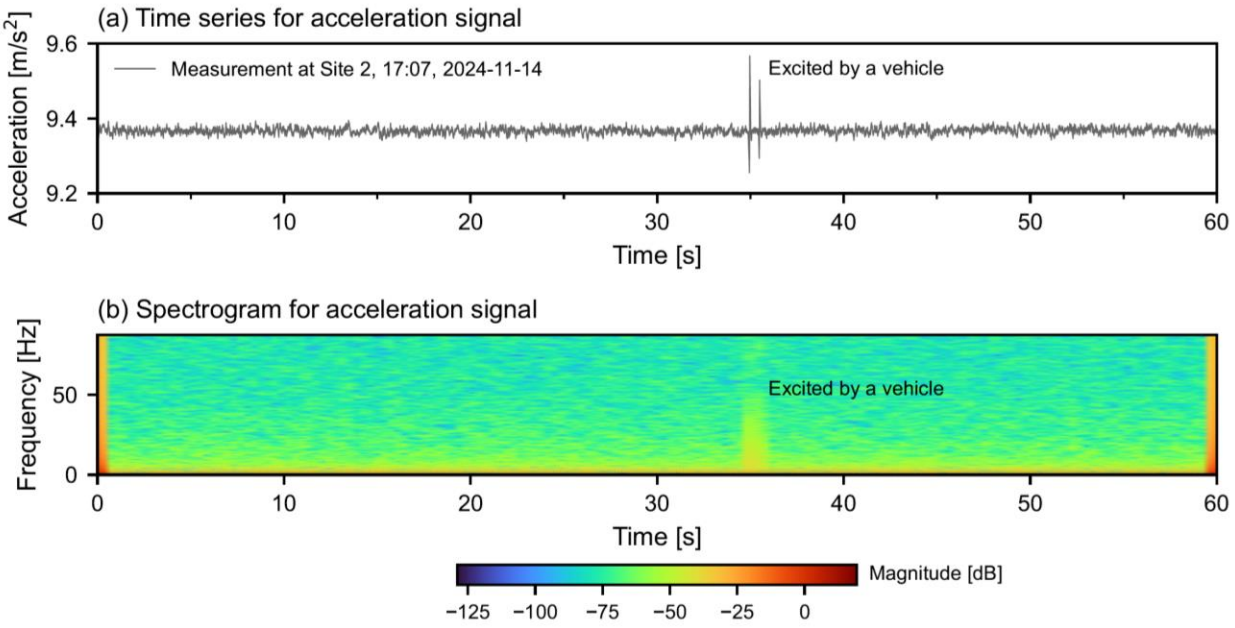


Figure 2-8 Example of acceleration data in (a) the time domain and (b) the frequency domain

Installation Configuration

Sensors were installed within a borehole extending approximately 6 to 6.5 feet below the pavement surface. Temperature sensors were distributed along the full depth, while moisture sensors were placed at representative depths within the subgrade.

This configuration enables continuous monitoring of thermal and hydraulic conditions that govern freeze–thaw processes. **Figure 2-9** provides details for the setup and installation of the sensors.

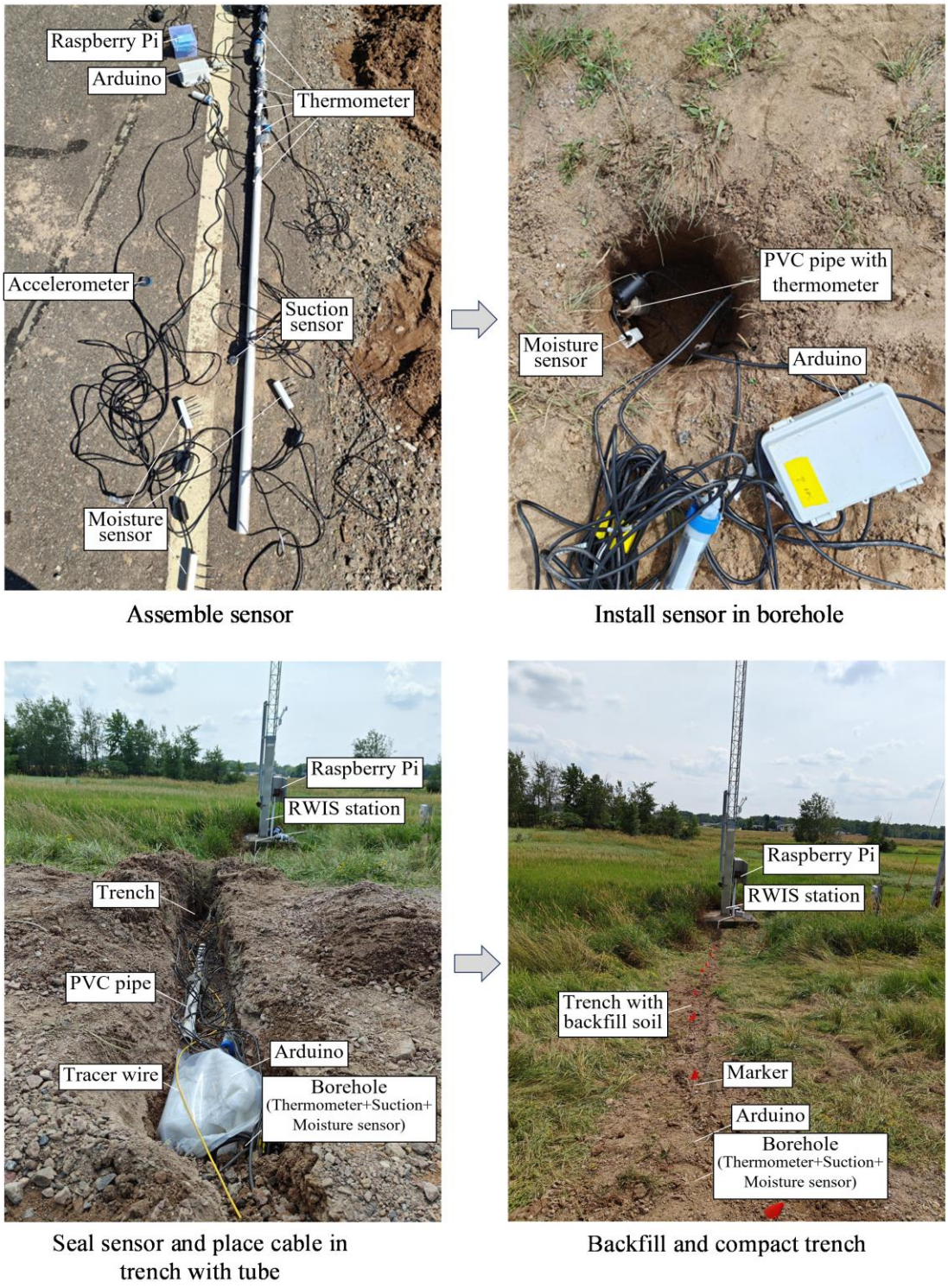


Figure 2-9 Sensor setup and installation

2.4 Data Acquisition System

The monitoring system was designed to provide reliable, continuous data collection using a combination of low-cost hardware and existing infrastructure as shown in **Figure 2-10**.

The data acquisition system consists of two main components:

- Sensor Interface and Data Logging: Sensors were connected to an Arduino-based data logger, which collected and formatted measurements into structured data packets.

- Data Processing and Transmission: A Raspberry Pi system was used for data storage, processing, and transmission. The Raspberry Pi received data from the data logger, stored it locally, and uploaded it to a cloud-based platform.

Power supply and internet connectivity were provided through integration with nearby RWIS stations maintained by WisDOT. This integration significantly reduced deployment complexity and improved system reliability.

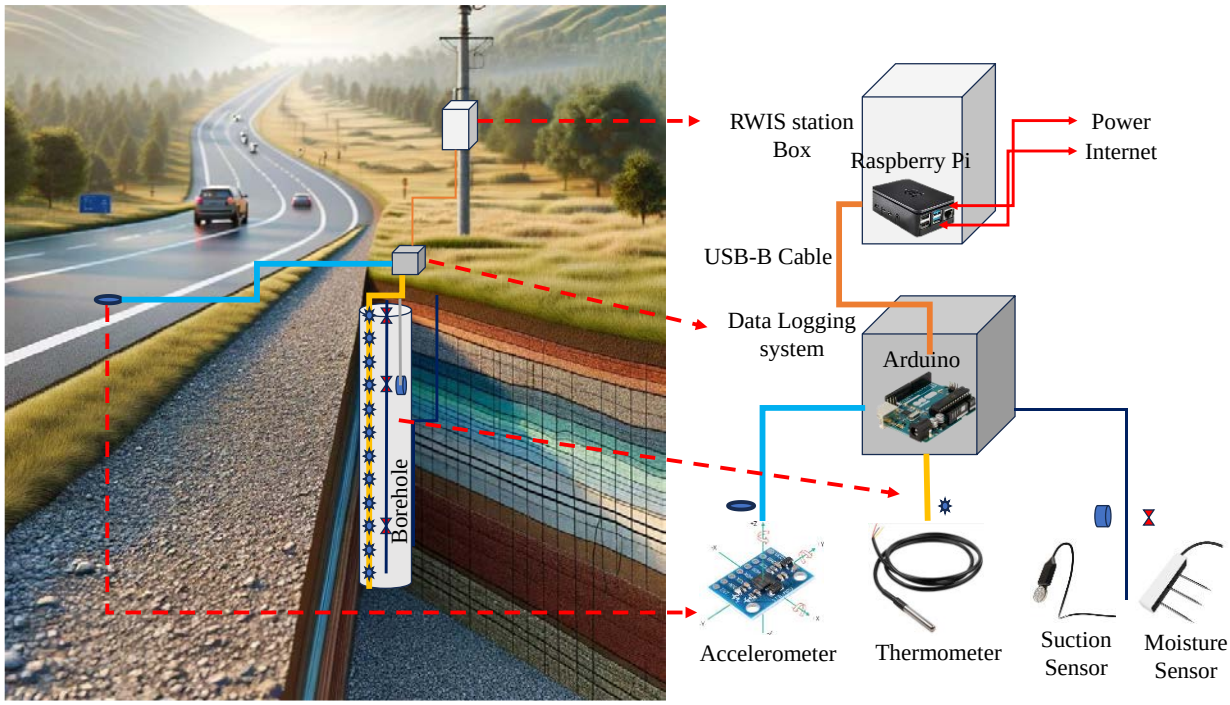


Figure 2-10 Data acquisition system architecture (Arduino + Raspberry Pi + RWIS)

The system was designed with fault tolerance in mind. Data acquisition and transmission were separated into independent subsystems, ensuring that temporary network interruptions did not disrupt sensor data collection.

2.5 Data Collection and Characteristics

The monitoring system collected multiple types of data at regular intervals including:

- Temperature profiles at multiple depths (starting at 6 inches below ground surface at the interval of 6 inches),
- Volumetric water content at three depths (0.5 ft, 2.0 ft, and 5.0 ft),
- Surface vibration signals (pavement surface).

Temperature and moisture measurements were typically recorded at intervals of approximately 15 minutes, providing high temporal resolution for tracking freeze–thaw processes. Vibration data were collected periodically at higher sampling frequencies (200 Hz) to capture dynamic responses.

The resulting dataset captures the full seasonal evolution of pavement conditions, including:

- Freeze progression during winter
- Onset of thaw and formation of saturated layers
- Peak thaw weakening conditions
- Gradual recovery during late spring

These data provide a direct basis for analyzing the relationship between environmental conditions and pavement structural performance.

2.6 Role of Field Data in This Study

The field monitoring program plays a central role in the overall research framework. Specifically, the collected data are used to

1. Characterize seasonal variations in pavement temperature and moisture

2. Identify critical conditions associated with thaw weakening
3. Provide input variables for physics-based modeling
4. Support validation of model predictions using independent field measurements (e.g., FWD)
5. Enable development of data-driven models for real-time estimation

By providing continuous, in-situ measurements, the monitoring system bridges the gap between environmental conditions and pavement performance. This capability is essential for developing reliable, data-driven approaches to SWR decision-making.

Chapter 3 Physics-Based Modeling of Pavement Behavior

3.1 Overview

Field monitoring provides continuous measurements of temperature and moisture; however, SWR decision-making requires translating these environmental variables into engineering parameters such as pavement stiffness and load-bearing capacity. To achieve this, a physics-based modeling framework was developed to estimate the resilient modulus of pavement layers throughout freeze–thaw cycles. The framework integrates field measurements with constitutive relationships that describe material behavior under unfrozen, frozen, and thawing conditions. Similar multi-stage approaches have been explored in previous studies on frozen soils and pavement systems, where temperature-dependent stiffness variation plays a critical role (Simonsen et al., 2002; Lu et al., 2025; Yu et al., 2024). The framework was structured as a three-stage formulation that captures the seasonal evolution of pavement behavior, with the freeze–thaw stages identified from the field data shown in **Figure 3-1**.

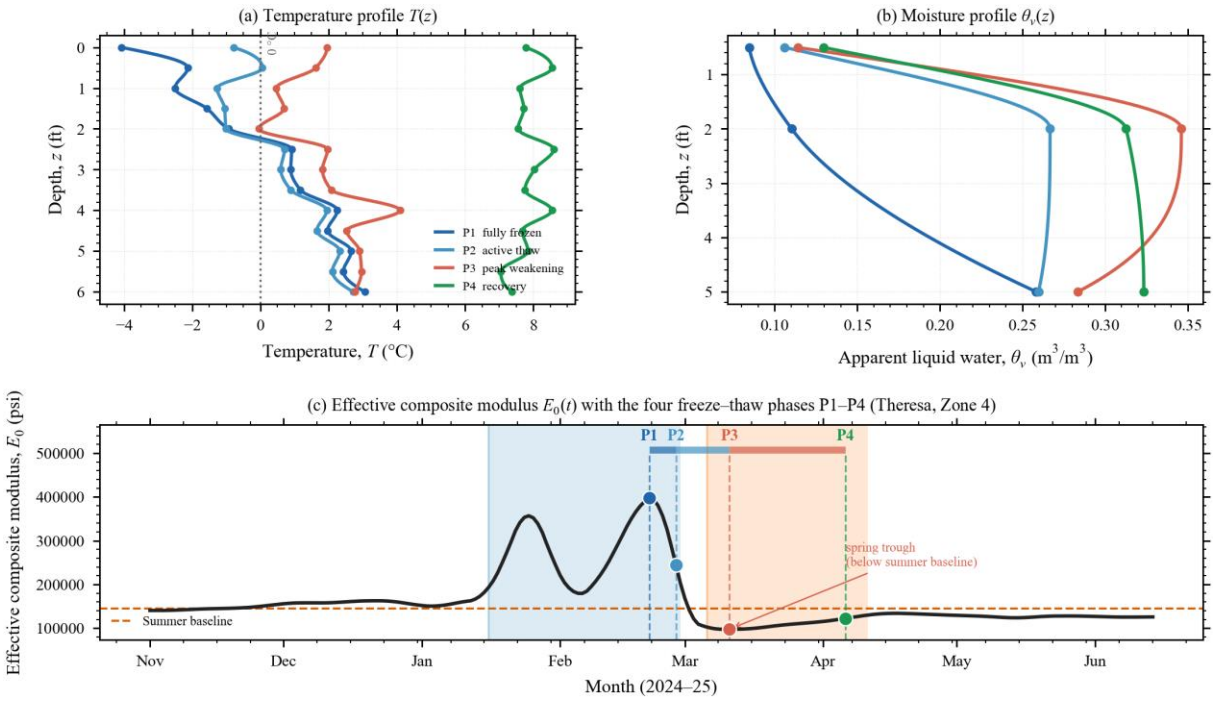


Figure 3-1 Freeze–thaw stage identification at the Theresa site (Zone 4): representative-day (a) temperature and (b) liquid-water-content profiles, and (c) the seasonal effective composite modulus E_0 through the four freeze–thaw phases (P1–P4)

In **Figure 3-1**, the two upper panels show representative-day temperature and liquid-water profiles, and the lower panel tracks the effective composite modulus E_0 of the pavement structure through one freeze–thaw cycle. Four critical phases are marked on the E_0 curve: P1 is the fully frozen peak, P2 is the active thaw as the frost front retreats, P3 is the peak-weakening trough that falls below the summer baseline, and P4 is the recovery back toward that baseline. These four phases are the observable expression of the three constitutive stages described below: Stage II produces P1, and Stage III produces P2 through P4.

3.2 Unfrozen Condition (Stage I)

Under unfrozen conditions, the resilient modulus of pavement materials follows stress-dependent relationships consistent with the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) (NCHRP, 2004). The general form is the generalized universal model (Uzan, 1985), as follows,

$$M_r = k_1 * \left(\frac{\theta}{p_a}\right)^{k_2} * \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$$

where M_r is the resilient modulus, θ is the bulk stress, τ_{oct} is the octahedral shear stress, p_a is the atmospheric pressure, and k_1, k_2, k_3 are material parameters.

This formulation has been widely used for unbound materials in pavement design and was validated through extensive experimental studies (NCHRP, 2004; Kestler et al., 2007).

To account for moisture effects observed in field measurements, a correction factor was introduced (Witczak et al., 2000):

$$M_{r,adj} = M_r \cdot f(w)$$

where w is the volumetric water content and $f(w)$ is the moisture correction factor.

The influence of moisture on stiffness reduction has been well documented in both laboratory and field studies, where increasing saturation leads to reduced effective stress and lower resilient modulus (Simonsen and Isacsson, 1999; Shoop et al., 2008).

3.3 Frozen Condition (Stage II)

When temperature drops below the freezing point, pore water transitions into ice, forming bonds between soil particles and increasing stiffness. This phenomenon has been studied extensively in frozen soil mechanics, where ice bonding significantly enhances stiffness and strength (Konrad and Morgenstern, 1982; Simonsen et al., 2002).

The frozen modulus was expressed using the following equation:

$$M_{r,frozen} = M_{r,adj} * (1 + \alpha \cdot F(T))$$

where α is the stiffness enhancement coefficient and $F(T)$ is the freezing function ($0 \leq F \leq 1$).

A hyperbolic relationship was adopted in this study to represent gradual freezing:

$$F(T) = (T_f - T) / (T_f - T + \beta), \text{for } T < T_f$$

where T is the temperature, T_f is the freezing temperature, and β is the fitting parameter.

This type of formulation is consistent with temperature-dependent stiffness models proposed for frozen geomaterials (Si et al., 2018; Lu et al., 2025). Previous studies report that the composite pavement stiffness rises to about 3.5 to 5.9 times its summer value during frozen conditions, with the shallow base modulus increasing roughly 9 to 17 times (from about 1,000 to 1,500 MPa unfrozen to about 12,000 to 16,000 MPa frozen, i.e., from roughly 150,000–220,000 psi to 1,700,000–2,300,000 psi), depending on frost depth, soil type, and moisture content (Simonsen et al., 2002; Liu et al., 2013).

3.4 Thawing Condition (Stage III)

During thawing, ice bonds break and water accumulates within the soil, leading to reduced effective stress and significant stiffness loss. This process is associated with thaw weakening, which has been identified as the primary cause of pavement damage during spring (Doré, 2004; Janoo and Shoop, 2004).

The thawed modulus was formulated in this study as

$$M_{r,thaw} = M_{r,adj} \cdot (1 - D(T,w))$$

where $D(T,w)$ is the damage factor ($0 \leq D \leq 1$).

The freeze–thaw damage factor F_d in **Table 3-1** was calibrated to 0.75, representing a 25 percent residual (permanent) stiffness loss after freeze–thaw cycling, paired with a time-dependent recovery function that restores stiffness as excess pore water drains.

The damage factor was defined in this study as

$$D(T,w) = \gamma \cdot S(T) \cdot g(w)$$

where γ is the calibration coefficient, $S(T)$ is the thawing function, and $g(w)$ is the moisture function. This formulation reflects that stiffness reduction is governed by both temperature and moisture conditions, particularly under saturated conditions with limited drainage (Simonsen and Isacsson, 1999; Shoop et al., 2008).

To account for post-thaw recovery, a time-dependent recovery function was introduced:

$$M_r(t) = M_{r,thaw} + \left(M_{r,ref} - M_{r,thaw}\right) \cdot (1 - exp(-\lambda \cdot t))$$

where $M_{r,ref}$ is the reference modulus, λ is the recovery rate parameter, and t is time.

This formulation is consistent with observed gradual recovery of pavement strength as excess moisture dissipates and drainage improves (Doré, 2004; Simonsen et al., 2002).

3.5 Model Integration

The three stages were integrated into a unified formulation based on temperature and freeze–thaw history as follows, where T is the temperature and T_f is the freezing temperature:

- Stage I (unfrozen): $T > T_f$ and no prior freezing
- Stage II (frozen): $T < T_f$
- Stage III (thawing): $T > T_f$ following freezing

At each time step, the model 1) reads temperature and moisture profiles, 2) determines freeze–thaw state, 3) computes layer-wise resilient modulus, and 4) aggregates layer responses.

This approach allows continuous estimation of pavement stiffness throughout seasonal transitions, consistent with recent efforts to integrate field monitoring with mechanistic modeling (Gao et al., 2023; Yu et al., 2024).

The parameters of the three-stage model described above were derived from multiple established sources to represent material behavior across all environmental conditions. The base stiffness coefficient k_1 and the sigmoid parameters (a, b, k_s) of the MEPDG moisture correction model were adopted from AASHTO MEPDG guidelines (NCHRP, 2004; Witczak et al., 2000), which provide standardized values for mechanistic-empirical pavement design. Stress-dependent exponents k_2 and k_3 were based on fundamental granular material characterization studies (Hicks & Monismith, 1971; Uzan, 1985), which established the universal stress-state dependency relationships for unbound materials. The optimal saturation ratio $S_{r,opt}$ was obtained via regression analyses of subgrade soil behavior (Mohammad et al., 1999), while the freeze-thaw damage factor was taken from cold regions research (Simonsen et al., 2002) and further calibrated against the project FWD measurements. Frozen state parameters, including the maximum modulus increment and hyperbolic shape factor, were determined from empirical studies on frozen unbound road materials (Si et al., 2018; Lee et al., 1995), which quantified ice-stiffness relationships under subzero conditions. The full parameter set and the source of each value are summarized in **Table 3-1**.

Table 3-1 Model parameters and sources

Parameter	Description	Value	Source
k_1	Base stiffness coefficient	35	NCHRP (2004)
k_2	Confining stress exponent	0.55	Hicks & Monismith (1971)
k_3	Octahedral shear exponent	-0.20	Uzan (1985)
F_d (Stage I)	Damage factor - unfrozen	1.0	N/A
F_d (Stage III)	Freeze-thaw damage factor	0.75	Simonsen et al. (2002)
a, b (moisture)	Sigmoid fitting parameters	-0.3123, 0.3010	Witczak et al. (2000)
k_s	Moisture sensitivity	6.8157	Witczak et al. (2000)
$\boldsymbol{S_{r,opt}}$	Optimal saturation ratio	0.65	Mohammad et al. (1999)
a (frozen)	Maximum modulus increment	8000 MPa	Si et al. (2018)
b (frozen)	Freezing shape factor	1.5	Si et al. (2018)

To evaluate the seasonal variation of overall pavement structural performance, a finite element modeling approach was developed using the FEniCS computational platform. The framework integrates field-measured seasonal resilient modulus variations from the three-stage constitutive model, using the calibrated parameters in **Table 3-1**, with advanced computational mechanics to predict the effective stiffness of the entire pavement system throughout annual freeze-thaw cycles.

3.6 Validation with Field Data

FWD Validation

FWD testing provides independent estimates of pavement stiffness and is widely used for structural evaluation (NCHRP, 2004). Model predictions were compared with FWD-derived

moduli obtained through backcalculation using the ELMOD program (Dynatest). The back-calculated moduli are equivalent elastic layer moduli, and they are used as a field check of the modeled seasonal stiffness trends.

The results in **Figure 3-2** support the model at both ends of the seasonal cycle: the FWD back-calculated subgrade moduli (stars) fall on or near the modeled 5.0 ft curves, and the modeled rise and drop of the shallower layers track the official Frozen-road and Class-II windows at every instrumented site. The model therefore captures the mechanical response of the pavement layers under varying environmental conditions.

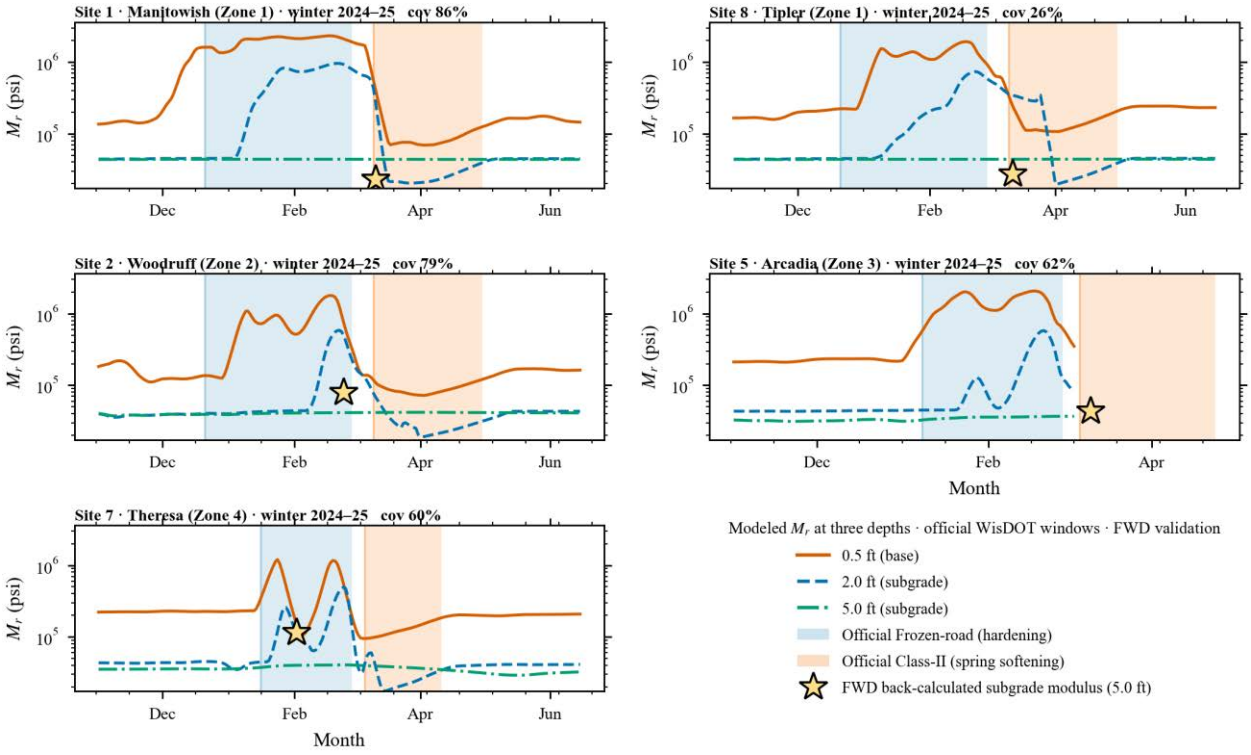


Figure 3-2 Modeled resilient modulus at 0.5, 2.0, and 5.0 ft for each instrumented zone, with the WisDOT Frozen-road and Class-II windows. Stars: the FWD back-calculated subgrade modulus (the 5.0 ft subgrade layer), one winter survey per site

Comparison with SWR Decisions

The finite element simulation was run for each site and period of interest, e.g., 365 daily calculations spanning July 2024 to July 2025. The calculated timing aligns closely with WisDOT's official FRD and SWR periods. The FWD-derived subgrade modulus matches the modeled 5.0 ft resilient modulus within a factor of two to three. Both 2026 FWD rounds were analyzed for all eight sites (winter, February–March; spring, April–May), together with the summer-2024 baseline survey, for 330 drop points in all. The back-calculated subgrade modulus shows the expected seasonal order at the responsive sites (frozen-winter stiffest, spring-thaw weakest, summer intermediate; for example Theresa (Dodge County) 114,000, 64,000, and 51,000 psi (787, 444, and 350 MPa) for winter, summer, and spring), independently confirming the modeled thaw-weakening signal. The FWD pavement-layer modulus is a composite structural value that swings with the survey-day freeze state, so it is reported in **Figure 2-4** rather than compared here.

Model predictions were also compared with the WisDOT SWR and Frozen Roads Declaration dates. The predicted periods of reduced stiffness align well with observed SWR implementation periods.

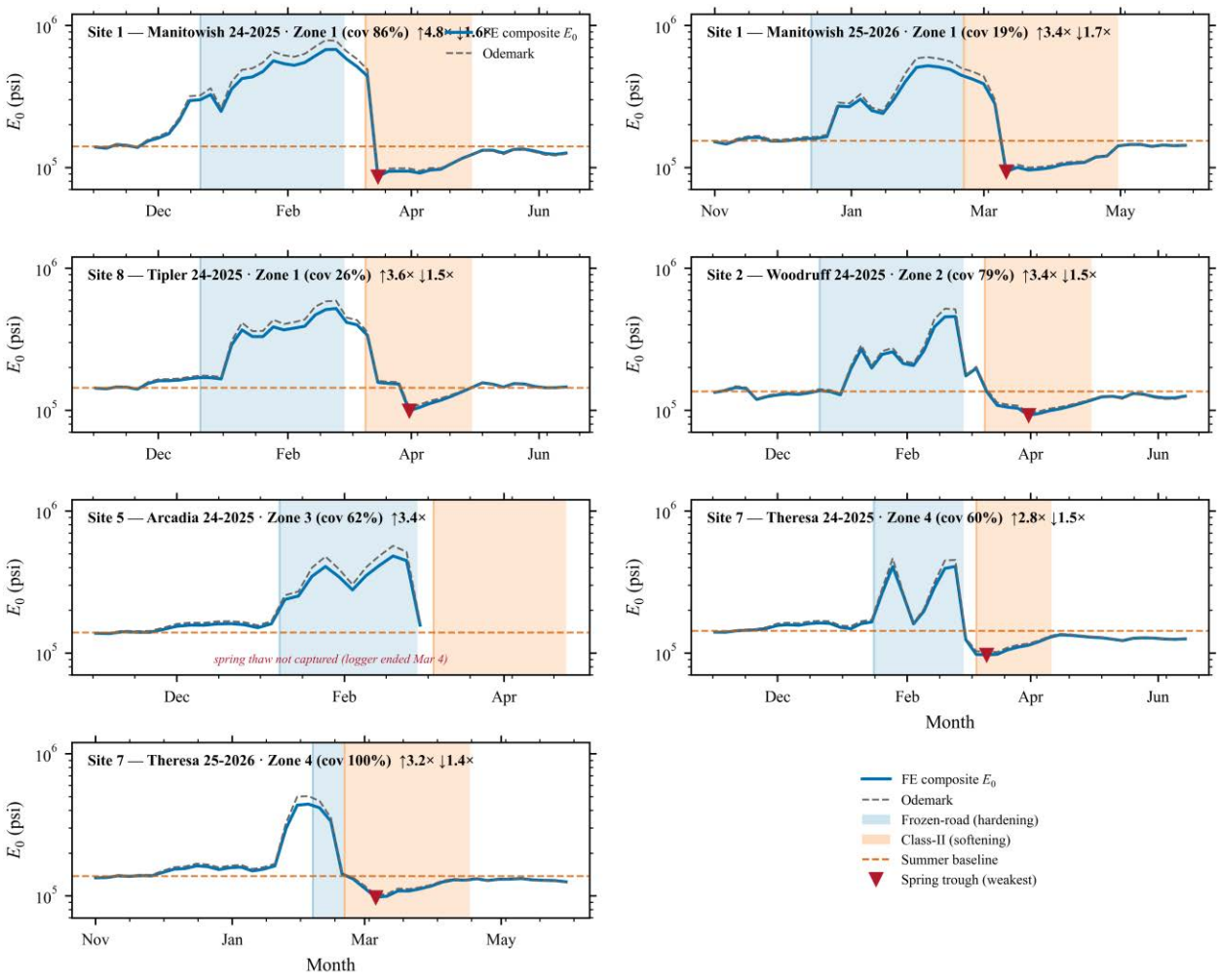


Figure 3-3 Seasonal effective composite (FWD-equivalent) surface modulus E_0 by instrumented site and winter, in psi. Blue band = official Frozen-road window (hardening); orange band = Class-II / Spring Weight Restriction window (softening); dashed line = summer baseline; red triangle = spring trough (weakest). Site labels are Site N – City. Arcadia 2024–25 has no spring data (logger ended Mar 4)

This agreement demonstrates that the model can capture the critical weakening period relevant to SWR decision-making, consistent with previous studies linking stiffness variation to seasonal load restrictions (Kestler et al., 2007; Bao et al., 2019).

3.7 Discussion

The modeling results show the importance of explicitly considering pavement mechanics in SWR decision-making. Environmental indicators alone are insufficient to determine pavement capacity, because the stiffness is governed by coupled thermal and hydraulic processes. The developed framework provides a physically based approach for linking environmental conditions to structural performance, leading to improved accuracy compared to simplified empirical methods.

Chapter 4 Data-Driven Estimation of Pavement Stiffness

4.1 Overview

The physics-based modeling framework presented in Chapter 3 provides a mechanistic interpretation of pavement behavior under freeze–thaw conditions. However, its implementation requires temperature and moisture measurements across pavement depth, as well as model calibration. In practice, such data may not always be available at sufficient spatial resolution for network-level decision-making.

To address this limitation, a data-driven modeling approach was developed to enable real-time and scalable estimation of pavement stiffness using easily obtainable measurements. The approach uses vibration responses of pavements induced by passing vehicles, combined with environmental data, to infer resilient modulus. This effort was made based on recent studies that explore the relationship between vibration signals and pavement mechanical properties (Bahrani et al., 2020; Ozer et al., 2014), while addressing limitations in continuous monitoring and practical deployment.

4.2 Motivation and Data Description

Conventional methods for estimating resilient modulus rely on in situ testing such as Falling Weight Deflectometer (FWD) combined with Ground Penetrating Radar (GPR). While accurate, these methods are resource-intensive and cannot provide continuous measurements over time.

To overcome this limitation, a field database was developed using the monitoring system described in Chapter 2. The dataset (**Figure 4-1**) includes:

- Pavement acceleration signals
- Soil temperature profiles
- Volumetric water content
- Reference back-calculated (elastic) layer moduli derived from FWD and GPR

Data were collected from multiple sites in Wisconsin, including Dodge County and Iron County, with thousands of time-stamped samples covering freeze–thaw conditions.

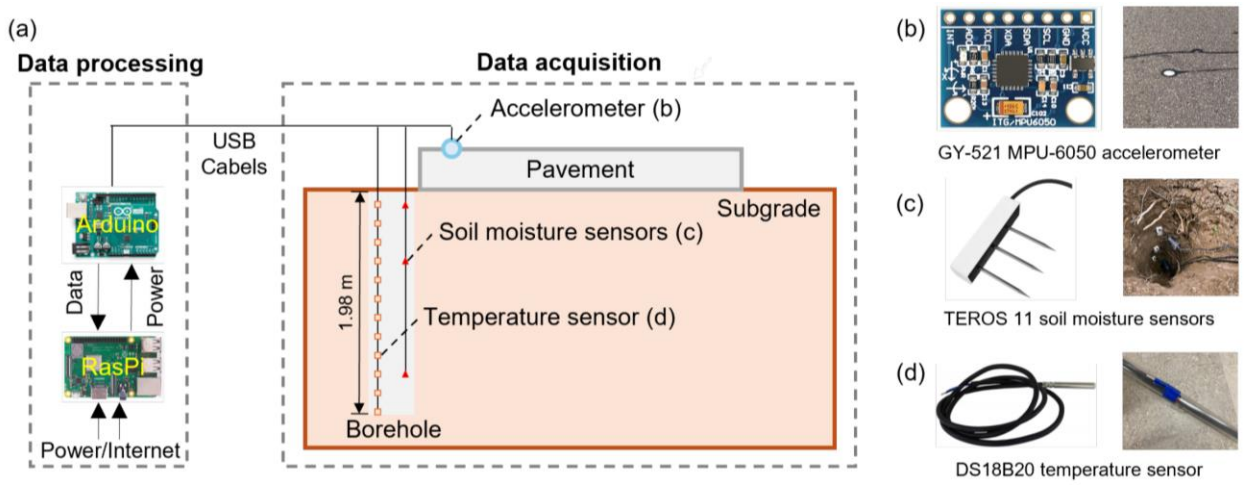


Figure 4-1 Schematic diagram of the monitoring system: (a) subsystems for data acquisition and processing, (b) accelerometer, (c) soil-moisture sensor, and (d) temperature sensors

The dataset captures the relationship between environmental conditions, dynamic response, and pavement stiffness, providing a basis for training data-driven models.

4.3 Model Architecture (Vib-Net)

A multimodal deep learning model, referred to as Vib-Net, was developed to estimate pavement stiffness from field measurements. As illustrated in **Figure 4-2**, the model integrates three types of input data: 1) Raw vibration signals from accelerometers, 2) Spectrogram representations of vibration signals, and 3) Pavement surface temperature.

To extract features from acceleration signals, the raw one-dimensional acceleration series of length 10000 datapoints is reshaped to include a channel dimension and then processed through three convolutional blocks, as shown in left-upper part of **Figure 4-2**. Each block applies a 1D convolution with a kernel size of five and symmetric padding to preserve temporal resolution, immediately followed by Group Normalization and a ReLU activation to stabilize and nonlinearize feature extraction. Between convolutional blocks, max-pooling with a window of four reduces the temporal dimension, while dropout regularization mitigates overfitting. The number of feature channels is progressively increased in three convolutional blocks, from one to four, then eight, and

finally sixteen, allowing the network to learn hierarchical representations for pavement stiffness and damping. A final global average pooling across the temporal axis collapses each channel's output to a single scalar, yielding a compact 16-dimensional embedding that encapsulates the key time-domain dynamics for resilient modulus prediction.

To extract features from spectrograms, three 2D convolutional blocks are employed, as shown in left-mid part of **Figure 4-2**. Each block begins with a 3*3 convolution and padding to preserve the input's time–frequency resolution, immediately followed by Group Normalization and a ReLU activation to stabilize training and introduce nonlinearity. A lightweight residual connection then refines local spectral–temporal patterns by reusing features across the block. After the residual unit, a 2*2 max-pooling layer downsamples both frequency and time dimensions by a factor of two, and a spatial dropout layer regularizes the representation. Across the three blocks, the number of feature channels grows from 1→4, 4→8, and 8→16, allowing the network to hierarchically learn from fine-grained frequency bands up to broader spectro-temporal structures. Finally, an adaptive average pooling collapses each feature map to a single scalar per channel, producing a fixed-length 16-dimensional embedding that succinctly captures the dominant spectral characteristics for downstream resilient-modulus regression.

To extract features from surface temperature, the raw temperature scalars are first normalized and then passed through a small fully connected network, as shown in left-lower part of **Figure 4-2**. Specifically, a linear layer projects the input to an intermediate 4-dimensional representation, followed by a ReLU activation and dropout for regularization; a second linear layer expands this to 8 dimensions with another ReLU; finally, a dedicated linear projection maps the 8-dimensional vector to a 16-dimensional embedding that matches the size of the other modalities. This learned temperature embedding captures the nonlinear influence of thermal conditions on asphalt modulus and moisture distribution, allowing the downstream fusion module to adjust resilient modulus predictions based on pavement temperature.

The extracted features were combined using a gated fusion mechanism and passed through fully connected layers to produce the final prediction of pavement stiffness, as shown in the right part of **Figure 4-2**. The gated fusion mechanism first concatenates the features extracted from acceleration, spectrogram, and temperature modalities, and then learns an element-wise gate to

adaptively regulate the contribution of the candidate fused feature. By multiplying the gate vector with the candidate representation, the model selectively preserves informative features while suppressing less relevant or noisy components, thereby improving the robustness and effectiveness of multimodal feature fusion.

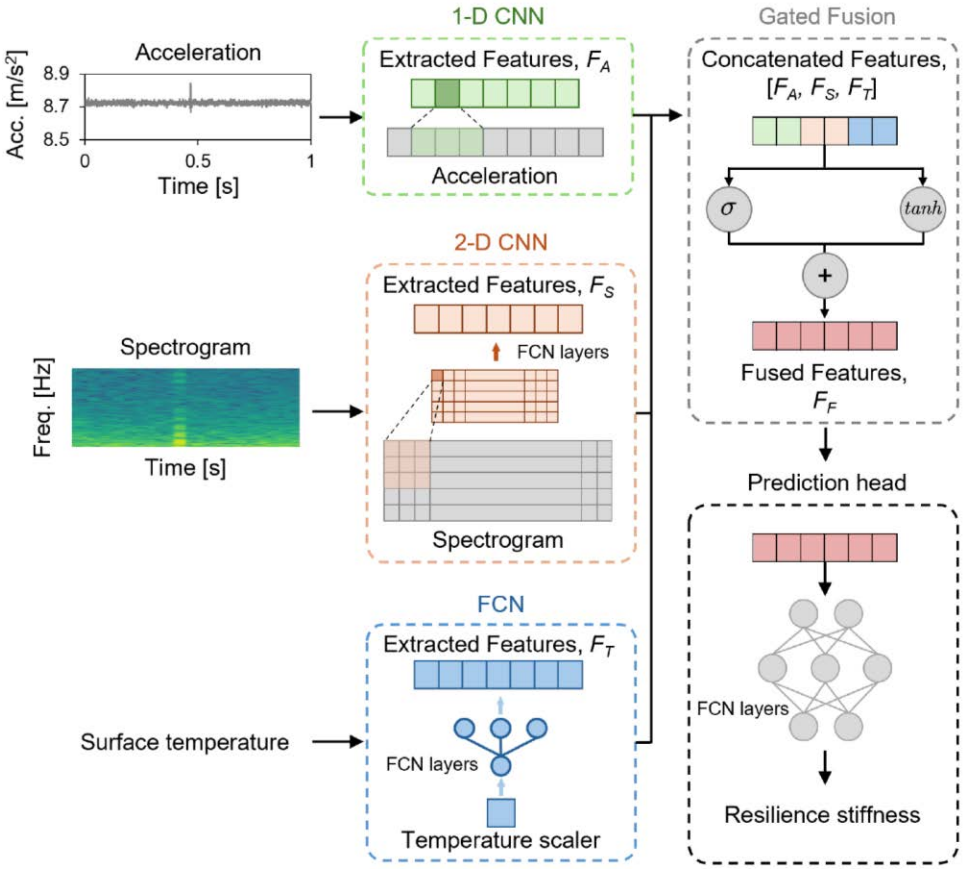


Figure 4-2 Schematic diagram of Vib-Net

4.4 Model Formulation

The model can be expressed in a general form as

$$M_r = F(x_{acc}, x_{spec}, T)$$

where M_r is the predicted resilient modulus, x_{acc} is the raw acceleration signal, x_{spec} is the spectrogram representation, and T is the temperature.

The spectrogram was computed from the acceleration signal using a Short-Time Fourier Transform (STFT) as follows,

$$S(f,t) = |\sum x(\tau) * w(\tau - t) * exp(-i * 2 * \pi * f * \tau)|$$

where $S(f,t)$ is the spectrogram magnitude and $w(\tau)$ is the window function.

The model combines the features extracted from acceleration, spectrograms, and temperature modalities (i.e., F_A, F_S, and F_T), using a gated fusion mechanism. It first concatenates three features into a single vector $C = [F_A, F_S, F_T\ ]$. Then, this mechanism uses two parallel linear projections to transform C into a gate vector (g) and a candidate vector (u):

$$g = \sigma\big(W_g C + b_g\big), u = \tanh(W_u C + b_u)$$

where W_g, b_g, W_u, and b_u are the weight and bias for gate vector, and the weight and bias for candidate vector; σ is the Sigmoid function. Finally, the fused feature is formulated as an element-wise gate vector and candidate vector.

$$z = g \odot u.$$

The final output was obtained through linear projection:

$$M_r = W \cdot z + b$$

where W and b are model parameters.

The above formulation enables the model to learn complex relationships between vibration behavior, environmental conditions, and pavement stiffness.

4.5 Training and Validation

The model was trained using the field dataset with modulus values derived from FWD-based backcalculation as reference labels. Standard training procedures were used, including data normalization, training-validation split, and optimization using gradient-based methods.

The training was performed on a single research GPU. The training dynamics of Vib-Net are shown in **Figure 4-3**. For Site 1 (Figure 4-3(a)), both training and validation losses decrease rapidly during the first 50 epochs, which indicates effective early-stage learning. Afterward, the training loss continues to decline gradually, whereas the validation loss stabilizes at a slightly higher level with minor oscillations. The persistent gap between the two curves in later epochs suggests mild overfitting. For Site 2 (**Figure 4-3**(b)), the validation loss plateaus and then fluctuates with a slight upward trend, while the training loss continues to decrease. These trends suggest overfitting. Therefore, training for Site 2 was stopped at epoch 100 to preserve generalization.

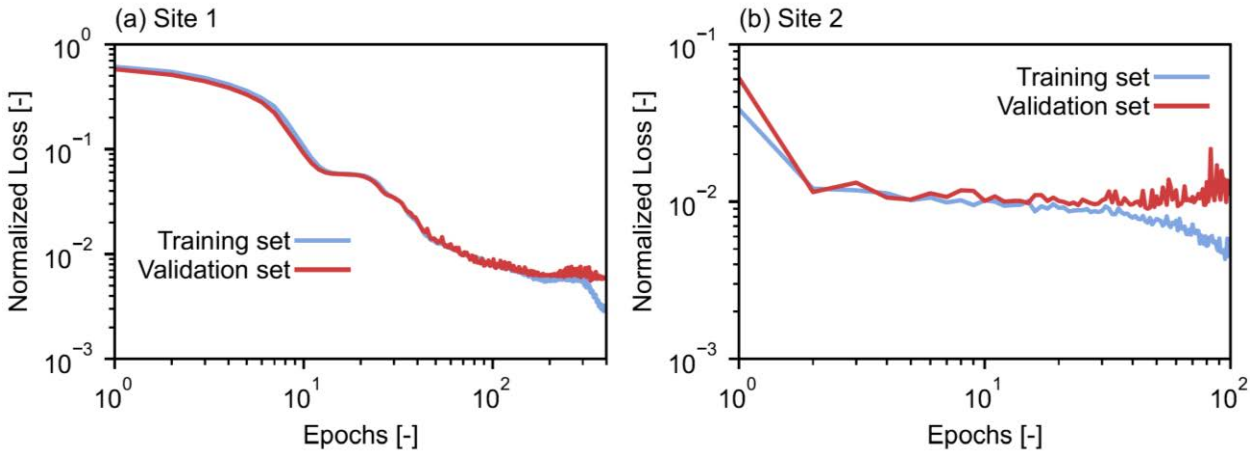


Figure 4-3 Evolutions of the loss function on the training and validation sets during the training process. (a) Site 1 (43.53656, -88.402713) and (b) Site 2 (46.1321, -90.011957)

Model performance was evaluated using R-squared (coefficient of determination) and error metrics. Results as shown in **Figure 4-4** show that the model achieves high predictive accuracy, with R-squared values of 0.898 and 0.895 on the two independent test sites.

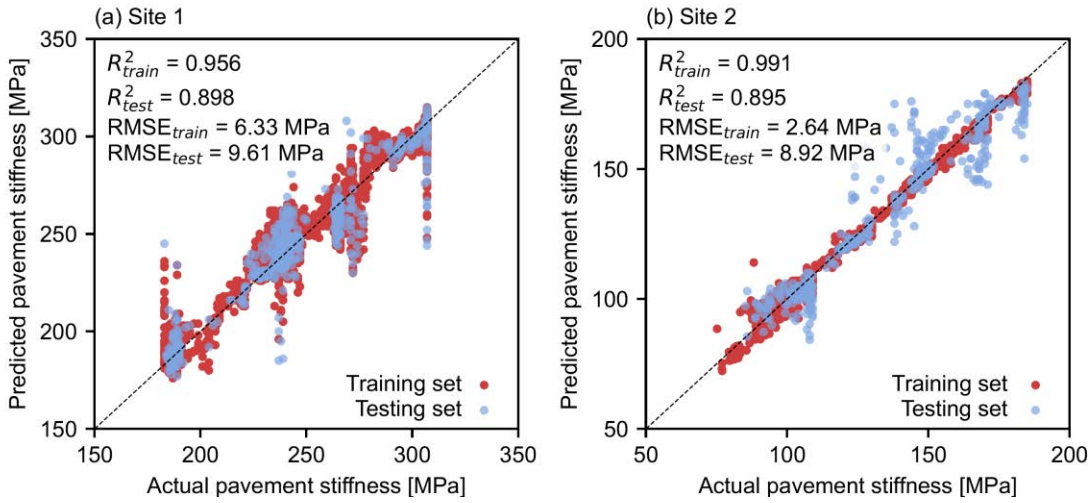


Figure 4-4 Comparison between the predicted pavement stiffness and actual values: (a) Site 1 and (b) Site 2. Values are reported in MPa; 1 MPa equals 145 psi

Additional analysis indicates that each input modality contributes to prediction performance. Vibration signals capture the dynamic structural response, spectrograms capture frequency-domain characteristics, and temperature provides environmental context.

A preliminary version of the Vib-Net model has been turned on for the project website. Each instrumented site's most recent accelerometer record is fed through the model together with the surface temperature for that day, and the model returns an estimated resilient modulus that the website displays alongside the layer-wise M_r values. This website feature is a preliminary research demonstration at the instrumented sites. It is separate from the validated model reported in this chapter, and it is not used for the zone-level SWR recommendations, which follow the threshold logic in Section 5.4.

4.6 Discussion

The data-driven approach provides several advantages compared to traditional methods:

- Scalability: Requires only a surface-mounted accelerometer and temperature measurement;

- Continuity: Enables near real-time estimation of pavement stiffness;
- Cost-effectiveness: Avoids the need for repeated FWD testing.

It is noted that this data-driven approach complements rather than replaces the physics-based framework. While the physics-based model provides interpretability and mechanistic understanding, the data-driven model has the potential to enable efficient estimation across larger spatial and temporal scales. In this project, the data-driven approach was explored as a complementary tool and adopted only when needed.

Chapter 5 Decision Support System for SWR Implementation

5.1 Overview

The field monitoring program and modeling frameworks presented in Chapters 2 through 4 provide the foundation for improved SWR decision-making. However, practical implementation requires integration of these components into an operational system that can deliver timely and actionable information to transportation engineers.

To address this need, a web-based decision support system, referred to as WiSWR (the Wisconsin Smart Weight Restriction website), was developed. The system integrates real-time environmental data, physics-based modeling results, and data-driven predictions to support SWR decision-making across Wisconsin.

WiSWR is designed to bridge the gap between research and practice by converting raw data and model outputs into interpretable indicators that can be used directly in operational settings.

5.2 System Architecture

The WiSWR system, as illustrated in **Figure 5-1**, integrates multiple data sources and modeling components into a unified platform. The overall architecture consists of four main layers:

- Data acquisition
- Data processing and storage
- Modeling and analysis
- User interface and visualization

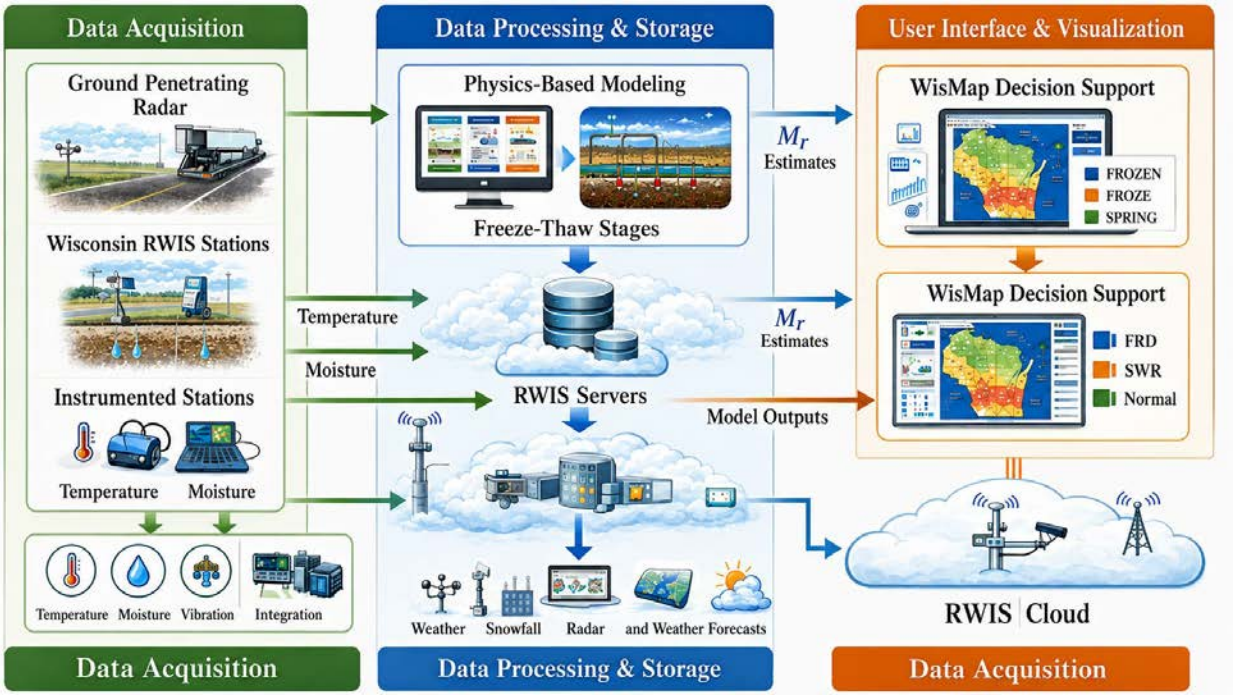


Figure 5-1 System architecture diagram for WiSWR

Data Sources

The primary data source is the Wisconsin RWIS, which includes 81 stations distributed across the state. These stations provide

- Air temperature
- Pavement surface temperature
- Subsurface temperature
- Precipitation and other weather variables

Additional inputs include

- Field monitoring data from instrumented sites (Chapter 2)
- Model outputs from physics-based and data-driven approaches

5.3 Climate Zone Framework

The five-zone framework used by WiSWR follows the existing administrative zoning published by WisDOT (WisDOT 2026a, WisDOT 2026b). It is reused here without modification so that the WiSWR outputs map onto the same operational vocabulary that WisDOT regional engineers already use for FRD, SWR, and NRM decisions. The system therefore does not introduce a new zoning convention.

To support statewide implementation, Wisconsin is divided into five climate zones as shown in **Figure 5-2** to be compliant with the current WisDOT practice. This zoning approach reflects regional differences in temperature, freeze–thaw cycles, and pavement response. The use of climate zones allows the system to 1) aggregate data within regions, 2) provide consistent recommendations for each zone, and 3) reduce variability caused by localized anomalies.

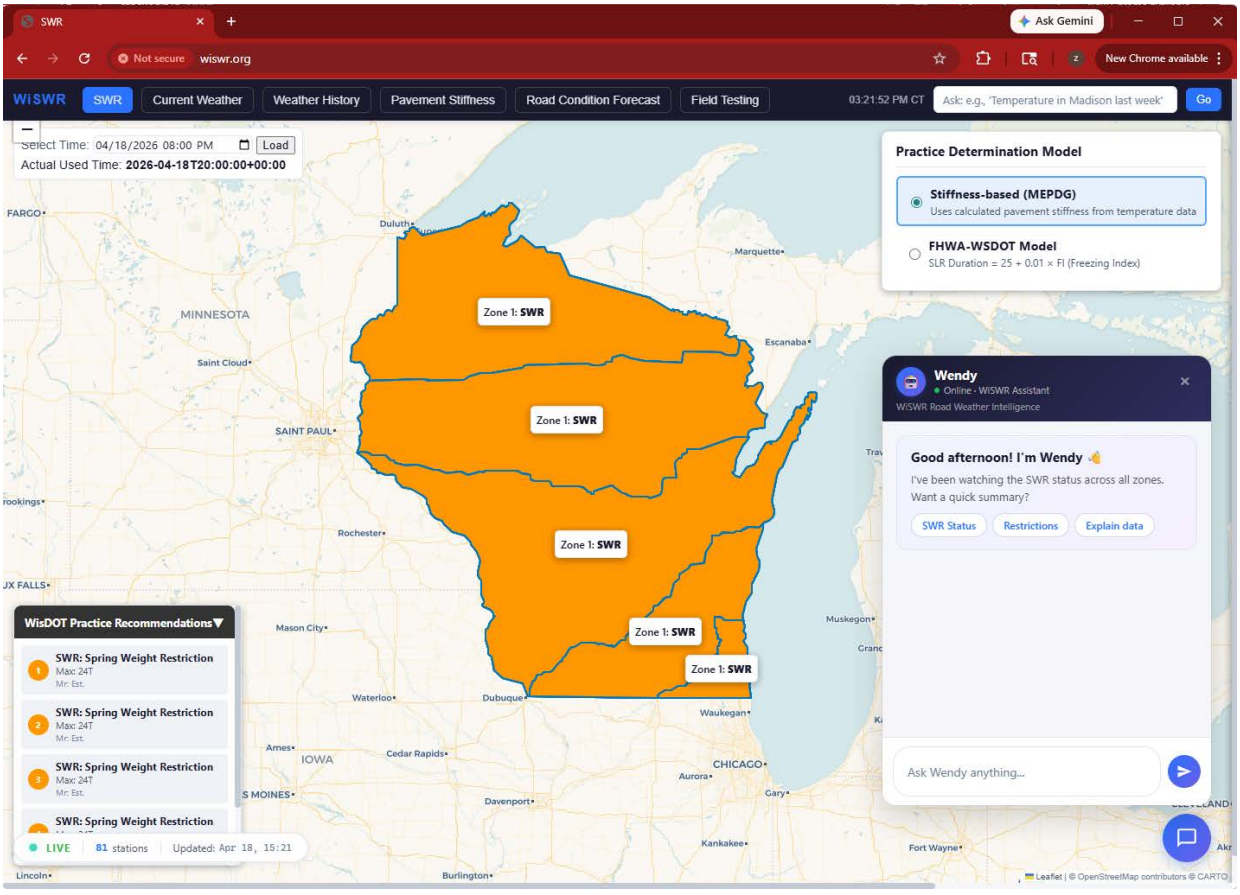


Figure 5-2 Home page/service of WiSWR (wiswr.org)

Within each instrumented zone (Zones 1 through 4), representative field stations evaluate pavement conditions and determine SWR status. The WHRP field network covers four of WisDOT's five climate zones (Zones 1 through 4); Zone 5, in far southern Wisconsin, is not yet instrumented, so the WiSWR map for Zone 5 reflects only the RWIS-driven recommendation, without local field monitoring or stiffness validation. The five-zone framework is retained unchanged to remain consistent with WisDOT operational practice.

5.4 SWR Decision Logic

The thresholds used in the current implementation are $M_{r,FRD}$ equal to 1,000,000 psi (about 6,900 MPa) for the frozen state, and $M_{r,SWR}$ equal to 30,000 psi (about 207 MPa) for the thaw-weakened state. The frozen-state threshold is consistent with the lower bound of the frozen-pavement resilient modulus reported by the MEPDG and was confirmed against the FWD-derived values measured at the Theresa site during the 2024-2025 monitoring season. The thaw-state threshold corresponds to the published WisDOT Class II posting boundary expressed as a resilient modulus equivalent for the surface layer.

The core function of WiSWR is to determine the appropriate operational status for each climate zone. Three primary states are defined:

- Frozen Road Declaration (FRD)
- Seasonal Weight Restriction (SWR)
- Normal Operations (NRM)

The decision logic is based on estimated pavement stiffness and environmental conditions.

In simplified form, the decision rule can be expressed as

If $M_r > M_{r,FRD}$ (or called M_{high}), then apply FRD

If $M_{r,SWR}$ (or called M_{low}) $< M_r \leq M_{high}$, then apply NRM

If $M_r \leq M_{low}$, then apply SWR

where M_r is the estimated resilient modulus, $M_{r,FRD}$ is the threshold for the frozen condition, and $M_{r,SWR}$ is the threshold for the weakened condition.

The thresholds are determined based on calibration with field data and observed SWR practices.

The estimation of M_r can be obtained from either Physics-based model (Chapter 3) or Data-driven model (Chapter 4). This flexible structure allows the system to adapt to available data and modeling capabilities.

5.5 System Functionality

Six operational services and one research service are deployed on https://wiswr.org as of May 10, 2026. The user manual in Appendix F walks the regional engineer through each one step by step.

Service 1 is the SWR Recommendation Map at https://wiswr.org/swr/, the default landing page. The map colors each of the five WisDOT zones by today's recommendation. Click a zone for the per-station details.

Service 2 is Current Weather at https://wiswr.org/current/. Air temperature is supported across all 81 RWIS stations; subsurface temperature and volumetric water content are shown where the upstream sensors are reporting on the Wisconsin RWIS feed.

Service 3 is Weather History at https://wiswr.org/weather/, a two-year trailing air-temperature time series at each RWIS station.

Service 4 is the Pavement Stiffness Map at https://wiswr.org/stiffness/. Click any WHRP-instrumented marker to see the per-station M_r trend at three depths (0.5 ft, 2.0 ft, 5.0 ft). The trend chart shows the freeze-thaw cycle with frozen winter peak (Jan 22 to Mar 1 per WisDOT Zone 4 averages), Class II thaw minimum (Mar 1 to Apr 16), and gradual recovery into summer. All M_r values are reported in psi (the WisDOT-standard unit).

Service 5 is the Road Condition Forecast at https://wiswr.org/forecast/. A seven-day forecast that combines the surface-temperature forecast input with the threshold logic in Section 5.4. A Vib-Net deep-learning stiffness curve is displayed below the threshold-based forecast.

Service 6 is Field Testing at https://wiswr.org/fieldwork/, a documentation page describing the eight WHRP-instrumented sites with photos.

A natural-language assistant called Wendy is reachable from every page through a small floating button in the lower-right corner. Wendy answers plain-English questions about the WiSWR system.

WiSWR provides four primary functional modules.

SWR Status Mapping

WISWR displays a color-coded map indicating the current status (FRD, SWR, or NRM) for each climate zone (**Figure 5-3**). This provides a clear and immediate overview of statewide conditions.

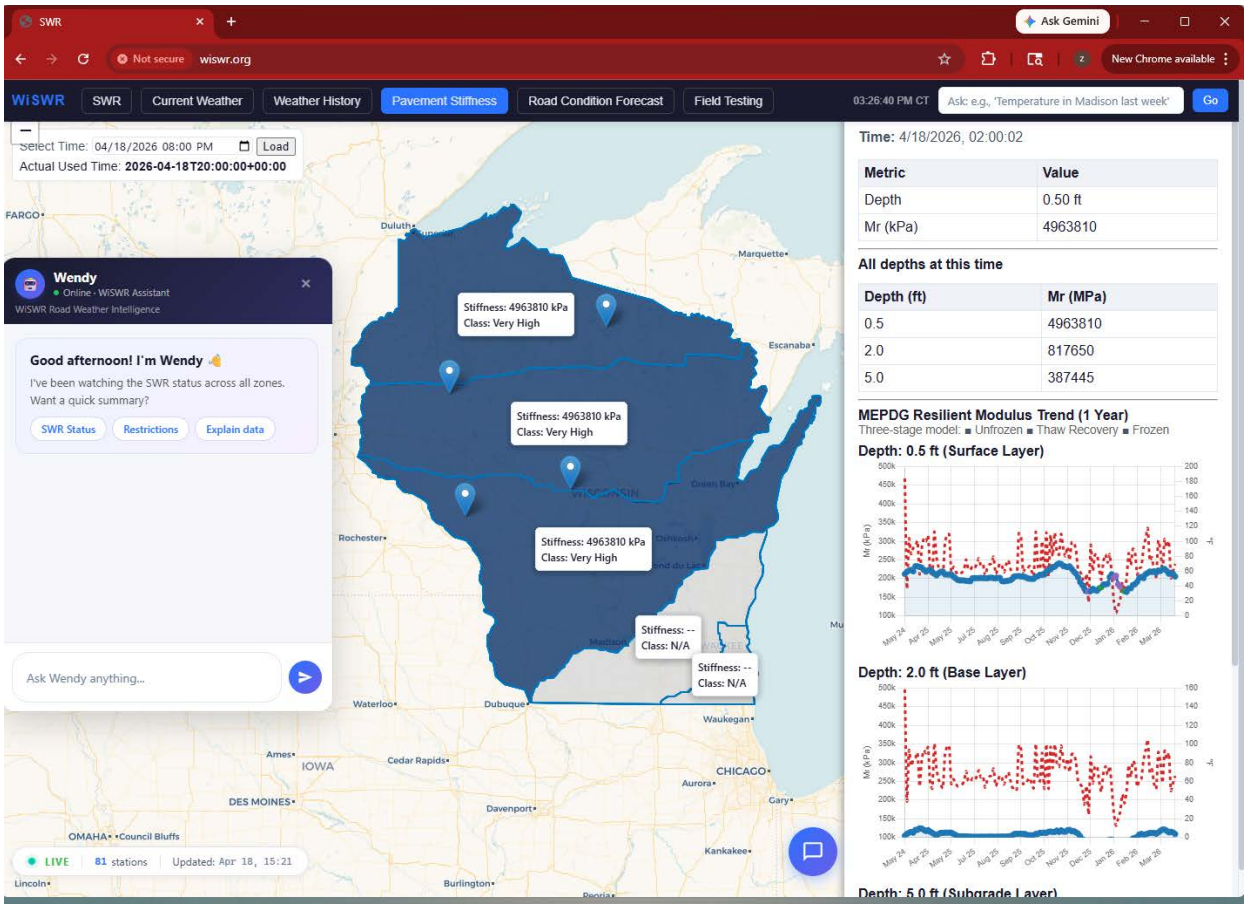


Figure 5-3 SWR Status Mapping

Real-Time Environmental Monitoring

The system provides access to real-time weather data from RWIS stations, including temperature and precipitation. Users can view current conditions at specific locations or across regions.

Historical Data Analysis

Historical data are available for analyzing trends in temperature, freeze–thaw cycles, and pavement conditions. This functionality supports (1) retrospective analysis of SWR decisions, (2) evaluation of seasonal variability, and (3) model calibration and validation.

Pavement Stiffness Monitoring

The system provides estimates of pavement stiffness over time based on model outputs. These estimates are presented as (1) time series plots and (2) stiffness classification levels (e.g., high, moderate, low), as shown in **Figure 5-4**.

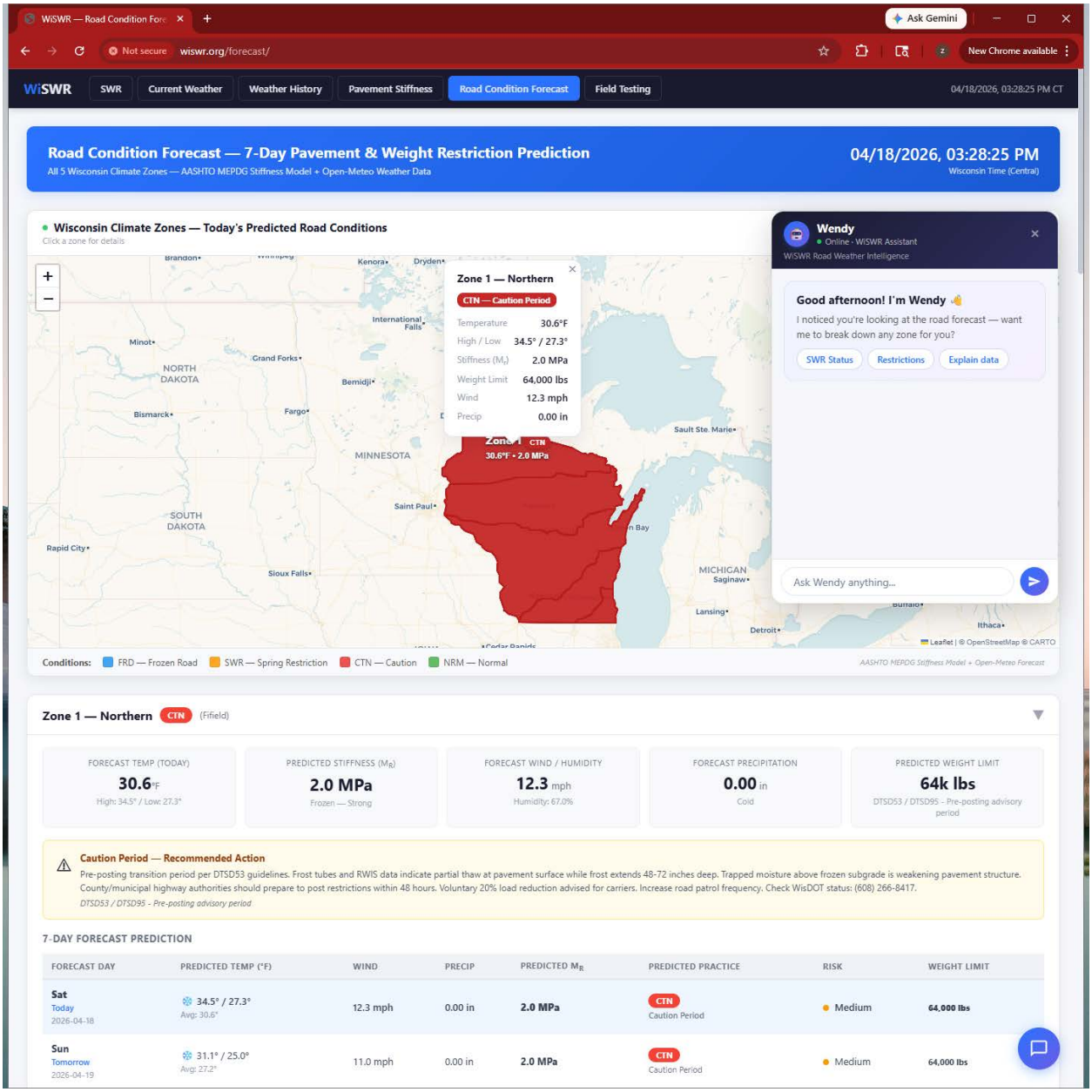


Figure 5-4 Detailed site status and forecast

This functionality directly links environmental conditions to pavement performance and supports decision-making.

5.6 Implementation Considerations

The design of WiSWR emphasizes practicality and scalability for real-world deployment.

Key considerations include

- Use of existing infrastructure: Integration with RWIS minimizes additional hardware requirements,
- Data availability: The system can operate with varying levels of data input,
- Flexibility: Both physics-based and data-driven models can be used,
- User accessibility: Web-based interface allows easy access without specialized software.

The system is designed to support both centralized decision-making at the state level and localized analysis by engineers.

5.7 Discussion

The WiSWR system demonstrates how field data and modeling approaches can be translated into an operational tool for SWR decision-making. By integrating environmental data, mechanistic modeling, and data-driven estimation, the system provides a more comprehensive and accurate representation of pavement conditions compared to traditional methods. The use of climate zones and real-time data enables consistent and adaptive decision-making across the state, while the modular design allows future enhancements as additional data and models become available.

Chapter 6 Conclusions and Recommendations

6.1 Summary of Work

This study developed an integrated framework for Seasonal Weight Restriction (SWR) decision-making in Wisconsin by combining field monitoring, physics-based modeling, data-driven analysis, and system-level implementation.

A statewide monitoring program was established to capture temperature, moisture, and vibration responses within pavement systems. These data were used to develop and validate a three-stage constitutive modeling framework that quantifies pavement stiffness under unfrozen, frozen, and thawing conditions. A complementary data-driven model was also developed to enable scalable estimation of pavement stiffness using vibration measurements. The research outcomes were integrated into a web-based decision support system, WiSWR, for operational use. The combined framework provides a direct link between environmental conditions and pavement structural performance, enabling more accurate identification of critical periods for SWR implementation.

6.2 Conclusions

Pavement Behavior under Freeze–Thaw Conditions

Field measurements and modeling results confirm that pavement structural capacity varies significantly throughout the freeze–thaw cycle. Frozen conditions increase stiffness due to ice bonding, while thawing leads to rapid weakening associated with increased moisture and reduced effective stress. The most critical condition occurs during the early thaw period when water is trapped above still-frozen layers, resulting in maximum reduction in stiffness. Recovery occurs gradually as drainage improves and moisture dissipates. These behaviors are consistent with established mechanisms of thaw weakening and cannot be captured using temperature-based indicators alone.

Performance of Physics-Based Modeling

The three-stage constitutive framework developed in this study provides a physically consistent representation of pavement behavior. The model captures key processes including moisture-dependent stiffness variation, temperature-driven freezing effects, and thaw-induced damage and recovery. Validation against Falling Weight Deflectometer (FWD) measurements shows strong agreement between predicted and observed stiffness values. In addition, the predicted timing of stiffness reduction aligns with WisDOT SWR and Frozen Roads Declaration periods. These results demonstrate that the model can provide a reliable basis for evaluating pavement capacity and determining SWR timing.

Role of Data-Driven Modeling

The data-driven model (Vib-Net) demonstrates that pavement stiffness can be estimated using vibration responses and temperature data. This approach enables continuous and scalable monitoring without the need for frequent in situ testing. While the data-driven model does not provide the same level of physical interpretability as the mechanistic model, it offers practical advantages in terms of cost, deployment, and spatial coverage. The results indicate that data-driven methods can complement physics-based approaches, particularly for network-level applications.

Implementation through WiSWR

The WiSWR system demonstrates how field data and modeling approaches can be integrated into a practical decision support tool. By combining real-time RWIS data with modeling outputs, the system provides zone-based SWR recommendations across Wisconsin. The system translates complex data and modeling results into clear operational indicators, enabling engineers to make informed decisions regarding SWR implementation.

6.3 Implications for SWR Practice

The results of this study have several important implications for SWR decision-making.

First, SWR decisions should be based on pavement structural response rather than solely on environmental indicators such as air temperature or calendar dates. The relationship between environmental conditions and pavement capacity is nonlinear and site-specific.

Second, field monitoring provides critical information that cannot be inferred from surface measurements alone. Subsurface temperature and moisture conditions play a key role in determining pavement behavior.

Third, integration of monitoring, modeling, and decision support is necessary to achieve practical implementation. Isolated use of data or models is insufficient for operational decision-making.

6.4 Recommendations for Implementation

Based on the findings of this study, the following recommendations are provided for WisDOT.

Short-Term Implementation

This project confirms the feasibility and benefits of the following recommended practice for short-term implementation:

- Use the WiSWR system to support SWR decision-making at the climate-zone level,
- Incorporate model-based stiffness estimates into existing decision workflows,
- Use field-monitored sites as reference locations for calibration and validation.

Extending the system to a new RWIS site calls for only a small set of sensors. The site is fitted with a vertical thermistor string that reads the temperature profile through the pavement and subgrade, with sensors spaced every 6 inches from 6 inches below the surface to a depth of about 6.5 feet; these readings track the freezing and thawing fronts as they move through the structure. Three capacitive probes record moisture at 0.5, 2.0, and 5.0 feet, the shallowest in the pavement and base and the deeper two in the subgrade, capturing the moisture buildup that drives thaw

weakening. The temperature and moisture sensors alone are sufficient to run the three-stage stiffness model; a surface accelerometer is optional and adds the independent vibration-based Vib-Net stiffness estimate. All sensors report to one low-cost Arduino and Raspberry Pi logger that draws its power and internet connectivity from the host RWIS station, so no new field infrastructure is required.

While this project confirmed the feasibility and outlined a framework, further work is highly recommended to facilitate the deployment of the framework especially via integration with the existing WisDOT workflows. If possible, a Phase 2 or continuing project is especially desired to boost the value of findings and products in the actual WisDOT practice.

Medium-Term Development

Besides, the work also led to the following suggestions for mid-term development.

- Expand the monitoring network to improve spatial coverage across different regions and pavement types.
- Integrate the modeling framework with existing WisDOT data systems, including RWIS and MDSS.
- Refine model parameters using additional field data collected over multiple seasons.

The project explored and confirmed a more modern and integrated way of performing SWR in Wisconsin. However, better resolution, coverage, and reliability are needed through the suggested improvements above. This may also be an opportunity to boost WisDOT's data infrastructure and data-driven decision support capabilities.

Long-Term Opportunities

In the long term, further opportunities were identified as follows.

- Develop hybrid approaches that combine physics-based and data-driven models for improved prediction accuracy

- Explore automation of SWR decision-making based on real-time data and model outputs
- Extend the framework to support other infrastructure management applications, such as maintenance planning and asset management

Over the longer term, these opportunities could strengthen WisDOT's SWR program and its broader road maintenance and operations practices, while delivering near-term economic, safety, and social benefits.

6.5 Limitations

Through the project, several limitations of the current study were noted. First, the number of monitoring sites is limited relative to the full roadway network (due to time and funding constraints). Second, model calibration was based on available field data and may require further refinement. Third, data-driven model performance depends on data availability and quality, and its integration with the framework for better scalability and flexibility needs to be further investigated. Finally, regional variability may require additional site-specific calibration. These limitations highlight the need for continued data collection, model validation, and tool development.

6.6 Closing Remarks

This study demonstrates that integrating field monitoring, physics-based modeling, and data-driven analysis provides a practical and effective framework for improving SWR decision-making. The developed approach offers a clear pathway for transitioning from traditional methods to data-driven practices that better reflect actual pavement conditions.

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Appendix A Site Inventory

The eight WHRP-instrumented stations are listed below with the canonical site number, site name, county, WisDOT zone, and approximate coordinates. The site numbers, names, and zones in this appendix are the canonical references used throughout the report and across the live wiswr.org system.

Site 1, Manitowish, Iron County, Zone 1, (46.13 N, -90.01W)

Site 2, Woodruff, Oneida County, Zone 2, (45.89 N, -89.69 W)

Site 3, Fifield, Price County, Zone 1, (45.86 N, -90.36 W)

Site 4, Chetek, Barron County, Zone 2, (45.31 N, -91.66 W)

Site 5, Arcadia, Trempealeau County, Zone 3, (44.25 N, -91.50 W)

Site 6, Pittsville, Wood County, Zone 3, (44.43 N, -90.13 W)

Site 7, Theresa, Dodge County, Zone 4, (43.5366 N, -88.4027 W)

Site 8, Tipler, Florence County, Zone 1, (45.96 N, -88.61 W)

Appendix B FWD Validation Summary

FWD testing at each instrumented site provided the anchor points used to calibrate the three-stage constitutive model in Chapter 3 and to validate the data-driven model in Chapter 4. For each site, the FWD campaign measured surface deflections under a controlled load, and the back-calculated layer moduli for the HMA, aggregate base, and subgrade layers were recorded in **Table 2-2** (Chapter 2). The validation comparisons in Section 3.6 (Figures 3-2 and 3-3) show good agreement between the three-stage model predictions and the FWD-derived values across the freeze-thaw cycle.

The Vib-Net work in Chapter 4 was anchored to FWD-derived resilient-modulus labels at the Theresa site (Dodge County, Site 7) and at the additional Iron County pilot site. The independent test R-squared at these two sites (**Figure 4-4**) is 0.898 at Theresa and 0.895 at Iron County.

Appendix C Forecast Methodology Notes

The forecast service (Service 5 in Section 5.5) ingests the surface-temperature forecast from the national-weather feed for each WisDOT zone, evaluates it against the threshold logic in Section 5.4, and suggests a daily practice category (FRD, SWR, NRM) for the upcoming seven days. The current implementation converts each day's forecasted surface temperature directly into a practice category through fixed temperature thresholds; it does not simulate how freezing or thawing progresses in the subgrade from day to day.

Because the forecast operates on surface temperature alone, it is a planning aid rather than an engineering decision. The page carries an explicit planning-aid label. The medium-term recommendation in Section 6.4 is to replace this heuristic with a physics-driven seven-day forecast that evolves the subsurface state day by day from the surface-forecast input through the three-stage constitutive model in Chapter 3.

A Vib-Net deep-learning stiffness curve is displayed below the threshold-based forecast. For each WHRP-instrumented site, the Vib-Net model (Paper 4) is evaluated at each of the next seven days' forecasted surface temperatures using the site's most recent accelerometer record. The curve gives a quick read on whether the predicted stiffness path crosses the WisDOT thresholds within the forecast horizon.

Appendix D Operations and Deployment

The WiSWR website is hosted on a project-owned server at the University of Virginia. This appendix records, in plain language, how the website is operated day to day, where the field data comes from, and what is needed to keep it running. No knowledge of computer programming is required to read this appendix.

Where the data comes from. Two streams feed the website. The first stream is the field stream: the Raspberry Pi monitoring controllers in the field record a fresh subsurface temperature profile, vibration record, and soil suction / moisture reading roughly every fifteen minutes and ship them over a cellular link to the project server. The second stream is the RWIS stream: every night the project server pulls the latest reading from each of the 81 Wisconsin RWIS stations through the public Wisconsin RWIS feed. Both streams populate the maps and charts shown on the website.

How the website is updated. Most of the visual maps refresh on their own. The SWR map and the Current Weather map pick up new RWIS readings as the nightly ingest writes them. The Pavement Stiffness chart and the seven-day forecast update once a day. The Wendy assistant answers questions in real time from the same feeds.

How to ask the project team for changes. Any question or change request goes to the project team in the University of Virginia Department of Civil and Environmental Engineering. Routine maintenance and bug fixes are covered through the contract close date (August 12, 2026). Two handover options are documented in Appendix E: keep the site at the current University of Virginia host, or migrate it to a WisDOT-owned host.

Appendix E Maintenance and Handover

Two handover paths are available for the WiSWR system. Path 1 keeps the system on the current University of Virginia host, with the project team retaining administrative access for minor maintenance and bug fixes through the close of the contract. Path 2 migrates the system to a WisDOT-owned host; the migration is approximately one work week of effort, mainly for transferring the project data store, the field-record archive, and the website credentials to the new host, and pointing the wiswr.org address at it.

The project end date is August 12, 2026. Technical work is complete and the budget is fully expended; any handover work after the project end date would require a separate task order. As of this revision (August 2026), the live site at https://wiswr.org continues to ingest the nightly RWIS feed, log new field records into the Raspberry Pi tree, and serve the public pages.

Appendix F User Manual for the WiSWR Website

This appendix is a non-technical, step-by-step user manual for the WiSWR website at https://wiswr.org. It is written for the WisDOT regional engineer who is responsible for FRD declarations and SWR (Class II) postings. No programming or database knowledge is required to use the site.

F.1 What WiSWR is, and what it adds to WisDOT practice

WiSWR (the Wisconsin Smart Weight Restriction website) is a public read-only decision-support website that complements the WisDOT regional engineer's existing FRD, SWR (Class II), and NRM decisions with a stiffness-based view of pavement condition for each of the five WisDOT zones. WiSWR does not replace any WisDOT procedure; it provides a second look at the same questions the regional engineer already answers, using continuous field instrumentation and RWIS-derived models.

The same operational vocabulary is preserved end-to-end. WiSWR labels zones 1 through 5 as WisDOT labels them. It reports decisions as FRD, SWR (Class II), or NRM as WisDOT does. All resilient modulus values are shown in psi, the WisDOT-standard unit.

F.2 Who this manual is for

- WisDOT Regional Engineers who are responsible for FRD declarations or for SWR (Class II) postings in their zone.
- Maintenance Supervisors who plan seasonal load restrictions.

The manual assumes a working familiarity with the FRD / SWR / NRM vocabulary and with the five WisDOT zones; no technical familiarity with machine-learning models, databases, or web servers is assumed.

F.3 Opening the site

Open any modern web browser (Microsoft Edge, Google Chrome, Mozilla Firefox, or Apple Safari are all supported), type https://wiswr.org into the address bar, and press Enter. No login is required

for the read-only views. The site is also designed to work on iPhone and Android phones, where pinching zooms the maps and tapping a marker opens the per-station detail cards.

F.4 The top navigation bar

Across the top of every page is a navigation bar with six tabs from left to right: SWR, Current Weather, Weather History, Pavement Stiffness, Road Condition Forecast, and Field Testing. The tab you are currently looking at is highlighted in orange. Click any tab to switch services. On phones the navigation bar scrolls horizontally; swipe left to reach tabs that do not fit on the screen.

F.5 Service 1: SWR Recommendation Map (default view)

Opening https://wiswr.org loads the SWR Recommendation Map. Each of the five WisDOT zones is colored by today's recommendation: green for NRM (Normal Operations), amber for FRD (frozen roads), and red for SWR (Class II thaw weight restriction). Click a zone to open the per-station details, which show the surface temperature, the resilient modulus at 0.5 ft (in psi), and the freshness of the underlying RWIS reading. **Figure F-1** shows this page.

How to use the SWR map: The recommendation is a flag to review against your own RWIS observation and your engineering judgement, not a directive. The website's decision logic is documented in Section 5.4 of this report and the thresholds are stated explicitly there. If the per-station freshness indicator is red (more than 24 hours stale at that station), give that station's recommendation less weight when making the call for the zone.

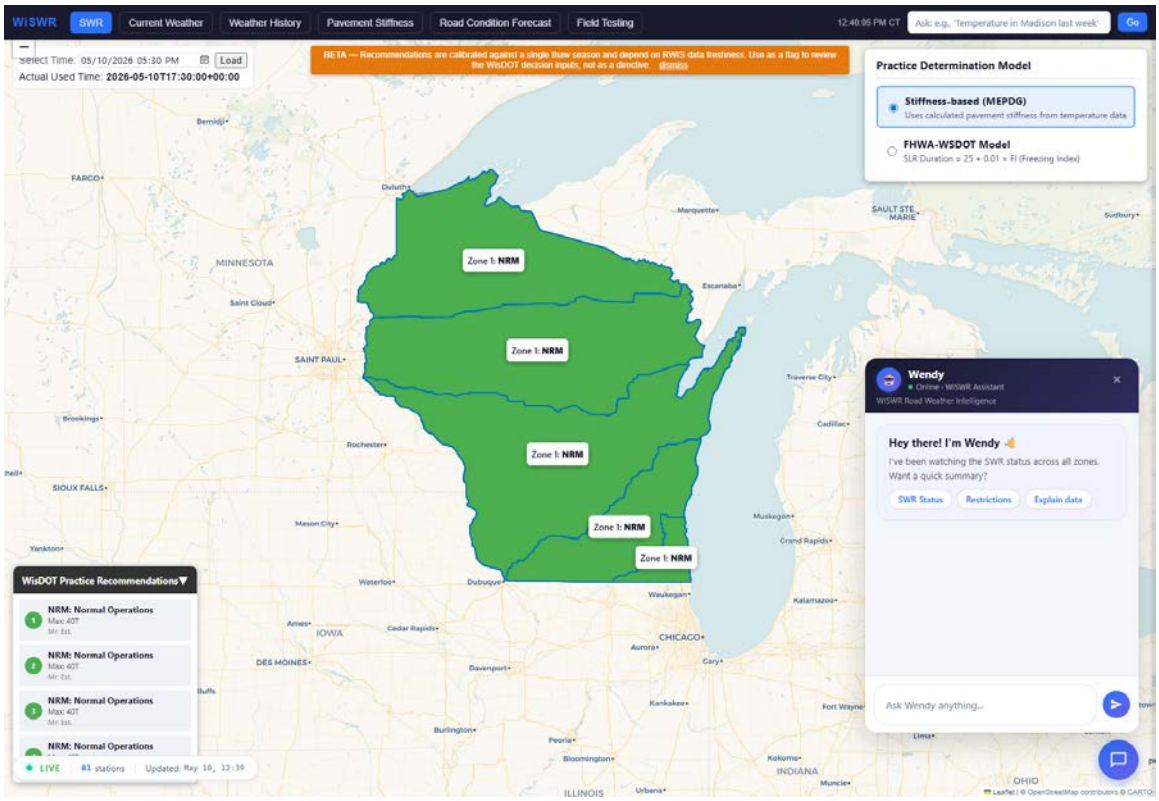


Figure F-1 SWR Recommendation Map at https://wiswr.org/swr/

F.6 Service 2: Current Weather

Click Current Weather in the top navigation bar to see the most recent reading at each of the 81 Wisconsin RWIS stations. Each station is shown as a marker on the state map. The color of the marker shows the freshness of the most recent reading: green for under six hours old, yellow for under twenty-four hours, and red for older than twenty-four hours. Click any marker for a per-station detail card showing air temperature, dewpoint, wind, and where available subsurface temperature and volumetric water content.

Air temperature is supported across all stations. Subsurface temperature and subsurface moisture appear only where the corresponding sensors are reporting on the Wisconsin RWIS feed at that station; this is documented in Section 5.6 (Implementation Considerations). **Figure F-2** shows this page.

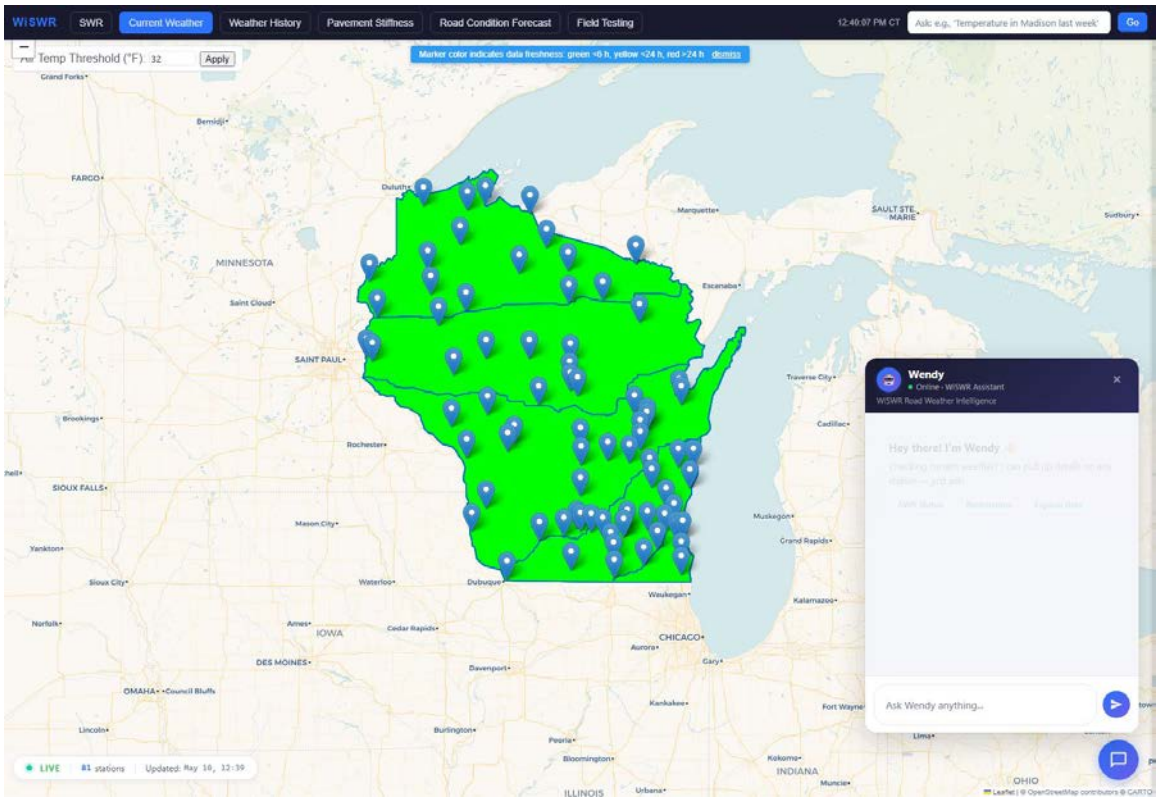


Figure F-2 Current Weather page at https://wiswr.org/current/

F.7 Service 3: Weather History

Click Weather History to see a two-year trailing air-temperature time series at each RWIS station. The two-year window is the default; for routine SWR review the most informative segment is the most recent three to five months, which can be viewed by scrolling the chart's time axis. **Figure F-3** shows this page.

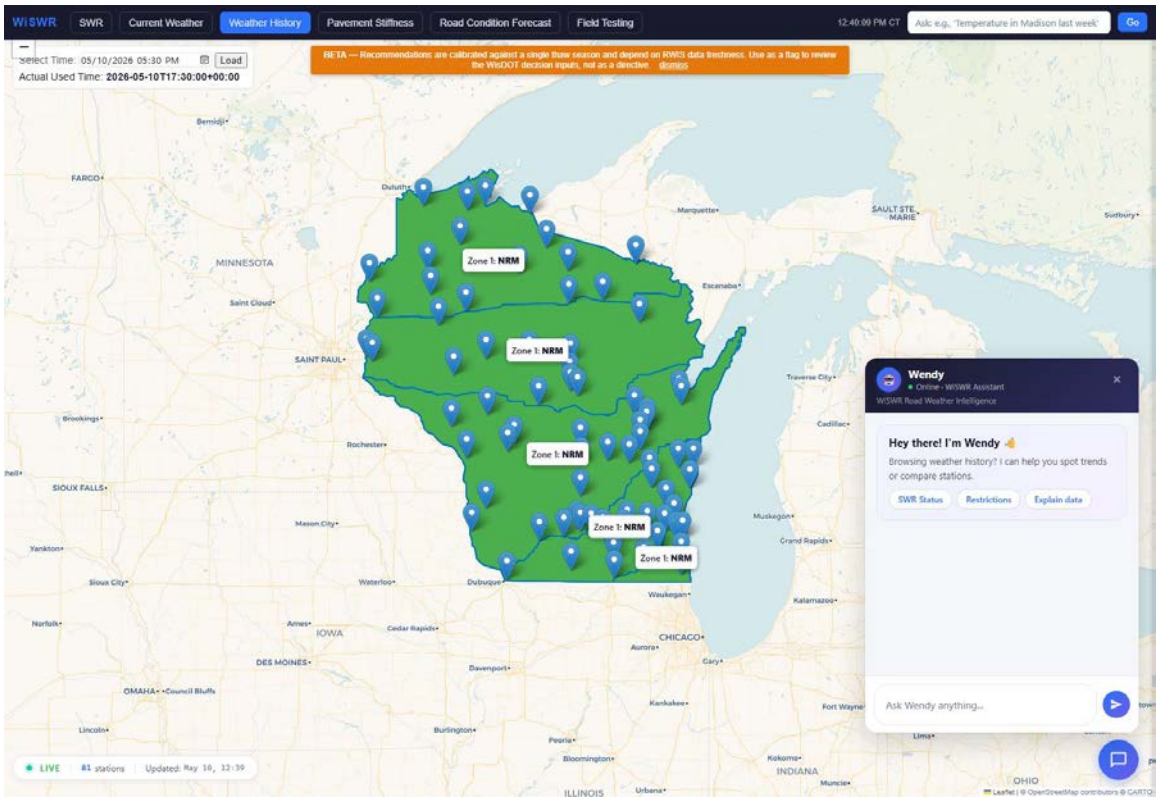


Figure F-3 Weather History page at https://wiswr.org/weather/

F.8 Service 4: Pavement Stiffness Map

Click Pavement Stiffness to see the resilient modulus (M_r) at each of the eight WHRP-instrumented sites. The map shows each site as a blue marker. Click any marker to open the per-station detail panel on the right side of the screen. The panel includes a multi-depth time series chart (M_r at 0.5 ft, 2.0 ft, and 5.0 ft) showing the seasonal freeze-thaw cycle in psi. **Figure F-4** shows this page.

How to read the trend chart: **From mid-October** the curve rises as the pavement cools. From about January 22, the curve enters the frozen plateau where M_r is at its annual peak (this is the WisDOT Frozen Roads Declaration period; on Zone 4 historical averages the plateau runs January 22 through March 1). Starting March 1 the curve drops steeply: this is the SWR (Class II) thaw weakening window, which on Zone 4 averages runs through April 16. After April 16 the curve gradually recovers from the thaw minimum back to the summer baseline, then the cycle repeats. The decision thresholds are $M_{r,FRD}$ 1,000,000 psi and $M_{r,SWR}$ 30,000 psi (Section 5.4).

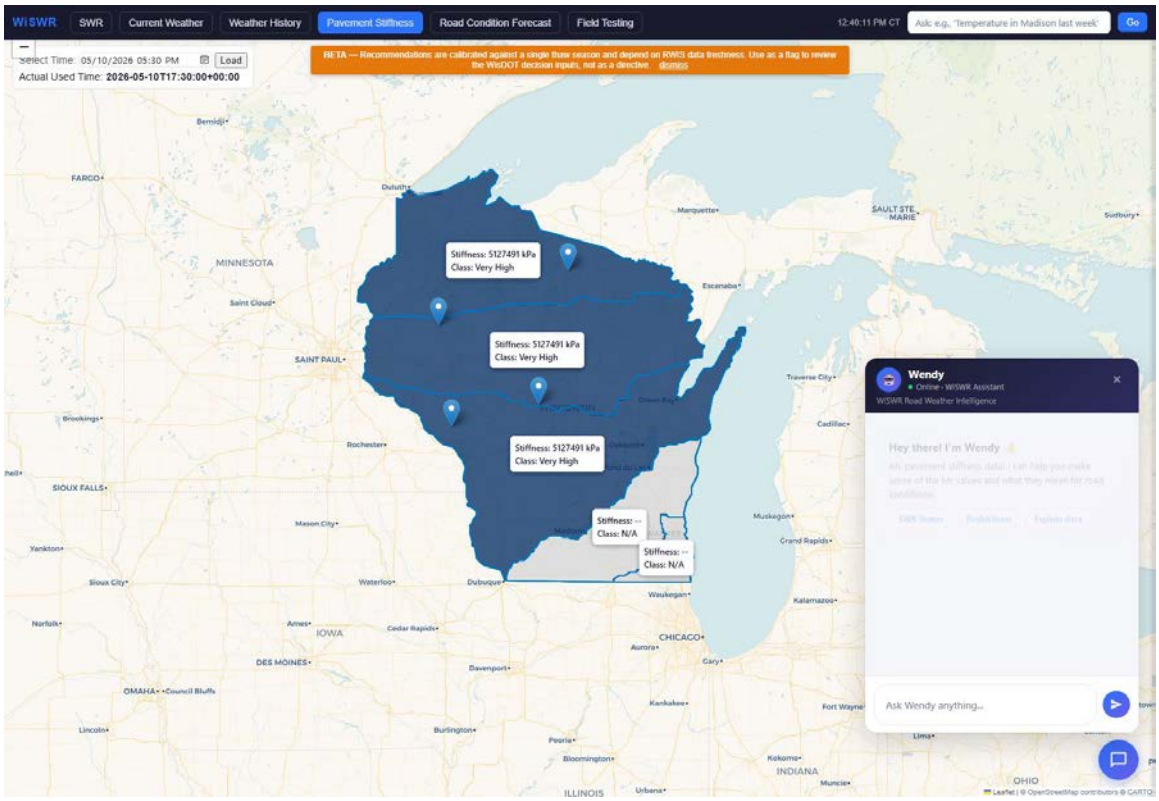


Figure F-4 Pavement Stiffness page at https://wiswr.org/stiffness/

F.9 Service 5: Road Condition Forecast

Click Road Condition Forecast to see a seven-day-ahead practice forecast for each zone. Each row of the forecast table is one day, color-coded by the predicted practice category. The forecast is generated by combining the surface-temperature forecast from the national-weather feed with the threshold logic documented in Section 5.4; it is a planning aid, not an engineering decision. **Figure F-5** shows this page.

Below the threshold-based forecast, the page shows a Vib-Net deep-learning stiffness curve for each WHRP-instrumented site, computed by feeding the most recent accelerometer record from the few instrumented sites into the preliminary Vib-Net model along with each of the next seven days' forecasted surface temperatures (Vib-Net is a per-site research feature available only where vibration instrumentation exists; the public zone-level map and forecast values come from the temperature-calibrated index, not from Vib-Net, and the two are expected to differ). The curve

gives a quick read on whether the predicted stiffness path crosses the WisDOT thresholds within the forecast horizon.

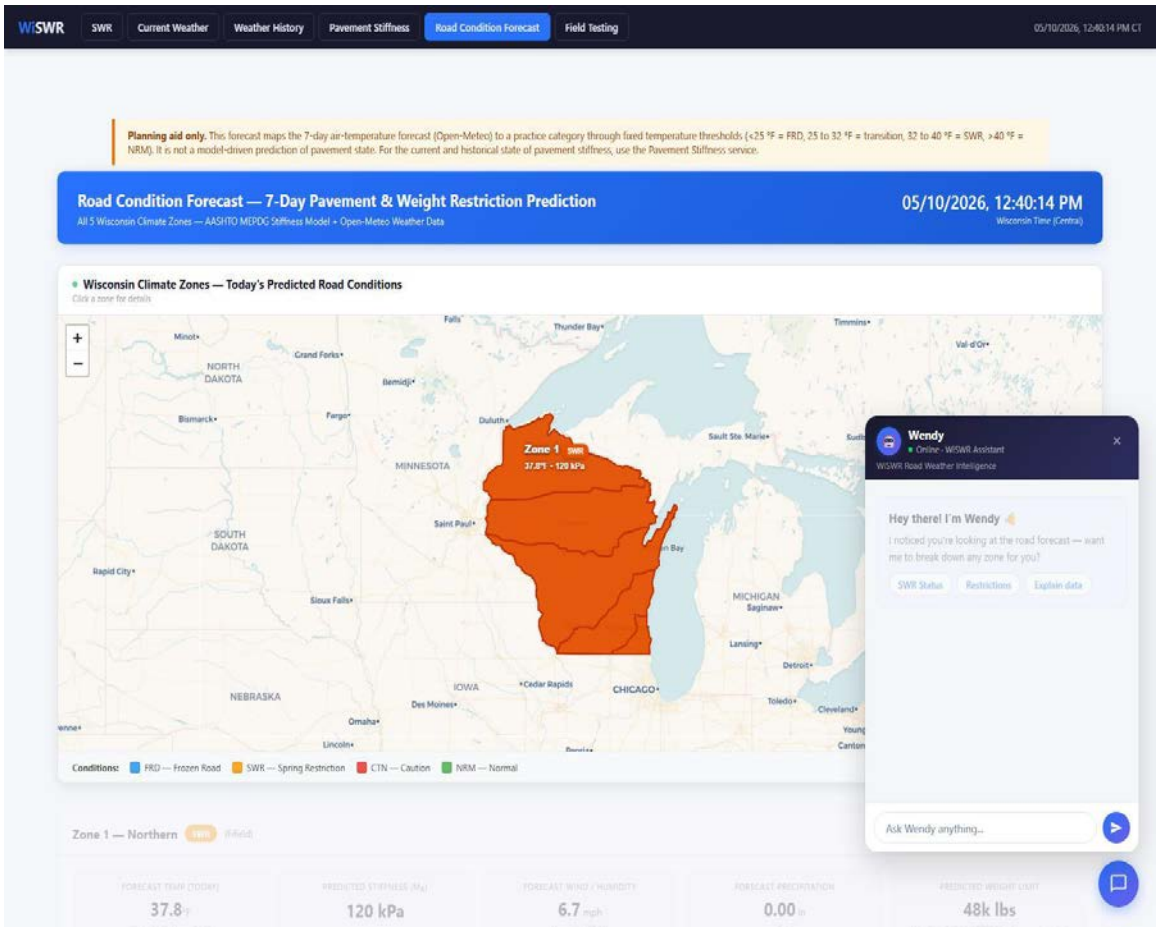


Figure F-5 Road Condition Forecast at https://wiswr.org/forecast/

F.10 Service 6: Field Testing

Click Field Testing to see the field-testing locations. As the on-page legend indicates, the page shows two datasets: blue markers for the eight WHRP-instrumented sites of the 2024 campaign (with photos, coordinates, county, and zone) and orange markers for the eight additional counties of the 2026 testing campaign. Use this page when you want to look up a specific site's installation details before interpreting the trend chart on the Pavement Stiffness page. **Figure F-6** shows this page.

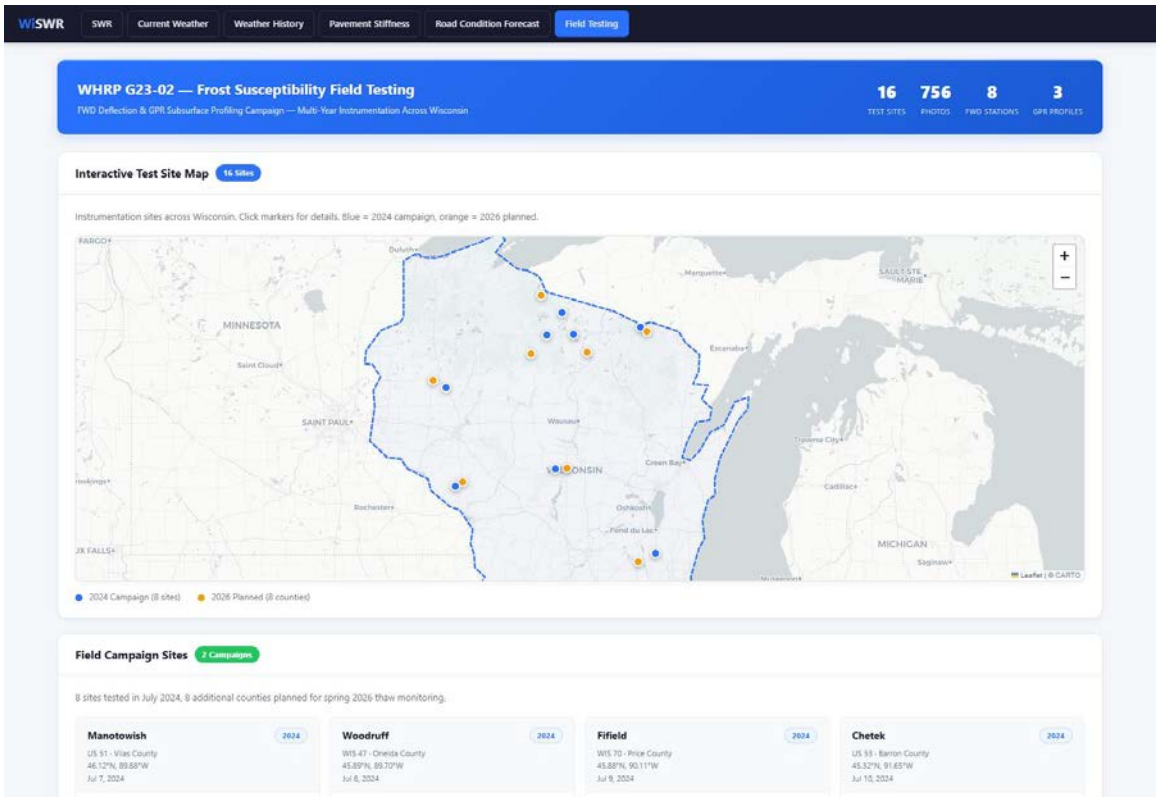


Figure F-6 Field Testing page at https://wiswr.org/fieldwork/

F.11 Wendy: ask questions in plain English

On every page a small orange button appears in the lower-right corner of the screen. This is Wendy, a natural-language assistant. Click the button and type a plain-English question. Wendy answers from the same JSON data feeds that drive the maps and the tooltips. Example questions: "What is the current SWR status in Zone 2?", "Why is Site 7 marked amber today?", "When was Class II posted in Zone 1 last year?". If the question is outside the WiSWR scope, Wendy will say so and link to the most relevant page.

F.12 Using WiSWR on a phone

Open https://wiswr.org in your phone's browser. The site auto-adapts to phone screen sizes. The top navigation bar scrolls horizontally; swipe left across the bar to reach tabs that do not fit. Pinch on the maps to zoom; tap any marker for the per-station detail card. Wendy's chat button stays in

the lower-right corner of the screen on phones as well; it is positioned to avoid the iPhone home indicator and the Android navigation bar.

F.13 Reporting issues and asking for help

If a problem with WiSWR is found or a new feature is needed, contact Zhen (Leo) Liu, Principal Investigator, at leoliu@virginia.edu (University of Virginia, Department of Civil and Environmental Engineering). The site is hosted by the project team during the contract period (project end date August 12, 2026). Two longer-term hosting paths are documented in Appendix E: a UVA-maintained option that keeps the current hosting in place, and a WisDOT-hosted option that takes approximately one work week of engineering effort to set up.