EFFECT OF TEMPORAL FWD AND PROFILE MEASUREMENTS ON DERIVED PAVEMENT PARAMETERS

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ABSTRACT

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Evaluating a pavement's structural capacity involves analyzing deflections measured by Falling Weight Deflectometer (FWD) while assessing surface roughness, estimated from longitudinal profile measurements, helps determine its functional performance. However, seasonal and diurnal changes (temperature and moisture) influence such measurements. Evaluating temporal variations and quantifying their impact on these measurements may aid in a better understanding of pavement parameters derived from these measurements.

Long-Term Pavement Performance (LTPP) Seasonal Monitoring Program (SMP) study is designed to understand environmental factors and their effects on pavement structural and functional performance. Analyzing data from the SMP study shows that FWD and profile measurement season and time of the day have a significant impact on parameters derived from these measurements. Relating the observed effects with recorded ambient temperatures helped developing general guidelines for FWD and profile measurements in different climatic regions.

The recommended temperature range for FWD testing on rigid and flexible pavements in freeze climates is 55 to 70^{o}F; 65 to 75^{o}F and 60 to 75^{o}F in the non-freeze climates for flexible and rigid pavements, respectively. The study recommends before-noon FWD testing for rigid, while no time limit within a day for the flexible pavements. Also, the research suggests a temperature range between 50 to 75^{o}F for flexible pavement profiles with no time limitation. For rigid pavements, profile measurements in the afternoon are recommended with temperature ranges of 50 to 65^{o}F, and 50 to 70^{o}F in freeze and non-freeze climates, respectively.

This thesis is dedicated to my family, my fellow graduate students, and all my mentors who supported me throughout my journey.

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CHAPTER 1 INTRODUCTION

1.1 Problem Statement

Evaluating a pavement's structural capacity involves Falling Weight Deflectometer (FWD) measurements and deflection analysis. On the other hand, assessing functional performance requires longitudinal profile measurements to estimate pavement surface roughness. These measurements are of vital importance in evaluating the structural and functional performance of pavements both at the network and project level. However, temporal variations (i.e., seasonal temperature and moisture and diurnal temperature changes) influence these measurements. Consideration of this influence over the FWD and longitudinal profile measurements is necessary for accurate assessment of the pavement condition and limiting chances of under- or over-estimating pavement structural and functional performance. Besides, the evaluation of these temporal variations and quantifying their effects on the measurements will assist in a better understanding of the derived pavement parameters: International Roughness Index (IRI) and backcalculated layer moduli based on the measured longitudinal profiles and FWD deflections, respectively.

The Long-Term Pavement Performance (LTPP) initiated the Seasonal Monitoring Program (SMP) study to better understand the environmental factors and their effects on pavement structural and functional performance. The two major environmental factors are temperature and moisture. The design of the SMP study aimed to evaluate the influence of temporal changes in the pavement structural characteristics due to the diurnal and seasonal variations of these factors. The primary measure of a change in the pavement structural characteristics is the FWD deflection data. The LTPP SMP sites were instrumented to measure the local weather, subsurface moisture, and temperature to explain the observed temporal changes in the FWD measurements. Therefore, the data can be analyzed to seek the full potential of the FWD deflection data for investigating the corresponding pavement condition for both flexible and rigid pavements.

In addition to FWD deflection measurements, the LTPP also collected daily and seasonal data on longitudinal surface profiles on the SMP test sections. The results and findings presented in published studies on LTPP data analysis showed that on some LTPP Jointed Plain Concrete Pavement (JPCP) sections, diurnal temperature variations could have a significant influence on the IRI computed from longitudinal pavement profile measurements [1-4]. Nearly all states collect roughness data on their interstate and primary highway network either annually or biennially. This collected data at the network level is used to (a) assess the current pavement condition, (b) forecast the future condition. Pavement agencies use such information to define policies, allocate and justify budget requests, and prioritize pavement rehabilitation works [2]. Variations in seasonal and diurnal IRI measurements can influence the current practices used by highway agencies to measure smoothness for payment management purposes, construction quality control, and determining construction-related pay factors. Based on such information, the LTPP implemented a program to measure diurnal changes in longitudinal profile on JPCP test sections. However, there is a need to perform statistical data analyses to quantify the impact of such measurements on the roughness indices such as IRI. Subsequently, based on the findings of such a study, the current procedures and guidelines on how to properly account for temporal variations in measured pavement parameters should be refined.

While the LTPP SMP was initiated to obtain data on the influence of temporal changes on pavement surface deflections and roughness, seasonal and diurnal data contained in the LTPP database, have not been analyzed to improve the deflection and roughness measurement practices. Besides, there is a need to evaluate the current availability of the data along with its extent to quantify the effect of temporal FWD and longitudinal profile measurements on derived pavement parameters.

1.2 Objectives

The objectives of this thesis are to;

a. Evaluate the availability and extent of current data in the LTPP SMP study database for both flexible and rigid (JPCP) pavement sections.
b. Assess the effects of temporal (seasonal and diurnal) FWD and longitudinal profile measurements on the derived pavement parameters.
c. Propose general recommendations for the improved use of FWD and profile measurements.

1.3 Outline of the Thesis

This thesis has five chapters. Chapter 1 documents the problem statement and the objectives of this thesis. Chapter 2 presents a literature review of the environmental effects on FWD and longitudinal profile measurements. Chapter 3 describes the data elements identified for the accomplishment of the objectives of this study, details of the available data, and the data extents. Chapter 4 contains the data analysis to quantify the temporal effects on each data element, an explanation of the observed effects along with some demonstrative examples to illustrate these effects. Chapter 5 summarizes the results along with general recommendations for undertaking the FWD and longitudinal profile measurements.

CHAPTER 2 LITERATURE REVIEW

2.1 Evaluating Structural Capacity of an Existing Pavement

As observed in early work on pavement deflections and fatigue failures, there is a strong correlation between pavement deflections and their ability to carry traffic loads at a prescribed minimum level of service [5]. Therefore, there is extensive use of deflection-based techniques for evaluation of the structural capacity of existing pavements and the estimation of the in-situ elastic moduli of the pavement systems.

Accurate assessment of the pavement structural condition and characterization of the materials in different layers is necessary to determine cost-effective pavement treatment types. It also helps highway agencies in the allocation of funds and resources to maintain and rehabilitate the deteriorating infrastructure. Any pavement management system, responsible for making suitable preventive and corrective decisions, largely depends on the assessment of the pavement's existing structural condition. The key to success is the proper assessment of the present condition of the pavement structure and an accurate prediction of its future performance. In either case, the characterization of the pavement properties plays a critical role [6]. The need for accurate characterization of the structural condition of existing pavements has also increased manifolds because of the technology developments, ongoing improvements, and implementation of the Mechanistic-Empirical Pavement Design Guide (MEPDG) which require several accurately defined material inputs [7].

2.2 Environmental Effects on FWD Measurements

Variations in environmental factors such as diurnal temperature, and seasonal temperature and moisture typically leads to change in the pavement material properties. Properties that get influenced by the changes in the environmental factors include the moduli values of asphalt bound materials or unbound materials such as base and subgrade.

2.2.1 Temperature Effects on AC Materials

The seasonal and diurnal variation of asphalt pavement temperature is related to environmental factors such as air and pavement surface temperature. The stiffness of an AC layer is directly related to its temperature. The temperature dependent property of AC materials results in diurnal and seasonal variations in their structural performance. Internal temperature changes within the AC layers caused by fluctuations in air temperature and solar radiation are the primary cause of the changes in their moduli and thus, the structural performance of AC materials. Besides, a part of the changes in stiffness can also be related to binder properties that change over time because of age hardening and micro-cracking [8]. Pavement surface temperature, therefore, is a critical factor that requires due consideration as part of any pavement deflection testing program.

A significant amount of work is available on the temperature correction of the FWD data. Temperature corrections have been applied to the measured FWD data on raw deflections [9-12], deflection basin parameters [8, 11, 13], or on the backcalculated modulus [14]. These temperature corrections make use of non-linear correction functions of temperature empirically. However, a work by Fernando et al. pointed out that temperature correction of the FWD deflections may not be suitable for project-level analysis because such correction methods alter the actual shape of the deflection basin. Instead, it recommends temperature correction of the backcalculated modulus [14]. Other literature also showed that correcting the raw FWD deflections or deflection basin parameters could be problematic because of the highly empirical, non-linear functions used for temperature correction [12].

Since AC materials, by nature, are viscoelastic (VE), their modulus values depend on temperature and loading time (or frequency). According to the well-established theory of viscoelasticity, the effect of time and temperature on the behavior of a linearly viscoelastic material can be addressed using the Time-Temperature Superposition Principle (TTSP). Although the TTSP may offer a more mechanistic means for temperature correction of the AC modulus, the use of this approach is not in practice due to the challenges associated with back-calculating the time- or frequency-dependent dynamic modulus (|E*|) from FWD time history data.

Recent developments in dynamic/ VE back-calculation methodologies have shown potential for back-calculating the time- or frequency-dependent E(t)/|E*(f)| of asphalt concrete from FWD load and deflection time histories. Contrary to static solutions, dynamic back-calculation methodologies involve wave propagation-based theories that can model the stress wave propagation within a pavement structure more realistically. Also, the elastic-viscoelastic correspondence principle can be used to consider the viscoelastic nature of the asphalt materials [15].

ViscoWave, a new finite layer solution recently introduced, can model the dynamics of a variety of flexible pavement structures, including elastic/ VE layers, with or without a stiff layer, and with or without free vibrations [16, 17]. Besides, the preliminary back-calculation performed (see Figure 1 and Figure 2), using ViscoWave has also shown the potential for back-calculating the VE |E*| and, the master curve of the asphalt from the FWD time histories (see Figure 3) [17].

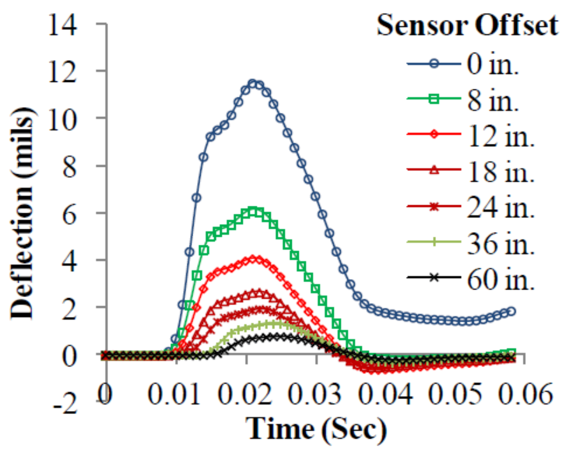


Figure 1 Measured FWD deflection time histories [17]

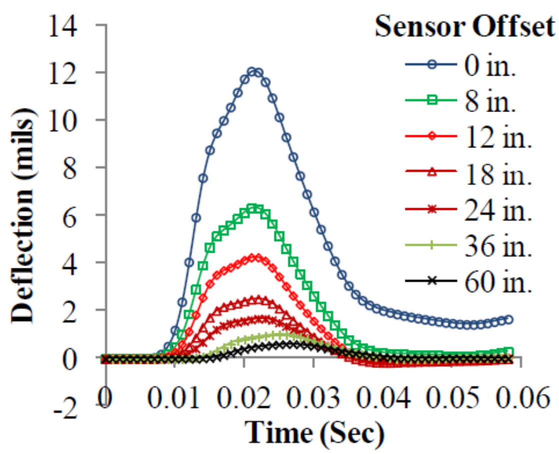


Figure 2 Backcalculated deflection time histories [17]

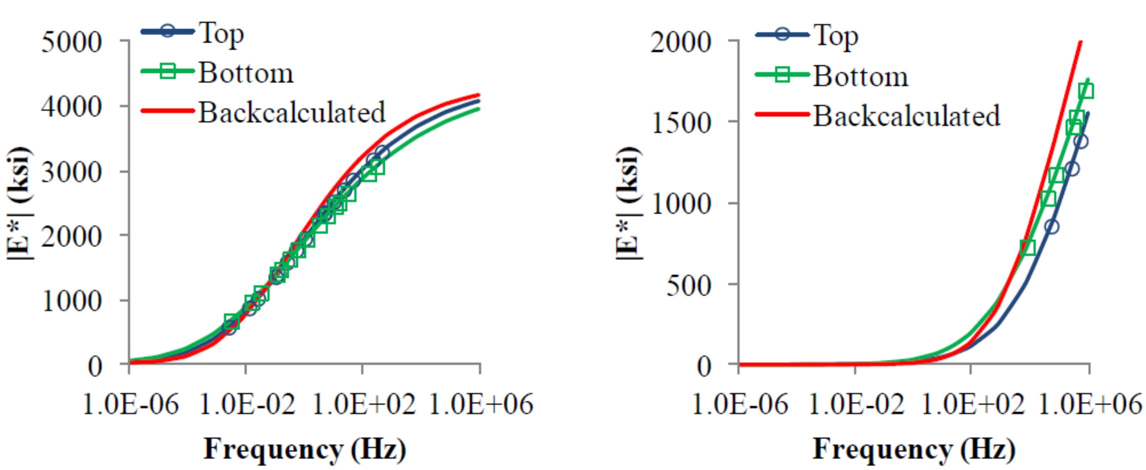


Figure 3 Backcalculated dynamic modulus master-curves at high and low temperatures [17]

2.2.2 Environmental Effects on Unbound Materials

Resilient modulus (MR) characterizes unbound materials used as a base, subbase, and subgrade layers in pavement structures. MR of the material is a function of its density, the applied stress, and moisture content and is generally assumed to be temperature independent property. The density of the unbound material may vary with time (related to rutting). However, it is usually considered constant in pavement design. Therefore, stress level and moisture variations are of primary interest with regards to changes in unbound material resilient moduli values.

A Kansas study investigated the seasonal variation of pavement material properties and behavior due to the changes in temperature and moisture. Temperature, moisture content, and FWD data were collected every month on four asphalt pavement sections for a year. The subgrade moduli were backcalculated using elastic layer theory using two different calculation schemes; MODULUS and AASHTO equations. Back-calculation of the subgrade moduli involved dividing the subgrade layer into two sub-layers; a compacted subgrade layer and a natural soil subgrade layer. The compacted subgrade layer resulted in being more sensitive to seasonal variations at all the sites. Although the seasonal temperature variations are expected not to affect the subgrade moduli values; however, the study observed that increasing temperature had a significant effect on the subgrade moduli values. The subgrade moduli value decreased with increasing temperature. The observed behavior was due to the temperature effects on the stiffness of the AC layer in a pavement structure, which in turn influences the deviatoric or bulk stresses in the subgrade layer. The increasing temperature softens the AC layer, thus increase the bulk stress. The increase in bulk stress resulted in a decrease of subgrade moduli values, as the subgrade soils were cohesive (silty clay soils). The study also concluded that the subgrade moduli calculated from FWD measurements taken at unusually higher pavement surface temperatures resulted in lower backcalculated subgrade moduli irrespective of the backcalculation scheme used. A possible reason is a violation of the linearity assumption resulting from variable deviatoric stresses on the subgrade. The monthly backcalculated subgrade moduli using AASHTO and MODULUS (combined), as seen in Figure 4 varied; however, the effective roadbed soil resilient moduli computed with AASHTO algorithm yielded similar results irrespective of the calculation scheme used. Based on this finding, the study recommended three FWD measurements (i.e., at 4-month interval) to capture the seasonal subgrade response [18].

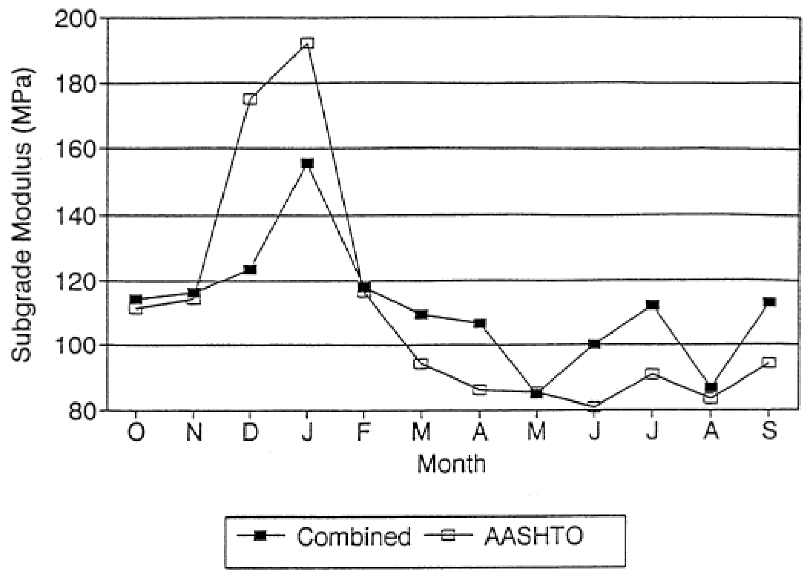


Figure 4 Monthly comparison of combined (MODULUS) and AASHTO subgrade moduli for Station 1 on US-160 [18]

The behavior of the unbound aggregate base (UAB) and subgrade layers are significantly affected by seasonal moisture and temperature fluctuations. These fluctuations eventually influence the overall performance of the pavements by changing the load-bearing capacity of these layers. High moisture content tends to decrease the stiffness of granular and subgrade layers, increase deflections, and, ultimately, reduce the life of the pavement systems [19]. Therefore, all pavement design procedures, including AASHTO and the MEPDG, rely on the use of M_R to characterize unbound granular and subgrade layers. A study carried out on five pavement sections in Minnesota observed the effects of seasonal moisture and temperature variations on UAB and subgrade layer. The study involved four different base/subbase aggregate material types commonly used in Minnesota. The study concluded that overall, subsurface material exhibited similar monthly moisture and temperature trends throughout the year. The moisture content increased as the temperature increased from spring to summer months; low moisture content was observed in the fall and winter months (see Figure 5). The study also observed seasonal variations in moisture content and temperature in different classes of base and subgrade material, with the highest and lowest moisture readings occurred in summer and winter, respectively (see Figure 6). Figure 7 shows the average seasonal temperature variations within the different classes of the base/subgrade layers [20].

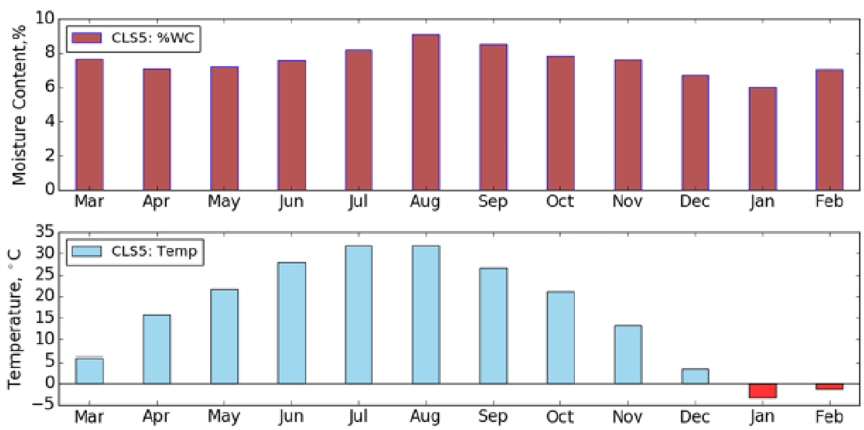


Figure 5 Monthly average moisture (top) and temperature (bottom) in a class 5 (base) layer [20]

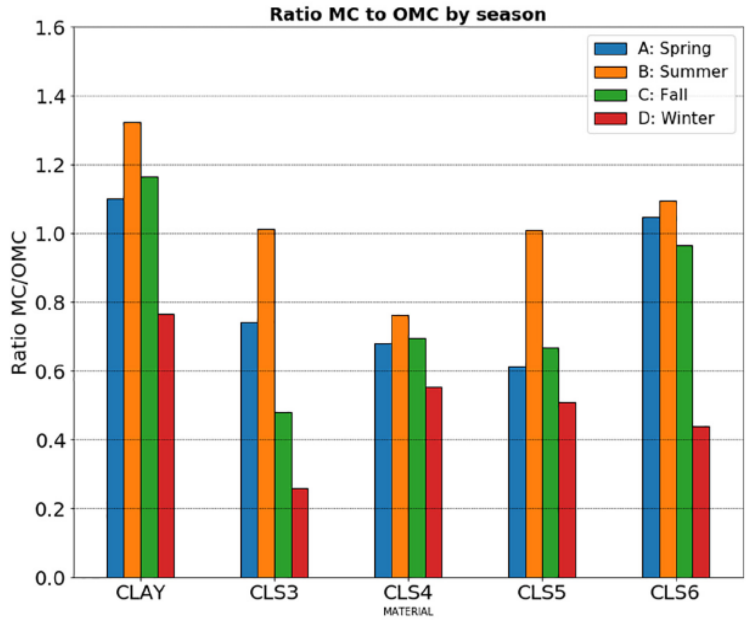


Figure 6 Seasonal average moisture variation in UAB and subgrade layers [20]

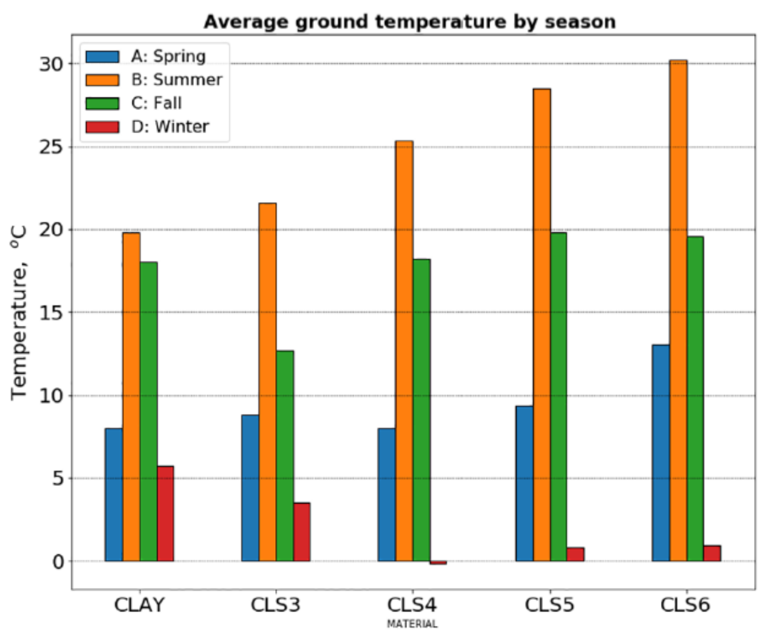


Figure 7 Seasonal average temperature variation in UAB and subgrade layers [20]

M_R is a crucial design parameter in rigid pavement design procedures as well, which is converted to the modulus of subgrade reaction (*k*) using empirical relationship in the design process. As an alternative to determining *k*-value by the static plate load test, the use of FWD is a popular choice for determining it based on measurements from the field [21]. However, seasonal temperature variations and freeze-thaw cycles affect the FWD based *k*-value. A two-year study, observing five rigid pavement sections in Iowa, concluded that mid-slab peak deflections (D_0) measured directly under the load in frozen conditions were 45% lower and were about the same once measured before freezing and during the thaw period, respectively. After thawing, D_0 values recovered to the same levels as before freezing and remained constant throughout summer. The corresponding *k*-values during the freezing period were twice as compared to pre-freeze conditions, dropped to and remained constant during the thaw period and summer, respectively [22].

Thus, seasonal variations in temperature and moisture conditions affect pavement deflection response of both flexible and rigid pavements due to the effect on the response of underlying layers. Typically, deflections are higher in the spring because of wet conditions and reduced pavement support and are lower in the winter when the underlying layers and subgrade are frozen. However, rigid pavements are less affected by seasonal variations in support conditions comparatively.

2.2.3 Environmental Effects on PCC Slab

The environmental effects on a PCC slab of a rigid pavement can unfold in two ways. One, deterioration of the concrete itself, which is generally related to concrete mixture design and construction (which is not the focus here). Two, volumetric changes that cause the concrete slab to change size in either the horizontal or vertical direction. The later is called curling, which develops due to differential volume changes across the slab thickness. The design of a JPCP involves either AASHTO [23] or PCA [24] methods. Temperature gradients (i.e., the difference between the top and bottom of the PCC slab at a particular time of the day) cause the slab to curl up or down during the night (negative gradient) and daytime (positive gradient), respectively (see Figure 9). Both upward and downward curling increases as the temperature gradients increase [25]. This curling results in loss of support at the corners or center coupled with the self-weight of the slab, and vehicle loads contribute to early-age slab cracking or even slab failure [25-27]. The distribution of the thermal stresses had been considered linear across the slab thickness historically [28]. However, now it is well known to be non-linear [25, 27, 29]. A drawback of considering non-linear thermal gradients result in under- and over-estimating the stresses during day and night time, respectively [26]. The tensile stresses on an edge and a corner position can be as high as 5.5 and 8.8 times compared to stresses induced by a standard axle; both once negative gradients occur. Such was a conclusion in a study on the effects of thermal gradients on JPCP slab behavior [30].

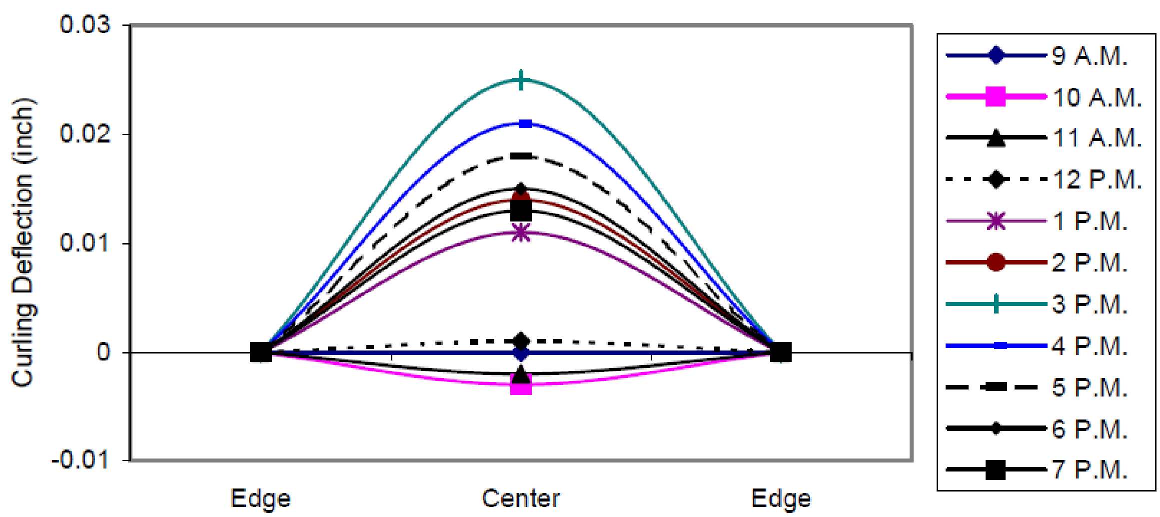


Figure 8 Measured curling on August 7, 2003 [25].

In addition to the curling of the concrete slabs due to temperature gradient, the differential moisture gradient can also induce volume changes and cause upward and downward warping in JPCP slabs [31-33]. Generally, in most cases, the top surface of the PCC slab is partially saturated while the bottom; close to saturation. Such moisture conditions produce an upward warping due to the presence of a negative moisture gradient for almost the entire duration of the day [34]. Besides warping, other moisture-related behaviors in JPCP slabs are the built-in curling and early age shrinkage, which cause the slab to curl upward within a few months after paving and remain curled up therein [27, 35, 36]. Such curling results in an increase in top-down fatigue cracking as opposed to the traditionally assumed bottom-up cracking [35]. A temperature model is proposed in a study to quantify the built-in curling in JPCP constructed in Pennsylvania. The state was divided into three climatic regions and using the developed model, monthly built-in temperature gradients in the ^{o}C/cm units were calculated [36].

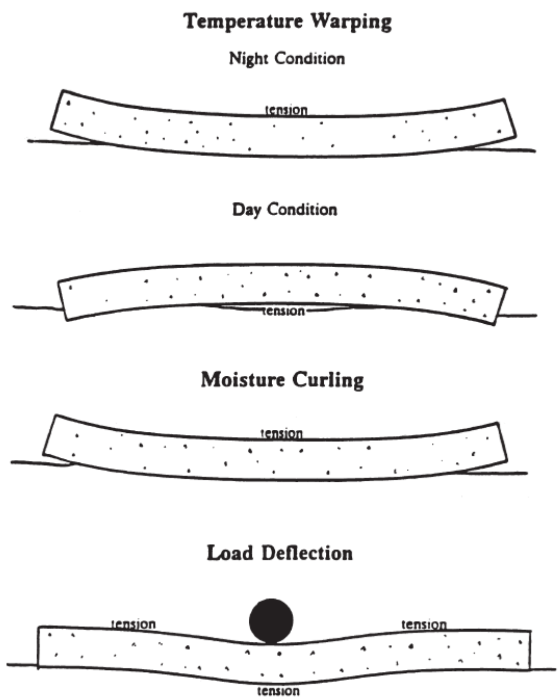


Figure 9 Tensile stress location under temperature-, moisture-, and load-related curvatures [33]

2.3 Recommended FWD Guidelines

As discussed earlier, pavement deflections under the application of load by an FWD device vary with the seasonal and diurnal variations of pavement temperature and moisture. The variability in the measured deflections influences the material properties obtained from these deflections using back-calculation analyses. The existing literature has some guidelines on how to conduct FWD measurements in the field that can help minimize the effects of temporal changes of temperature and moisture on the backcalculated pavement parameters. The current recommended FWD deflection measurement guidelines include [37]:

a. Temperature measurements should be collected during FWD testing on flexible pavements. Since HMA is a temperature-dependent material, the equivalent modulus obtained during backcalculation represents the material's temperature at the time of testing. Having accurate temperature data helps to determine the correction factor to apply to the backcalculated HMA modulus to obtain a value at a standard temperature (typically 21°C (70°F)) for use in design.

b. FWD testing on PCC pavements must consider the temperature at the time of the testing. Ideally, testing should be performed at a time (typically night or early morning hours) when the slab is flat (i.e., when the slab edges or center are not lifted off the base). However, this may be impractical for an agency that must test many kilometers (miles) of pavement every day. In general, deflection testing on PCC pavements should be conducted when the ambient temperature is below 27 °C (80 °F). While the backcalculation procedures for PCC pavements do not currently incorporate temperature corrections, such measurements are useful in evaluating backcalculation results for PCC pavements. This information is useful to determine the potential for slab curing severity that may be affecting the results. Also, knowledge of the temperature conditions at the time of testing assists in evaluating LTE data.

c. Air and surface temperature should be recorded at each test location, and most FWD equipment has temperature sensors for obtaining such data. The daily average temperatures for five days preceding testing should also be obtained, mainly if the air and surface temperatures will be used to predict the mean pavement temperature.

d. For rigid pavements, it is essential to obtain the temperature gradients. Such data can be obtained by drilling holes at various depths and measuring temperatures with thermometers. A minimum of three temperature readings, roughly correlated with the beginning, middle, and end of testing, should be obtained for smaller projects with shorter testing times.

A recent Federal Highway Administration (FHWA) study [6] regarding FWD data collection to conduct viscoelastic and dynamic analyses of deflection data recommended:

a. The temperature of the asphalt concrete (AC) layer needs to be collected during the FWD testing, preferably at every 2 inches of depth of the AC layer.

b. Either a single FWD run on an AC layer with a large temperature gradient or FWD runs at different temperatures can be sufficient to compute the relaxation modulus, $E(t)$ and the dynamic modulus, $|E^*|$ master curve of asphalt pavements.

c. Tests should be conducted at a minimum of two different temperatures, preferably 18 °F or more apart. FWD data collected at a set of temperatures between 68 and 104 °F will maximize the accuracy of backcalculated $E(t)$ or $|E^*|$ master curve up to less than 10-percent error.

d. For backcalculation, using a single FWD test dataset at a known AC temperature profile, the FWD test should be conducted under a temperature gradient of preferably ±9°F or more.

e. Either temperature variation with depth needs to be measured (and included in the analysis) or the FWD test (with multiple pulses) needs to be run at different pavement temperatures (e.g., different times of the day) to obtain the time-temperature shift factor coefficients.

The above recommended FWD measurement guidelines mostly cover the seasonal or diurnal variations of pavement temperature and moisture so that the influence of these variations on material properties may be quantified by using backcalculation analyses.

2.4 Evaluating Functional Performance of an Existing Pavement

One of the essential elements of any pavement management system is a means to measure the performance of the pavement system in terms of surface roughness, distresses, and other properties. The use of devices that measure the longitudinal profile of the pavements to assess its surface roughness is common in most of the pavement management systems. When longitudinal profile measurements are used to determine the functional condition of the road surface, these are always summarized by an index that reduces the thousands of elevation values into a single value. The IRI was developed in research sponsored by NCHRP and the World Bank and is the most broadly used index [38, 39]. However, no matter which index is calculated from a longitudinal profile, the quality of the information is only as good as the profile measurement [2].

2.5 Environmental Effects on IRI Measurements

Similar to surface deflections measured by FWD, diurnal and seasonal temperature and moisture variations also influence the longitudinal profile measurements. As compared to flexible pavements, this effect can be more pronounced for rigid pavements due to curling and warping of slabs. Concerns for measuring longitudinal profiles related to the environmental variables (i.e., temperature and moisture), as documented in an NCHRP report, include several aspects of the pavement surface shape that confound profile measurements, such as [2]:

a. Transverse, daily, and seasonal variations in profile all combine to make an individual measurement a mere sample of the road shape.
b. The lateral position of the measurement has a strong influence on the longitudinal profile because the pavement surface shape changes across the lane.
c. In PCC pavements, roughness variations of 10 percent are common over a 24-hour cycle.
d. Thin asphalt pavements over a granular base are subject to large temporary increases in roughness in winter caused by frost heave.

An FHWA study examined the roughness and roughness progression of 21 rigid pavement test sections on the LTPP Specific Pavement Studies-2 (SPS-2) experiment site in Arizona over the first 16 years of the experiment. The site included 12 test sections from the standard experiment and nine supplemental test sections selected by the Arizona Department of Transportation [3]. The findings of the investigation showed that:

a. Traditional profile analyses revealed roughness is caused by transverse and longitudinal cracking on some test sections and some localized roughness caused by built-in defects.
b. Detailed profile analyses showed that curl and warp contributed significantly to the roughness of many of the test sections.
c. Surface roughness did not increase steadily with time because of diurnal and seasonal changes in slab curl and warp.

To better understand the effects of curling and warping, the study documented an objective profile analysis method known as the Second Generation Curvature Index (2GCI) analysis procedure for quantifying the level of curl and warp on each section. Automated algorithms estimated the gross strain gradient needed to deform each slab into the shape present in the measured profile in terms of a pseudo strain gradient (PSG) value. The average PSG values summarized the levels of curl and warp within each profile. For the JPCP test sections, variations in average PSG over time explained many of the changes in roughness over time. Such changes include diurnal variations in slab curl. The overall curl and warp levels increased throughout the life of the pavements with corresponding increases in the roughness [3, 40, 41].

According to the study, the roughness on a JPCP has two components; (a) a curvature-related component (i.e., due to curling/ warping), (b) a non-curvature-related component (i.e., due to pavement distresses). Based on the procedure developed, the diurnal changes in slab curvatures were analyzed in terms of PSG and plotted in a global curvature plot, as shown in Figure 10, which demonstrates the effect of diurnal measurements on the shape of the slab, hence its roughness. According to the study, the diurnal impacts of slab curling on a Half-car Roughness Index can be as high as 0.63 m/km averaging around 0.16 m/km. This finding makes it essential to emphasize the time of roughness measurement in specifications, primarily where agencies use incentive-disincentive specifications. The diurnal impacts on roughness can also affect maintenance programming as it is likely that the estimated pavement functional condition may vary significantly, depending on survey timings and pavement curling characteristics. The study also reports significant diurnal variations in joint edge geometry (see Figure 11) [40].

In a recent study, a new method of separating the curvature- and non-curvature-related IRI have been proposed using only a single profile measurement. The new approach builds on the existing 2GCI analysis procedure; however, it eliminates the need for establishing linear regression between IRI and PSG, which requires multiple surveys of the same pavement section with slabs subjected to different thermal gradients. The study also showed the diurnal and seasonal variation in IRI for a JPCP section, as shown in Figure 12, where the diurnal variation in IRI measured on a particular day is as significant as the seasonal variation assessed from the dataset [42].

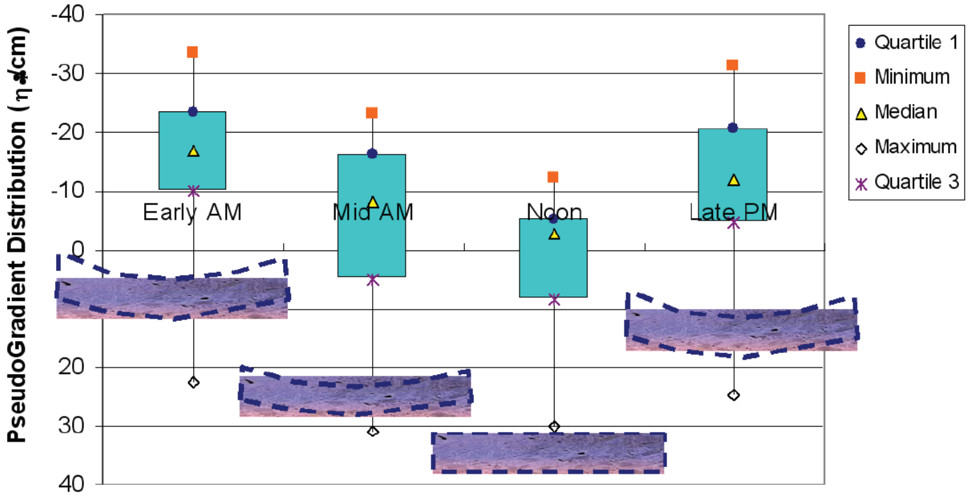


Figure 10 Diurnal curvature analysis [40]

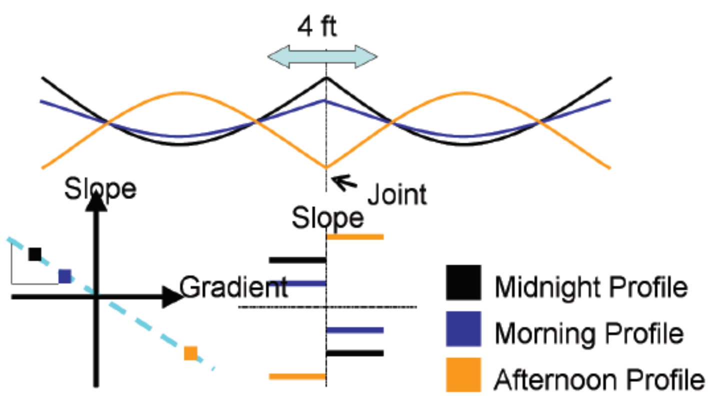


Figure 11 Joint functionality analysis showing diurnal effects [41]

Another investigation on flexible pavement longitudinal profiles in Michigan showed the effects of seasonal variations on profile measurements, especially frost action [1]. According to the study, pavements subject to frost action are rougher in the winters as opposed to summers. On the other hand, a pavement not exposed to frost action behaves oppositely; it tends to be rougher in summer than in winter. Moreover, the study results illustrated that using a longitudinal profile has far greater utility than simply determining pavement surface roughness. The winter and summer longitudinal profiles of three flexible and composite pavements were used to determine the cause of deterioration, appropriate maintenance, rehabilitation, and reconstruction treatments to improve ride quality.

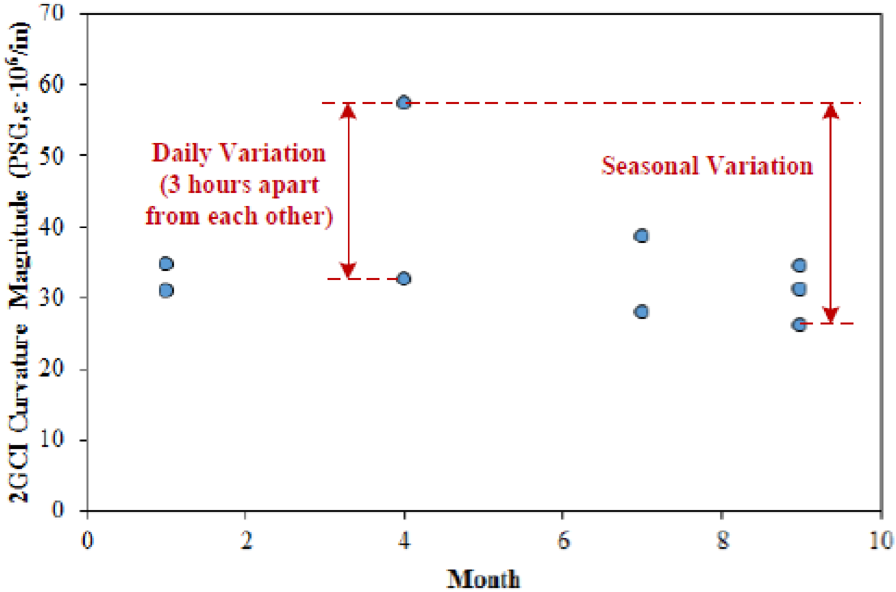


Figure 12 Pavement IRI plotted against curvature index for LTPP section 04-0215 (Based on profiles collected in 1997) [42]

2.6 Summary

Literature shows that there is an essential influence of the seasonal and diurnal FWD and longitudinal profile measurements, which ultimately translates into the parameters obtained from these measurements: IRI and the different pavement layers moduli. Consideration of such effects is essential to know the pavement condition accurately. Also, the correct interpretation of the IRI will help agencies manage the pavements systems more effectively.

Thus, there is a need to evaluate and quantify these effects. Also, based on the analysis, formulation of the general guidelines for the FWD and profile measurements are needed, which could help agencies in better interpretation of the obtained deflections and profiles.

CHAPTER 3 DATA EVALUATION

The data to be used for this work should have multiple FWD and longitudinal profile measurements, both within a day to evaluate the diurnal effects and over a year for the evaluation of seasonal effects. For example, the needed data should include multiple FWD and profile measurements for the same sections during a day to capture morning (i.e., before noon) and afternoon temperature variations and the impact of such changes on slab curling for rigid pavements. Therefore, data from the LTPP SMP study were used to accomplish the objectives of this thesis. The data were evaluated to (a) identify the required data elements, (b) quantify the various attributes to determine its suitability and appropriateness.

The three major tasks set up to accomplish the objectives are summarized below.

a. **Task 1**: Identify the data elements required for accounting for the effect of temporal variations on FWD and longitudinal profile measurements.
b. **Task 2**: Review the contents of the LTPP SMP study database and discuss the availability of the data elements identified in Task 1.
c. **Task 3**: Analyze the data, determine the findings, and recommend guidelines related to FWD and longitudinal profile measurements.

3.1 Task 1: Identification of Data Elements

Temperature, moisture, and freeze/thaw related changes in pavement layers within a day and over a year can have a significant impact on the structural characteristics of pavement layers. Such variations in temperature and moisture can influence the material properties of pavement layers and, therefore, affect the response of the pavement structure under traffic loads, and ultimately the life of the pavement. However, the magnitude and relationship of these effects are not fully understood, making them difficult to address with any degree of confidence, in pavement design and evaluation. The LTPP SMP study can overcome this limitation.

The primary objective of the SMP study is to provide data needed to attain a fundamental understanding of the magnitude and impact of temporal variations in pavement response and material properties due to the separate and combined effects of temperature, moisture and frost/thaw variations. The SMP experiment data and subsequent analysis can provide [43]:

a. "The means to link pavement response data obtained at random points in time to critical design conditions;
b. The means to validate models for relationships between environmental conditions (e.g., temperature and precipitation) and in situ structural properties of pavement materials; and
c. Expanded knowledge of the magnitude and impact of the changes involved."

Parallel to the above goals, the SMP data may also assist in developing guidelines for FWD and longitudinal profile measurements to account for seasonal and diurnal temperature and moisture variations.

The LTPP SMP test sections were instrumented and monitored temperature and moisture at a higher rate than the regular measurement intervals for deflections, distresses, and longitudinal profiles. Table 1 shows the list of devices that were used to instrument the SMP sections. The table also indicates the data item that was measured by each device for sections in the SMP study [44]. The critical elements of the monitoring plans for the SMP study include [43]:

a. Deflection basin testing to evaluate temporal variations in structural properties
b. Load transfer testing on joints and cracks in rigid pavements for monitoring load transfer conditions

c. Joint faulting and joint opening measurements, for determining the effects of temperature variations on joint condition

d. Surface elevation measurements for evaluating the effects of frost heave and swelling soil

e. Transverse and longitudinal profile measurements for characterizing pavement rutting and roughness

f. Distress surveys for monitoring the progression of pavement distress over time.

g. In-situ ambient temperature and precipitation measurements over time

h. Subsurface temperatures and moisture contents with depth over time

i. Frost and thaw depth measurements, where applicable, for defining changes in support conditions over time

Table 1 Devices used for measurements specific to SMP test sections [44]

Measurement Device	Measured Data Item
Time-Domain Reflectometry	Subsurface moisture changes
Thermistor Probes	Subsurface temperature changes
Electrical Resistivity	Frost/thaw depth
Piezometer	Groundwater table determination
Air Temperature Probes	Ambient temperature
Tipping-Bucket Rain Gauge	Precipitation

For evaluating the temporal (i.e., diurnal temperature and seasonal temperature/ moisture) effects of FWD and longitudinal profile measurements on derived pavement parameters, e.g., pavement layer moduli or IRI, the first step was to identify the required data elements. Based on the discussion presented earlier in this section, several data elements, needed to accomplish the objective of this thesis, were identified in the LTPP SMP study database. Of particular interest were the pavement structure data, pavement site-specific data, over time monitored performance data, and pavement deflection data along with derived parameters. Additionally, the longitudinal profile data measured overtime for all the flexible and JPCP sections included in the LTPP SMP study. The LTPP Standard Data Release (SDR) 33 (the most up-to-date version of the available data) was examined and used in this study. The identified data elements were extracted from the LTPP InfoPave, imported into a Microsoft Access® database, and stored in different data tables. These tables were set up as a relational database so that these can be manipulated and linked together for various analysis purposes. These data elements are briefly listed below and summarized in Table 2, along with the used LTPP database tables and description of the contained data within the tables:

a. Pavement structure details: cross-sections, age, and material types for all pavement layers
b. Pavement site-specific data: ambient temperatures, sub-surface temperatures, sub-surface moisture, and precipitation data, and the climatic regions
c. Measured longitudinal profile data, testing dates, and timings
d. Monitored FWD deflection data, with air and surface temperatures, temperature gradients, testing dates, and timings
e. Monitored performance data over time (IRI, LTE)
f. FWD testing based derived pavement parameters (backcalculated layer moduli and k-values) with testing dates and timings

Table 2 LTPP database tables

Data Elements	LTPP Table	Description
Layer no., type, representative thickness, and material types	SECTION_LAYER_STRUCTURE	The table contains a consolidated set of pavement layer structure information for all LTPP test sections.
State code, SHRP ID, experiment name, no., assign date, const no, const. no. change reason, and de-assign date	EXPERIMENT_SECTION	It is the master control table for all test sections and project sites included in the LTPP database.
Precipitation and Climatic Regions	TRF_ESAL_INPUTS_SUMMARY	The contents of this table include average annual precipitation and freeze index, LTPP experimental climate region, and the source for this classification.
Subsurface moisture content	SMP_TDR_AUTO_MOISTURE	This table contains the volumetric and gravimetric moisture contents from TDR.
	SMP_TDR_DEPTHS_LENGTHS	This table contains information on the physical characteristics of the TDR probes, including the depth, the length of the probe, and its installation date.
Subsurface temperature	SMP_MRCTEMP_AUTO_HOUR	This table contains most of the subsurface average hourly temperature data at a series of depths.
	SMP_MRCTEMP_DEPTH	This table contains the installation depths for each temperature probe at an SMP section and the date of installation.
Mean IRI, visit date, visit no., run no., start time, cloud conditions, air temperature, average speed	MON_HSS_PROFILE_SECTION	High-speed profile computed parameters and statistics based on a 150 mm interval.
	MON_HSS_RUN_NO	Identification of each high-speed survey run during each visit
Test date, time, deflection unit identifier, point location, drop height, load, peak deflection sensor, layer temperature gradient, and depths	MON_DEFL_DROP_DATA	Peak deflection, peak load, and other drop-specific FWD measurements
	MON_DEFL_TEMP_DEPTHS	It contains the location and depth at which temperature gradient measurements were performed during FWD testing.
	MON_DEFL_TEMP_VALUES	In-pavement temperature gradient measurements obtained during FWD testing
Load Transfer Efficiency (LTE)	MON_DEFL_LTE	This table contains the load transfer efficiency (LTE) computed parameter. LTE is computed from FWD measurements at transverse joints and cracks on PCC pavements
Test date, FWD pass, average modulus, backcalculated layer number, average k-value, std. k-value	BAKCAL_MODULUS_SECTION_LAYER	Backcalculated modulus values averaged for each FWD pass.
	BAKCAL_BEST_FIT_SECTION_MASTER	Best-fit back-calculation quality measures and other non-layer specific information for each FWD pass for PCC surfaced sections only

3.2 Task 2: Data Availability and Extents

The purpose of initiating the LTPP SMP study was to measure the effects of diurnal and seasonal temperature and moisture variations on pavement structures and its response to loads. The original SMP design included 64 LTPP test sections arranged in a factorial design that covered different pavement types, subgrade types, and the climate regions. Table 3 shows the design setup under the SMP study. Planning included 48 flexible and 16 rigid sections to be part of this study. The flexible pavements were divided into two categories based on HMA thickness; thick HMA pavements with a layer thickness of greater than five inches (125 millimeters) and thin with fewer than five inches HMA thickness. Three flexible pavement test sections each were planned for every combination of the pavement and subgrade soil type (i.e., fine and coarse) in each of the four climate regions (i.e., dry, freeze (DF), dry, no-freeze (DNF), wet, freeze (WF) and wet, no-freeze (WNF)). Moreover, one rigid pavement test section for the two pavement types (i.e., jointed reinforced concrete pavement (JRCP) and JPCP) was planned for each combination of subgrade soil type and climate region [43].

Table 3 Original SMP experiment design [43]

Pavement Type	Subgrade Soil	No Freeze		Freeze	
		Dry	Wet	Dry	Wet
Flexible – Thick AC (> 5-inch surface)	Fine	3	3	3	3
	Coarse	3	3	3	3
Flexible – Thin AC (< 5-inch surface)	Fine	3	3	3	3
	Coarse	3	3	3	3
JPCP	Fine	1	1	1	1
	Coarse	1	1	1	1
JRCP	Fine	1	1	1	1
	Coarse	1	1	1	1

Note: Number in a cell indicates the desired number of pavement sections.

Task 2 had two parts; one was to evaluate the availability of the data in terms of the sections currently present in the LTPP database as part of the SMP study, while the second was to evaluate the extent of the extracted data for the critical data element identified in Task 1.

As per SDR 33, the SMP study data in the LTPP database has 67 flexible and 22 rigid pavement sections, including six JRCP sections. Table 4 shows the number and distribution of the flexible pavement sections by HMA thickness, subgrade type, and climatic zone. The table also shows the number and distribution of JPCP pavement sections within each climatic zone. The table excludes the six JRCP pavement sections as the analysis undertaken in this thesis excluded them. Also, a significantly fewer number of sections are available in the dry climatic regions as opposed to wet climates. The same is true while comparing the available number of thin HMA flexible pavement sections with thick HMA sections.

Table 4 Available pavement sections in the LTPP SMP database

Pavement Type	Subgrade	DF	DNF	WF	WNF	Total
Flexible - Thick (HMA > 5 inches)	Fine	4	-	3	4	11
	Coarse	4	6	26	6	42
	Subtotal	*8*	*6*	*29*	*10*	*53*
Flexible – Thin (HMA < 5 inches)	Fine	-	-	2	3	5
	Coarse	1	1	2	5	9
	Subtotal	*1*	*1*	*4*	*8*	*14*
Total Flexible		9	7	33	18	67
JPCP		2	2	6	6	16

After the availability of the pavement sections in the LTPP SMP study database was evaluated, the next part of Task 2 was to assess the extent of the available data. The later part of this section presents the assessment of the extents of the data for each data element identified in Task. It is noteworthy that the precipitation data confounds within the climatic regions.

3.2.1 Pavement Cross-Sections

Pavement cross-section is one of the vital property which has a significant bearing on its performance. Tables 5 and 6 show the descriptive statistics regarding the pavement structures within each climatic region for the 67 flexible and 16 JPCP pavement sections currently available within the LTPP SMP study, respectively.

Table 5 Layer thicknesses of flexible pavement sections located in different climates

Layer Type	Thickness Statistics, in	DF	DNF	WF	WNF
Available Sections		*9*	*7*	*33*	*18*
HMA	Average	5.69	6.43	7.18	5.59
	Std*	2.46	2.05	2.41	3.00
	Minimum	2.80	4.40	1.40	1.00
	Maximum	10.70	11.00	14.30	11.30
Base	Average	10.40	14.39	13.36	10.66
	Std	5.41	7.48	6.38	4.64
	Minimum	5.40	6.30	4.00	4.80
	Maximum	22.80	24.00	25.80	24.00
Subbase	Average	21.82	24.00	24.19	20.78
	Std	6.13	0.00	5.78	10.31
	Minimum	2.50	24.00	7.80	1.60
	Maximum	24.00	24.00	66.00	39.00

* Standard deviation.

3.2.2 FWD Based Parameters

The primary objective of the data mining was to obtain the availability of FWD deflection based parameters during a given day and in different seasons for all the SMP pavement sections. This section presents the data extents of all such critical pavement parameters identified in Task 1. These parameters include the backcalculated HMA, base, and subgrade layer moduli for the SMP flexible pavement sections and PCC layer moduli, *k*-value, and the LTE for SMP JPCP sections.

The BAKCAL tables of the LTPP database were used to summarize the available number of backcalculated moduli values for each pavement layer within the pavement structure. Table 7 shows the available FWD backcalculated moduli values for flexible pavement sections by the number of passes on the same day. The data includes FWD tests performed between the years 1989 to 2012. An FWD pass serves to distinguish multiple runs of the same lane number on the same day [44]. The results show that several flexible pavement sections contain multiple FWD passes on the same day. Most pavement sections have at least three passes per day. A few test sections have more than five FWD passes on the same day.

Table 6 Layer thicknesses of JPCP pavement sections located in different climates

Layer Type	Thickness Statistics, in	DF	DNF	WF	WNF
Available Sections		*2*	*2*	*6*	*6*
PCC	Average	10.70	10.16	9.79	9.34
	Std*	0.74	1.07	1.19	0.97
	Minimum	10.20	8.80	8.40	8.00
	Maximum	11.80	11.00	11.80	11.20
Base	Average	4.69	5.62	7.22	6.68
	Std	1.02	0.87	4.39	2.47
	Minimum	4.00	4.50	2.50	1.50
	Maximum	6.20	6.30	14.40	9.30
Subbase	Average	20.50	5.80	9.36	6.13
	Std	0.00	0.00	4.80	1.95
	Minimum	20.50	5.80	5.90	3.80
	Maximum	20.50	5.80	16.00	8.00

* Standard deviation

To further explain the table, consider the DF climatic zone as an example. There are 340 FWD test days with only one pass per day, i.e., a total of 340 FWD test runs involving all the nine pavement sections (number in parentheses). Out of those 340 test days, there were 267 test days where deflections on the section were measured for a second time, i.e., a second FWD pass on the same day; 230 test days where a third FWD pass measured deflections on the same day; 104 test days involving a fourth FWD pass on the same day. On the other hand, there were only 14 test days, which included only four of the nine sections where deflections measurement took place for a fifth time on the same day.

Pavement age and maintenance history of the pavement structure are critical factors that could affect pavement deflection response or roughness. The construction number assigned to a pavement section in the LTPP database reflects the later one. The construction number identifies changes in the pavement structure caused by the application of maintenance or rehabilitation treatments. When a test section first enters the LTPP program, it is assigned a construction number of 1. The construction number is then incremented by 1 for each subsequent maintenance or rehabilitation event regardless of its impact on the pavement structure. For example, crack sealing causes the generation of a new construction event, even though it does not create a significant change in the experiment assignment or pavement structure [44]. It is, therefore, essential to consider the construction number of the pavement section at the time of the FWD test and the corresponding measured deflections used for back-calculating pavement structural parameters.

Table 7 Available backcalculated pavement structural parameters by FWD pass—SMP flexible sections

FWD Passes	DF	DNF	WF	WNF
1	340 (9)	207 (7)	779 (33)	599 (18)
2	267 (9)	160 (5)	445 (23)	458 (17)
3	230 (9)	139 (5)	349 (14)	318 (17)
4	104 (9)	59 (5)	150 (13)	114 (17)
5	14 (4)	17 (5)	4 (3)	23 (8)

Note: Values in parenthesis are the number of sections.

Based on the discussion above, the available data presented in Table 7 were subdivided based on the construction number assigned to each flexible pavement section in the LTPP database. The maintenance and rehabilitation activities that cause a change in the construction number assigned to the pavement sections have been divided into four categories (see Table 8).

Table 8 Maintenance work categorization details

Maintenance Category	Description
0	No maintenance at all
1	Maintenance work with no significant effect on FWD deflections or profile measurements
2	Localized patchwork
3	Maintenance works with a potential effect on pavement structure or response, i.e., deflections or IRI

Table 9 shows the distribution of the available backcalculated structural parameters of the SMP flexible pavements by the maintenance category based on the assigned construction number for the different climate regions. For example, referring to Table 8, there are 340 backcalculated pavement structural parameters in the DF region for a single pass of the FWD test. Among these 340 measurements, 233 took place while the pavement sections had a construction number of 1 (newly constructed or maintenance category 0) 81 FWD measurements were undertaken after some minor maintenance works. (category 1; i.e., crack seal, fog seal, etc.) .18 measurements took place after localized maintenance/ rehabilitation works (category 2; i.e., patchworks) while, the last eight happened after a major maintenance/rehabilitation work (category 3; i.e., overlays or full-depth patchworks, etc.).

Table 9 Available backcalculated pavement structural parameters by FWD pass and maintenance category in different climatic regions—SMP flexible pavements

Maintenance category	FWD Pass	DF	DNF	WF	WNF
0	1	233 (8)*	117 (4)	382 (28)	381 (17)
	2	192 (7)	98 (4)	284 (11)	284 (14)
	3	167 (7)	80 (4)	228 (11)	208 (13)
	4	77 (7)	36 (4)	97 (11)	77 (13)
	5	8 (3)	15 (4)	3 (2)	12 (5)
1	1	81 (5)*	53 (4)	54 (5)	130 (6)
	2	61 (4)	48 (4)	42 (3)	119 (6)
	3	54 (4)	47 (4)	36 (3)	82 (6)
	4	25 (4)	15 (3)	17 (3)	31 (5)
	5	6 (1)	-	1 (1)	10 (2)
2	1	18 (3)*	17 (1)	92 (6)	21 (4)
	2	14 (3)	14 (1)	53 (3)	13 (3)
	3	9 (2)	12 (1)	44 (3)	1 (1)
	4	2 (1)	8 (1)	18 (3)	
	5	-	2 (1)	-	-
3	1	8 (4)*	20 (3)	251 (29)	67 (8)
	2	-	-	66 (14)	42 (3)
	3	-	-	41 (5)	27 (3)
	4	-	-	18 (4)	6 (1)
	5	-	-	-	1 (1)

Note: Values in parenthesis are the number of sections.
*233 + 81 + 18 + 8 = 340

Another aspect that required consideration while data mining was the distribution of the data over different months, necessary for the investigation of the seasonal effects. Similarly, the daily distribution of the data with time was essential to look at the diurnal effects. The number of the available backcalculated moduli within each month of the year was determined for each pavement section.

Table 10 shows the monthly distribution of the backcalculated layer moduli data for the flexible pavement sections. The data distribution was irrespective of the FWD pass number, maintenance category, and the year of measurement. Table 10 also shows that most of the sections have multiple FWD measurements within every month of the year. Similarly, the section-wise hourly distribution of data was also determined (see Appendix). The majority of the available FWD measurements are between 8:00 am and 4:00 pm. Preparing such data distribution helped in identifying different factors and the number of levels within each factor, which will be discussed later in the text.

Similar to flexible pavement sections, FWD deflections based parameters were summarized to isolate the effect of diurnal and seasonal measurements on rigid pavement sections (i.e., E and k-values). Table 11 shows up-to-date available data for rigid pavement sections of the LTPP SMP study that are extracted from the BAKCAL tables of the LTPP monitoring module database. The data includes FWD tests performed during the years 1989 to 2012. The table shows the available FWD measurements by different passes on the same day. As mentioned earlier, the FWD pass serves to distinguish multiple runs of the same lane on the same day [44]. The numbers in parentheses indicate the number of sections involved. The tables show that several rigid pavement sections contain multiple FWD passes on the same day, with the majority having three passes a day. Note that the number of LTE values available for the same number of SMP rigid pavement sections is double of the values shown in Table 11 since each LTE measurement requires two deflection measurements (i.e., J4 and J5).

Table 10 Monthly data distribution of backcalculated pavement parameters - SMP AC sections

Climate region	State	State code & section ID	Month												Total
			1	2	3	4	5	6	7	8	9	10	11	12	
DF	Colorado	8_1053	12	8	23	13	10	6	3	6	7	7	12	11	118
DF	Idaho	16_1010	4	9	16	15	8	8	4	5	5	6	10	6	96
DF	Montana	30_0114	9		13		13	1	25		18		12		91
DF	Montana	30_8129	2	3	23	28	13	7	7	9	8	13	9	4	126
DF	Nevada	32_0101	14	7	19	6	15	7	9	10	15	3	15	7	127
DF	Saskatchewan	90_6405			6	14	11	16	8	7	7	10	8		87
DF	South Dakota	46_0804			17	26	21	11	16	12	17	5	12		137
DF	South Dakota	46_9187	3	4	7	12	6	8	8	4	8	7	5	2	74
DF	Wyoming	56_1007	11	9	16	9	8	6	3	12	5	4	11	7	101
DNF	Arizona	4_0113	6	22	9	19	9	15	9	20	4	12	9	14	148
DNF	Arizona	4_0114	6	22	8	17	8	15	7	18		17	10	15	143
DNF	Arizona	4_1017	3	1		2					2	1	1		10
DNF	Arizona	4_1018	1	1	1						2			1	6
DNF	Arizona	4_1024	8	7	9	7	7	6	8	10	4	3	5	7	81
DNF	New Mexico	35_1112	3	11	7	11	11	9	13	9	6	6	9	8	103
DNF	Utah	49_1001	6	11	12	20	3	3		6	4	6	9	11	91
WF	Connecticut	9_1803	9	4	23	17	13	9	5	5	5	9	8	6	113
WF	Maine	23_1026	3		7	15	15	11	7	10	12	7	10	7	104
WF	Manitoba	83_1801			4	28	23	8	21	10	14	12	13		133
WF	Manitoba	83_3802				1		1							2
WF	Massachusetts	25_1002	7	6	20	18	11	17	7	3	8	2	5	6	110
WF	Minnesota	27_1018			10	11	16	10	10	13	8	8	9		95
WF	Minnesota	27_1028	5		9	8	13	8	8	5	5	8	10	3	82
WF	Minnesota	27_6251			14	28	30	9	19	11	26	13	16	3	169
WF	Nebraska	31_0114		13	8	3	13	1	16	11	9	10	10	3	97
WF	New Hampshire	33_1001	3		11	11	14	14	8	6	9	10	6	3	95
WF	New Jersey	34_0501	1	2	1	1				1	1	2	3	2	14
WF	New Jersey	34_0502	1	2	2	1				1	1	3	3		14
WF	New Jersey	34_0503	1	2	3	1				2	1	3	3	2	18
WF	New Jersey	34_0504	1	2	3	2				1	1	2	3	1	16
WF	New Jersey	34_0505	1	2	3	2				1	1	2	2	1	15
WF	New Jersey	34_0506	1	2	4	1				2	1	2	3	2	18
WF	New Jersey	34_0507	1	2	4	1				2	1	3	3	2	19
WF	New Jersey	34_0508	1	2	3	1				2	1	2	3	2	17
WF	New Jersey	34_0509	1	2	3	1				2	1	2	3	2	17
WF	New Jersey	34_0559	1	1	1	2				1	1	3	2	1	13
WF	New Jersey	34_0560	1	2	2	1				1	1	3	3	1	15
WF	New Jersey	34_0901		2	1		1				2		2	2	10
WF	New Jersey	34_0902		2	2		1				2		1	2	10
WF	New Jersey	34_0903		2	1		1				2		1	2	9
WF	New Jersey	34_0960		2	1		1				2		1	2	9
WF	New Jersey	34_0961		2	2		1				2	1	1	2	11
WF	New Jersey	34_0962		2	3		1				2	1	1	2	12
WF	New York	36_0801	4	16	21	10	19	5	15	15	13	10	11	9	148
WF	Ohio	39_0901		16	16	10	21	5	10	5	32	11	6	6	138
WF	Ontario	87_1622			4	16	11	8	8	4	9	6		1	67
WF	Quebec	89_3015					2				1		1		4
WF	Vermont	50_1002	2	3	15	25	11	22	6	14	13	11	17	5	144
WNF	Alabama	1_0101	7	5	10	8	9	8	6	6	6	11	9	6	91
WNF	Alabama	1_0102	4	4	10	8	9	6	4	6	5	11	8	7	82
WNF	Delaware	10_0102	4	6	1	8	2	3	5	6	2	13	4	4	58
WNF	Georgia	13_1005	6	6	6	4	5	4		7	8	14	10	6	76
WNF	Georgia	13_1031	8	12	3	11	10	5	3	12	12	15	8	9	108
WNF	Maryland	24_1634	7	10	2	30	7	1	3	1	5	7	3	7	83
WNF	Mississippi	28_1016	1	2	4	4	4	5	5		5	12	4	4	50
WNF	Mississippi	28_1802	4	6	4	6	6	6	7	4	8	13	10	5	79
WNF	North Carolina	37_1028	10	7	9	9	9		7	4	7	9	5	4	80
WNF	Oklahoma	40_4165	3	5	12	6	16	6	5	6	2	2	6	3	72
WNF	Texas	48_1060	11	9	9	7	10	10	7	7	6	4	7	8	95
WNF	Texas	48_1068	10	6	9	8	9	10	6	9	8	1	10	10	96
WNF	Texas	48_1077	10	9	10	8	8	10	7	7	9	11	7	10	106
WNF	Texas	48_1122	11	12	10	10	10	16	13	11	9	7	14	13	136
WNF	Texas	48_3739	7	6	14	12	9	7	11	8	7	8	6	14	109
WNF	Virginia	51_0113	5	7	11	9	5	9	7	4	5	12	9	7	90
WNF	Virginia	51_0114	12	9	16	7	7	9	12	3	14	14	7	11	121
WNF	Washington	53_3813	1												1

Table 11 Available backcalculated pavement structural parameters (E and k-values) by FWD pass in different climatic regions—SMP JPCP sections

FWD passes	DF	DNF	WF	WNF
1	54 (2)	73 (2)	153 (6)	131 (6)
2	43 (2)	59 (2)	105 (5)	85 (4)
3	14 (2)	23 (2)	37 (5)	18 (3)
4	2 (1)	1 (1)	2 (2)	2 (2)

Note: Values in parenthesis are the number of sections.

As for flexible pavement sections, the available data for JPCP pavement sections were also summarized based on the assigned construction numbers and the maintenance activities that these pavement sections have undergone. Table 12 shows the distribution of the available backcalculated structural parameters in the LTPP database by the FWD pass and maintenance category for the different climate regions. For instance, referring to Table 11, there are 54 backcalculated pavement structural parameters in the dry freeze climate region for a single pass of the FWD test. Table 12 shows that among the 54 measurements: 22 measurements happened while the pavement sections did not undergo any maintenance activity, 18 took place after some minor maintenance (i.e., crack seal), while 14 took place after significant maintenance/ rehabilitation work (i.e., PCC slab replacement and full-depth patchwork).

Table 12 Available backcalculated pavement structural parameters by FWD pass and maintenance category in different climatic regions—SMP JPCP sections

Maintenance category	FWD pass	DF	DNF	WF	WNF
0	1	22 (1)*	61 (2)	81 (6)	130 (6)
	2	19 (1)	51 (2)	54 (4)	85 (4)
	3	8 (1)	23 (2)	16 (3)	18 (4)
	4	-	1 (1)	-	2 (2)
1	1	18 (2)*	12 (1)	16 (1)	-
	2	12 (1)	8 (1)	13 (1)	-
	3	2 (1)	-	11 (1)	-
	4	-	-	1 (1)	-
3	1	14 (1)*	-	56 (4)	1 (1)
	2	12 (1)	-	38 (3)	-
	3	4 (1)	-	10 (3)	-
	4	2 (1)	-	1 (1)	-

Note: Values in parenthesis are the number of sections.
* 22 + 18 + 14 = 54

The data shown in Table 11 was also stratified in a way to know its section-wise monthly and hourly distribution, as was done for flexible pavement sections. Tables 13 and 14 presents the discussed data distribution for the JPCP sections of the LTPP SMP database irrespective of the maintenance category, age, and measurement year. It can be observed from Table 13 that 12 out of the available 16 JPCP pavement sections have multiple FWD measurements (and the corresponding backcalculated parameters) in each month. Table 14 shows that the majority of the FWD measurements lie between 8:00 am and 2:00 pm. As mentioned earlier, such data distribution tables helped in deciding the number of levels of factors used in the analysis, which will be discussed later in the text.

Table 13 Monthly data distribution of backcalculated parameters - SMP JPCP sections

Climate region	State	State code & section ID	Month												Total
			1	2	3	4	5	6	7	8	9	10	11	12	
DF	Nevada	32_0204	4	3	5	4	2	4	2	2	2	3	1	3	35
DF	Utah	49_3011	7	5	14	10	5	5	5	5	6	4	10	2	78
DNF	Arizona	4_0215	3	10	10	12	6	10	5	14	3	12	6	13	104
DNF	California	6_3042	3	4	5	6	5	4	6	5	2	2	6	4	52
WF	Indiana	18_3002	5	3	2	5	3	1	3	2	8	4	3	1	40
WF	Manitoba	83_3802			4	6	7	9	3	5	5	7	2		48
WF	Nebraska	31_3018	3	8	11	3	11		10	11	8	8	14	1	88
WF	Ohio	39_0204		3	4	4	7	5	4		5	3	2	2	39
WF	Quebec	89_3015	1	2	10	11	6	11	8	4	10	2	10	3	78
WF	South Dakota	46_3010					2			1		1			4
WNF	Georgia	13_3019	6	6	8	10	8	5	2	9	10	9	6	2	81
WNF	North Carolina	37_0201	6	5	6	7	15	2	15	4	7	10	7	7	91
WNF	North Carolina	37_0205					2						1	2	5
WNF	North Carolina	37_0208				1	2					1	1	2	7
WNF	North Carolina	37_0212				2	2					2	1	2	9
WNF	Washington	53_3813	4	2	2	4	2	2	7	4	2	4	4	6	43

Table 14 Hourly data distribution of backcalculated parameters - SMP JPCP sections

Climate region	State	State code & section ID	Hour of the day												Total
			7	8	9	10	11	12	13	14	15	16	17	19	
DF	Nevada	32_0204	1	1	8	8	4	8	4	1					35
DF	Utah	49_3011	1	7	17	13	6	17	5	5	6	1			78
DNF	Arizona	4_0215	2	16	20	20	20	13	7	4	2				104
DNF	California	6_3042	1	6	13	9	8	9	5	1					52
WF	Indiana	18_3002		7	11	7	5	6	3	1					40
WF	Manitoba	83_3802		15	8	4	6	10	4	1					48
WF	Nebraska	31_3018	2	10	20	20	13	16	4	3					88
WF	Ohio	39_0204	3	2	9	9	4	6	4	1		1			39
WF	Quebec	89_3015	1	5	15	16	15	12	11	2			1		78
WF	South Dakota	46_3010		2	2										4
WNF	Georgia	13_3019	4	10	11	15	4	17	6	5	6	3			81
WNF	North Carolina	37_0201		2	23	15	14	28	6	2			1		91
WNF	North Carolina	37_0205			1	2		1			1				5
WNF	North Carolina	37_0208			2	1				1		2		1	7
WNF	North Carolina	37_0212		1	1	1		1	3	1		1			9
WNF	Washington	53_3813	1	1	7	12	8	9	4	1					43

3.2.3 Sub-surface Temperature Data

The sub-surface temperature data from the SMP module were obtained for both the flexible and rigid pavement sections. For flexible pavements, the obtained data helped determine the HMA layer mid-depth temperature used to correct the moduli values. Table 15 shows the available data by the FWD pass that was measured within 30 minutes of the FWD test. Again, more data in the wet regions are due to a larger number of sections in these regions.

For rigid pavements, the temperature data were essential to calculate the temperature gradient (i.e., top minus bottom) for the PCC slab. Temperature gradients were calculated within ±1.25 inches of the top or bottom surface of the PCC layer. The available gradients data were matched for each FWD based parameter according to the location of the FWD test (i.e., J1, J4/J5, etc.). Tables 16 and 17 show the details of the available temperature gradients data with the FWD pass of the day.

Table 15 Available HMA layer mid-depth temperatures on FWD measurement days—SMP sections

FWD Passes	DF	DNF	WF	WNF
1	539 (9)	301 (7)	1303 (30)	1149 (17)
2	389 (9)	229 (5)	557 (19)	819 (17)
3	323 (9)	200 (5)	445 (13)	566 (17)
4	132 (9)	98 (5)	193 (13)	211 (17)
5	15 (4)	28 (5)	7 (3)	48 (8)

Note: Values in parenthesis are the number of sections.

Table 16 Available temperature gradients on FWD measurement days matched with LTE values—SMP JPCP sections

FWD Passes	DF	DNF	WF	WNF
1	37 (1)	79 (2)	113 (6)	187 (6)
2	32 (1)	57 (2)	73 (5)	121 (3)
3	8 (1)	19 (2)	21 (2)	30 (3)
4		2 (1)	1 (1)	4 (2)

Note: Values in parenthesis are the number of sections.

Table 17 Available temperature gradients on FWD measurement days matched with backcalculated moduli values—SMP JPCP sections

FWD Passes	DF	DNF	WF	WNF
1	37 (1)	85 (2)	104 (6)	164 (6)
2	35 (1)	68 (2)	74 (5)	133 (3)
3	9 (1)	23 (2)	23 (4)	30 (3)
4		1 (1)	1 (1)	2 (1)

Note: Values in parenthesis are the number of sections.

3.2.4 Longitudinal Profile Measurements

The longitudinal profile is measured five times as an LTPP standard practice on every visit [44] at a pavement section. MON_HSS_RUN_NO is the LTPP table contains the calculated left wheel path, right wheel path, and the mean IRI values for each run of a visit. Table 18 shows the overall availability of longitudinal profile measurements for all the SMP pavement sections (83 sections), excluding the six JRCP sections, where a single measurement is the mean IRI value of the five runs per visit. Similar to FWD deflection based parameter availability, more longitudinal profile measurement data are available for pavement sections located in wet climates, mainly because of a higher number of pavement sections. Also, the data has been classified based on the maintenance category.

Table 18 shows that all 16 SMP JPCP sections (highlighted in bold) were subjected at some point in time to multiple profile measurements during the same day; on the other hand, only five flexible sections (highlighted in bold) had multiple profile measurements during the same day. A higher number of multiple profile measurements on JPCP sections is logical since diurnal profile variations are significant only in rigid pavements (upward versus downward curling). While the number of multiple measurements during a day varies for each section, more data per day are available for rigid pavements.

Table 18 Available profile measurements in different climatic regions—SMP experiment

Pavement type	Cate-gory	DF			DNF			WF			WNF		
		Visit number			Visit number			Visit number			Visit number		
		1	2	3	1	2	3	1	2	3	1	2	3
AC	0	134 (9)			72 (4)			245 (29)	4 (1)		206 (16)	2 (2)	
	1	60 (5)	4 (2)		51 (6)			42 (5)			63 (6)		
	2	11 (3)			7 (1)			83 (7)			14 (4)		
	3	25 (6)			38 (4)			313 (26)			65 (8)		
Total by visit		230 (9)	4 (**2**)		168 (7)			683 (30)	4 (**1**)		348 (17)	2 (**2**)	
AC Total		234 (9)			168 (7)			687 (30)			350 (17)		
JPCP	0	11 (1)	1 (1)	1 (1)	51 (2)	24 (2)	1 (1)	71 (6)	16 (4)	5 (5)	142 (6)	39 (6)	8 (3)
	1	22 (2)	6 (2)		15 (1)	5 (1)	1 (1)	13 (1)	12 (1)				
	2										1 (1)		
	3	10 (2)	3 (1)		1 (1)			72 (4)	15 (4)	5 (3)	6 (2)		
Total by visit		43 (2)	10 (**2**)	1 (1)	67 (2)	29 (**2**)	2 (2)	156 (6)	43 (**6**)	10 (6)	149 (6)	39 (**6**)	8 (3)
JPCP Total		54 (2)			98 (2)			209 (6)			196 (6)		

Note: Values in parenthesis are the number of sections.

3.3 Summary

To investigate the effects of seasonal and diurnal FWD deflections and profile measurements on the derived pavement parameters, the determination of the required data elements along with the data extents, was critical. The desired data needed to have multiple FWD and profile measurements to achieve the objectives of this study. The LTPP SMP study database has the required data for each element identified with multiple FWD deflections and profile measurements. This chapter presented a brief account of all the identified data elements, the LTPP data tables that contained the required data, and the extents of the availability of data for each of the data elements used in this study. More data are available for flexible pavements (64 sections) as compared to JPCP (16 sections), primarily due to the number of sections for each pavement type in the database.

CHAPTER 4 DATA ANALYSIS

The data analysis to accomplish the objectives of the thesis required looking into the effects of seasonal and diurnal FWD and profile measurements on the different deflection- and profile-based parameters. For each pavement type and data element, a relational database was prepared for the data analysis. The data analysis and findings for each pavement type are presented in this chapter.

4.1 Analysis for Flexible Pavements (by climatic region)

FWD deflection-based parameters for flexible pavements include the backcalculated layer moduli values. The backcalculated moduli for each pavement layer were obtained from the LTPP SMP database. Each of these parameters was analyzed separately within all climatic regions. Dividing the data and analysis by climatic regions helped to understand better the effects of seasonal and diurnal measurements on these parameters. Also, it aided in explaining the variance in the parameters. As compared to including all the climates together, it also helped reduce the data required while improving the power of the analysis.

Similarly, using available IRI data from the LTPP SMP database, the seasonal and diurnal effects on pavement roughness were investigated. The IRI data extracted from the database was analyzed similarly, dividing the data by climatic region, to gain the benefits as mentioned earlier.

4.1.1 FWD based Pavement Parameters

HMA, base, and subgrade layer moduli are backcalculated using deflections measured with an FWD device. To investigate the effects of seasonal and diurnal FWD measurements on these moduli values, the main factors included (a) month and, (b) time of FWD measurement. HMA layer thickness is also used as a factor since it is a part of the SMP original design. The maintenance category of the pavement sections is used as a blocking factor. Blocking is a technique that increases the precision in an experiment by reducing the experimental error variance. It is achieved by considering factors believed to affect the response; however, not considered to be of primary importance in the analysis.

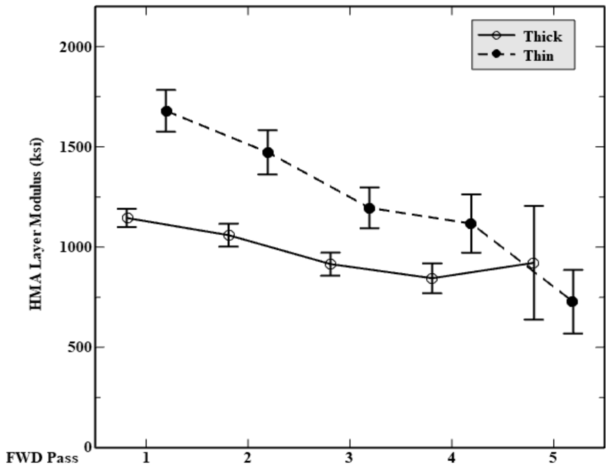
An analysis for investigating the seasonal and diurnal effects on each of the mentioned parameters is presented next. The data analysis for each data element involved the following steps:

1. The pavement structure details, layer moduli values, FWD measurement dates and timings, maintenance history, pavement surface temperature, air temperature, and temperature gradient measurements are variables identified to perform the analysis.
2. The investigation of the problem at hand required an analysis involving a group of sections within each climatic region.
3. The flexible pavements sections in the SMP LTPP database were identified in each of the four climatic regions. Note that climatic regions are defined in terms of temperature (i.e., freeze/no freeze), and moisture conditions (i.e., wet/dry).
4. The structural details, including layer types and thicknesses, were also obtained.
5. The backcalculated layer moduli, along with the date and time of FWD measurements, the air and pavement surface temperatures measured at the time of FWD testing, and the temperatures measured at different depths of the structure were obtained. Also, the maintenance history details for all the sections were also extracted from the database (i.e., construction no. and type of treatment) and categorized.
6. The data was arranged in a relational database.

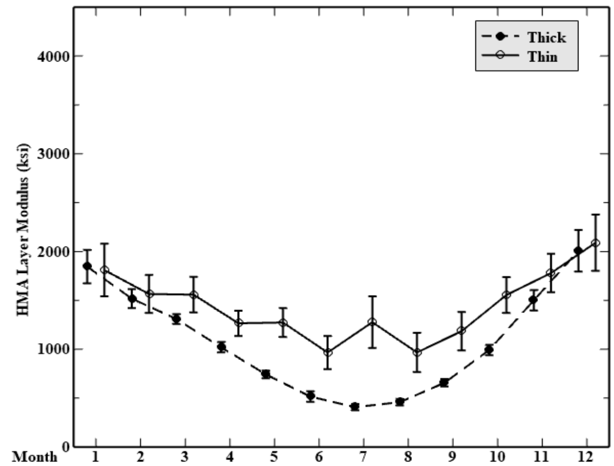
7. The data were evaluated by using a histogram and boxplot to identify outliers.
8. The factors used in the analysis include; (a) measurement month discretized into four seasons (i.e., levels) to look at the seasonal effects, (b) measurement time with two levels (before noon and afternoon) for the diurnal effects, (c) maintenance category, (d) HMA layer thickness with two levels; thick (>5 inches) and thin (<5 inches) based on the original SMP experiment [43].
9. Analysis of Variance (ANOVA) was conducted for flexible pavement sections within each climatic region to investigate the temporal effects on each of the layer moduli values. A level of significance of 5% (α= 0.05) is used in the analysis.

HMA Layer Moduli

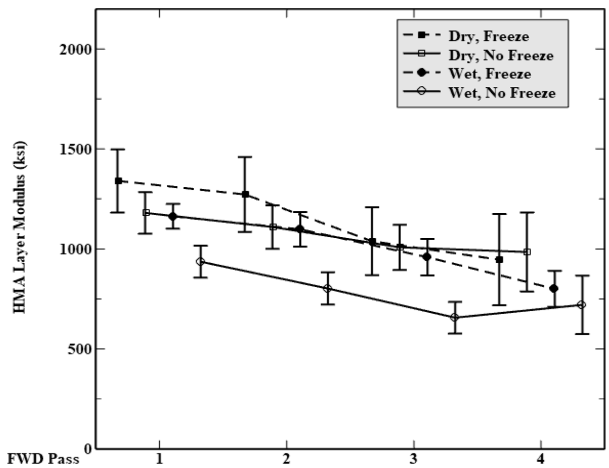
To evaluate the effects of seasonal and diurnal FWD measurements, observing the general trends of the backcalculated HMA layer moduli is useful. Figure 13 shows the diurnal and seasonal HMA layer variations by FWD pass and months, respectively. Figure 13(a) indicates that the HMA layer moduli decrease with FWD pass (i.e., from morning to afternoon) for both thin and thick HMA layers. However, the data show somewhat mixed trends between different climatic regions, which could be because of varying HMA mixtures and field aging on the pavement sections [see Figure 13(b) and (c)]. As expected, the HMA layer moduli display significant variations with higher values in winter months and lower values in the summer months [Figure 13(d)]. Also, there is less overall variation in the backcalculated moduli values within the summer season (i.e., May, June, and July) than winters (December, January, and February).



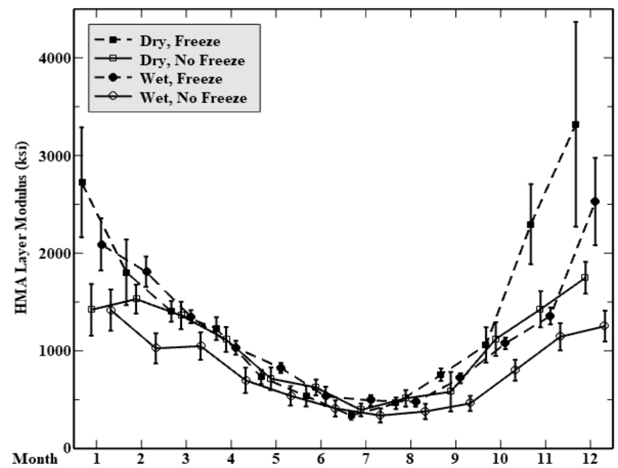
(a) Overall by FWD pass



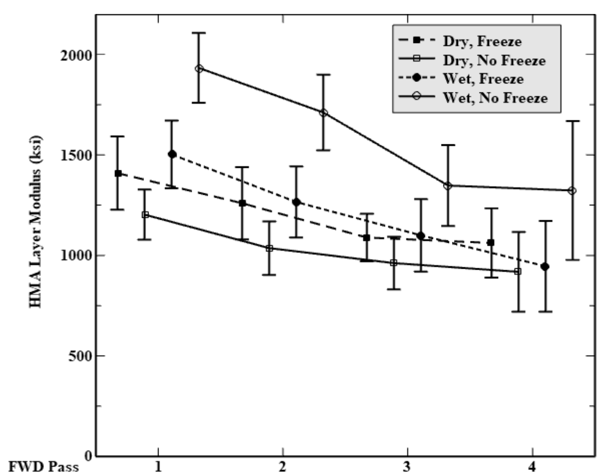
(d) Overall by month



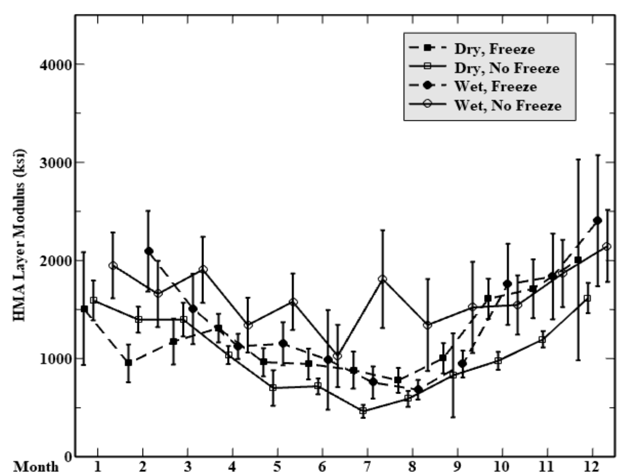
(b) Thick HMA Layer by FWD pass



(e) Thick HMA Layer by month



(c) Thin HMA Layer by FWD pass



(f) Thin HMA Layer by month

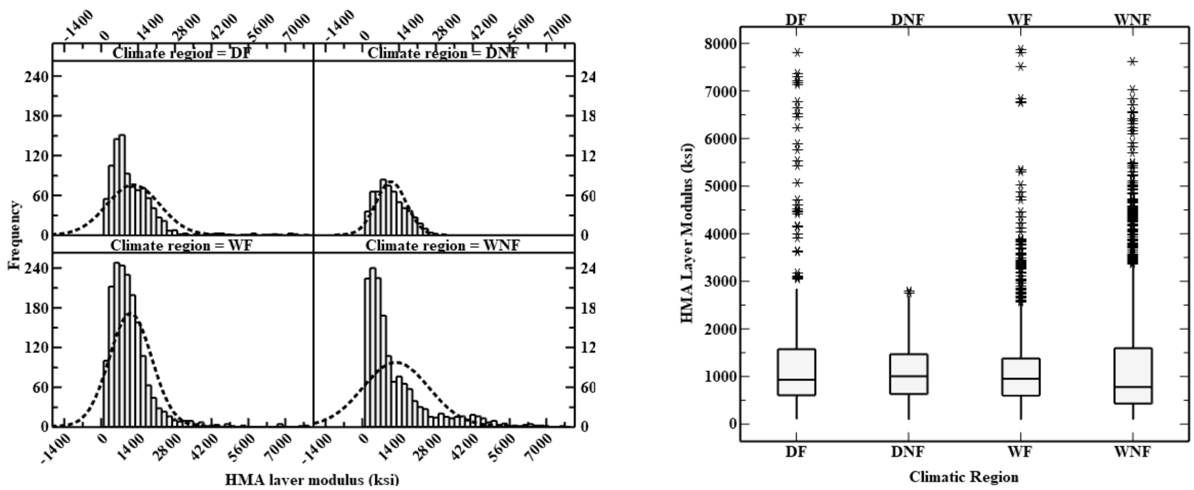
Figure 13 Seasonal and diurnal variations in HMA layer moduli

Table 19 shows the descriptive statistics of the available HMA layer moduli values with the number (N) of measurements within each climatic region. The HMA moduli value considerably varies within each climatic region, especially in the DF, WF, and WNF regions. The variation can be explained by looking at the histogram and box-plot of the available data in Figure 14. HMA moduli values over 3000 ksi exist in the database for the three climatic regions mentioned earlier, which is potentially a reason for higher standard deviations in these climatic regions.

Table 19 Descriptive statistics HMA layer moduli—SMP flexible pavements

Climatic region	N	Mean	Std.	Minimum	Q1[1]	Median	Q3[1]	Maximum
DF	957	1219.8	1009.9	113.1	613.9	940.9	1581.0	7817.9
DNF	582	1085.6	577.8	102.3	639.2	1015.2	1474.9	2805.2
WF	1739	1113.2	809.1	105.2	606.2	959.5	1387.6	7880.9
WNF	1533	1268.5	1259.5	109.9	438.6	789.8	1605.0	7634.9

Note: HMA moduli values shown are in ksi units.
[1] 1st and 3rd quartiles.



(a) Histogram - Available HMA moduli data (b) Box-plot - Available HMA moduli data

Figure 14 Visualizing available HMA layer moduli data—SMP flexible pavements

Figure 15 demonstrates the normality of the data for the DNF climatic region after a suitable transformation used in the analysis. This study excludes HMA modulus values higher than 2000 ksi, as these can potentially mask the findings. The satisfaction of the normality assumptions is essential to draw meaningful conclusions from the ANOVA analysis. Similarly, the data were transformed adequately for the rest of the climatic regions to ensure the satisfaction of the normality assumptions.

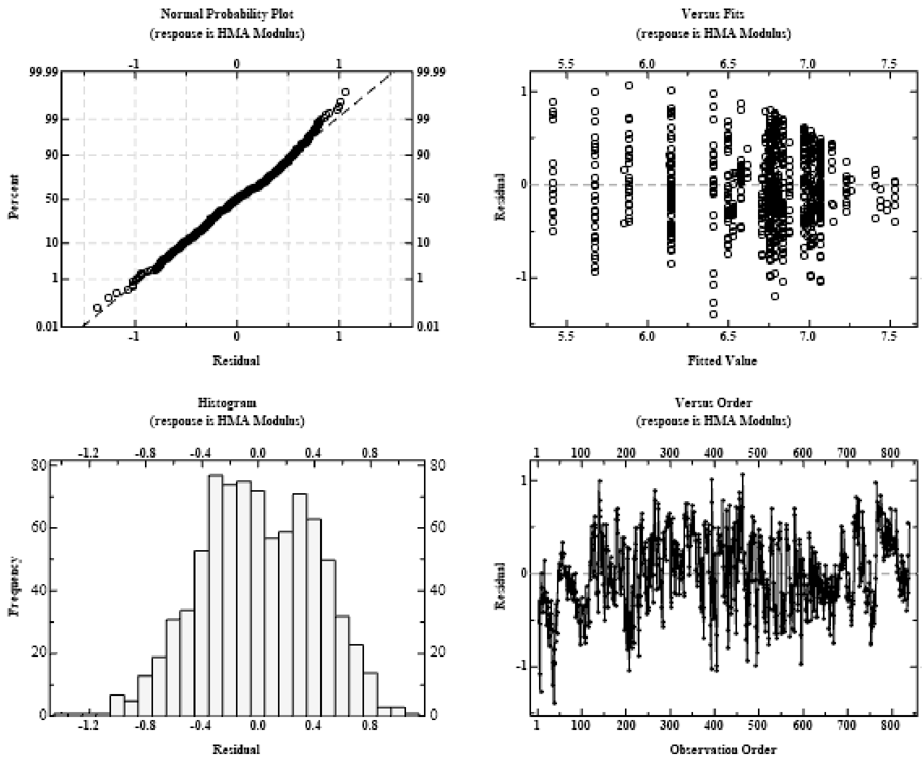


Figure 15 Evaluating normality of the HMA moduli data - DNF climatic region

Table 20 demonstrates the results of the ANOVA for the DF climatic region. FWD measurement season, time, AC thickness, and the maintenance category (blocking factor) are significant factors affecting the HMA layer modulus values based on a type-I error rate of 5% ($\alpha = 0.05$). However, the interaction (highlighted in bold font) between the FWD measurement season, time, and AC thickness also has a significant influence on the HMA layer moduli values. Thus, one should look at the interaction means plot rather than the main effects plot for interpreting the results for the analysis.

Table 20 ANOVA results for HMA moduli values – DF climatic region

Source	DoF[1]	Seq SS[2]	Contribution	Adj SS[3]	Adj MS[4]	*F*-value	*p*-value
Season	3	76.161	26.27%	73.624	24.5414	141.20	0.000
Time	1	12.279	4.23%	9.170	9.1697	52.76	0.000
AC_th	1	7.251	2.50%	1.358	1.3583	7.82	0.005
Maint. Cat.	3	28.197	9.72%	21.716	7.2386	41.65	0.000
Season*Time	3	2.122	0.73%	2.401	0.8005	4.61	**0.003**
Season*AC_th[5]	3	19.957	6.88%	20.589	6.8630	39.49	**0.000**
Time*AC_th	1	0.781	0.27%	0.781	0.7814	4.50	**0.034**
Error	824	143.211	49.39%	143.211	0.1738		
Lack-of-Fit	31	9.819	3.39%	9.819	0.3167	1.88	0.003
Pure Error	793	133.393	46.00%	133.393	0.1682		
Total	839	289.960	100.00%				

[1]Degrees of freedom. [2]Sequential sum of squares. [3]Adjusted sum of squares. [4]Adjusted mean squares. [5]AC thickness.

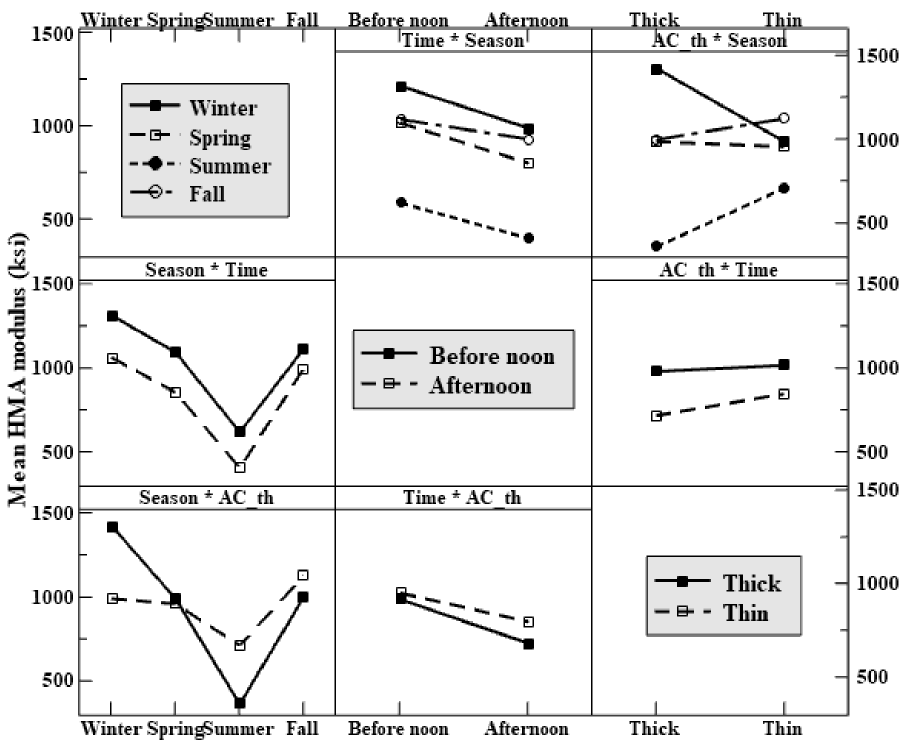
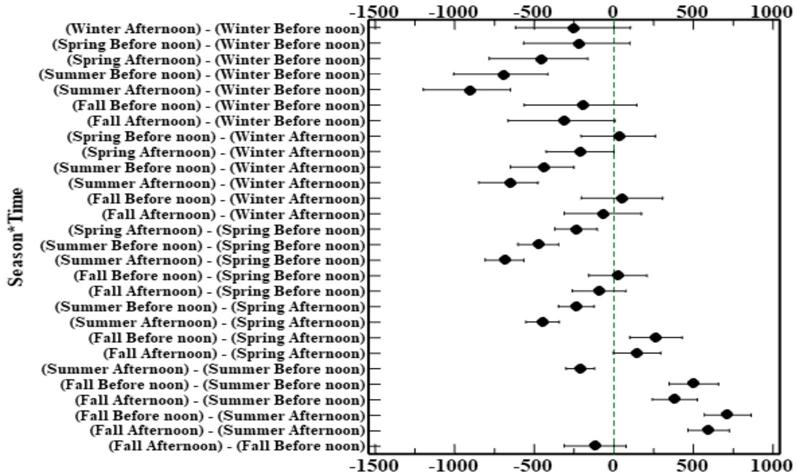
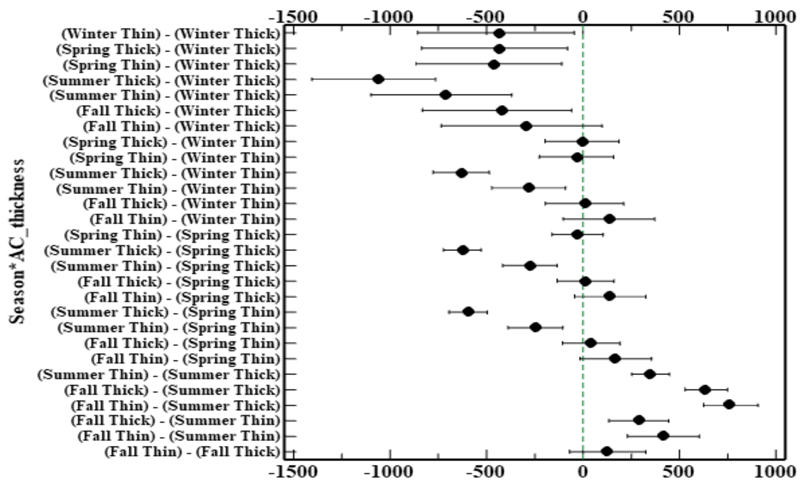


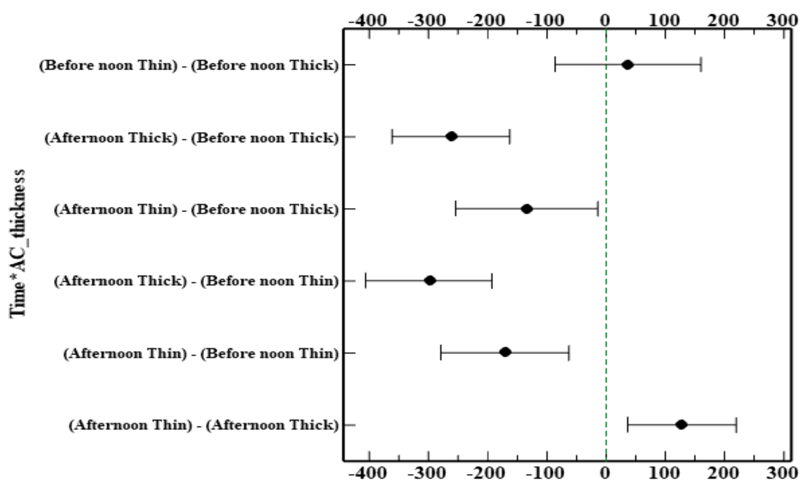
Figure 16 Interaction means plot - DF climatic region



(a) Mean HMA moduli difference for season and time interaction



(b) Mean HMA moduli difference for the season and AC thickness interaction



(c) Mean HMA moduli difference for time and AC thickness interaction

Figure 17 Multiple mean comparisons with 95% confidence intervals - DF climatic region

Diurnally, the HMA moduli values backcalculated using FWD measurements conducted before noon are higher than the afternoon measurements (see Figure 16). Such a difference can be explained due to the absorption of heat throughout the day by the pavement. There is a significant mean difference (around 200 ksi) between HMA backcalculated moduli values obtained from FWD measurements taken before-noon and in the afternoon between spring and summer seasons [see Figure 17(a)]. Also, the time has a pronounced effect on HMA moduli values backcalculated from FWD measurements obtained over pavements with thick and thin HMA layers. Generally, thin HMA layers tend to display higher moduli values as compared to thick HMA layers. Such a trend can be due to the back-calculation process that estimates higher stiffness values for thin HMA layers than thicker ones. Figure 17(c) shows that the mean moduli difference is higher (260 ksi) for thick HMA layers than pavements with a thin HMA layer (170 ksi).

Seasonally, HMA moduli values are generally highest for winters, as expected, followed by spring and fall seasons, while the summer season has the lowest moduli values (see Figure 16). A noticeable mean difference (around 400 ksi) exists between moduli values obtained in winter and summer seasons over pavements with different HMA layers. In winters, thicker HMA layers are stiffer than thin layers due to low temperatures, while in summers, the opposite is true. However, higher moduli values for thin HMA layers can also be due to the back-calculation process, which tends to calculate higher moduli values for thinner layers.

A similar analysis for the DNF climatic region shows that the interaction of season and time influences the HMA moduli values. The AC layer thickness, on the other hand, does not have a significant effect (see Table 21). The maintenance category being the blocking factor also appears to contribute towards the variation of HMA moduli values in the DNF climatic region.

Winter season FWD measurements result in higher HMA moduli values as compared to other seasons. Lowest values are obtained once FWD deflections measured in the summer season are used to back-calculate the HMA layer moduli (see Figure 18). Also, the mean difference between the HMA layer moduli values based on before-noon and afternoon FWD deflections is significant (>170 ksi) among all seasons except for fall (see Figure 19) in the DNF climatic region.

Table 21 ANOVA results for HMA moduli values – DNF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	13479.0	40.55%	13289.5	4429.84	188.72	0.000
Time	1	809.4	2.44%	904.6	904.64	38.54	0.000
AC_th	1	307.5	0.93%	6.9	6.91	0.29	0.588
Maint. Cat.	3	6214.6	18.70%	6005.0	2001.68	85.28	0.000
Season*Time	3	224.8	0.68%	227.2	75.72	3.23	**0.022**
Season*AC_th	3	129.2	0.39%	128.2	42.73	1.82	0.142
Time*AC_th	1	7.4	0.02%	7.4	7.37	0.31	0.575
Error	514	12064.8	36.30%	12064.8	23.47		
Lack-of-Fit	29	1117.1	3.36%	1117.1	38.52	1.71	0.013
Pure Error	485	10947.7	32.94%	10947.7	22.57		
Total	529	33236.7	100.00%				

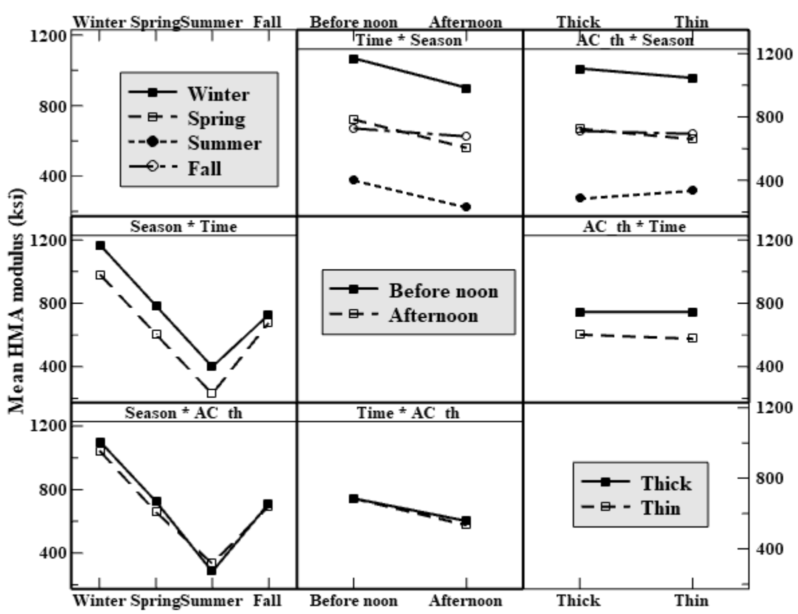


Figure 18 Interaction means plot - DNF climatic region

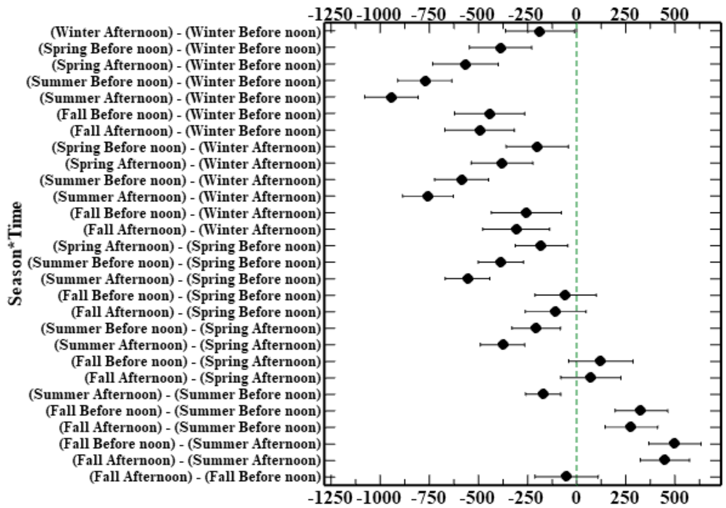
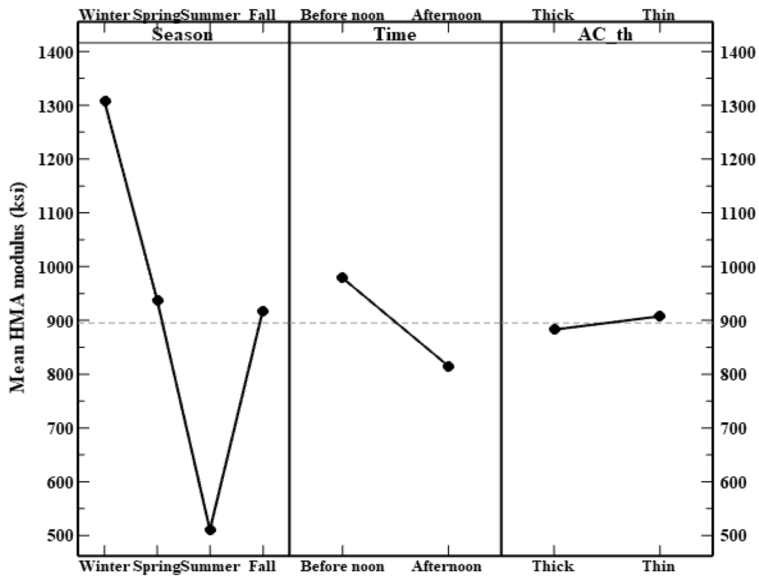


Figure 19 Mean HMA moduli difference for season and time interaction – DNF climatic region

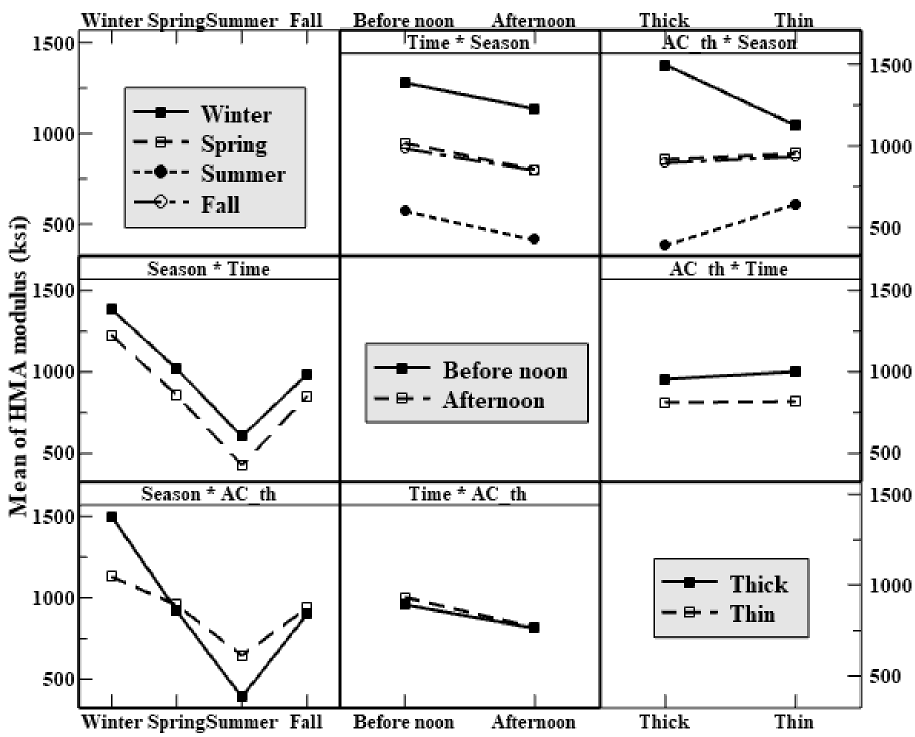
Table 22 ANOVA results for HMA moduli values – WF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	34775.9	37.50%	13091.8	4363.93	132.47	0.000
Time	1	2467.8	2.66%	1322.7	1322.72	40.15	**0.000**
AC_th	1	251.2	0.27%	19.2	19.21	0.58	0.445
Maint. Cat.	3	1591.4	1.72%	2140.8	713.61	21.66	0.000
Season*Time	3	236.6	0.26%	162.6	54.19	1.64	0.177
Season*AC_th	3	1665.9	1.80%	1633.0	544.32	16.52	**0.000**
Time*AC_th	1	22.5	0.02%	22.5	22.53	0.68	0.408
Error	1570	51719.4	55.77%	51719.4	32.94		
Lack-of-Fit	36	2648.1	2.86%	2648.1	73.56	2.30	0.000
Pure Error	1534	49071.3	52.92%	49071.3	31.99		
Total	1585	92730.7	100.00%				

ANOVA for the WF climatic region shows that the interaction of season with HMA layer thickness has a significant effect on its stiffness (see Table 22). Time also plays a role in defining the variation of HMA moduli values. Figure 20 presents the interaction means plot for the season and HMA thickness interaction and the main effects plot for time. Figure 20(a) shows that FWD deflections measured before-noon results in higher backcalculated HMA layer moduli values as compared to those measured in the afternoon. FWD deflections measured in the winter season show higher HMA moduli values as compared to the winter season FWD tests, with noticeable differences among HMA thick and thin layer pavement sections. On the other hand, there is no difference between tests conducted in the fall and spring seasons irrespective of HMA layer thickness [see Figure 20(b)].



(a) Main effects plot



(b) Interaction means plot

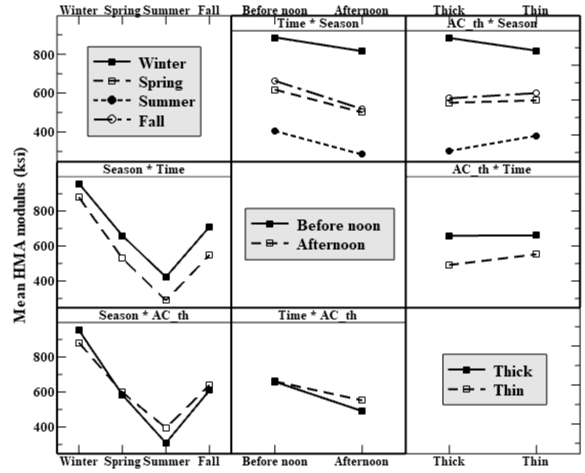
Figure 20 Factorial plots ANOVA for HMA layer moduli data – WF climatic region

The interactions between season and time and season and HMA layer thickness appeared to influence the HMA moduli values in the WNF climatic regions (see Table 23). Generally, winter season FWD measurements give the highest HMA moduli values, while summers provide the lowest. Fall and spring season FWD tests bear similar backcalculated HMA moduli values [see Figure 21(a)]. Also, before-noon tests show higher HMA modulus values than afternoon ones. The interaction means plot shows a noticeable difference (> 130 ksi) between mean HMA moduli values for all seasons backcalculated from FWD tests conducted before-noon and afternoon except winter season [see Figure 21(b)].

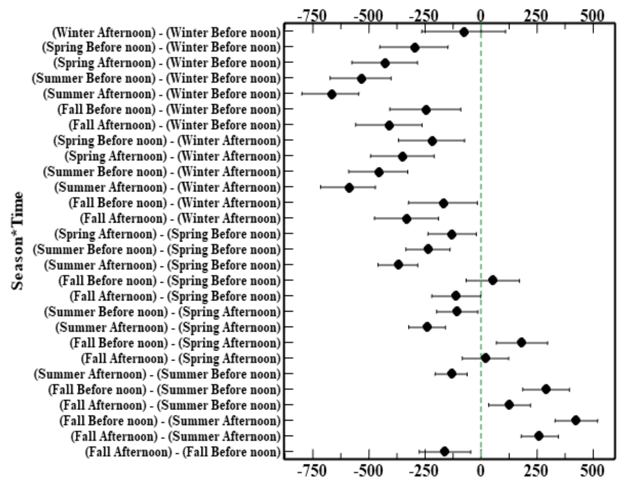
Table 23 ANOVA results for HMA moduli values - WNF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	126.701	21.61%	132.221	44.0738	142.42	0.000
Time	1	16.195	2.76%	17.220	17.2197	55.64	0.000
AC_th	1	8.013	1.37%	0.966	0.9665	3.12	0.077
Maint. Cat.	3	45.048	7.68%	43.764	14.5879	47.14	0.000
Season*Time	3	3.081	0.53%	3.135	1.0451	3.38	**0.018**
Season*AC_th	3	3.878	0.66%	3.933	1.3110	4.24	**0.005**
Time*AC_th	1	0.996	0.17%	0.996	0.9956	3.22	0.073
Error	1236	382.489	65.23%	382.489	0.3095		
Lack-of-Fit	38	39.671	6.77%	39.671	1.0440	3.65	0.000
Pure Error	1198	342.818	58.46%	342.818	0.2862		
Total	1251	586.400	100.00%				

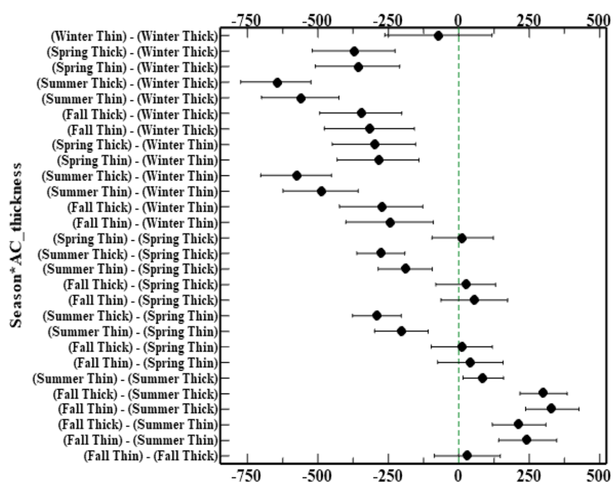
Figure 21(c) shows the mean comparison plot for the season and HMA layer thickness interaction. There is no significant difference between the HMA moduli values with a different layer thickness (i.e., thick or thin) in all three seasons except summer season. FWD deflections measured in the summer season result in a mean difference of about 100 ksi between backcalculated HMA moduli values once conducted on pavements with thick (>5inches) HMA layers as opposed to thin layers (<5 inches).



(a) Interaction means plot



(b) Mean difference with 95% confidence intervals for season and time interaction



(c) Mean difference with 95% confidence intervals for season and HMA thickness interaction

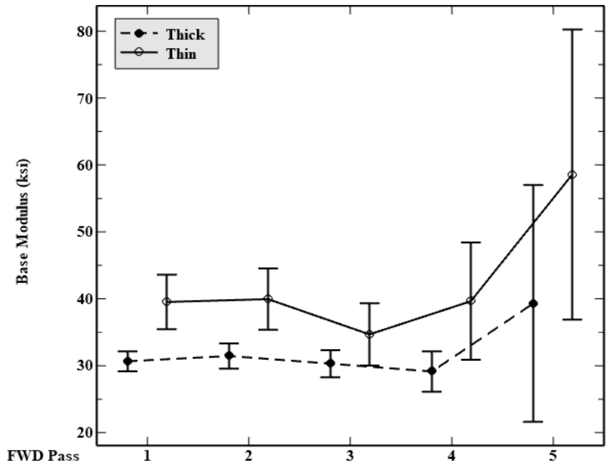
Figure 21 ANOVA plots - WNF climatic region

Base Layer Moduli

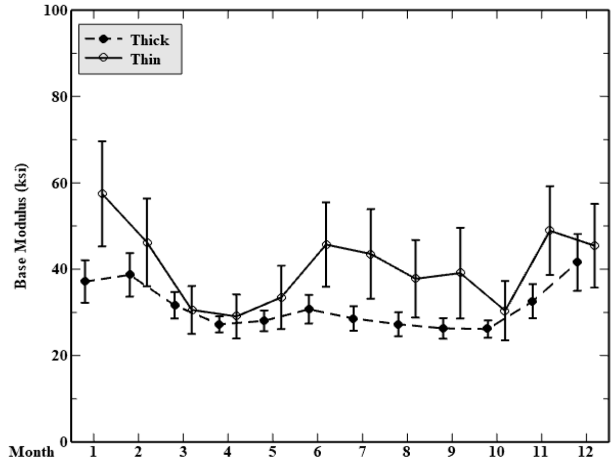
Figure 22(a) shows the overall variations in the granular base moduli with different FWD passes between SMP thick (>5 inches) and thin (<5 inches) HMA layer pavements. As expected, there is no significant difference in the base layer moduli values with FWD pass number (i.e., from morning to evening) with different HMA layer thicknesses and different climatic regions. Overall, the base layer moduli for pavements with thin or thick HMA layers show moduli values ranging between 20-40 ksi [see Figure 22(b) and (c)]. However, base moduli for pavements in the WNF region with thin HMA layers are significantly higher [see Figure 22(c)].

A general expectation is that granular base moduli values may show a significant influence of seasons (months). As expected, substantial differences are observed in the aggregate base moduli for flexible pavements with thin and thick HMA layers in different months [see Figure 22(d)]. Back-calculation results in higher base layer moduli values in winter months, probably due to freezing conditions, as compared to summer months irrespective of HMA layer thickness in the freeze climates. However, the aggregate base layers moduli values for flexible pavement sections having thin HMA layers are highest in the summer months within the WNF climatic region [see Figure 22(f)].

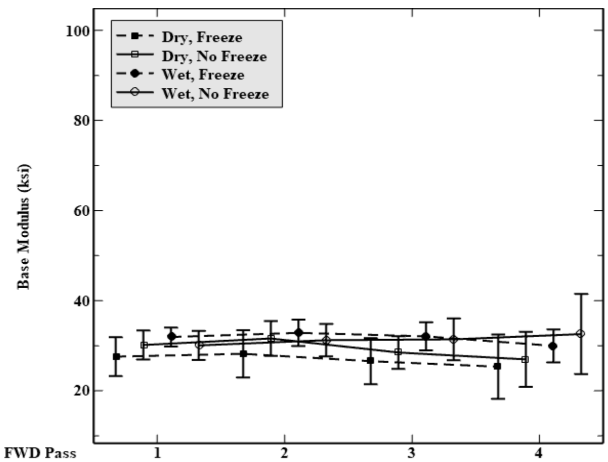
Table 24 shows the descriptive statistics for the granular base moduli data along with the number (N) within each climatic region. The WNF climatic region has a higher variability with a standard deviation of 46.5 ksi. The DNF climatic region has the lowest variability; however, it may be due to fewer data in this region as compared to the others. Histogram and box-plot for the available data reveal values beyond the range of 10-50 ksi. For the analysis, it is beneficial to exclude any such values to prevent masking of the ANOVA results (see Figure 23).



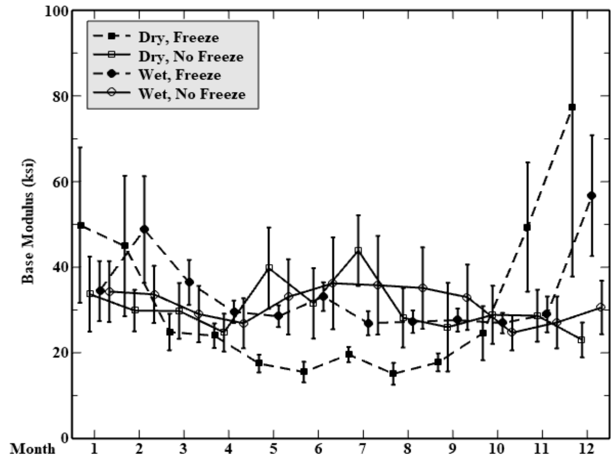
(a) Overall by FWD pass



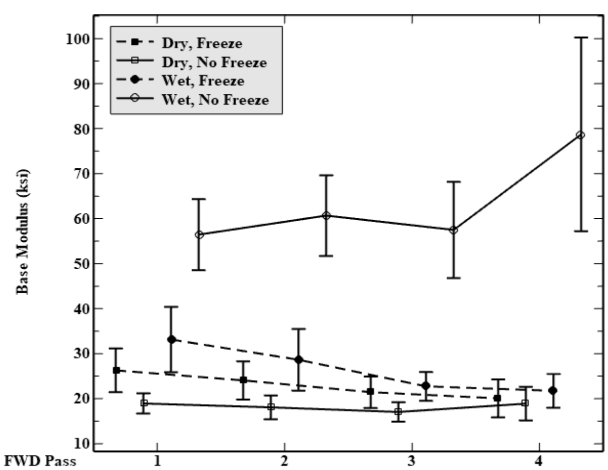
(d) Overall by month



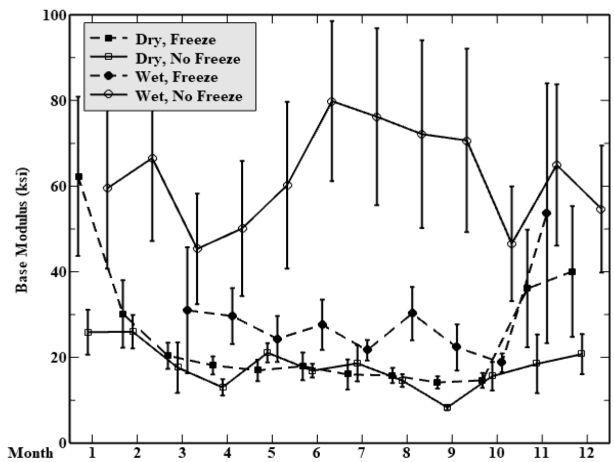
(b) Thick HMA Layer by FWD pass



(e) Thick HMA Layer by month



(c) Thin HMA Layer by FWD pass



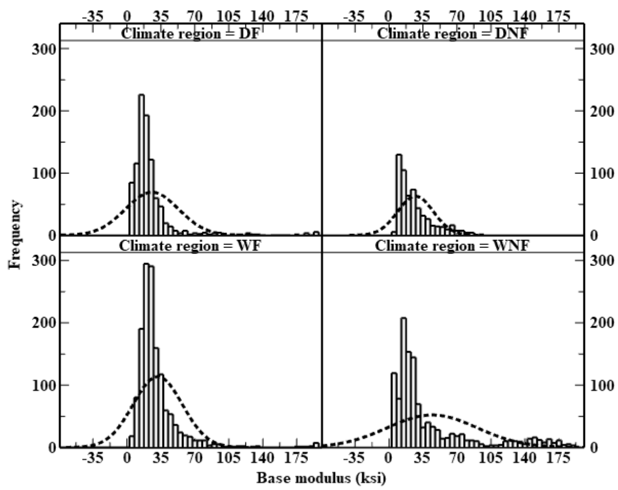
(f) Thin HMA Layer by month

Figure 22 Seasonal and diurnal variations in base layer moduli

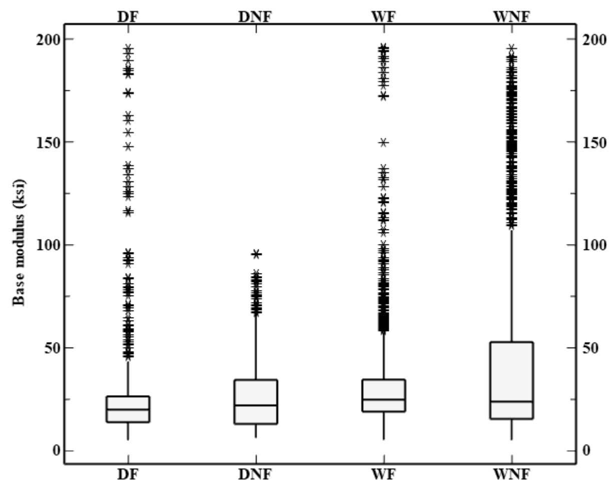
Table 24 Descriptive statistics for aggregate base layer moduli data—SMP flexible pavements

Climatic region	N	Mean	Std.	Minimum	Q1	Median	Q3	Maximum
DF	957	25.6	27.6	5.1	13.7	19.8	26.2	195.4
DNF	582	27	18.4	6.2	12.8	21.8	34.3	95.8
WF	1458	31.6	25.5	5.2	18.8	24.7	34.4	195.8
WNF	1219	44.3	46.5	5.1	15.3	23.7	52.7	195.4

Note: Base moduli values shown are in ksi units.



(a) Histogram - Available base moduli data



(b) Box-plot - Available base moduli data

Figure 23 Visualizing available base layer moduli data—SMP flexible pavements

To investigate the effects of diurnal and seasonal FWD deflection measurements on base layer moduli, a similar ANOVA was performed as for HMA moduli values. Factors used in the analyses included season, time, HMA layer thickness, and maintenance category (as a blocking factor). Ensuring the normality of the data used was critical. The satisfaction of the normality assumptions was achieved by suitably transforming the data (see Figure 24).

ANOVA results for the DF climatic region show that the interaction of season and HMA layer thickness is an essential factor that can explain the variations in base layer moduli due to temporal (seasonal and diurnal) changes affecting FWD based deflections (see Table 25). Thus, looking at the means plot for the significant interaction will help understand the effects on base layer moduli. Also, the maintenance category shows to be a significant contributing factor in the base layer moduli variations; however, this factor is used as a blocking factor only.

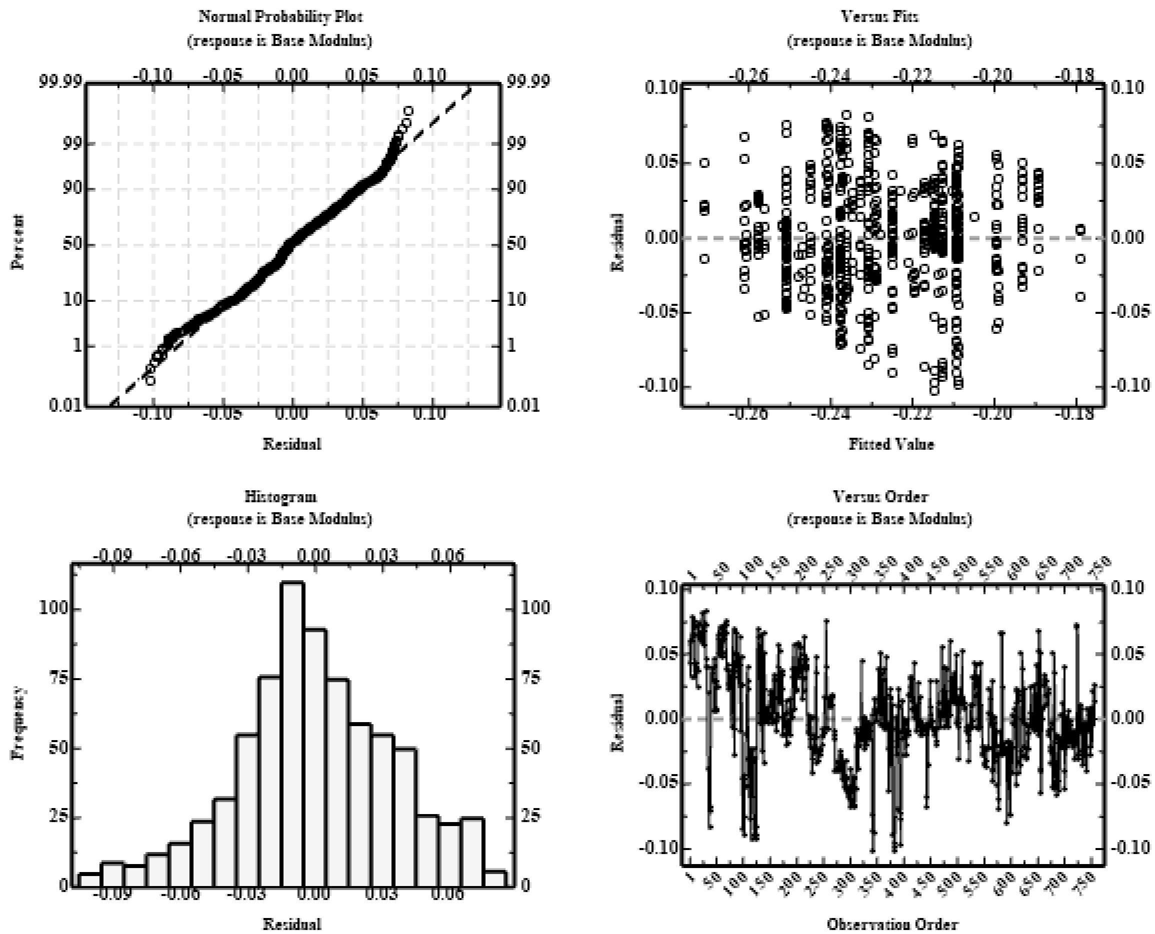
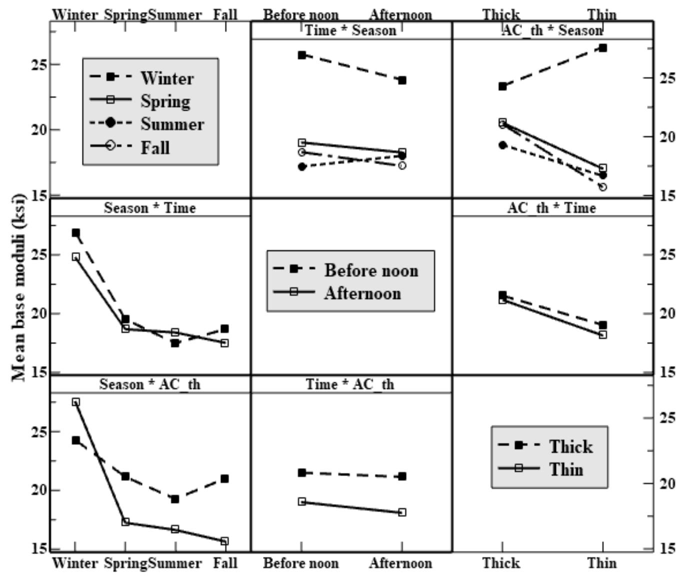


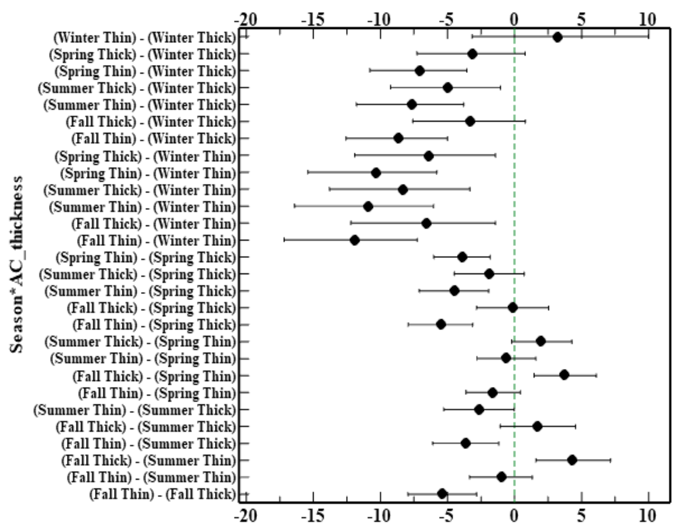
Figure 24 Evaluating normality of the aggregate base moduli data - DF climatic region

Table 25 ANOVA results for base layer moduli values – DF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	0.07817	6.50%	0.096508	0.032169	24.93	0.000
Time	1	0.00352	0.29%	0.002027	0.002027	1.57	0.211
AC_th	1	0.08118	6.76%	0.035506	0.035506	27.51	0.000
Maint. Cat.	3	0.04372	3.64%	0.052592	0.017531	13.58	0.000
Season*Time	3	0.00488	0.41%	0.005118	0.001706	1.32	0.266
Season*AC_th	3	0.03073	2.56%	0.031172	0.010391	8.05	**0.000**
Time*AC_th	1	0.00066	0.06%	0.000663	0.000663	0.51	0.474
Error	743	0.95885	79.79%	0.958846	0.001291		
Lack-of-Fit	30	0.03892	3.24%	0.038918	0.001297	1.01	0.460
Pure Error	713	0.91993	76.55%	0.919928	0.001290		
Total	758	1.20171	100.00%				



(a) Interaction means plot



(b) Mean difference with 95% confidence intervals for season and HMA thickness interaction

Figure 25 ANOVA plots for base moduli data - DF climatic region

The interaction means plot, and the multiple comparison plot shows that the base moduli values are significantly different for all seasons except winters between HMA layers with different thicknesses (thick or thin) [see Figure 25(a) and (b)]. The difference in base layer moduli is highest for the fall season (> 5ksi), while the summer season shows the lowest (< 3ksi). The differences are also practical to alter pavement performance. Another noteworthy finding demonstrated by the interaction means plot is that in the winter season where the thick HMA layers showed higher AC moduli corresponds to a lower base layer moduli and vice versa for the rest of the seasons. Low or sub-freezing temperatures are an explanation of the observed trends; where a stiffer HMA layers lead to underestimation of the modulus for the underlying base layers in the winter season.

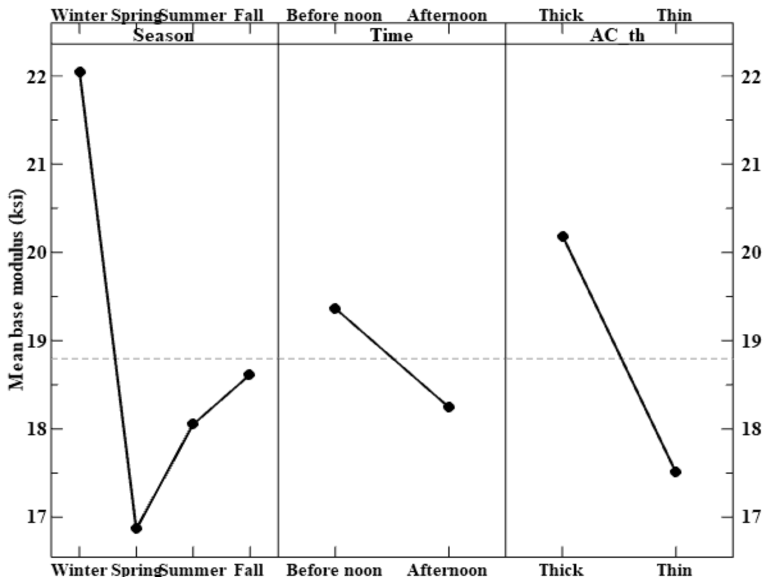
Table 26 shows the ANOVA results for the DNF climatic region. HMA layer thickness and the interaction of FWD deflections measurement season and time appears to be significantly contributing to the seasonal and diurnal effects on base moduli. The main effects plot shows that the difference between base moduli values backcalculated using FWD deflections on pavements with thick and thin HMA layers differ by 3 ksi, enough to cause a change in the pavement performance [see Figure 26(a)]. Interaction means plot for the season, and time interaction shows that, generally, base layer moduli are higher in the winter season and those resulting from FWD deflections measured before-noon; however, the differences are not practically significant [see Figure 26(b)].

Table 26 ANOVA results for base layer moduli values – DNF climatic region

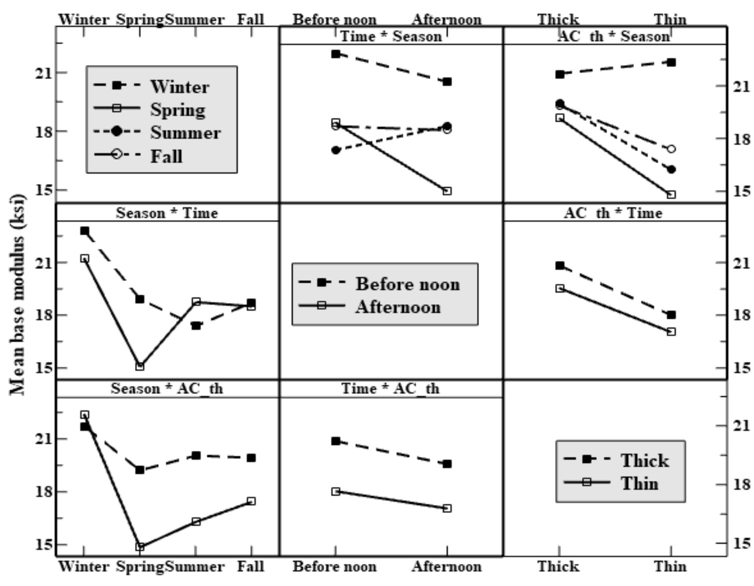
Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	4.1379	4.76%	4.0706	1.35686	8.32	0.000
Time	1	0.2737	0.32%	0.3089	0.30890	1.89	0.169
AC_th	1	2.3093	2.66%	1.6189	1.61887	9.93	**0.002**
Maint. Cat.	3	6.9675	8.02%	7.1733	2.39110	14.67	0.000
Season*Time	3	1.3266	1.53%	1.3697	0.45658	2.80	**0.040**
Season*AC_th	3	1.2617	1.45%	1.2494	0.41648	2.55	0.055
Time*AC_th	1	0.0016	0.00%	0.0016	0.00155	0.01	0.922
Error	433	70.5893	81.26%	70.5893	0.16302		
Lack-of-Fit	28	14.1451	16.28%	14.1451	0.50518	3.62	0.000
Pure Error	405	56.4442	64.98%	56.4442	0.13937		
Total	448	86.8674	100.00%				

ANOVA of the base layer moduli data available for the WF climatic region shows that FWD deflections measured in different seasons have an imprint on these values (see Table 27).

Besides, HMA layer thickness also contributes to the variations in base moduli due to seasonal and diurnal FWD tests. Maintenance category and either of the interactions, on the other hand, does not appear to be contributing factors.



(a) Main effects plot



(b) Interaction means plot

Figure 26 Factorial plots ANOVA for base layer moduli data – DNF climatic region

The main effects plot shows that base layer moduli are highest for the winter season (see Figure 27). Also, there is a clear difference between the base layer moduli values between the winter and spring (2.5 ksi) and winter and fall (3.5 ksi) seasons. The plot also shows that base moduli values obtained from FWD deflections measured on pavements with thick HMA layers are noticeably higher than those measured over thin HMA layers with a difference greater than 3 ksi.

Table 27 ANOVA results for base layer moduli values – WF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	2.218	1.43%	1.845	0.61501	5.06	**0.002**
Time	1	0.008	0.00%	0.001	0.00107	0.01	0.925
AC_th	1	2.076	1.34%	2.458	2.45803	20.21	**0.000**
Maint. Cat.	3	0.620	0.40%	0.640	0.21338	1.75	0.154
Season*Time	3	0.567	0.37%	0.567	0.18893	1.55	0.199
Season*AC_th	1	0.000	0.00%	0.000	0.00004	0.00	0.986
Time*AC_th	1227	149.236	96.45%	149.236	0.12163		
Error	37	12.949	8.37%	12.949	0.34998	3.06	0.000
Lack-of-Fit	1190	136.287	88.08%	136.287	0.11453		
Pure Error	1239	154.725	100.00%				
Total	3	2.218	1.43%	1.845	0.61501	5.06	0.002

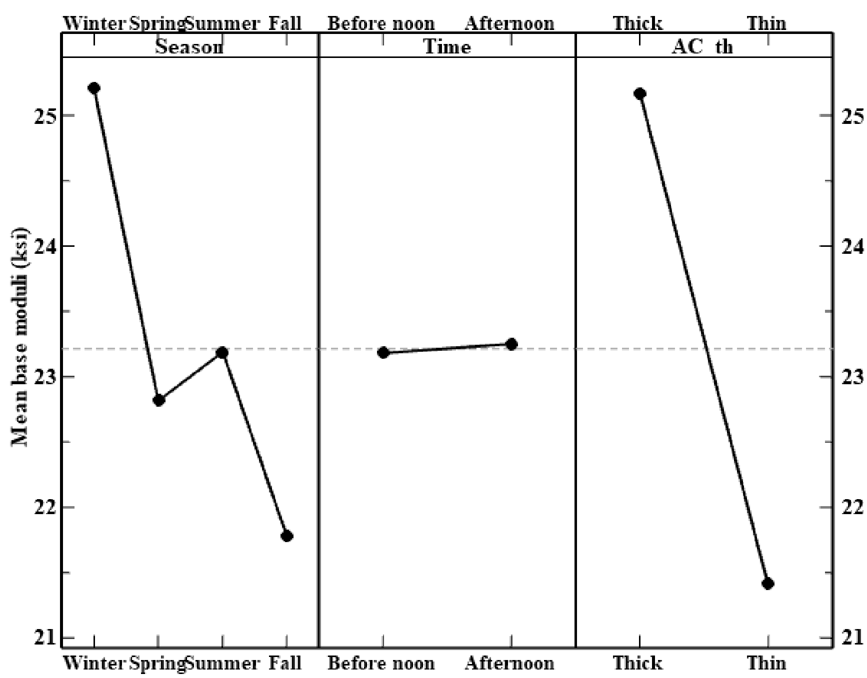


Figure 27 Main effects plot for base layer moduli – WF climatic region

ANOVA for available base moduli data within the WNF climatic region resulted in similar findings except that higher base moduli values are observed within fall as compared to other seasons (see Table 28 and Figure 28). Also, base moduli obtained from FWD deflections measured in the spring season are the lowest. Moisture variations can be a possible explanation of such effects. Also, there is a clear mean difference of base moduli between values obtained from FWD tests conducted in spring and winter (3 ksi) and fall and spring seasons (4 ksi).

Table 28 ANOVA results for base layer moduli values – WNF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	0.05553	3.66%	0.05380	0.017933	9.46	**0.000**
Time	1	0.00407	0.27%	0.00435	0.004346	2.29	0.130
AC_th	1	0.06641	4.37%	0.05749	0.057486	30.32	**0.000**
Maint. Cat.	3	0.00501	0.33%	0.00482	0.001608	0.85	0.468
Season*Time	3	0.00433	0.29%	0.00436	0.001454	0.77	0.513
Season*AC_th	3	0.01292	0.85%	0.01293	0.004310	2.27	0.079
Time*AC_th	1	0.00004	0.00%	0.00004	0.000041	0.02	0.883
Error	723	1.37058	90.24%	1.37058	0.001896		
Lack-of-Fit	39	0.18683	12.30%	0.18683	0.004791	2.77	0.000
Pure Error	684	1.18375	77.93%	1.18375	0.001731		
Total	738	1.51890	100.00%				

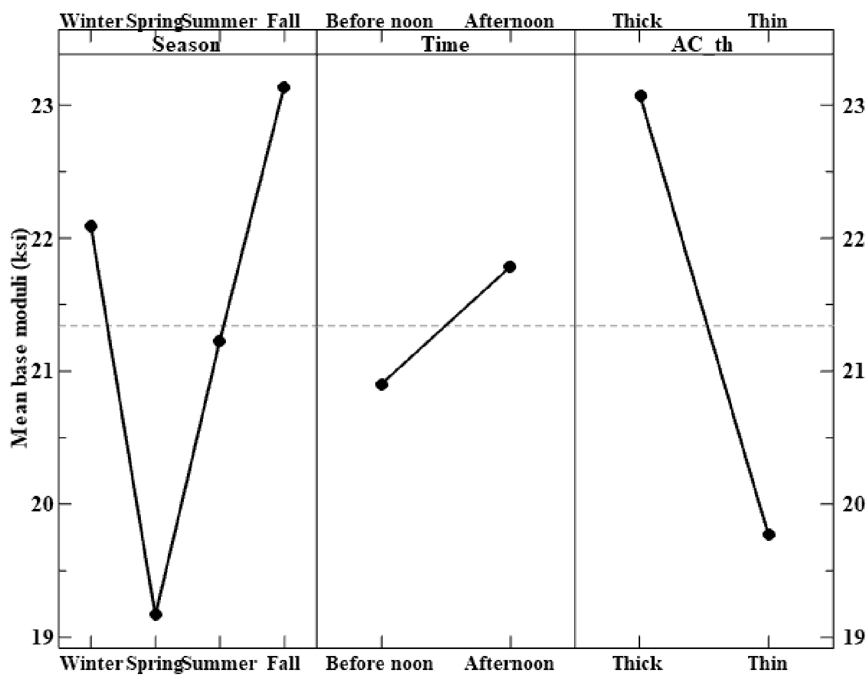


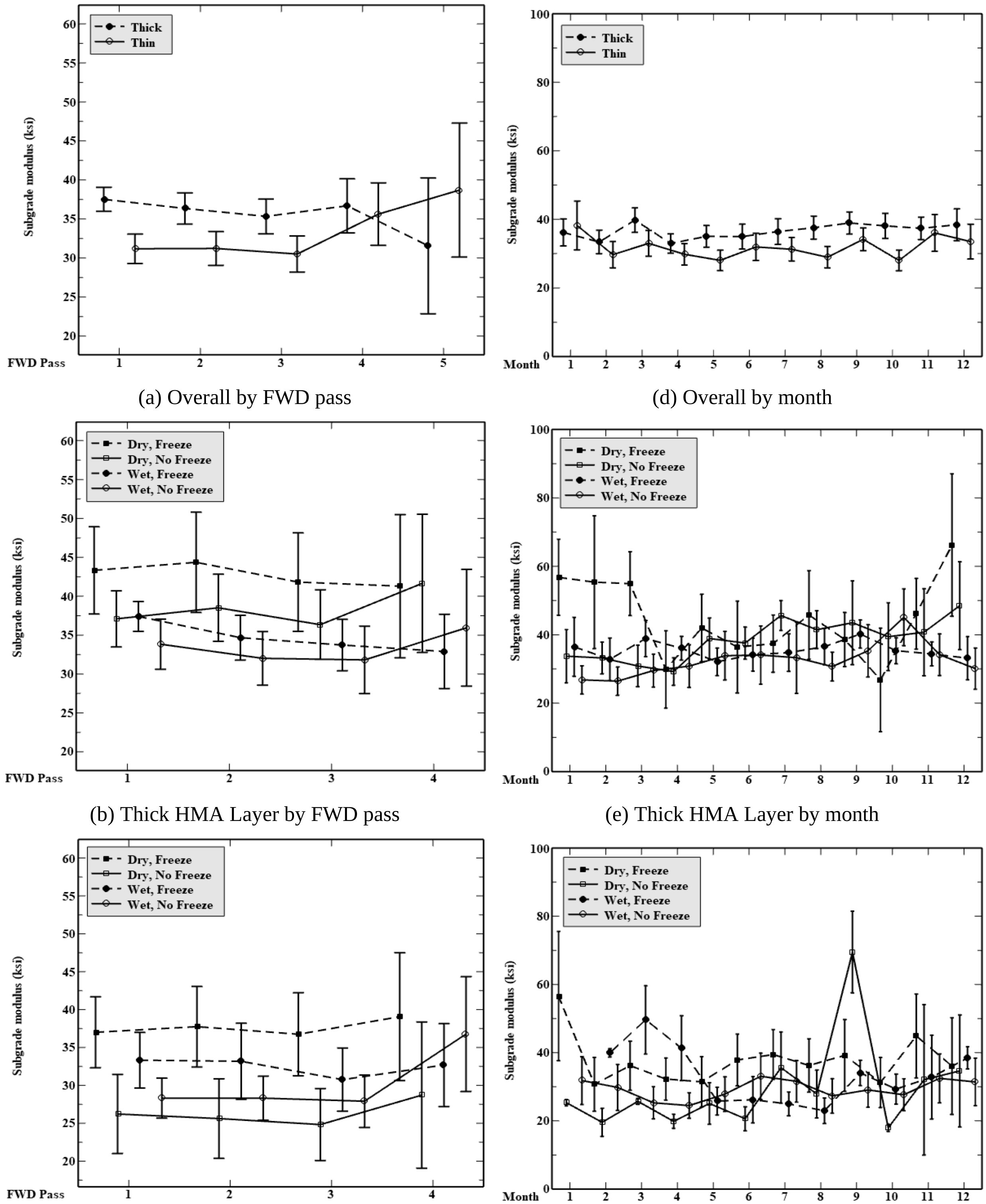
Figure 28 Main effects plot – WNF climatic region

Subgrade Layer Moduli

The subgrade layer moduli values found in the LTPP SMP study database are evaluated similar to the HMA and base layers for analyzing the diurnal (i.e., by FWD pass) and seasonal (i.e., monthly) variation in the moduli values. Generally, the unbound layer moduli are expected not to demonstrate noticeable changes within a day. Figure 29(a) shows the overall variations in the subgrade layer moduli with different FWD passes between SMP thick (>5 inches) and thin (<5 inches) HMA layer pavements. No significant variation exists in the moduli values with FWD pass number (i.e., morning to afternoon) with different HMA layer thicknesses and different climatic regions. Overall, pavements with thick HMA layers show higher subgrade moduli values [see Figure 29(b)]. Also, for pavements with thick HMA layers, higher subgrade moduli values are observed in the dry climates. On the other hand, higher moduli values are seen in the freeze regions for pavements with thin HMA layers [see Figure 29(c)].

It is likely to see a significant influence of seasons (months) in subgrade layer moduli values. Overall, not many variations are observed in the subgrade layer moduli for flexible pavements with thin and thick HMA layers [see Figure 29(d)] within different months. However, somewhat mixed trends occur in the subgrade moduli values within different climatic regions irrespective of HMA layer thickness [see Figure 29(e) and (f)].

Table 29 shows the descriptive statistics for the available subgrade moduli data in the LTPP SMP database. The data reveal a higher variability in the backcalculated subgrade moduli values in the DF climatic region, which also has the highest mean subgrade modulus. The absence of moisture in the DF climatic region might be the reason for the highest mean subgrade modulus value.



(a) Overall by FWD pass

(d) Overall by month

(b) Thick HMA Layer by FWD pass

(e) Thick HMA Layer by month

(c) Thin HMA Layer by FWD pass

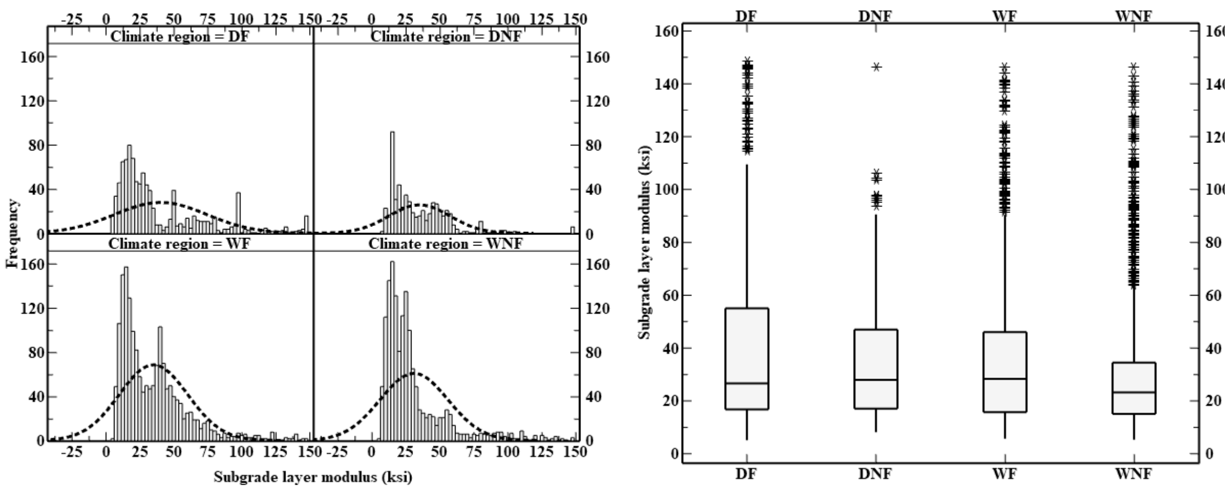
(f) Thin HMA Layer by month

Figure 29 Seasonal and diurnal variations in subgrade layer moduli

Table 29 Descriptive statistics subgrade layer moduli—SMP flexible pavements

Climatic region	N	Mean	Std.	Minimum	Q1	Median	Q3	Maximum
DF	957	40.3	34.2	5.1	16.7	26.6	55	148.9
DNF	582	34.8	22.6	8.1	17.1	27.9	47	146.6
WF	1739	35	25.3	5.7	15.7	28.3	46	146.6
WNF	1533	30.7	25.1	5.3	15	23.2	34.5	146.6

Note: Subgrade moduli values shown are in ksi units.



(a) Histogram - Available subgrade moduli data (b) Box-plot - Available subgrade moduli data

Figure 30 Visualising available subgrade layer moduli data—SMP flexible pavements

Figure 30 demonstrates the backcalculated subgrade layer moduli data obtained from the SMP database. The data shows backcalculated subgrade moduli values higher than 40 ksi. Such values are better to exclude from the analysis to prevent masking of the ANOVA results.

Table 30 ANOVA results for subgrade layer moduli values – DF climatic region

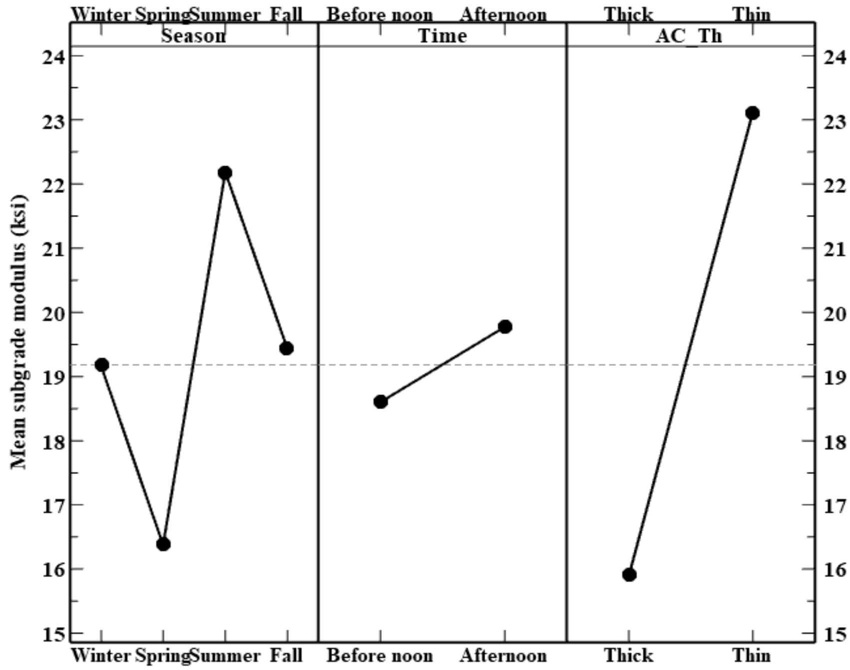
Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	5.707	4.28%	8.4809	2.8270	19.40	**0.000**
Time	1	0.356	0.27%	0.4684	0.4684	3.21	0.073
AC_th	1	23.619	17.71%	14.8824	14.8824	102.13	**0.000**
Maint. Cat.	3	11.590	8.69%	11.5644	3.8548	26.45	0.000
Season*Time	3	0.517	0.39%	0.5880	0.1960	1.35	0.259
Season*AC_th	3	0.036	0.03%	0.0287	0.0096	0.07	0.978
Time*AC_th	1	0.440	0.33%	0.4398	0.4398	3.02	0.083
Error	625	91.075	68.30%	91.0749	0.1457		
Lack-of-Fit	31	5.769	4.33%	5.7694	0.1861	1.30	0.133
Pure Error	594	85.306	63.98%	85.3055	0.1436		
Total	640	133.341	100.00%				

The available subgrade data were transformed to ensure the normality assumptions that are critical for drawing meaningful conclusions from an ANOVA. Table 30 demonstrates the ANOVA results for the subgrade layer moduli values available for the DF climatic region. The results reveal that the FWD measurement season and HMA layer thickness are critical factors that can influence the subgrade moduli values in the DF climatic region. Figure 31(a) illustrates the main effects of these factors. Subgrade moduli obtained from FWD tests conducted in the summer season result in higher values while spring season tests bear the lowest. The absence of moisture in the summer season can be a possible explanation of such effects. There is a sizeable mean subgrade moduli difference between backcalculated values obtained from deflections measured in different seasons [see Figure 31(b)]. Also, subgrade moduli obtained from FWD tests over thick HMA layers are lower than the opposite [see Figure 31(a)].

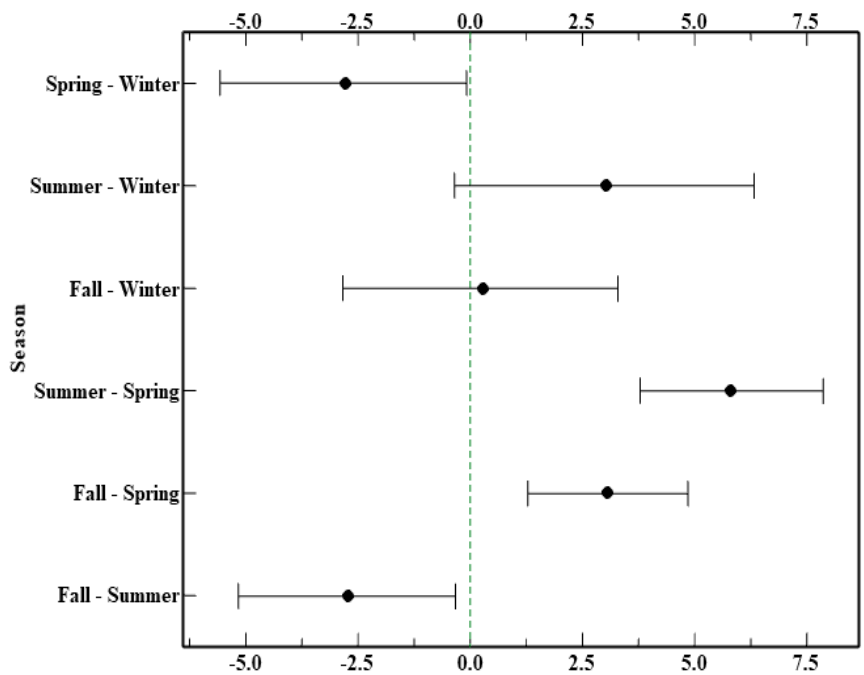
ANOVA results for DNF climatic region show that the interaction of the FWD measurement season and HMA layer thickness is contributing to the variations in subgrade moduli (see Table 31). Explanation of the interaction effects warrants looking into the interaction means plot.

Table 31 ANOVA results for subgrade layer moduli values – DNF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	3.8321	7.25%	4.7716	1.59052	13.11	0.000
Time	1	0.0020	0.00%	0.0511	0.05109	0.42	0.517
AC_th	1	0.0782	0.15%	0.0055	0.00551	0.05	0.831
Maint. Cat.	3	3.8304	7.24%	3.6687	1.22290	10.08	0.000
Season*Time	3	0.4036	0.76%	0.2903	0.09676	0.80	0.496
Season*AC_th	3	1.1690	2.21%	1.2046	0.40152	3.31	**0.020**
Time*AC_th	1	0.3742	0.71%	0.3742	0.37422	3.08	0.080
Error	356	43.1967	81.68%	43.1967	0.12134		
Lack-of-Fit	27	7.6753	14.51%	7.6753	0.28427	2.63	0.000
Pure Error	329	35.5214	67.17%	35.5214	0.10797		
Total	371	52.8863	100.00%				



(a) Main effects plot



(b) Seasonal mean difference with 95% confidence intervals

Figure 31 ANOVA plots for subgrade moduli data - DF climatic region

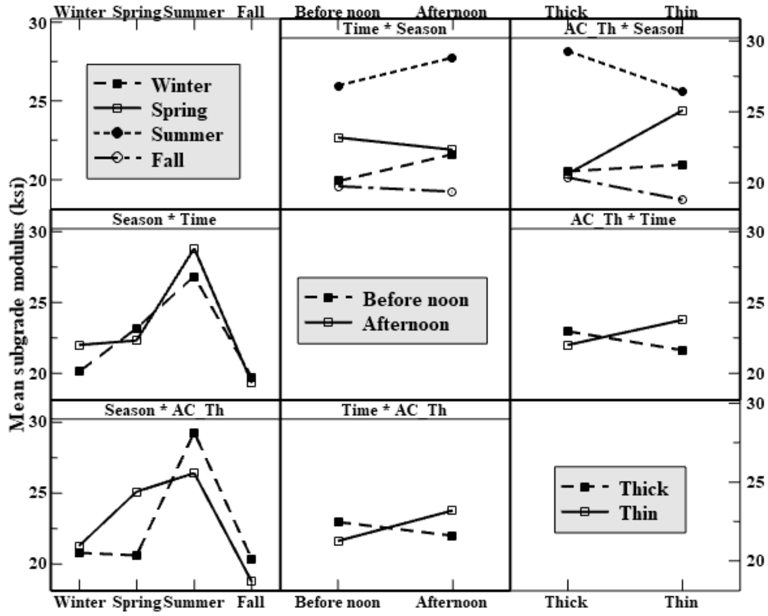


Figure 32 Interaction means plot for subgrade moduli data – DNF climatic region

Observing the interaction between season and HMA layer thickness in Figure 32 shows that there is no noticeable difference between the subgrade moduli values in the winter and fall seasons irrespective of the HMA layer thickness. However, there is a clear distinction between subgrade moduli values in spring season backcalculated for pavements with thin and thick HMA layers (around 5 ksi). Also, a noticeable difference exists between subgrade moduli values in the fall season as well for values obtained from testing on pavements with different HMA layer thickness. Overall, moduli values related to summers are the highest, while those related to the fall season are the lowest.

Results from a similar ANOVA for the WF region also show that the interaction between season and HMA layer thickness influences the subgrade moduli of the pavements. Table 32 displays the ANOVA results for the WF climatic region. Figure 33 shows the interaction means plot along with the mean comparisons for the two interacting factors. There is a clear difference between the moduli values obtained in different seasons from pavements with different HMA layer thicknesses. A minimum mean difference of 4 ksi (for spring season) exists between subgrade moduli values obtained for a thick and a thin HMA layered pavement in all seasons. The maximum mean (21 ksi) difference exists between mean subgrade moduli measured over thick and thin HMA layer pavements in the winter season; a possible explanation can be extremely low temperatures.

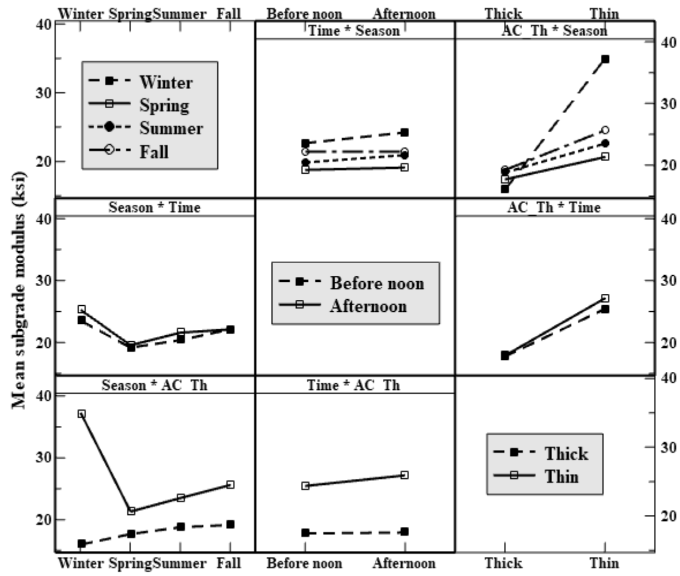
Table 32 ANOVA results for subgrade layer moduli values – WF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	2.829	1.16%	3.404	1.1348	5.97	0.000
Time	1	0.020	0.01%	0.209	0.2093	1.10	0.294
AC_th	1	5.737	2.36%	16.808	16.8082	88.40	0.000
Maint. Cat.	3	13.447	5.53%	11.792	3.9306	20.67	0.000
Season*Time	3	0.160	0.07%	0.183	0.0610	0.32	0.810
Season*AC_th	3	4.853	2.00%	4.960	1.6532	8.70	**0.000**
Time*AC_th	1	0.140	0.06%	0.140	0.1395	0.73	0.392
Error	1135	215.795	88.81%	215.795	0.1901		
Lack-of-Fit	36	18.451	7.59%	18.451	0.5125	2.85	0.000
Pure Error	1099	197.343	81.22%	197.343	0.1796		
Total	1150	242.981	100.00%				

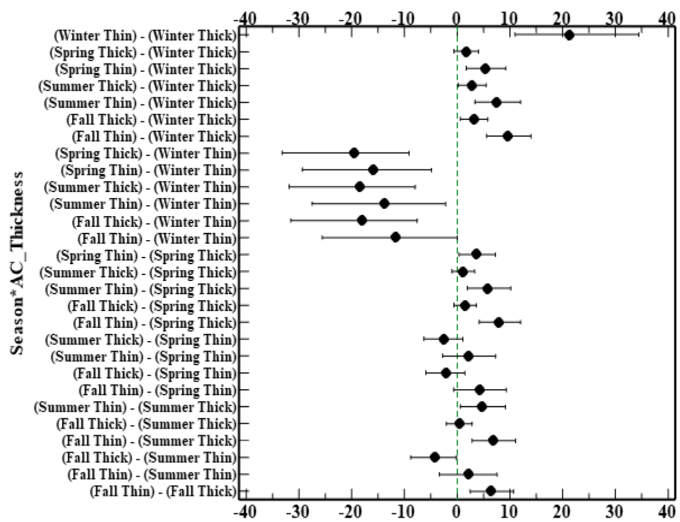
Table 33 ANOVA results for subgrade layer moduli values – WNF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	3.231	1.58%	3.493	1.16436	7.30	**0.000**
Time	1	0.044	0.02%	0.091	0.09104	0.57	0.450
AC_th	1	0.527	0.26%	0.117	0.11658	0.73	0.393
Maint. Cat.	3	9.983	4.87%	10.030	3.34322	20.97	0.000
Season*Time	3	0.358	0.17%	0.397	0.13219	0.83	0.478
Season*AC_th	3	0.573	0.28%	0.574	0.19127	1.20	0.309
Time*AC_th	1	0.001	0.00%	0.001	0.00063	0.00	0.950
Error	1193	190.202	92.82%	190.202	0.15943		
Lack-of-Fit	45	11.801	5.76%	11.801	0.26225	1.69	0.003
Pure Error	1148	178.400	87.06%	178.400	0.15540		
Total	1208	204.919	100.00%				

A similar ANOVA analysis for the WNF climatic region reveals that the season of FWD testing has an impact on the subgrade modulus backcalculated from the measured deflections (see Table 33). The mean difference plot within different seasons shows that the difference of subgrade moduli values between summer and winter (about 2 ksi), fall and winter (about 2.5 ksi), and fall and spring (about 1.5 ksi) seasons are noticeable enough to alter pavement's performance (see Figure 34).

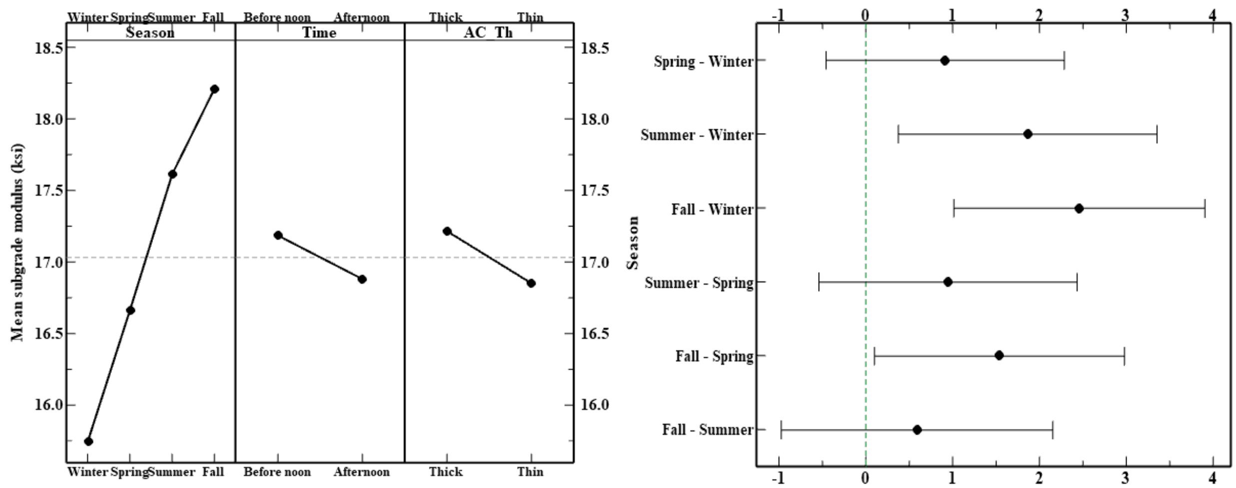


(a) Interaction means plot



(b) Mean difference with 95% confidence intervals for season and HMA layer thickness

Figure 33 ANOVA plots for subgrade moduli data - WF climatic region



(a) Main effects plot

(b) The seasonal mean difference with 95% confidence interval

Figure 34 ANOVA plots – WNF climatic region

Discussion on ANOVA Results (HMA, Base and Subgrade Moduli)

Different techniques are used in practice to correct the HMA layer moduli values to a standard temperature of 77°F. The LTPP SMP database contains the uncorrected backcalculated HMA moduli values. This study presents the correction of these values based on the Asphalt Institute equation:

$$log\,E_0 = log\,E + 1.47362 \times 10^{-4}(t^2 - t_0^2)$$

Where;

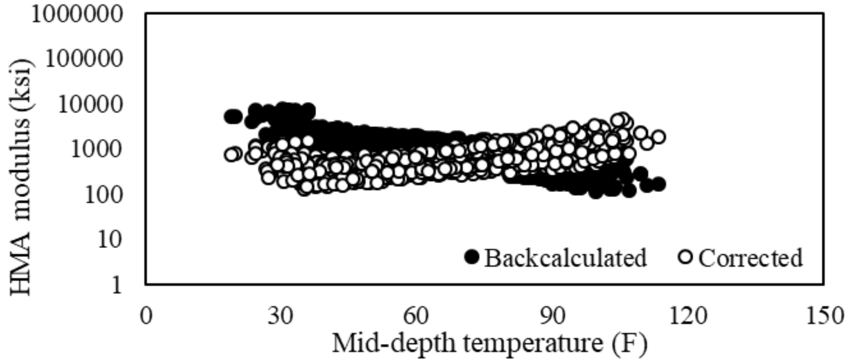
E_0 = corrected HMA layer modulus in psi;

E = backcalculated uncorrected HMA layer modulus in psi;

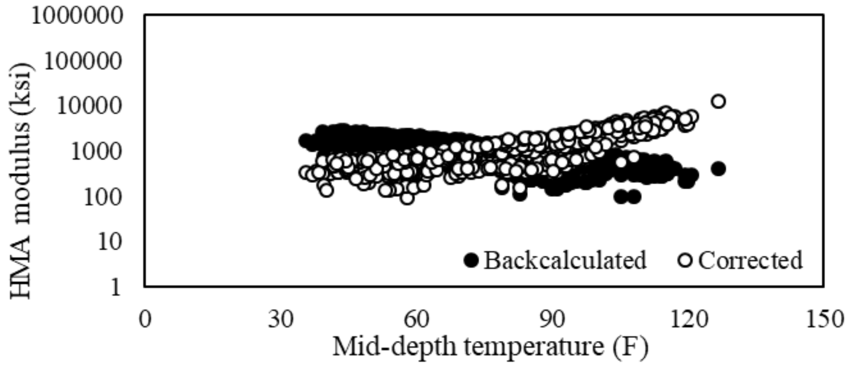
t = test temperature in degree Fahrenheit; and

t_0 = reference temperature = 77°F.

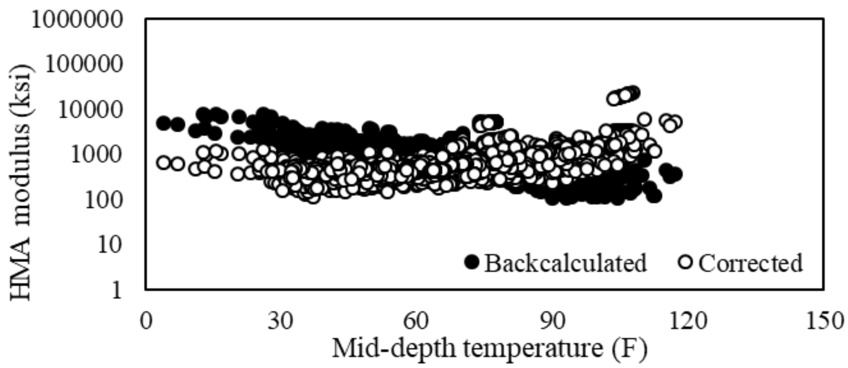
The calculation of the mid-depth HMA layer temperatures for each pavement section involved using the data from the MON_DEFL_TEMP_DEPTH table of the LTPP monitoring module.



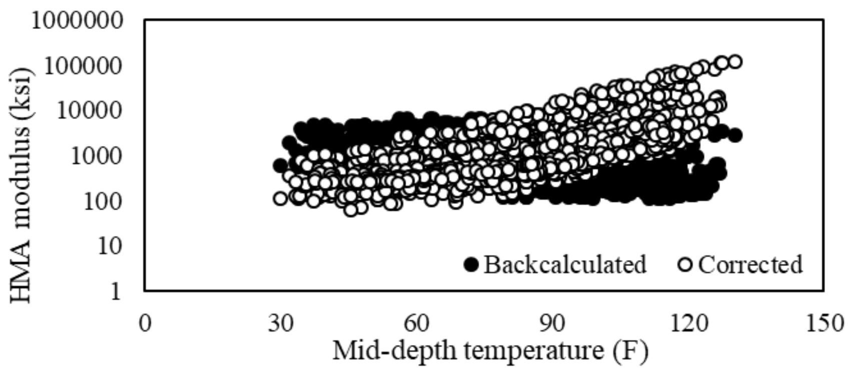
(a) HMA layer moduli correction - DF climatic region



(b) HMA layer moduli correction - DNF climatic region



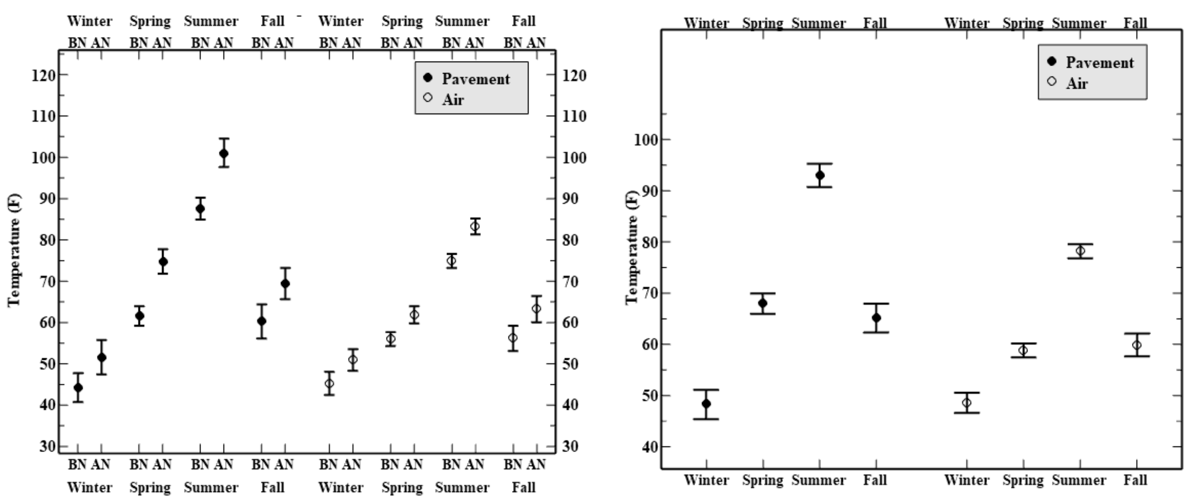
(c) HMA layer moduli correction – WF climatic region



(d) HMA layer moduli correction – WNF climatic region

Figure 35 HMA layer moduli temperature correction using the Asphalt Institute equation

Figure 35 shows the corrected HMA moduli values for each climatic region using the Asphalt Institute equation. The equation performed well in correcting the available HMA moduli values, as shown in the figure. The data showed the highest variation in HMA layer moduli values in the WNF climatic region; hence, the high variation in the corrected values can also be seen. Thus, it may not be critical at what temperature or weather conditions the FWD deflections are measured on flexible pavements for the HMA layer. Since a single FWD measurement gives the moduli for all the layers (i.e., surface, base, and subgrade), the underlying unbound layers become critical. Therefore, the general guidelines should consider the variation of moduli values for the unbound layers together for all layers.



(a) Temperature ranges for season and time interaction

(b) Seasonal temperature ranges

Figure 36 Pavement surface and ambient temperatures during FWD measurements on flexible pavements - DF climatic region

Figure 36 presents the temperature ranges during FWD measurements in the DF climatic region. ANOVA results showed that the interaction of season and time and season and HMA thickness were significant factors for HMA and base layer moduli in the DF climatic region, respectively. Subgrade moduli analysis showed the main effects of the season as a prominent feature in defining change in the moduli. The ambient temperature ranges occurring in the spring and fall seasons appear to have the least variation of the moduli values in the HMA layer. Thus, the subgrade and the base moduli backcalculated from using FWD deflection in these temperature ranges would result in values close to the actual. Consequently, the suggested ambient temperature range for conducting FWD in the DF climatic region is between 55 - 70°F.

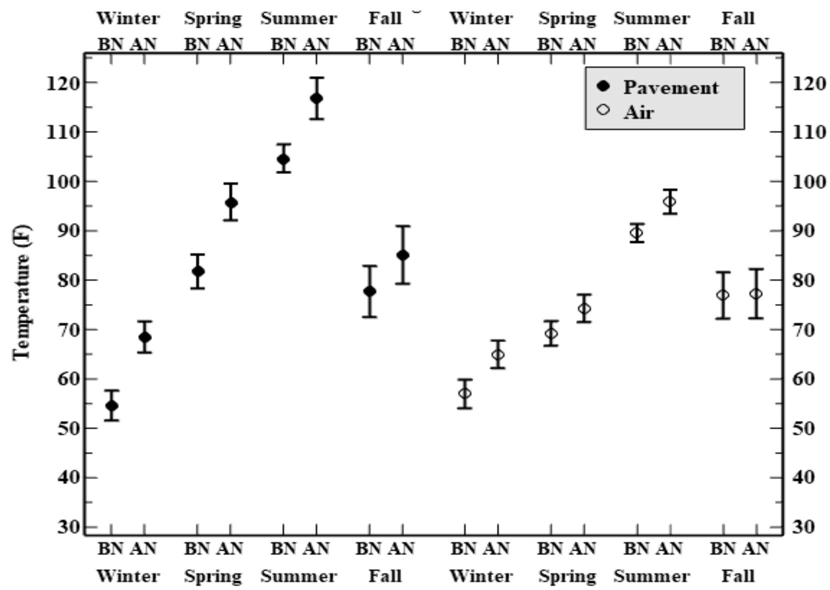
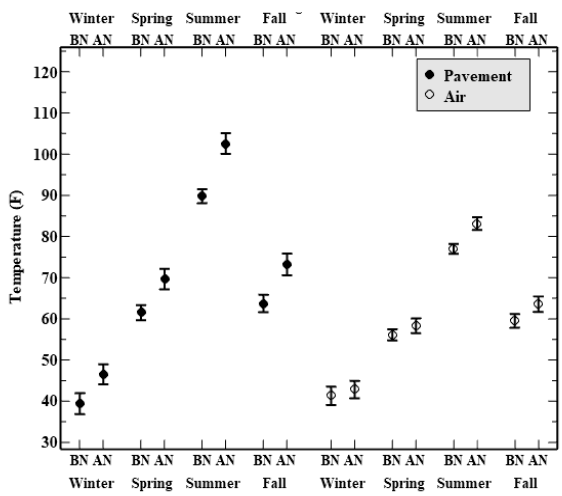


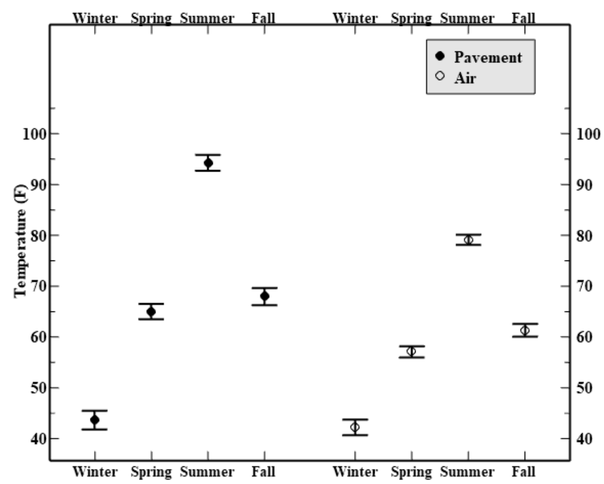
Figure 37 Pavement surface and ambient temperatures during FWD measurements on flexible pavements - DNF climatic region

Figure 37 shows the temperature ranges recorded during FWD measurements in the DNF climatic region. In this climate, the season and time interaction showed noticeable effects on HMA and base layer moduli values according to ANOVA results. For subgrade, season and HMA layer thickness interaction was deemed critical. Based on the ANOVA results presented earlier and the observed effects of each of the layer moduli, the spring and fall season ambient temperatures appear to have minimal variation in the base and HMA layer moduli, respectively. The unbound layer moduli did not show considerable difference in the spring and fall seasons as well. Therefore, the ambient temperatures between 65 – 80°F appear to result in the unbound layer moduli values that may be closest to the actual.

In the WF climate, the interaction of season and time appears significant for effects in HMA layer moduli according to ANOVA results. Season and season and HMA layer thickness interaction showed to have a noticeable impact on base and subgrade layer moduli, respectively. Figure 38 shows the temperature ranges for season and time interaction, and the seasonal temperature ranges in the WF climatic region. HMA moduli showed the least variation between the spring and fall seasons. Base moduli showed no change between spring and summer seasons, while subgrade moduli remained similar in the spring season. Based on the observed effects, the ambient temperatures within the spring season can help in determining the actual unbound layer moduli in the WF climatic region. Consequently, the ambient temperature range suggested for FWD deflection measurements is between 55 – 65°F.



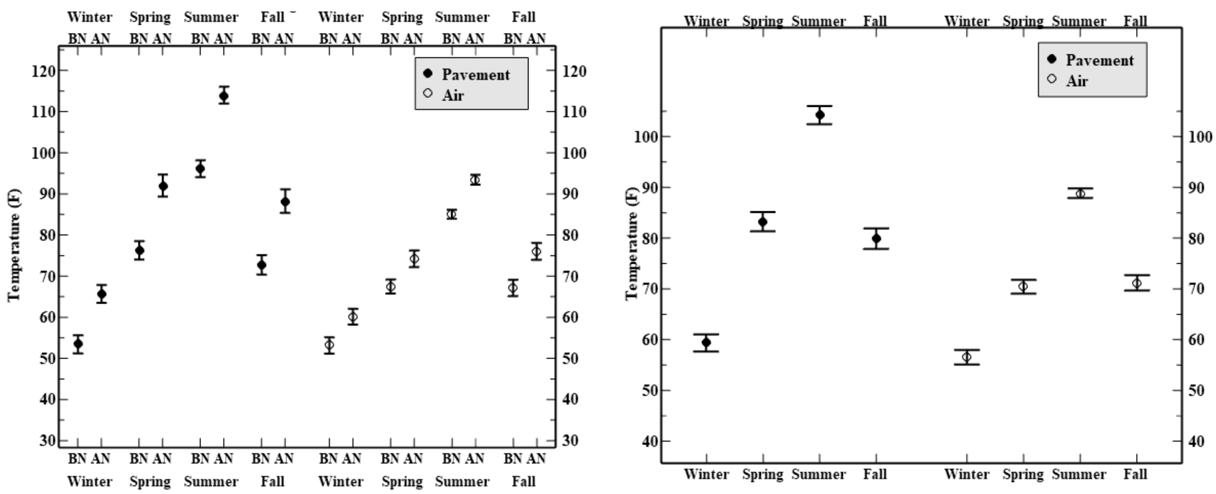
(a) Temperature ranges for season and time interactions



(b) Seasonal temperature ranges

Figure 38 Pavement surface and ambient temperatures during FWD measurements on flexible pavements - WF climatic region

The season and time interaction was termed significant as per the ANOVA results for WNF climatic region concerning HMA layer moduli. The interaction means plot showed minimal variation in the HMA layer moduli values between fall and spring seasons. ANOVA results for the base and subgrade layers revealed the FWD measurement season as an essential factor affecting their moduli. Based on the effects seen on the unbound layers, the FWD deflections measured within the ambient temperatures occurring in the spring season can result in moduli values closest to the actual. Figure 39 shows the ambient temperature in the spring season to be 65 – 75^{o}F; thus, suggested to conduct FWD deflection measurements in the WNF climatic region.

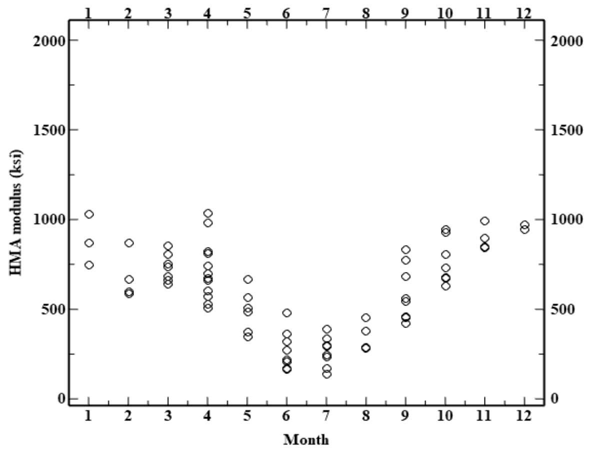


(a) Temperature ranges for season and time interactions

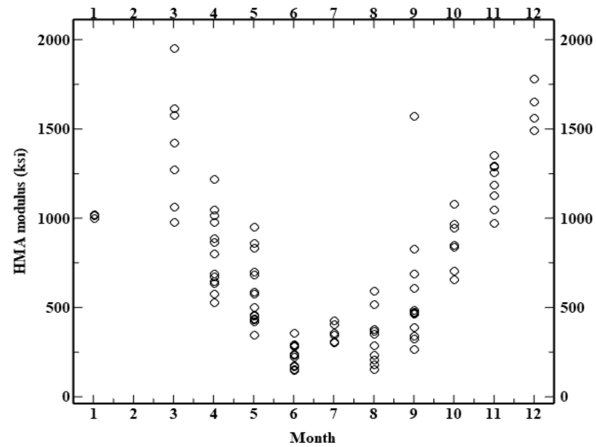
(b) Seasonal temperature ranges

Figure 39 Pavement surface and ambient temperatures during FWD measurements on flexible pavements - WNF climatic region

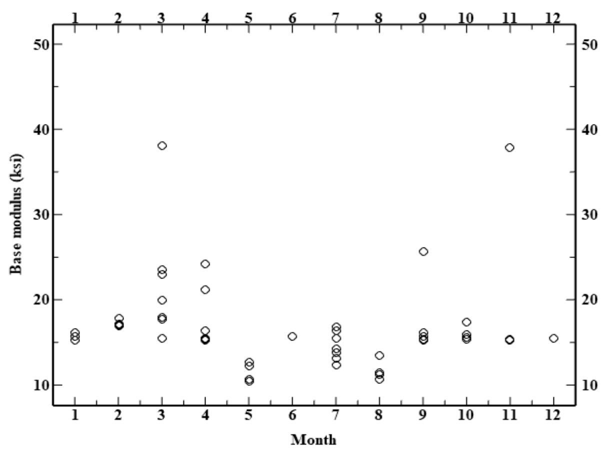
Consequently, based on the discussion presented in this section, the suggested ambient temperature deemed appropriate to result in the unbound layer moduli, which represents their actual condition, is between 55 – 75^{o}F. Also, since the time of the day did not appear to affect the unbound layers, as expected, FWD deflections can be measured at any time of the day with the ambient temperature in the suggested range.



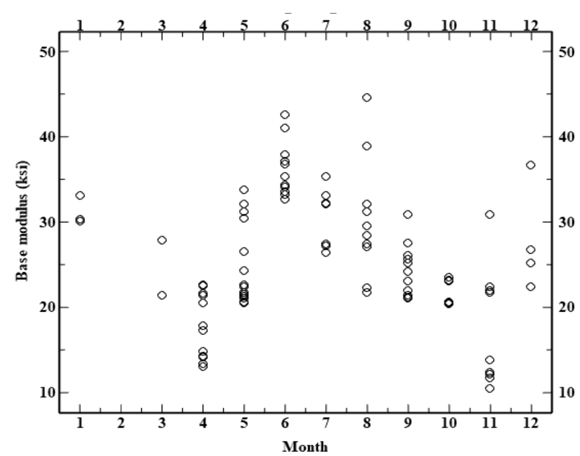
(a) HMA moduli for South Dakota section ID 46-9187 – DF climatic region



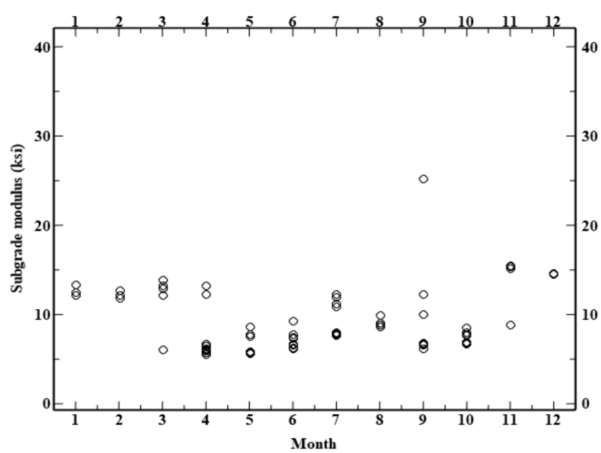
(b) HMA moduli for Maine section ID 23-1026 – WF climatic region



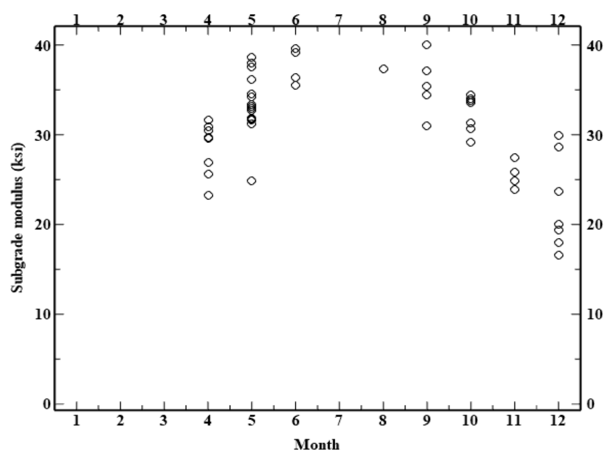
(c) Base moduli for South Dakota section ID 46-9187 – DF climatic region



(d) Base moduli for Maine section ID 23-1026 – WF climatic region



(e) Subgrade moduli for South Dakota section ID 46-9187 – DF climatic region



(f) Subgrade moduli for Maine section ID 23-1026 – WF climatic region

Figure 40 Monthly variation in layer moduli values - SMP flexible pavement sections

Figure 40 shows the monthly variation in layer moduli values for two sections, each in the DF and WF climatic region. The plots show that the HMA layer moduli decrease in the summer months while these increase as the temperatures get colder (i.e., winter and fall months). The corresponding base and subgrade moduli values also show monthly (i.e., seasonal) variation, which is in agreement with the ANOVA results for these climatic regions.

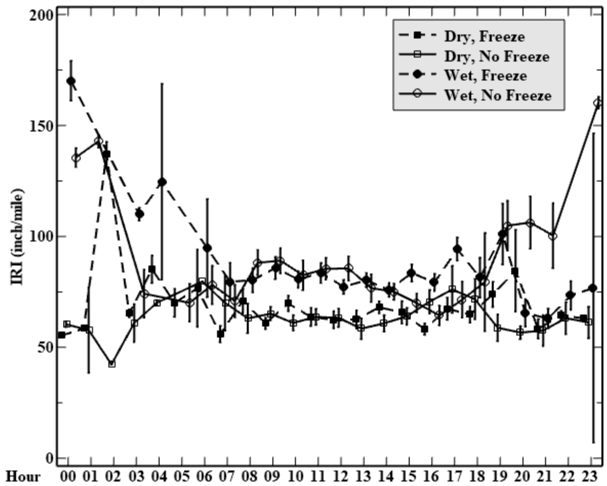
4.1.2 Longitudinal Profile Measurements (IRI) – Flexible Pavements

The smoothness of a pavement surface determines its functional performance, evaluated using longitudinal profile measurements. The longitudinal profile measurements are commonly summarized by the International Roughness Index (IRI) that reduces the thousands of elevation values into a single value [38, 39]. However, no matter which index is calculated from a longitudinal profile, the quality of the information is only as good as the profile measurement [2]. But seasonal and diurnal (temperature/moisture) changes influence these profile measurements. Therefore, there is a need to evaluate the impacts of temporal (seasonal temperature/moisture and daily temperature) variations on longitudinal profile measurements.

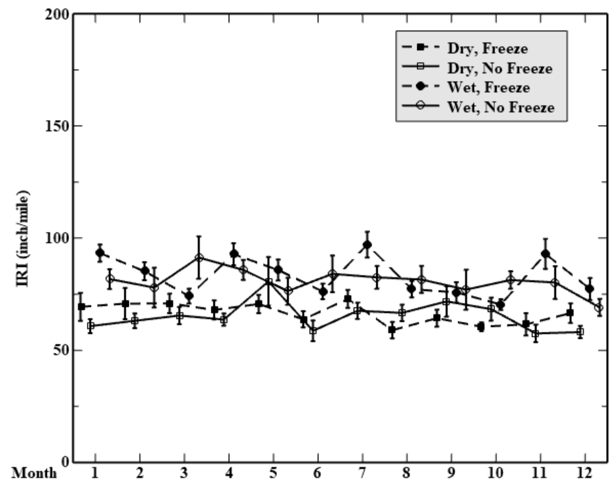
The steps involved in the analysis are enumerated as follows:

1. The pavement structure details, IRI values, profile measurement dates and timings, maintenance history, pavement surface temperature, and air temperature were some of the variables identified to perform the analysis.
2. The investigation required an analysis involving the available flexible pavement sections in the LTPP SMP database.
3. The available flexible pavement sections were identified in the SMP LTPP database with their climatic region. Note that the climatic regions are defined based on temperature (i.e., freeze/no freeze), and moisture (i.e., wet/dry).

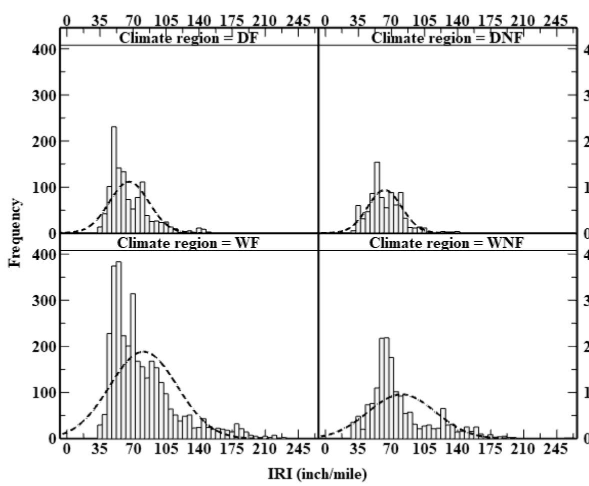
4. The structural details of the identified sections (i.e., layer types and thicknesses) were obtained.
5. The IRI values, along with the date and time of profile measurements, the air and pavement surface temperatures were obtained. Also, the maintenance history details for the section were extracted from the database (i.e., construction no. and type of treatment) and categorized.
6. Five profile measurements (runs) per visit are the LTPP standard [44]; the analysis used each of the calculated IRI values.
7. All the required data elements were arranged in a relational database.
8. Inspected the data using a histogram and boxplot to identify outliers.
9. Two factors were used in this analysis; (a) measurement month discretized into four seasons (i.e., levels) to look at the seasonal effects, (b) measurement time with two levels (before noon and afternoon) for the diurnal effects. Besides, the maintenance category was used as a blocking factor. Additionally, an additional factor used was the HMA layer thickness with two levels (i.e., thick and thin) based on the original SMP study design [43].
10. Analysis of Variance (ANOVA) was conducted for JPCP sections within each climatic region to investigate the temporal effects on the joint LTE values.



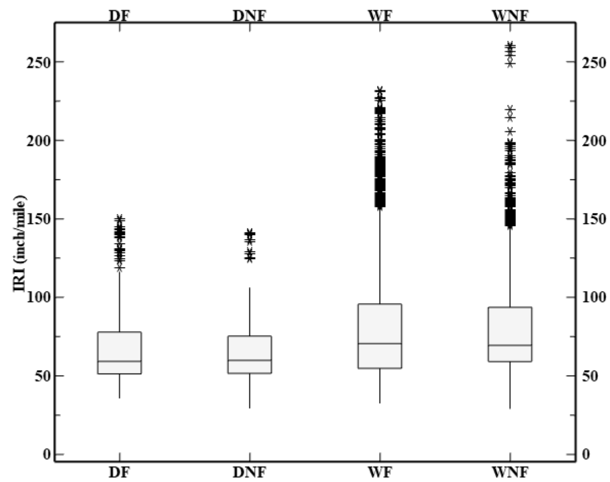
(a) IRI by hour



(b) IRI by month



(c) Histogram – Available IRI data



(d) Box-plot – Available IRI data

Figure 41 Assessing available IRI data – SMP flexible pavement sections

Figure 41 shows the overall variations in the mean IRI values by the hour and month of profile measurements within different climatic regions. The IRI values show an important hourly influence, i.e., the IRI values are different in each hour among the different climatic regions [see Figure 41(a)]. Also, significant variations can be seen in the IRI values among different months. [see Figure 41(b)]. Figure 41(c) and (d) show the histogram and box-plots, while Table 34 displays the descriptive statistics of the data within each climatic region. There is generally higher variability in the IRI values within different climates, with the highest in the wet climates.

The variation in these climates may be due to IRI values over 170 inch/mile. Such higher values can potentially mask the results of ANOVA. The IRI analysis for the flexible pavement section presented in this study uses values between 30-170 inch/mile.

Table 34 Descriptive statistics IRI values—SMP flexible pavement sections

Climatic region	N	Mean	Std.	Minimum	Q1	Median	Q3	Maximum
DF	1163	65.9	20.8	35.8	51.2	59.2	77.8	149.9
DNF	840	63	17.9	29.2	51.5	59.8	75.2	141.4
WF	3387	81.1	35.8	32.5	54.6	70.5	95.8	231.8
WNF	1727	81.1	35.7	29.1	59.1	69.4	93.6	261.1

Note: IRI values shown are in inch/mile units.

Table 35 ANOVA results for IRI data for flexible pavements – DF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	0.006833	1.95%	0.003750	0.001250	7.97	0.000
Time	1	0.000001	0.00%	0.000265	0.000265	1.69	0.194
AC_th	1	0.089827	25.63%	0.045984	0.045984	293.25	0.000
Maint. Cat.	3	0.064755	18.48%	0.057951	0.019317	123.19	0.000
Season*Time	3	0.003519	1.00%	0.004306	0.001435	9.15	**0.000**
Season*AC_th	3	0.005018	1.43%	0.004505	0.001502	9.58	**0.000**
Time*AC_th	1	0.000635	0.18%	0.000635	0.000635	4.05	**0.044**
Error	1147	0.179856	51.32%	0.179856	0.000157		
Lack-of-Fit	31	0.029292	8.36%	0.029292	0.000945	7.00	0.000
Pure Error	1116	0.150564	42.96%	0.150564	0.000135		
Total	1162	0.350443	100.00%				

ANOVA results for DF climatic region show that the interaction of season and time influences the IRI of the flexible pavement sections. Also, the interactions of season and time with HMA layer thickness has a bearing on the pavement’s IRI (see Table 35). The data was transformed to satisfy the normality assumptions to draw meaningful conclusions from the ANOVA (see Figure 42).

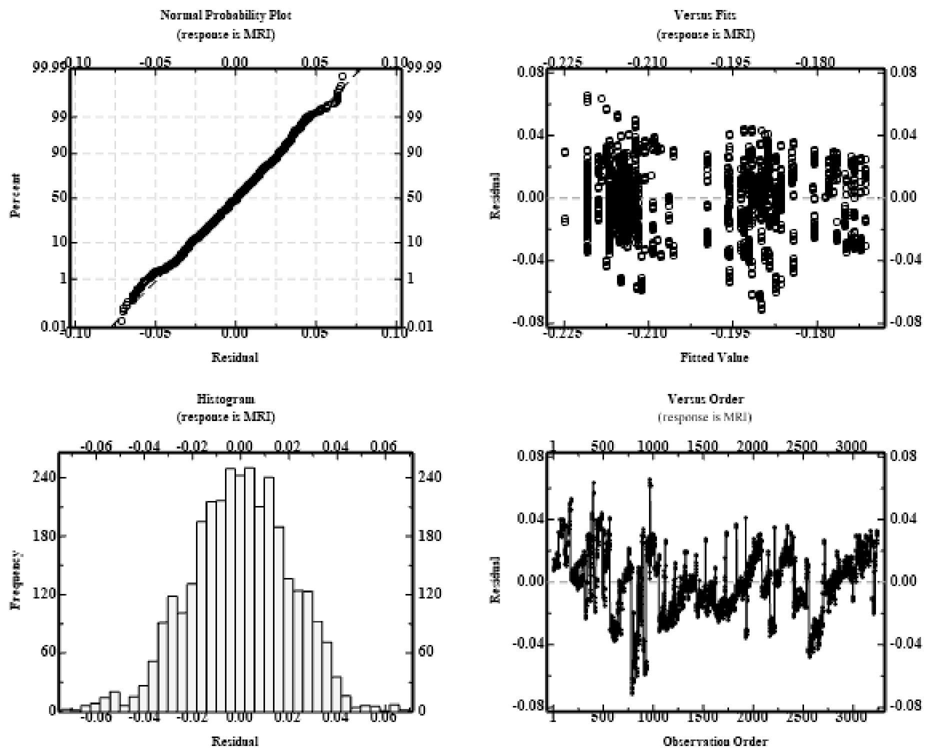


Figure 42 An example of ensuring normality of the IRI data - WF climatic region

Figure 43 shows the interaction means plot from the ANOVA for the IRI data of the DF climatic region. There is no considerable difference between the IRI values obtained in the morning (i.e., before-noon) and the afternoon with seasons. The fall season shows a variation of the morning and afternoon IRI of around 8 inches/mile, which is not practically relevant. The IRI changes considerably between thick (> 5inches) and thin (< 5inches) HMA layered pavements with different seasons and times of the day. The thin HMA layered pavements exhibited higher IRI values overall. The IRI differs around 15 – 20 inches/mile in all seasons except fall between thick and thin HMA layered pavements [see Figure 44(a)]. A similar IRI difference exists between pavements with thick and thin HMA layers across different times (i.e., before noon and afternoon) of the day [see Figure 44(b)].

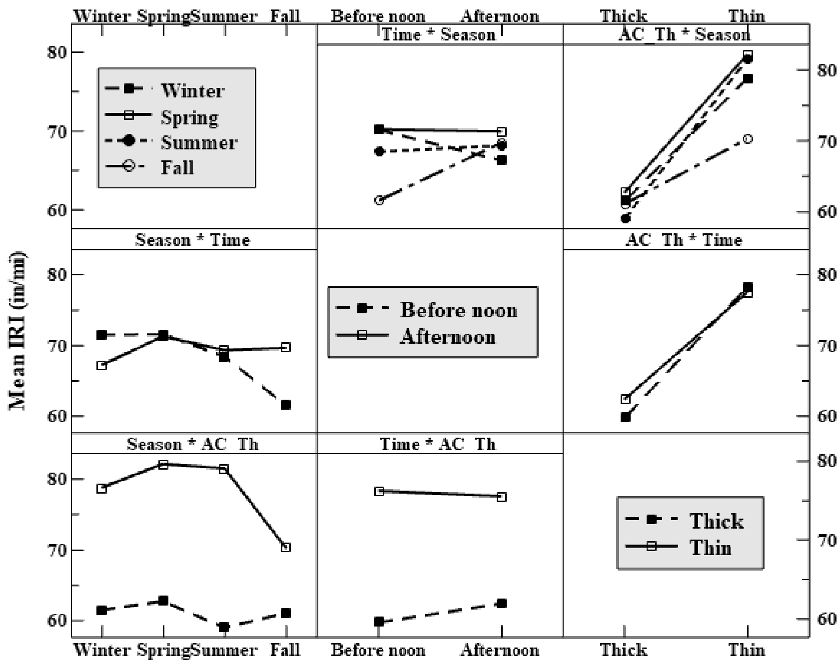
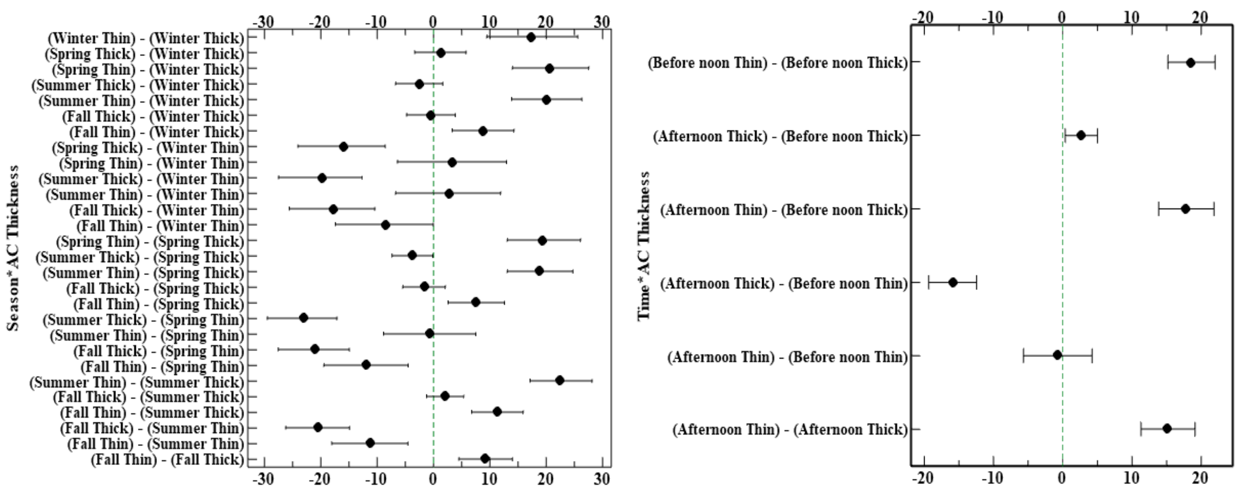


Figure 43 Interaction means plot for IRI data - DF climatic region



(a) Mean differences with 95% confidence intervals for season and HMA layer thickness interaction

(b) Mean differences with 95% confidence intervals for time and HMA layer thickness interaction

Figure 44 Mean IRI multiple comparison plots – DF climatic region

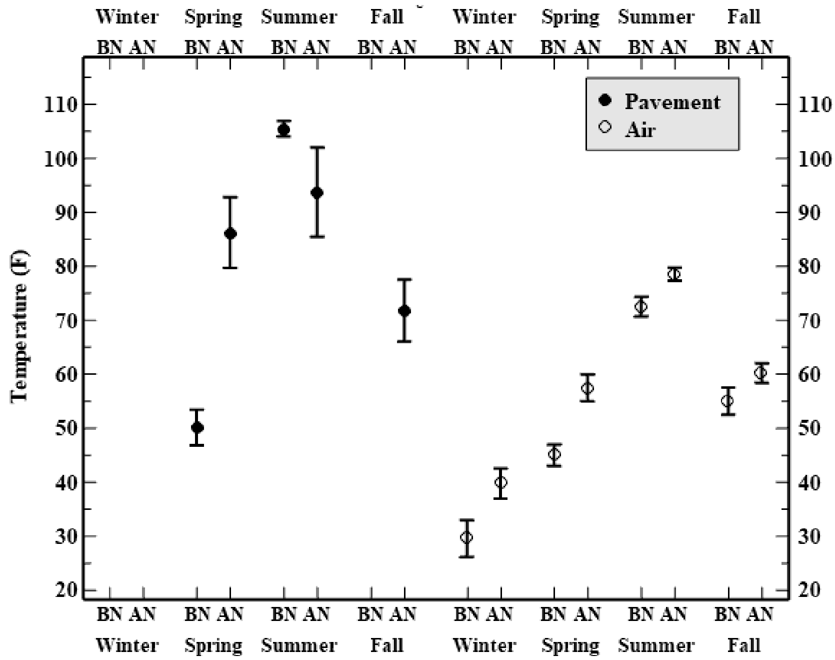


Figure 45 IRI measurement temperatures with 95% confidence intervals - DF climatic region

Figure 45 displays the temperatures at the time of profile measurements. A comparison of Figures 43 and 45 infers that the ambient temperatures related to the fall season produce IRI with less variation irrespective of the season, time of the day, and HMA layer thickness. The ambient temperatures in the fall season range between 50 - 65°F. Such temperatures are suggested for profile measurements in DF climates on flexible pavements. Besides, at such temperatures where possible, the pavement profile should be measured in the morning times (i.e., before noon).

Table 36 ANOVA results for IRI data for flexible pavements – DNF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	2.2935	3.55%	0.1371	0.04570	1.11	0.343
Time	1	0.0044	0.01%	0.4303	0.43033	10.49	0.001
AC_th	1	16.0635	24.83%	9.3492	9.34916	227.79	0.000
Maint. Cat.	3	9.2876	14.36%	8.2945	2.76482	67.36	0.000
Season*Time	3	2.5753	3.98%	2.4898	0.82994	20.22	**0.000**
Season*AC_th	3	0.4597	0.71%	0.3531	0.11770	2.87	**0.036**
Time*AC_th	1	0.3952	0.61%	0.3952	0.39516	9.63	**0.002**
Error	819	33.6137	51.96%	33.6137	0.04104		
Lack-of-Fit	24	7.2782	11.25%	7.2782	0.30326	9.15	0.000
Pure Error	795	26.3355	40.71%	26.3355	0.03313		
Total	834	64.6929	100.00%				

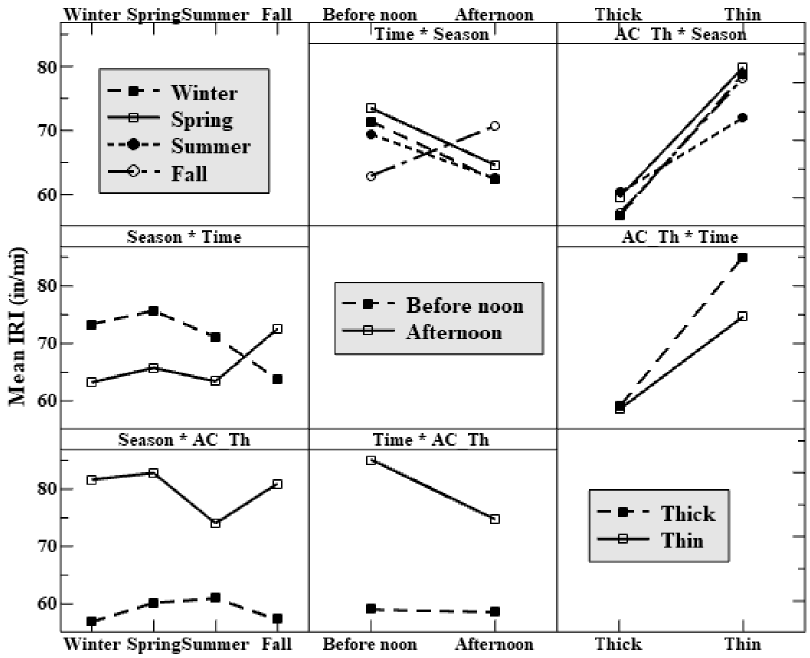
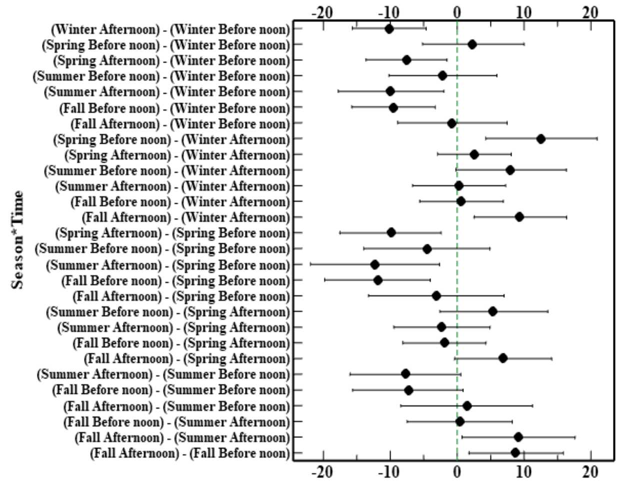
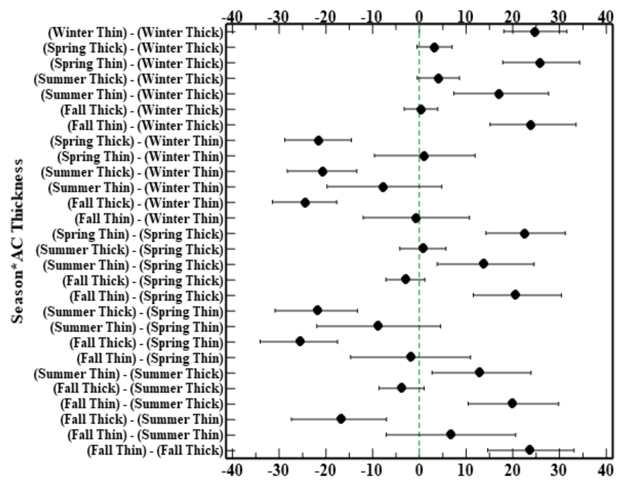


Figure 46 Interaction means plot for IRI data - DNF climatic region

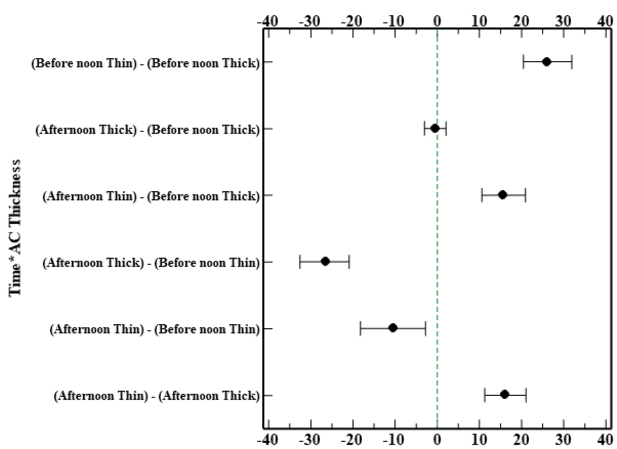
Table 36 displays the results from ANOVA on IRI data for DNF climatic region. The three interactions between profile measurement season, time, and the HMA layer thickness appears significant. To dissect these interactions, one needs to look at the interaction means plots for each significant interaction. Figure 46 shows the interaction means plot for the ANOVA for DNF climatic region. Noticeable differences exist between IRI obtained from profile measurements undertaken in different seasons. Similar to the DF climate, pavements with thick HMA layer has lower IRI, with little variation, as compared to thin HMA layered pavements across different seasons in the DNF climatic region. Also, pavements with thick HMA layers display low IRI without any changes across the day as compared to pavements with thin HMA layer thickness; it has higher IRI and varies with time in the day.



(a) Mean difference with 95% confidence interval for season and time interaction



(b) Mean difference with 95% confidence interval for season and HMA layer thickness



(c) Mean difference with 95% confidence interval for time and HMA layer thickness

Figure 47 Mean IRI multiple comparison plots – DNF climatic region

Figure 47 shows the multiple comparison plots for the significant interactions for the DNF climatic region. There is an IRI difference of less than 10 inches/mile between morning (i.e., before noon) and afternoon within every season [see Figure 47(a)]. A considerable difference in mean IRI values also exists between thick and thin HMA layered pavements within every season. The lowest difference (< 15 inches/mile) occurs in the summer season in IRI values determined with different HMA layer thickness; 22 – 25 inches/mile difference exists among the rest of the seasons [see Figure 47(b)]. Pavements with different HMA layer thickness also show considerable variation (> 16 inches/mile) in IRI during the day from morning to afternoon [see Figure 47(c)]. Figure 48 shows the profile measurement temperatures for the DNF climatic region. Based on the discussion and observing the temperatures, a range between 50 - 75°F can be suggested for IRI measurements in the DNF climatic region

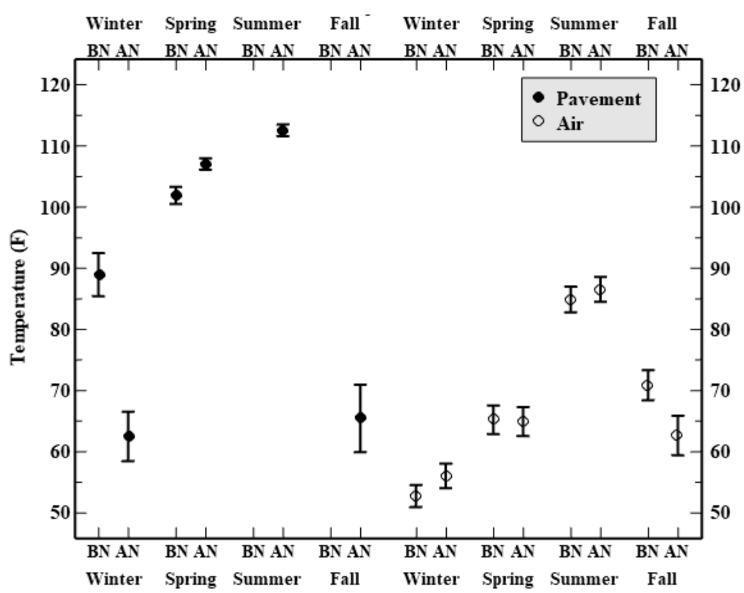


Figure 48 IRI measurement temperatures with 95% confidence intervals - DNF climatic region

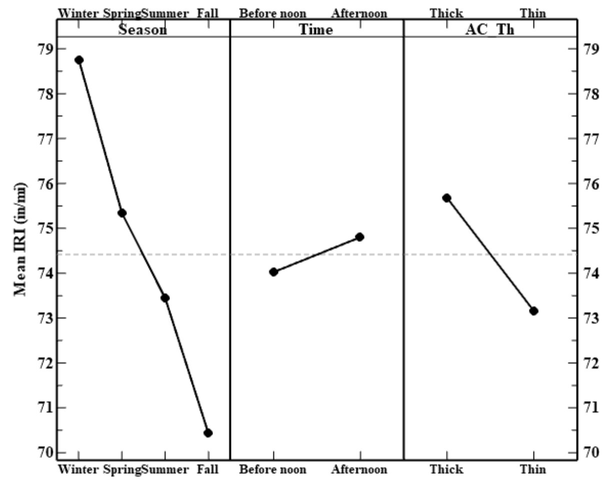
For the WF climatic region, ANOVA declares HMA layer thickness and interaction between profile measurement season and time to be driving the IRI variations (see Table 37). The main effects plot illustrates that, although statistically significant, there is no practical difference between IRI of pavements with different HMA layer thickness [see Figure 49(a)].

Considering the ANOVA termed statistically significant season and time interaction, the interaction means plot does not show any practical IRI differences within a day between various seasons [see Figure 49(b)]. No difference exists between IRI values determined during the day, irrespective of the time, in spring and summer seasons. The preceding discussion, along with the temperatures shown in Figure 49(c), suggests that it might be better to determine IRI using profile measurements conducted within the ambient temperatures ranging between 50 – 75°F.

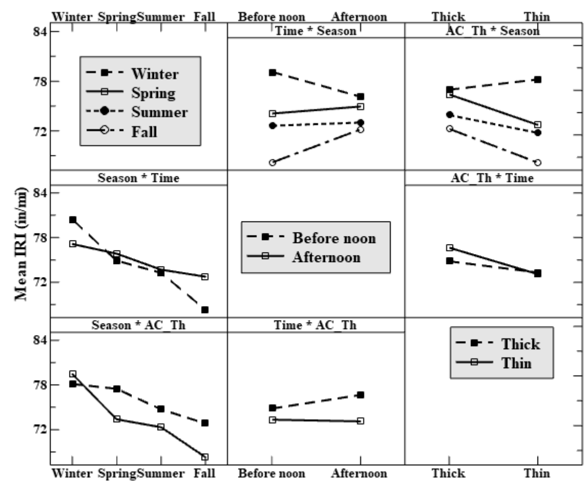
Table 37 ANOVA results for IRI data for flexible pavements – WF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	0.04613	2.14%	0.01814	0.006048	13.66	0.000
Time	1	0.00051	0.02%	0.00034	0.000340	0.77	0.381
AC_th	1	0.04056	1.88%	0.00318	0.003181	7.18	**0.007**
Maint. Cat.	3	0.63157	29.24%	0.61529	0.205098	463.07	0.000
Season*Time	3	0.00519	0.24%	0.00556	0.001853	4.18	**0.006**
Season*AC_th	3	0.00260	0.12%	0.00283	0.000945	2.13	0.094
Time*AC_th	1	0.00058	0.03%	0.00058	0.000577	1.30	0.254
Error	3235	1.43280	66.33%	1.43280	0.000443		
Lack-of-Fit	43	0.26613	12.32%	0.26613	0.006189	16.93	0.000
Pure Error	3192	1.16668	54.01%	1.16668	0.000365		
Total	3250	2.15995	100.00%				

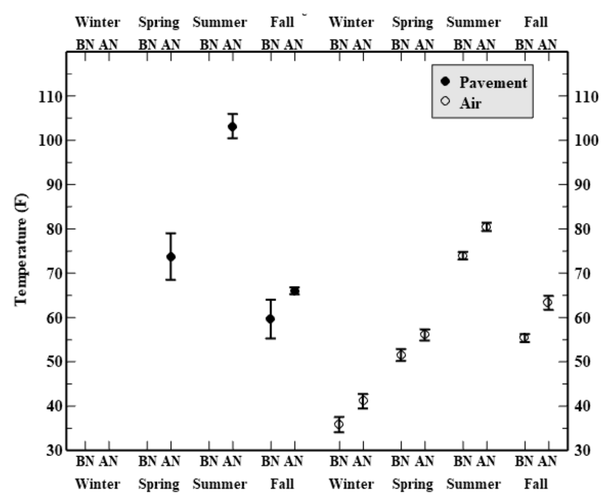
Table 38 displays the ANOVA results for the WNF climatic region. It shows that the profile measurement season, time of the day, and the HMA layer thickness has an essential influence on the pavement’s IRI. However, the main effects plot shows that there is only a practically significant difference (about 22 inches/mile) between IRI in pavements with different HMA layer thickness [see Figure 50(a)]. No practical difference between the pavement IRI exists within seasons or different times of the day.



(a) Main effects plot



(b) Interaction means plot

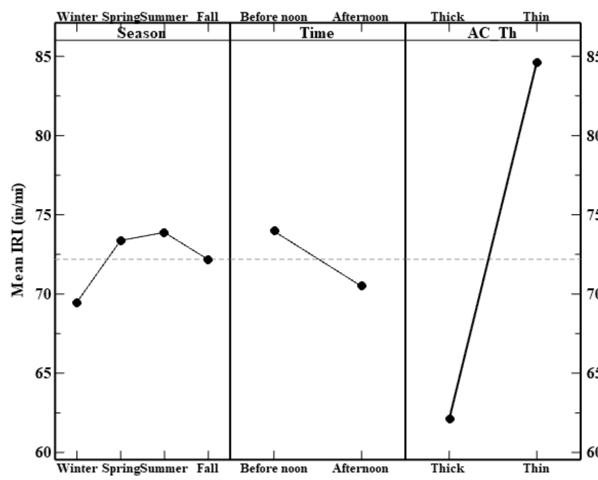


(c) Profile measurement temperatures with 95% confidence intervals

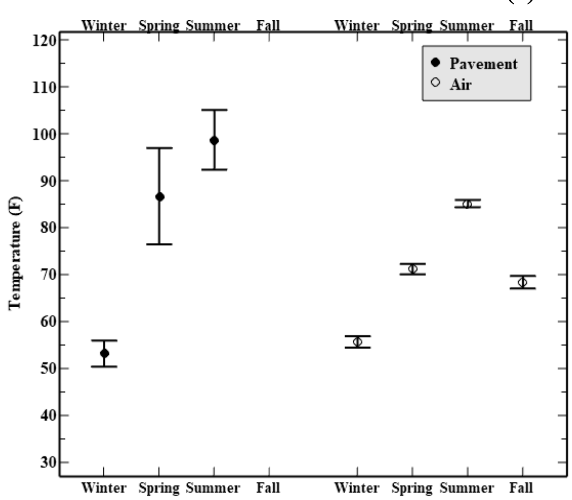
Figure 49 ANOVA results for IRI data of flexible pavements – WF climatic region

Table 38 ANOVA results for IRI data for flexible pavements – WNF climatic region

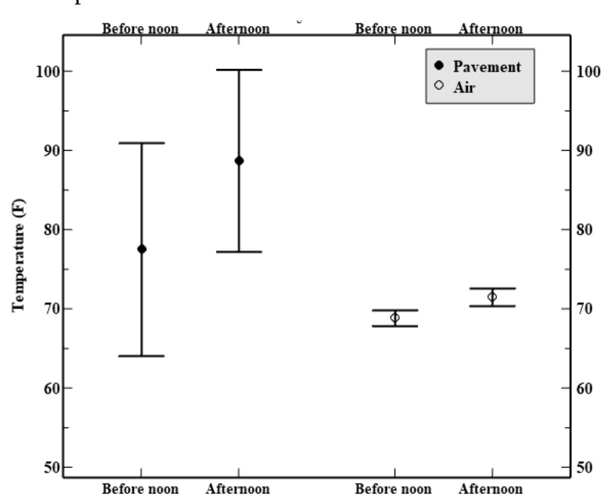
Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	0.00542	0.38%	0.005599	0.001866	3.15	**0.024**
Time	1	0.03279	2.28%	0.005389	0.005389	9.08	**0.003**
AC_th	1	0.31419	21.84%	0.202213	0.202213	340.85	**0.000**
Maint. Cat.	3	0.09186	6.39%	0.090810	0.030270	51.02	0.000
Season*Time	3	0.00252	0.18%	0.002422	0.000807	1.36	0.253
Season*AC_th	3	0.00325	0.23%	0.003165	0.001055	1.78	0.149
Time*AC_th	1	0.00051	0.04%	0.000505	0.000505	0.85	0.356
Error	1665	0.98778	68.68%	0.987783	0.000593		
Lack-of-Fit	41	0.14180	9.86%	0.141802	0.003459	6.64	0.000
Pure Error	1624	0.84598	58.82%	0.845981	0.000521		
Total	1680	1.43832	100.00%				



(a) Main effects plot



(b) Seasonal temperature ranges



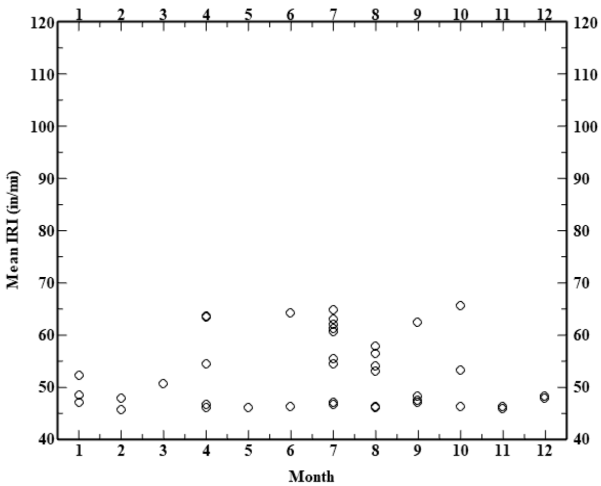
(c) Diurnal temperature ranges

Figure 50 ANOVA results for IRI of flexible pavements – WNF Climatic region

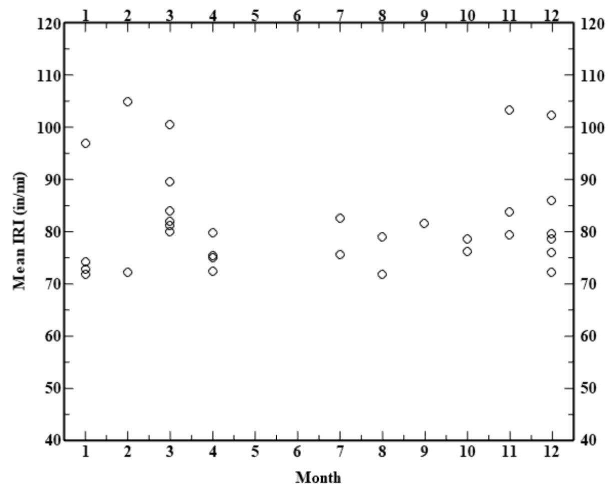
Figure 50(b) and (c) show the temperature ranges during pavement profile measurements used to determine their IRI. These plots show that temperatures in the WNF climatic region vary between 50 - 85°F. As discussed earlier, there is no considerable difference in IRI between different seasons as well as within different times of the day; the temperature plot suggests that ambient temperature range between 55 - 75°F may produce IRI with less variability irrespective of season and time.

Generally speaking, the IRI of flexible pavements do not show a definite trend at a group or climatic region level. Such effects may result from the variation of the initial pavement IRI values determined just after construction. Based on the discussion for individual climatic regions, the ambient temperature range between 50 - 75°F appears to show less difference in IRI values across all climates with no limitation on time of the day.

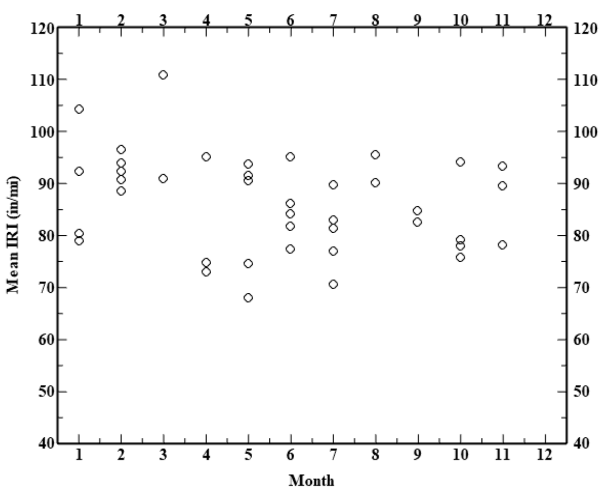
Figure 51 presents four flexible pavement sections, each from a climatic region. No particular trend exists for IRI values determined from profile measurements in different months. It is in agreement with ANOVA results, which showed statistically significant seasonal differences; however, these were not practically important.



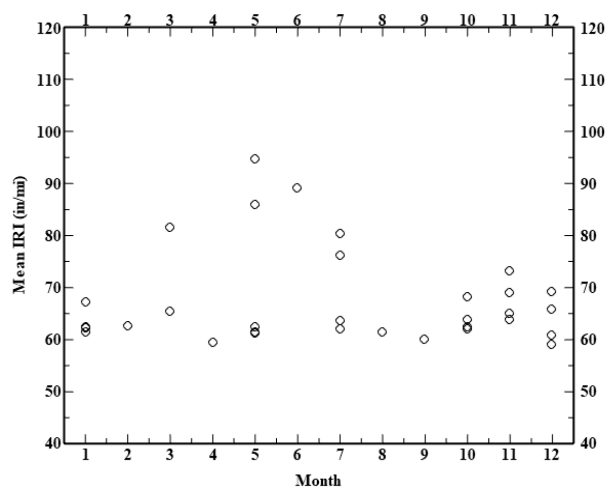
(a) IRI for Montana section ID 30-0114 – DF climatic region



(b) IRI for Arizona section ID 4-0113 – DNF climatic region



(c) IRI for Vermont section ID 50-1002 – WF climatic region



(d) IRI for Virginia section ID 51-0114 – WNF climatic region

Figure 51 Monthly IRI variation - SMP flexible pavements

4.2 Analysis for Rigid Pavements (by climatic region)

FWD deflection-based parameters for rigid pavements include the PCC layer modulus, the modulus of subgrade reaction (*k*-value), load transfer efficiency (LTE) at joints/cracks, estimation of edge support, and determination of void potential under the slab. Estimation of PCC layer modulus and the *k*-value uses mid-slab deflections measured by an FWD device. The evaluation of joint or crack LTE uses deflections measured at these locations. Corner and edge deflections help determine the edge support and void potential under the PCC slab, respectively. This study used the available PCC layer moduli, k-values, and LTE values to assess the effects of seasonal and diurnal measurements on these parameters. A relational database was prepared for the obtained data from the LTPP SMP database. Each of these parameters was analyzed separately for each climatic region; it aided to exclude a factor, i.e., the climatic region from the analysis. The removal of one factor helped reduce the data required while improving the power of the analysis.

Similarly, using the available IRI data from the LTPP SMP database, the seasonal and diurnal effects on pavement roughness were investigated for the available JPCP sections of the SMP study. The IRI data extracted from the database was analyzed similarly, dividing the data by climatic region, to gain the benefits as mentioned earlier.

4.2.1 FWD based Pavement Parameters

Elastic modulus of the PCC slab and modulus of the subgrade reaction (*k*-value) are calculated using deflections measured with an FWD device at the center of the slab. The main factors to investigate the effects of seasonal and diurnal FWD measurements on these moduli values include (a) FWD testing month and (b) time of FWD measurement. The maintenance category of the pavement sections is used as a blocking factor.

An analysis for investigating the seasonal and diurnal effects on each of the mentioned parameters is presented next. The data analysis for each data element involved the following steps:

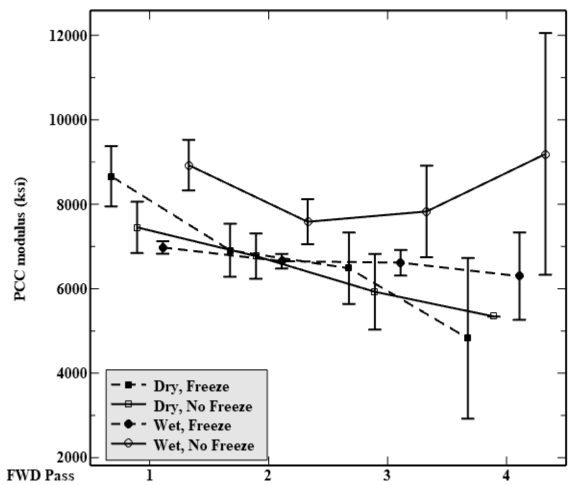
1. The pavement structure details, layer moduli values, FWD measurement dates and timings, maintenance history, pavement surface temperature, air temperature, and

temperature gradient measurements were some of the variables identified to perform the analysis.

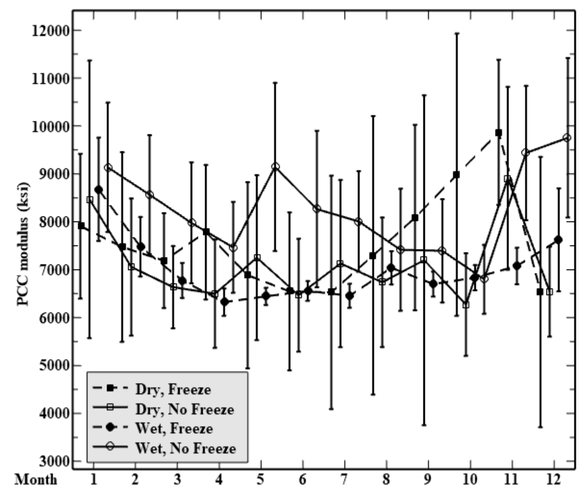
2. The investigation required an analysis involving a group of sections within each climatic region.
3. The JPCP pavement sections in the SMP LTPP database were identified in each of the four climatic regions. Note that climatic regions are defined in terms of temperature (i.e., freeze/no freeze), and moisture (i.e., wet/dry).
4. The structural details, including layer types and thicknesses, were also obtained.
5. The backcalculated layer moduli values, along with the date and time of FWD measurements, the air and pavement surface temperatures measured at the time of FWD testing, and the temperatures measured at different depths of the structure were obtained. Also, the maintenance history details for all the sections were also extracted from the database (i.e., construction no. and type of treatment) and categorized.
6. The data was arranged in a relational database.
7. The data were inspected using a histogram and boxplot to identify outliers.
8. Two factors were used in this analysis; (a) measurement month discretized into four seasons (i.e., levels) to look at the seasonal effects, (b) measurement time with two levels (before noon and afternoon) for the looking into the diurnal effects.
9. Analysis of Variance (ANOVA) was conducted for JPCP sections within each climatic region to investigate the temporal effects on each data element using a level of significance of 95% (i.e., $\alpha = 0.05$).

PCC Layer Moduli

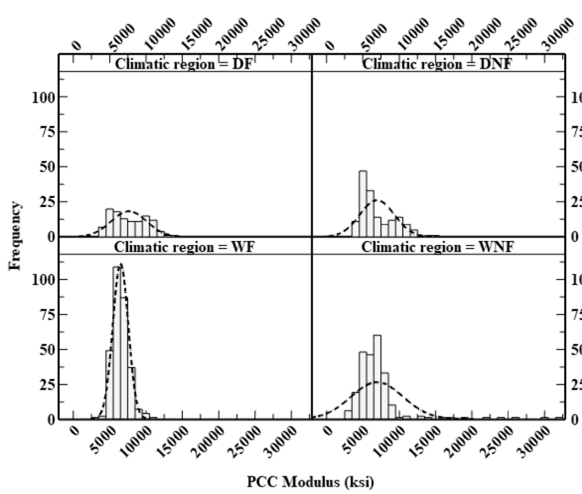
Figure 52(a) shows the overall variations in the PCC moduli with different FWD passes in various climatic regions. The PCC moduli decrease with increasing pass number (i.e., morning to afternoon) which may be due to the curling down of the PCC slab with the rise in temperature as the day progresses. However, somewhat mixed trends were observed within months between different climates [see Figure 52(b)]. Lower moduli values in the summer months may be due to the curl down of the PCC slabs.



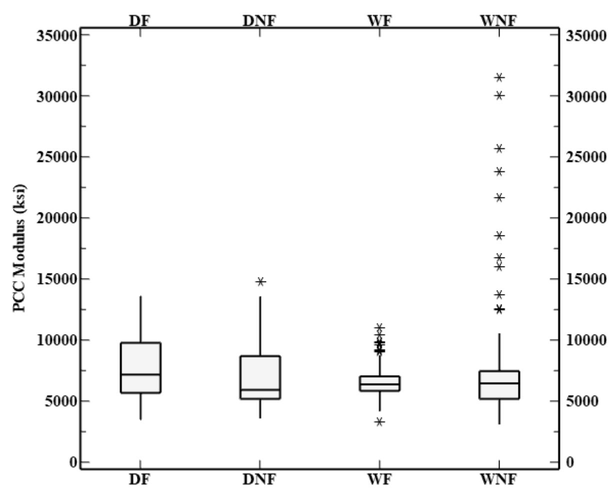
(a) FWD pass



(b) FWD measurement month



(c) Histogram – available PCC moduli data



(d) Box-plot – available PCC moduli data

Figure 52 Assessing available PCC moduli data – SMP JPCP pavement sections

Table 39 Descriptive statistics PCC moduli—SMP JPCP pavements

Climatic region	N	Mean	Std.	Minimum	Q1	Median	Q3	Maximum
DF	113	7653	2462	3513	5699	7197	9788	13612
DNF	156	6953	2374	3606	5200	5942	8717	14801
WF	297	6506	1064	3268	586	6397	7042	10978
WNF	236	6945	3567	3146	5208	6485	7489	31574

Note: PCC moduli values shown are in ksi units.

Table 39 shows the descriptive statistics for PCC layer moduli values for the available JPCP sections along with the available number (N) of the FWD measurements within each climatic zone. The DF climatic region has the highest variability in the PCC layer moduli values found in the database. Figure 52 also shows the histogram and box-plot for the backcalculated PCC moduli data. It appears that each climatic region has some PCC moduli values higher than 10,000 ksi. ANOVA presented in the study excluded such high values as these can influence the findings from the analysis.

Table 40 ANOVA results for PCC moduli values – DF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	0.74327	11.37%	0.78846	0.26282	10.59	**0.000**
Time	1	0.12278	1.88%	0.42028	0.42028	16.93	**0.000**
Maint. Cat.	2	3.70207	56.65%	3.69586	1.84793	74.45	0.000
Season*Time	3	0.00595	0.09%	0.00595	0.00198	0.08	0.971
Error	79	1.96099	30.01%	1.96099	0.02482		
Lack-of-Fit	13	0.34869	5.34%	0.34869	0.02682	1.10	0.377
Pure Error	66	1.61230	24.67%	1.61230	0.02443		
Total	88	6.53506	100.00%				

Table 40 displays the ANOVA results for the available PCC layer moduli data within the DF climatic region. The data was transformed to satisfy the normality assumptions, which is essential for drawing meaningful conclusions from ANOVA (see Figure 53). A similar data transformation was undertaken for the rest of the climatic regions as well. Results show that FWD measurement season and time of the day impacts the PCC layer backcalculated moduli values. The maintenance category, although used as a blocking factor, also influences the PCC layer moduli.

The main effects plot in Figure 54(a) shows that there is a significant difference in mean PCC modulus within the summer season compared to the rest of the seasons. High temperatures causing the curling down of the slab rendering it unsupported at the center could be a possible explanation for the lowest PCC moduli values in the summer season. The opposite is true for the winter season, where curling up causes a full contact between the slab center and the underlying frozen layers. The minimum mean difference between PCC moduli obtained from FWD tests conducted in summer and any other season is more than 850 ksi [see Figure 54(b)]. The highest mean PCC modulus difference (more than 1600 ksi) exists between summer and winter seasons.

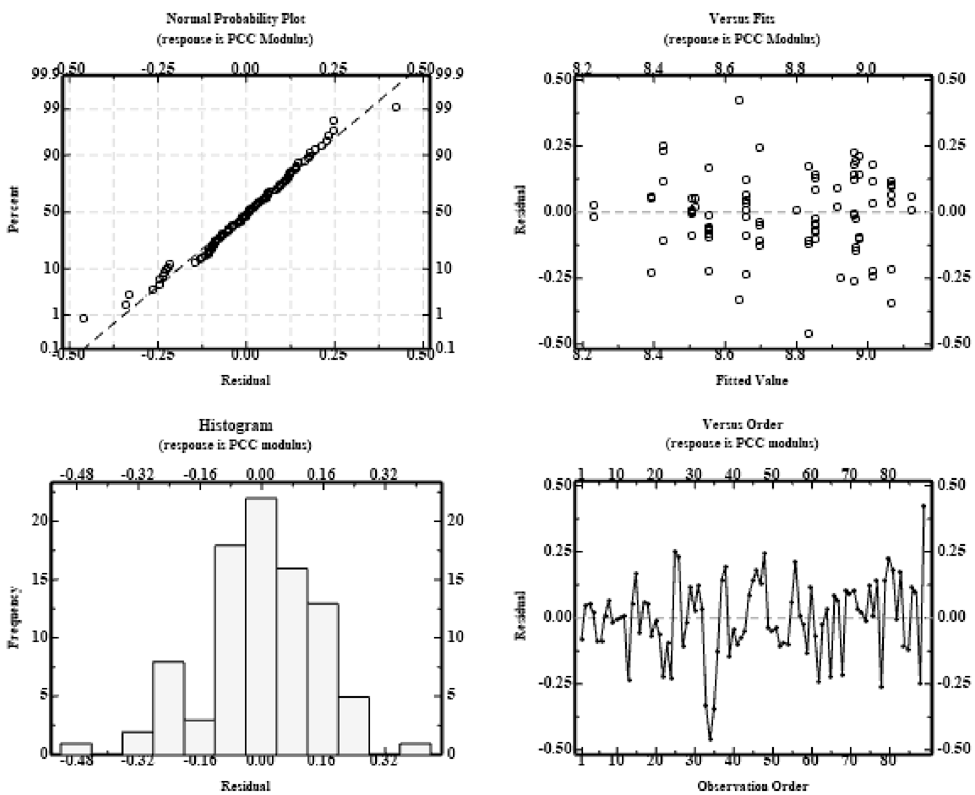
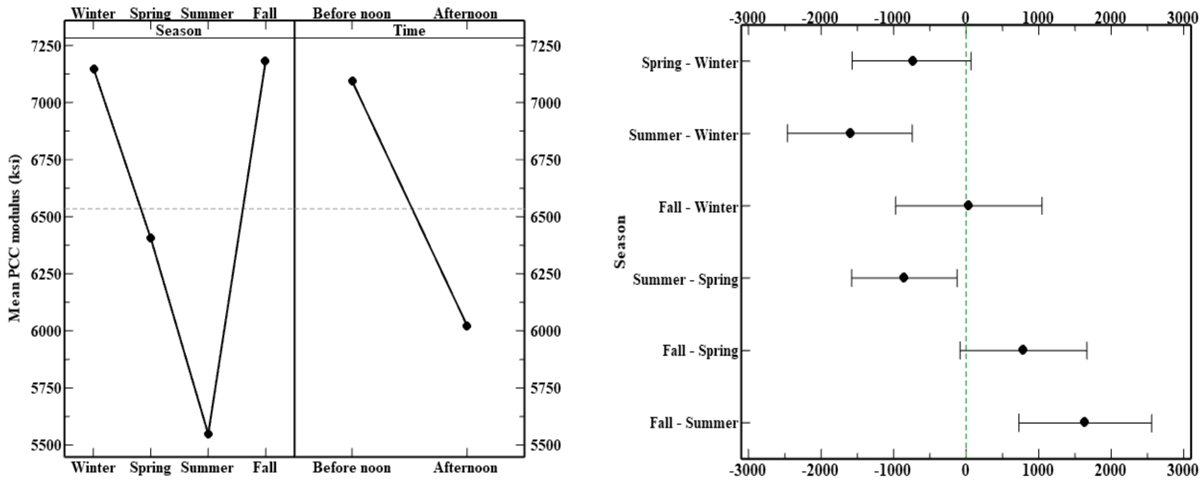


Figure 53 Ensuring normality of the PCC moduli data - DF climatic region



(a) Main effects plot

(b) Seasonal mean differences with 95% confidence intervals

Figure 54 ANOVA plots for PCC moduli data - DF climatic region

There is a noticeable difference (more than 1000 ksi) between the PCC moduli obtained using FWD deflections measured before-noon and afternoon within a day. Such effects are possible due to the temperature difference between the two times of the day, causing the slab to transition from curled up in the morning to curled down in the afternoon. This transition in the slab's shape changes the support conditions underneath its center, hence the change in its moduli values from morning (i.e., before noon) to the afternoon.

Table 41 ANOVA results for PCC moduli values – DNF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	4937928	1.34%	1989360	663120	0.33	0.801
Time	1	1374659	0.37%	923473	923473	0.46	0.497
Maint. Cat.	1	100613678	27.38%	92756115	92756115	46.59	0.000
Season*Time	3	9746626	2.65%	9746626	3248875	1.63	0.185
Error	126	250842641	68.25%	250842641	1990815		
Lack-of-Fit	4	8903891	2.42%	8903891	2225973	1.12	0.349
Pure Error	122	241938750	65.83%	241938750	1983105		
Total	134	367515533	100.00%				

ANOVA results for the DNF climatic region, as shown in Table 41, displays that only the maintenance category, used as a blocking factor, is significant having an influence on the PCC modulus values in this climatic region. Neither the FWD measurement season nor the time of the day has any essential effects on the PCC layer moduli (see Figure 55). Insufficient data could be a reason for such results as only two JPCP sections are available within the SMP database in this climatic region.

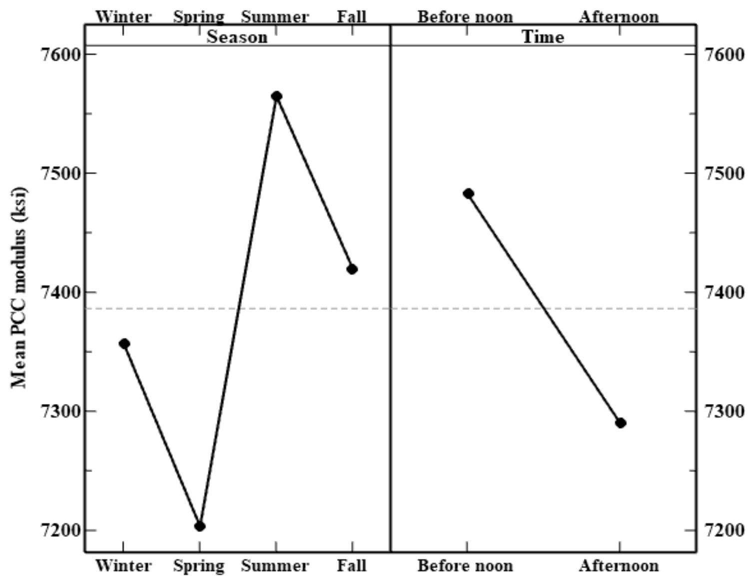
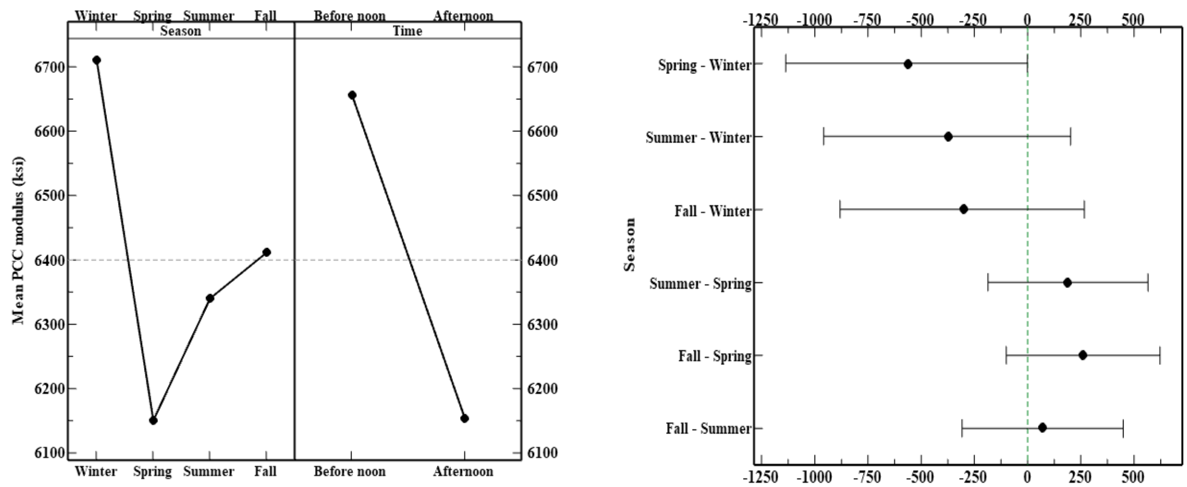


Figure 55 Main effects plot for PCC moduli data – DNF climatic region

Table 42 ANOVA results for PCC moduli values – WF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	0.25083	3.54%	0.14709	0.049030	2.57	0.055
Time	1	0.48332	6.83%	0.28108	0.281082	14.74	**0.000**
Maint. Cat.	2	0.88365	12.48%	0.88449	0.442246	23.18	0.000
Season*Time	3	0.02572	0.36%	0.02572	0.008572	0.45	0.718
Error	285	5.43628	76.79%	5.43628	0.019075		
Lack-of-Fit	14	0.46040	6.50%	0.46040	0.032885	1.79	0.040
Pure Error	271	4.97589	70.28%	4.97589	0.018361		
Total	294	7.07980	100.00%				

The ANOVA results for the WF climatic region shows that FWD measurement time has a noticeable bearing on the PCC modulus (see Table 42). FWD testing season, on the other hand, appears an insignificant factor with no influence on the PCC modulus. Figure 56(a) shows the main effects plot for the WF climatic region. There is a considerable difference (500 ksi) between the PCC moduli obtained from FWD deflection measured before-noon and in the afternoon. The higher PCC moduli in the before-noon can be related to the close contact between the slab and the layer beneath due to curling (i.e., curl up in the morning while curl down in the afternoon). Figure 56(b) shows the seasonal differences between PCC moduli values for different seasons. Although statistically insignificant at the type-I error rate of 5%, it can be termed significant practically (or at a type-I error rate of 10%, α=0.1) due to the observed differences (greater than 400 ksi) between some of the seasons (winter versus spring and summer).



(a) Main effects plot

(b) Seasonal mean differences with 95% confidence intervals

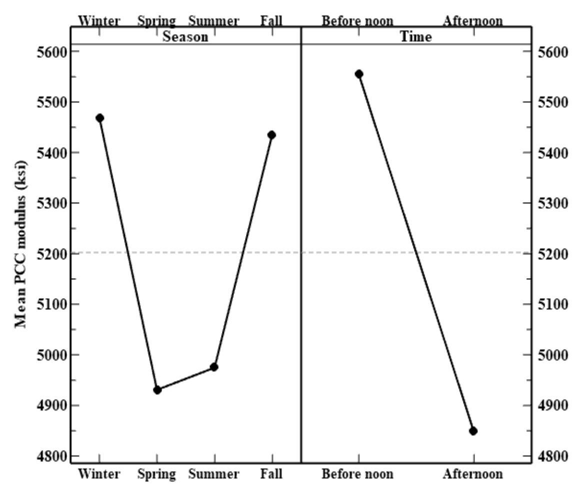
Figure 56 ANOVA plots for PCC moduli data - WF climatic region

Table 43 ANOVA results for PCC moduli values – WNF climatic region

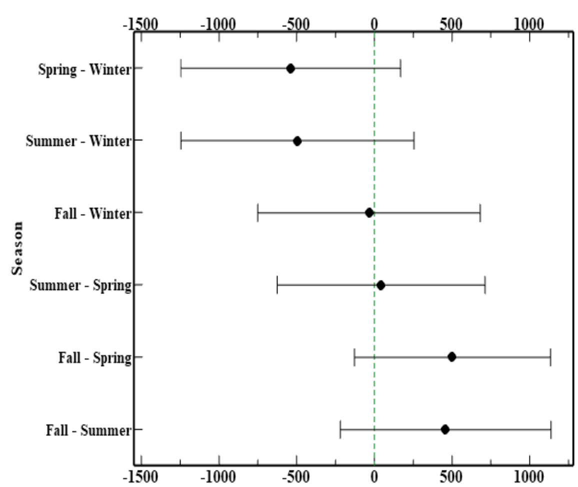
Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	17449689	3.93%	13337363	4445788	2.40	0.069
Time	1	25240885	5.69%	25853245	25853245	13.95	**0.000**
Maint. Cat.	1	4217980	0.95%	4045433	4045433	2.18	0.141
Season*Time	3	131875	0.03%	131875	43958	0.02	0.995
Error	214	396734753	89.40%	396734753	1853901		
Total	222	443775183	100.00%				

The ANOVA results for the WNF climatic region are similar to those of the WF region. Table 43 displays the ANOVA results for WNF climatic region; deflections measurement time appears to influence the PCC layer moduli values while the FWD measurement season has no bearing the PCC layer moduli. Figure 57(a) displays the main effects plot for the ANOVA on the PCC moduli data within WNF climatic region. The mean PCC moduli values obtained from deflections measured in the morning (i.e., before-noon) are significantly higher (> 700 ksi) than those obtained from the afternoon FWD tests.

The deflection measurement season, although statistically insignificant (at $\alpha = 0.05$), appears to have a practical impact and can be termed significant a type-I error rate of 10% ($\alpha = 0.10$). Figure 57(b) shows that considerable differences (higher than 500 ksi) between PCC moduli exist within different seasons (i.e., winter versus spring and summer, fall versus spring, and summer). Wider confidence intervals for the seasonal mean PCC moduli differences observed in the WF and the WNF climatic regions may be due to insufficient data to explain the seasonal and diurnal effects on these moduli [see Figure 56(b) and Figure 57(b)].



(a) Main effects plot

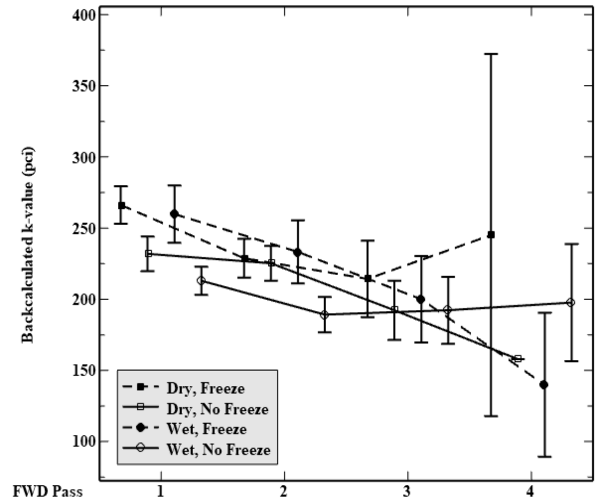


(b) Seasonal mean differences with 95% confidence intervals

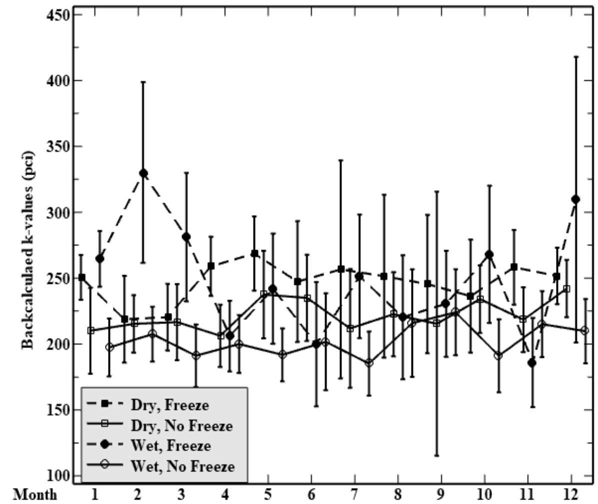
Figure 57 ANOVA plots for PCC moduli data - WNF climatic region

Modulus of Subgrade Reaction (k-value)

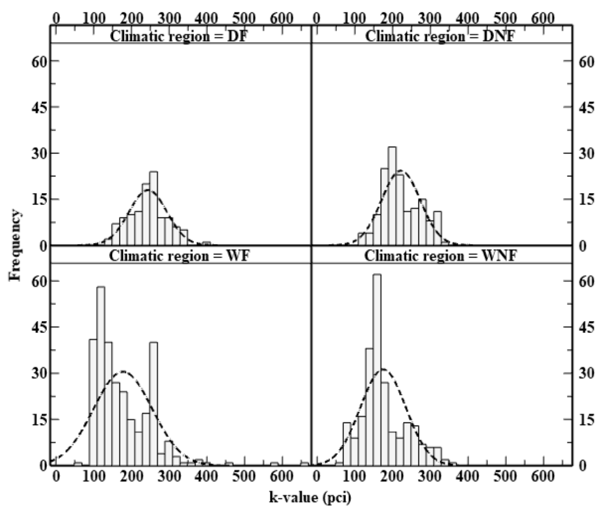
Similar to the PCC layer modulus, FWD mid-slab deflections are also used to calculate the modulus of subgrade reaction (*k*-value). This study uses the available k-values in the LTPP SMP database to investigate the effects of seasonal and diurnal on this pavement parameter. Figure 58(a) shows the overall variations in the *k*-values with different FWD passes in different climatic regions. The *k*-values decrease with increasing pass number (i.e., morning to afternoon), which may be related to the curling down of the PCC slab with the rise in temperature as the day passes. However, there are somewhat mixed trends observed in the *k*-values with months between different climates [see Figure 58(b)].



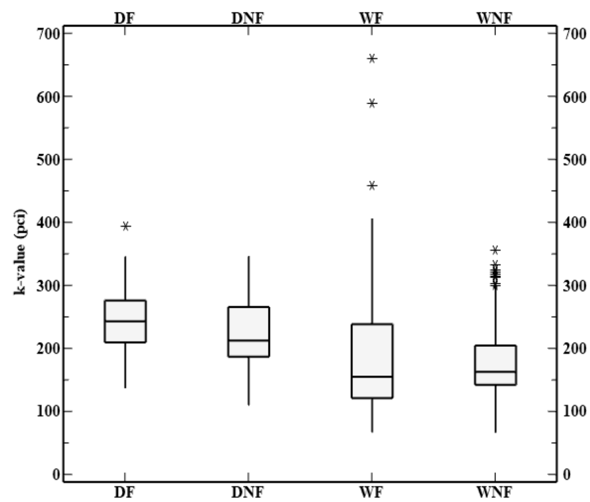
(a) FWD Pass



(b) FWD Measurement Month



(c) Histogram – available *k*-values



(d) Box-plot – available *k*-values

Figure 58 Assessing available *k*-values

Figure 58(c) and (d) displays the distribution of the *k*-values within different climatic regions, and Table 44 presents its descriptive statistics. The wet climatic regions show higher variability in the backcalculated *k*-values. The data also shows very high *k*-values within each climate. Including such values in the ANOVA can mask the findings. Thus, *k*-values higher than 250 pci were not used in the analysis.

Table 44 Descriptive statistics *k* -values—SMP JPCP pavements

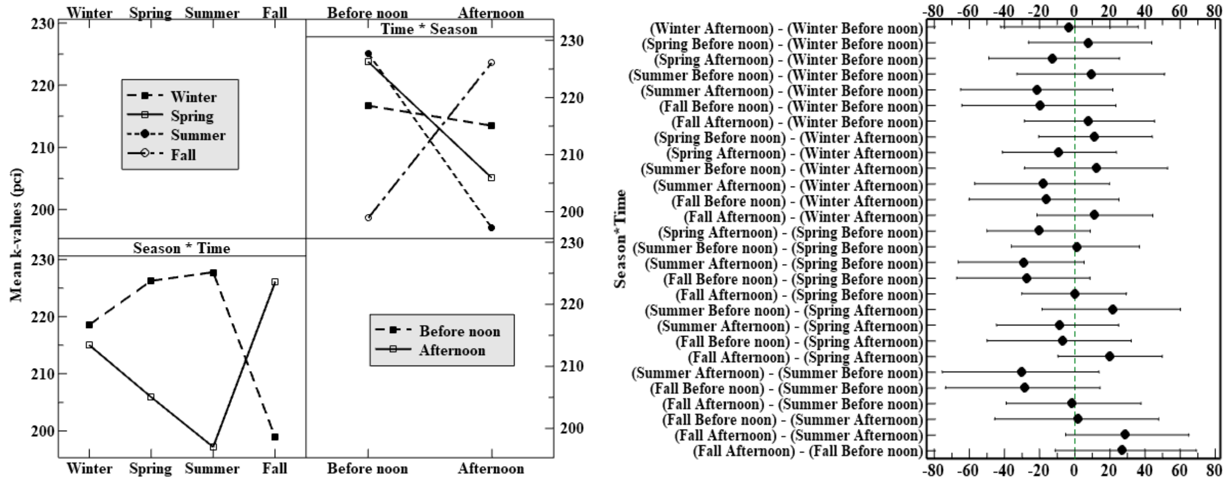
Climatic region	N	Mean	Std.	Minimum	Q1	Median	Q3	Maximum
DF	113	245.1	50.1	137	209.5	243	276	394
DNF	156	223	51.2	110	187	212.5	265.7	346
WF	297	178.5	77.6	67	121	155	238.5	661
WNF	236	175.9	60.2	66	142	163	204.7	355

Note: k-values shown are in pci units.

Table 45 ANOVA results for *k*-values – DF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	1635	3.16%	163.8	54.61	0.10	0.957
Time	1	6286	12.14%	554.2	554.25	1.06	0.308
Maint. Cat.	2	10252	19.79%	10333.4	5166.71	9.90	0.000
Season*Time	3	7530	14.54%	7529.7	2509.89	4.81	**0.005**
Error	50	26093	50.38%	26093.3	521.87		
Lack-of-Fit	11	5080	9.81%	5079.8	461.80	0.86	0.587
Pure Error	39	21013	40.57%	21013.5	538.81		
Total	59	51796	100.00%				

ANOVA results revealed that interaction between the deflections measurement season and time of the day influences the *k*-values rather than the individual factors (see Table 45). Interaction being of significance is interesting because one would expect the season to be more relevant as compared to the time of the day for unbound layers. Figure 59(a) shows the interaction means plot for season and time interaction effects on *k*-values. Before-noon FWD deflection measurements result in higher values, which is consistent with the trend seen for PCC moduli. During this time of the day, the slab is in close contact with the layers beneath it due to curling down during the winter season and near-flat slab condition in the spring and summer seasons. Curling down of the PCC slab is a possible explanation for the lower values in the afternoon for all the seasons except fall. The fall season is an exception where the *k*-values are lower in the morning (i.e., before-noon) than in the afternoon. The mean differences between all seasons except winter are practically noticeable (higher than 20 pci), but broader confidence intervals (due to insufficient data) are displaying the differences to be otherwise [see Figure 59(b)].



(a) Interaction means plot

(b) Seasonal mean differences with 95% confidence intervals

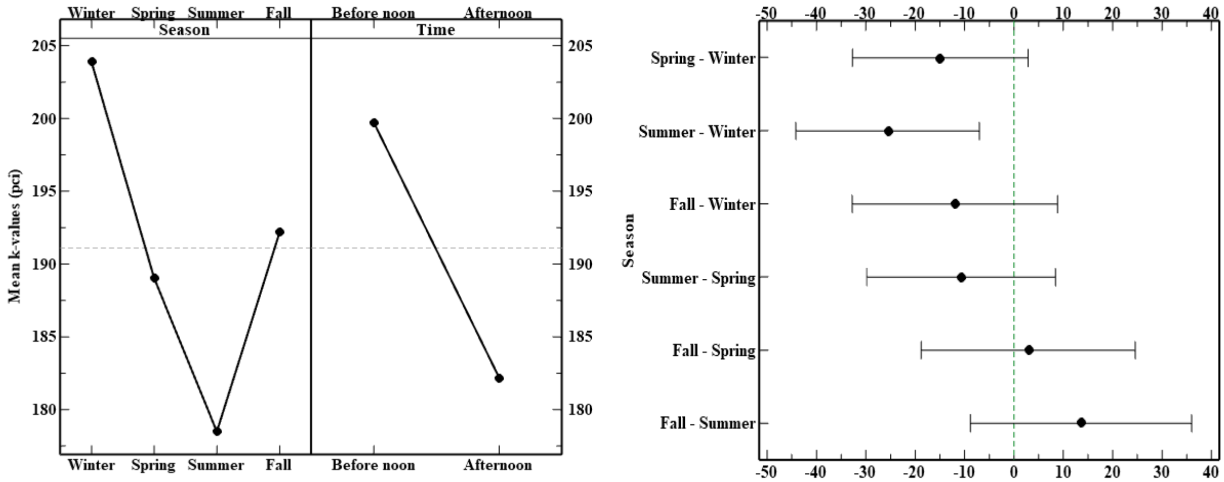
Figure 59 ANOVA plots for *k*-values - DF climatic region

Table 46 ANOVA results for *k* -values – DNF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	1171133182	9.68%	1266565893	422188631	4.40	**0.006**
Time	1	920437865	7.61%	1009560297	1009560297	10.52	**0.002**
Maint. Cat.	1	145359751	1.20%	146136486	146136486	1.52	0.220
Season*Time	3	270840478	2.24%	270840478	90280159	0.94	0.424
Error	100	9592745466	79.28%	9592745466	95927455		
Lack-of-Fit	5	386114724	3.19%	386114724	77222945	0.80	0.555
Pure Error	95	9206630742	76.08%	9206630742	96911903		
Total	108	12100516743	100.00%				

For the DNF climatic region, ANOVA reveals the deflection measurement season and time of the day as significant factors having an impact on the *k*-values (see Table 46). Curling of the PCC slab may be the reason for the effect of time on the *k*-values. Figure 60(a) shows the main effects plot from the ANOVA analysis. It shows that k-values are highest in the winter season and have a mean difference of 15-20 pci as compared to the values in spring and summer seasons [see Figure 60(b)]. The figure also shows a noticeable difference of around 20 pci between *k*-

values obtained from deflections measured in the morning and the afternoon. The reason for the diurnal change, as mentioned earlier, is linked to the curling of the PCC slab.



(a) Main effects plot

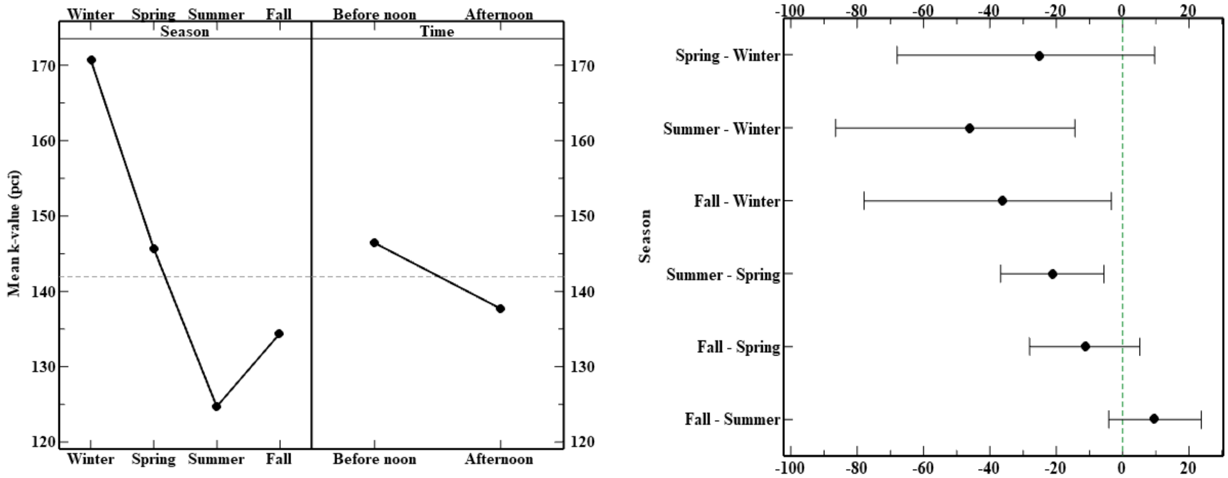
(b) Seasonal mean differences with 95% confidence intervals

Figure 60 ANOVA plots for *k* -values - DNF climatic region

Looking at the seasonal and diurnal effects on the *k*-values in the WF climatic region, ANOVA shows that the deflections measurement season has a noticeable impact (see Table 47). The main effects plot and the seasonal mean difference plot, in Figure 61, show that the difference of *k*-values between fall season as compared to spring and summers is not significant (about 10 pci). However, the *k*-values in winters are considerably different (difference higher than 20 pci) then the rest of the seasons.

Table 47 ANOVA results for *k* -values – WF Climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	0.000080	9.10%	0.000071	0.000024	7.37	**0.000**
Time	1	0.000022	2.47%	0.000006	0.000006	1.83	0.177
Maint. Cat.	2	0.000048	5.43%	0.000046	0.000023	7.24	0.001
Season*Time	3	0.000005	0.57%	0.000005	0.000002	0.52	0.668
Error	226	0.000721	82.44%	0.000721	0.000003		
Lack-of-Fit	14	0.000079	9.03%	0.000079	0.000006	1.86	0.032
Pure Error	212	0.000642	73.41%	0.000642	0.000003		
Total	235	0.000875	100.00%				



(a) Main effects plot

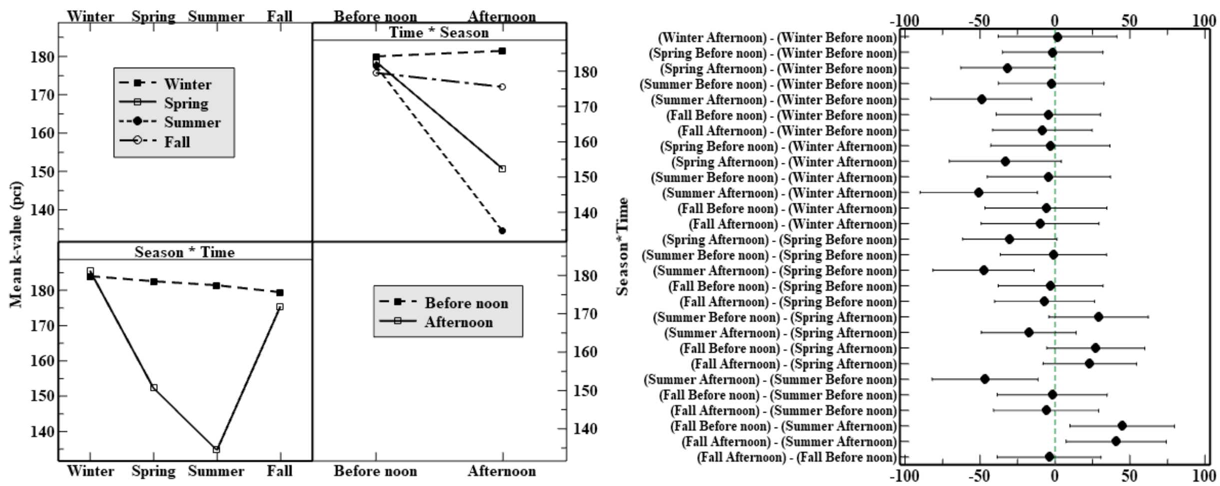
(b) Seasonal mean differences with 95% confidence intervals

Figure 61 ANOVA plots for k-values - WF climatic region

Table 48 ANOVA results for *k*-values – WNF Climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	26.754	4.98%	28.308	9.436	4.05	0.008
Time	1	32.703	6.09%	29.396	29.396	12.61	0.000
Maint. Cat.	1	2.473	0.46%	1.877	1.877	0.81	0.371
Season*Time	3	27.581	5.14%	27.581	9.194	3.94	**0.009**
Error	192	447.504	83.33%	447.504	2.331		
Total	200	537.016	100.00%				

The ANOVA results using the available *k*-values in the WNF climatic region shows that the interaction between the deflections measurement season and time of the day has a bearing on these values (see Table 48). This warrants looking at the interaction means plot to understand the temporal (seasonal and diurnal) effects on the obtained *k*-values. Figure 62(a) shows that there is no noticeable difference between *k*-values obtained at different times of the day in the winter and fall seasons. However, a considerable difference exists between *k*-values obtained using FWD deflections measured in the spring and summer seasons. The mean difference in *k*-values is about 30 pci in spring, while in the summer season, the mean difference reaches up to 60 pci from morning to the afternoon [see Figure 62(b)].



(a) Interaction means plot

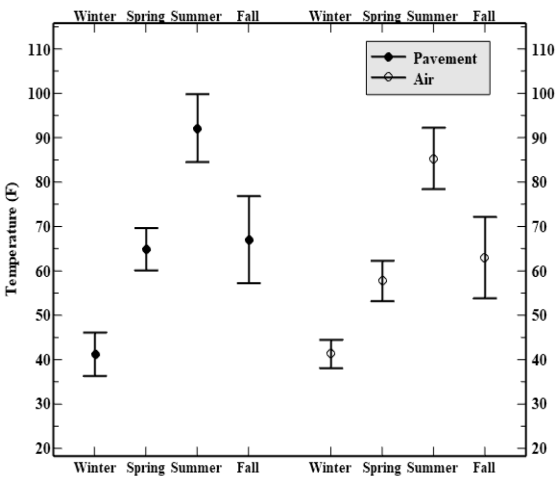
(b) Seasonal mean differences with 95% confidence intervals

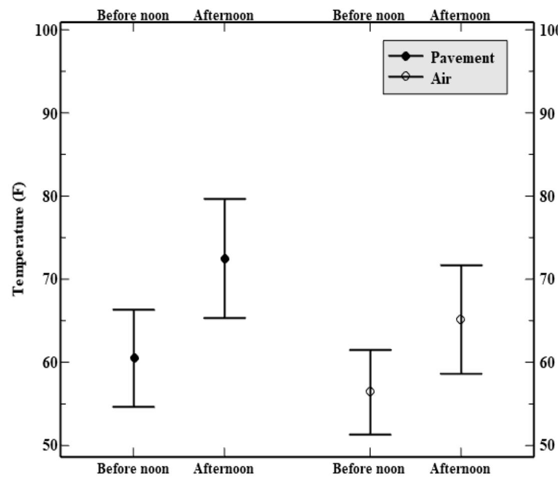
Figure 62 ANOVA plots for k-values - WNF climatic region

Discussion on ANOVA Results (PCC modulus and k-values)

The same FWD deflection measurements conducted on the mid-slab of a rigid pavement are used to obtain the elastic modulus of the PCC slab and the modulus of subgrade reaction (*k*-value). Ambient and surface temperature values accompany each of the FWD drops. A better insight into the effects discussed earlier on the PCC moduli and *k*-values is possible by considering the measured temperatures. This section presents a discussion on the temperatures obtained from the LTPP SMP database while linking them to the observed effects.

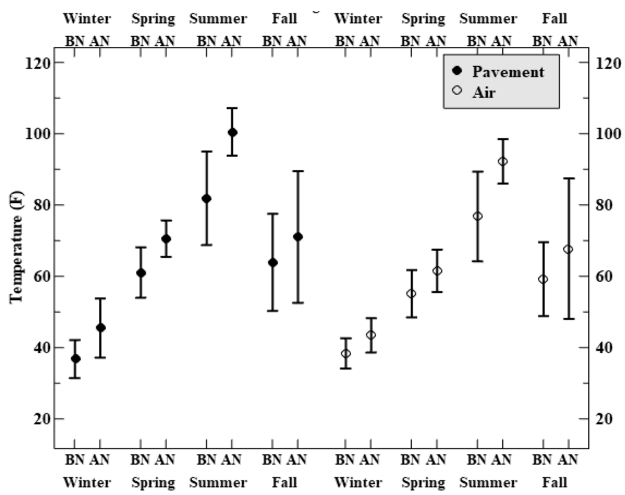
Figure 63 shows the pavement surface and ambient temperatures recorded during FWD measurements in the DF climatic region. Figure 63(a) and (b) are useful as the main effects of season and time were significant factors according to ANOVA on the PCC moduli values in the DF climate. Figure 63(c) is essential as the interaction of the two factors (i.e., season and time) turned out to be significant while looking into the effects on *k*-values.





(a) Seasonal temperatures ranges

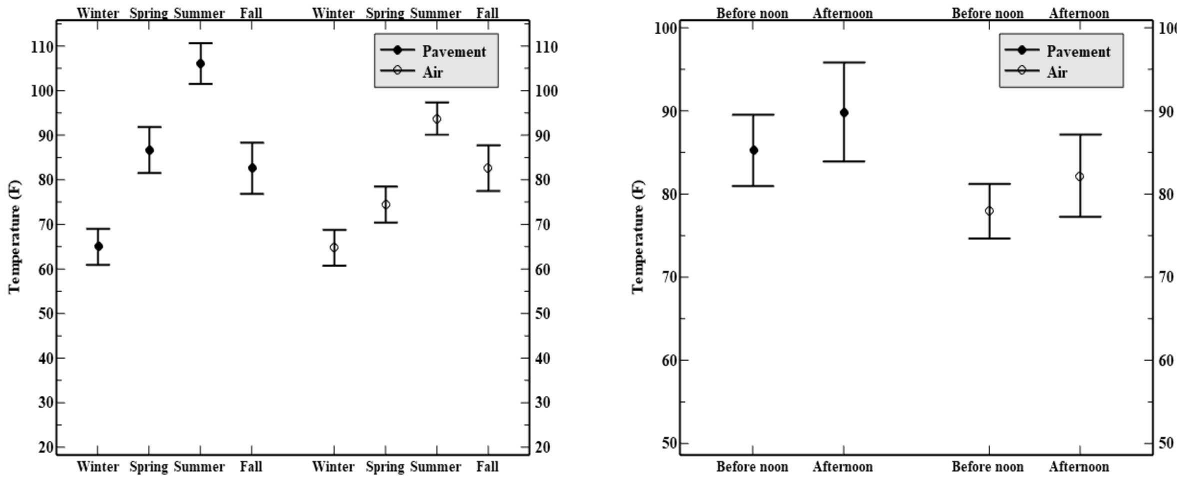
(b) Diurnal temperature ranges



(c) Temperature ranges for season and time interaction

Figure 63 Pavement surface and ambient temperatures – DF climatic region

PCC slab modulus (E_{pcc}) and the corresponding *k*-values are lowest in the summer in DF climatic region. The high ranges of the ambient temperatures (75 – 90^{o}F) in the summer season are the reason for such effects that causes the slab to curl down, rendering the slab unsupported at the center. Avoiding FWD tests at such high temperatures is beneficial as the obtained values (E_{pcc} and *k*) will not be the true representative of the actual pavement condition. Moderate ambient temperatures (55 – 70^{o}F) recorded in the spring season in the DF climatic region are probably better to obtain these values. Diurnally, Figure 63(b) suggests that before-noon deflection measurements will produce results close to the in-field pavement conditions. However, avoiding early morning times may prove useful.

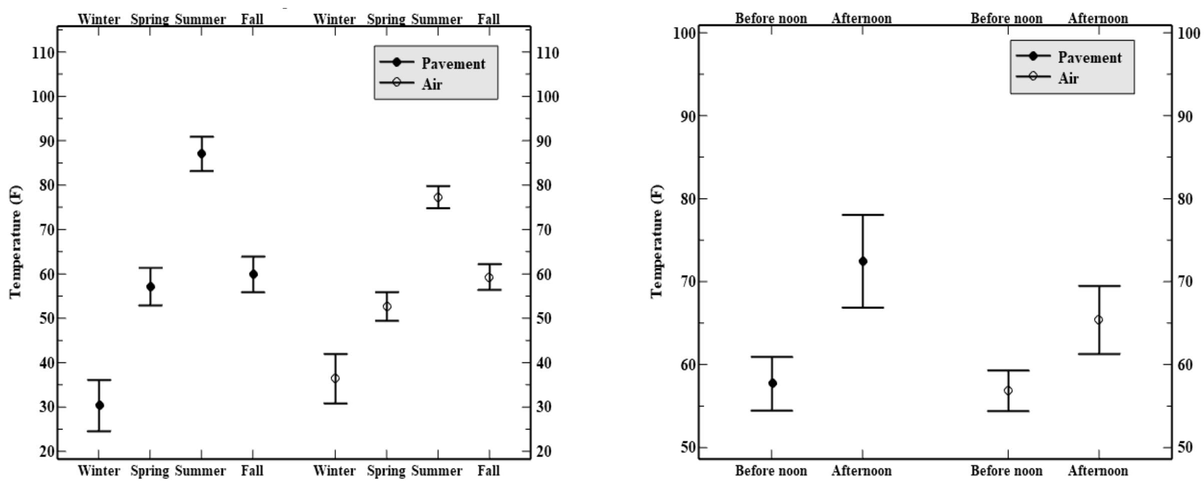


(a) Seasonal temperature ranges (b) Diurnal temperature ranges

Figure 64 Pavement surface and ambient temperatures – DNF climatic region

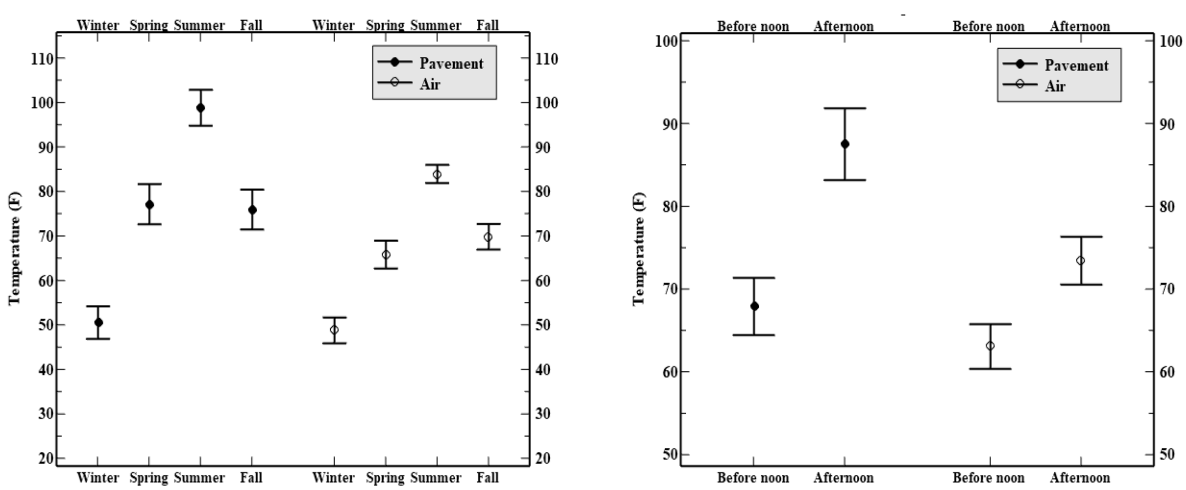
Based on the ANOVA results, none of the factors, i.e., season and time, significantly affect the PCC slab modulus in the DNF climatic region. However, a probable reason for such effects is insufficient data for the JPCP sections in the SMP database. On the other hand, looking at *k*-values, ANOVA showed significant season and time influence. Figure 64(a) suggests the best temperature ranges to conduct FWD in the DNF climatic region are between 60 – 70^{o}F shown within the spring season. Such temperatures will result in PCC moduli values that are near to the mean (see Figure 55). Thus, the obtained *k*-value will represent the in-field modulus accurately. As far as a better time of the day is concerned, where possible, before-noon measurements could be beneficial. Figure 64(b), however, shows that ambient temperatures recorded in the morning are in the high 70's within the DNF climatic region.

Figure 65 shows the seasonal and diurnal temperature ranges recorded during FWD measurements in the WF climatic region. ANOVA for the region showed that season (α =0.10) and time of the day have a bearing on the PCC layer modulus. On the other hand, only the season impacts *k*-values as per ANOVA results in the WF climate. Figure 65(a) suggests the ambient temperature range of 55 - 65^{o}F occurring in the fall seasons to be a better candidate for FWD measurements in the WF climate that can result in representative E_{pcc} and *k*-values closest to the real conditions. Also, the suggested ambient temperature ranges (55 - 65^{o}F) advocates before-noon FWD measurements [see Figure 65(b)].



(a) Seasonal temperature ranges (b) Diurnal temperature ranges

Figure 65 Pavement surface and ambient temperatures – WF climatic region



(a) Seasonal temperature ranges (b) Diurnal temperature ranges

Figure 66 Pavement surface and ambient temperatures – WNF climatic region

ANOVA results showed that the time of FWD measurement within a day is an influencing factor for the PCC layer modulus in the WNF climatic region. On the other hand, season and time interaction is essential to explain variations of *k*-values in the WNF climatic region, as shown by the ANOVA results. Figure 66 suggests that the ambient temperature range between 60 - 75^{o}F occurring in the fall season is ideal in the WNF climatic region that will result in realistic E_{pcc} and *k*-value. Diurnally, such a temperature range also suggests before-noon FWD measurements.

Figure 67 shows the histogram of the available temperature gradients data available in the SMP database for the JPCP sections (for E_{pcc} and *k*-values). Zero or near-zero temperature gradients would be ideal for measuring deflections resulting in E_{pcc} and *k*-values that are close to the in-field actual values. Around 50 FWD measurements used to obtain these pavement parameters had a temperature gradient between -1 to 1. All these measurements occurred from 8 am to about noon. Thus, suggesting that diurnally before noon measurements are better, based on the available data, to find a zero gradient temperature condition.

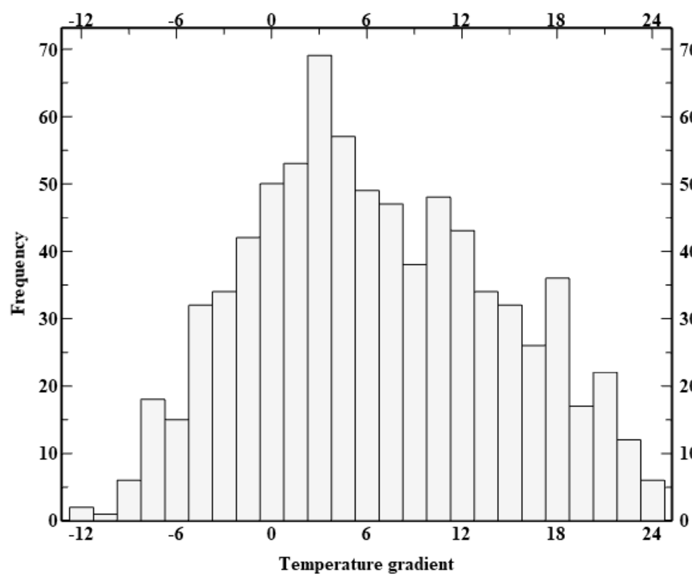
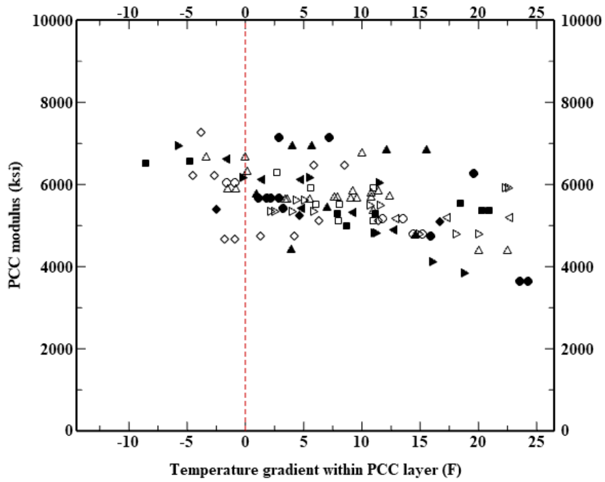
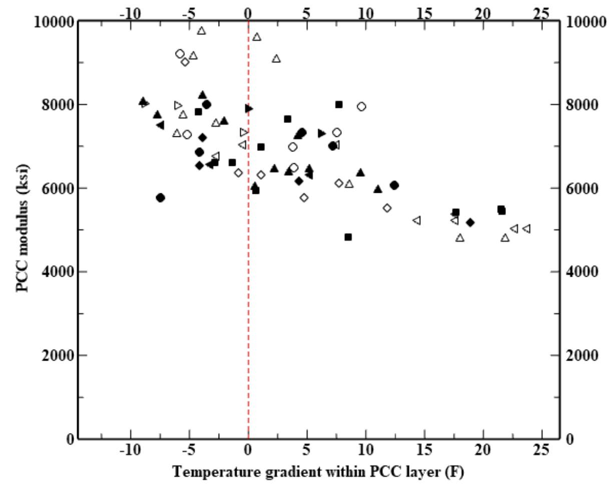


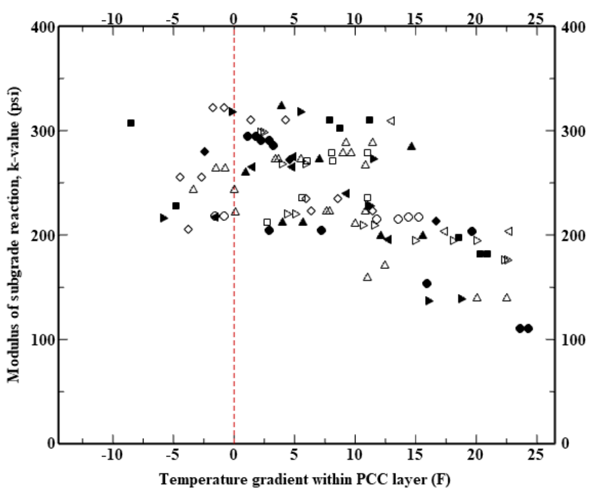
Figure 67 Histogram of the available temperature gradients data for E_{pcc} and *k*-values – SMP JPCP sections



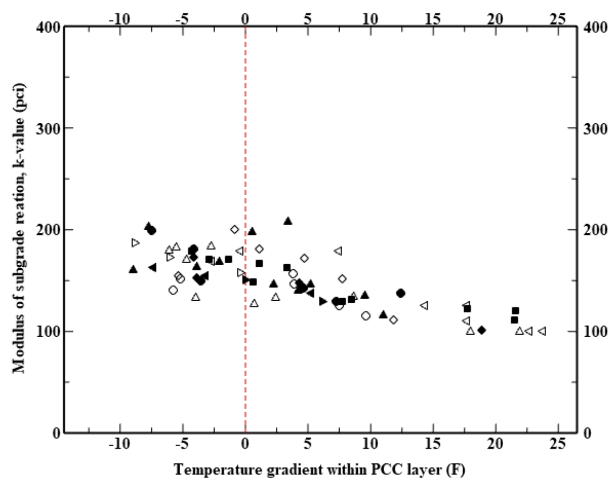
(a) PCC moduli for Arizona section ID 4-0215 – DF climatic region



(b) PCC moduli for Nebraska section ID 31-3108 – WF climatic region



(c) k-Values for Arizona section ID 4-0215 – DF climatic region



(d) k-Values for Nebraska section ID 31-3108 – WF climatic region

Figure 68 Variation in PCC layer moduli and k-values with temperature gradient within the PCC layer

Figure 68 shows examples of two JPCP sections, each from the DF and the WF climatic regions. The plots show PCC moduli and k-values determined from FWD measurements on different days in multiple years. The plots display a decreasing trend in the PCC slab modulus and the corresponding *k*-values as the temperature gradient shifts from negative to positive (i.e., before noon to afternoon). The higher PCC layer moduli and *k*-values when the temperature gradient is negative are due to the PCC slab curling up with the bottom of the mid-slab in complete contact with the underlying layers. The opposite happens as the temperature gradient becomes positive, causing the PCC slab to curl down; when the mid-slab is unsupported. Also, it is noteworthy that both the rigid pavement parameters (E_{pcc} and *k*-value) follow a similar trend while the temperature gradients change from negative to positive. Thus, PCC moduli are more critical in formulating general guidelines for FWD testing on rigid pavements than *k*-values.

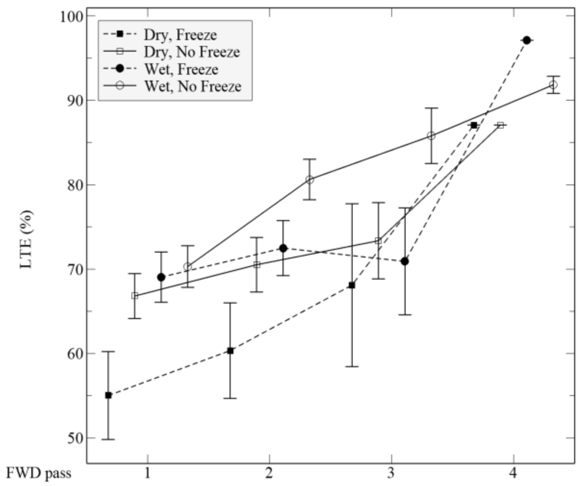
Load Transfer Efficiency (LTE)

Figure 69 illustrates the effects of diurnal and seasonal FWD deflection-based LTE values in different climatic zones for all JPCP pavement sections in the SMP experiment. It also presents the distribution of the available data within each climatic region. It shows that LTE values are affected by diurnal and seasonal measurements. Higher LTE values are expected at higher temperatures due to slab expansion and joint locking while lower LTE value corresponds to slab contraction in lower temperatures. Table 49 shows the descriptive statistics for LTE values for the available JPCP sections along with the available number (N) of the LTE measurements within each climatic zone. A higher variation evident from the higher standard deviation (Std.) in the freeze regions. Therefore, it is essential to consider the diurnal and seasonal temperatures for such measurements for rigid pavements.

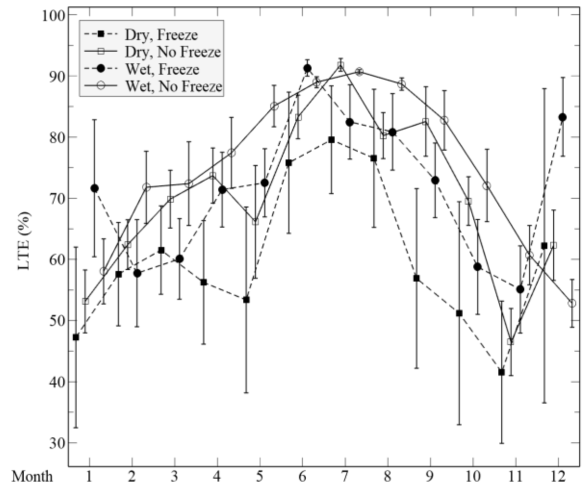
Table 49 Descriptive statistics LTE values

Climatic region	N	Mean	Std.	Minimum	Q1	Median	Q3	Maximum
DF	234	58.9	27.5	15.2	30.7	66.2	85.3	96.8
DNF	326	69.2	17	25	53.8	71.6	84.2	96.9
WF	610	70.6	26	16	44.3	85	91.5	98.2
WNF	478	75.2	19	18.4	57.8	86.700	90.3	97

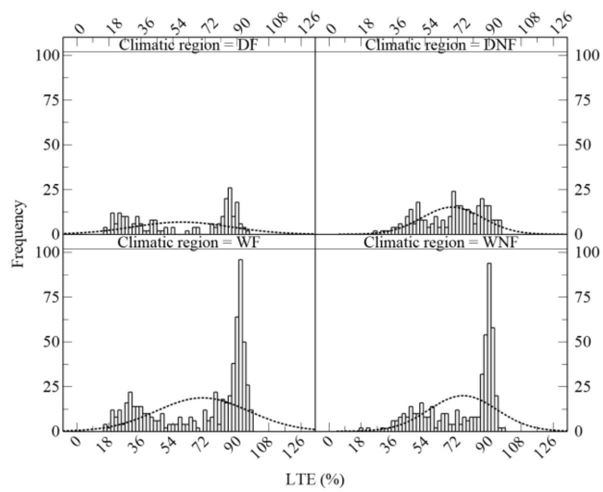
Note: LTE values shown as a percentage (%).



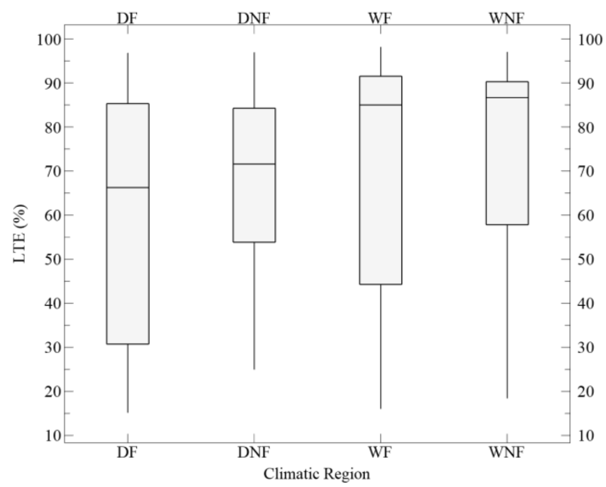
(a) LTE(%) by FWD pass



(b) LTE(%) by FWD measurement month



(c) Histogram - available LTE (%) values



(d) Box-plot - available LTE (%) values

Figure 69 Assessing available LTE data

Figure 70 demonstrates the normality of the data for the DNF climatic region that was used in the analysis. As mentioned earlier, the satisfaction of the normality assumptions is essential to draw meaningful conclusions from the ANOVA analysis. Similarly, the data were transformed adequately for the rest of the climatic regions to ensure the satisfaction of the normality assumptions.

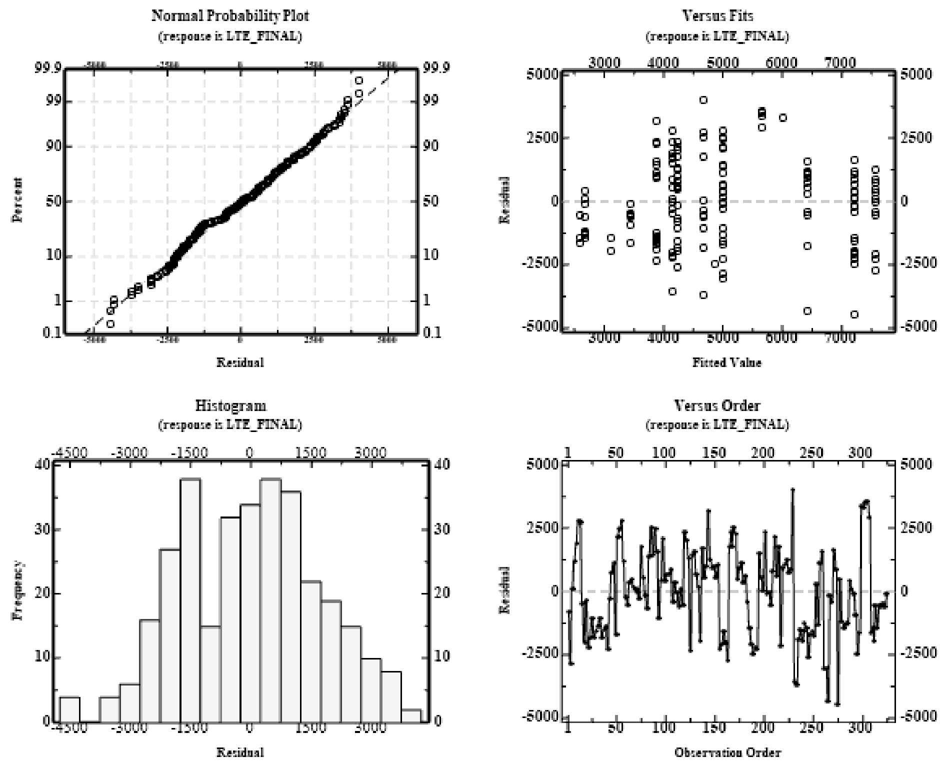


Figure 70 Evaluating normality of the LTE data - DNF climatic region

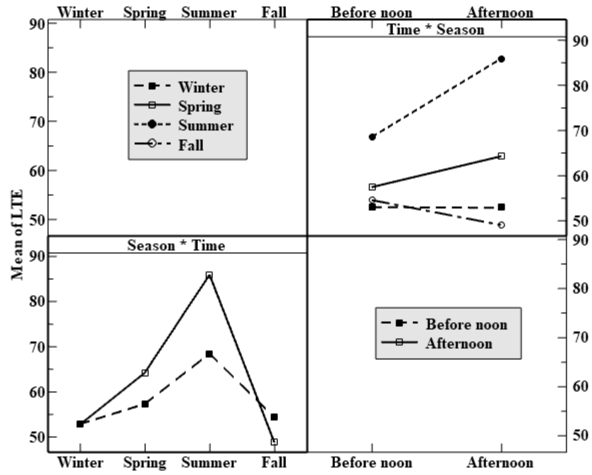
Table 50 presents the results of the ANOVA analysis for the DF climatic region. The results show that the FWD measurement season significantly affects the LTE values based on a type-I error rate of 5% ($\alpha = 0.05$). The FWD measurement time, on the other hand, has no significant effect on the LTE values at the same error rate. The results also show that the interaction between the two factors, i.e., season and time, also contributes significantly to the variations in the LTE values. Thus, looking at the interaction effects rather than the main effects is essential. Figure 71(a) shows the mean LTE value in the summer season varies from 68% for before-noon measurement to 85% in the afternoon. Also, the LTE values change in the spring and fall seasons in between before-noon and afternoon measurements; however, the difference is not as significant as in summer. Figure 71(b) also shows that the difference of mean LTE values between any pair of season and time interaction involving the summer season is substantial. Thus, these results suggest that summer season LTE values are significantly higher from other seasons irrespective of the time of the day with a more significant difference in the afternoon measurements.

Table 50 ANOVA results for LTE values – DF climatic region

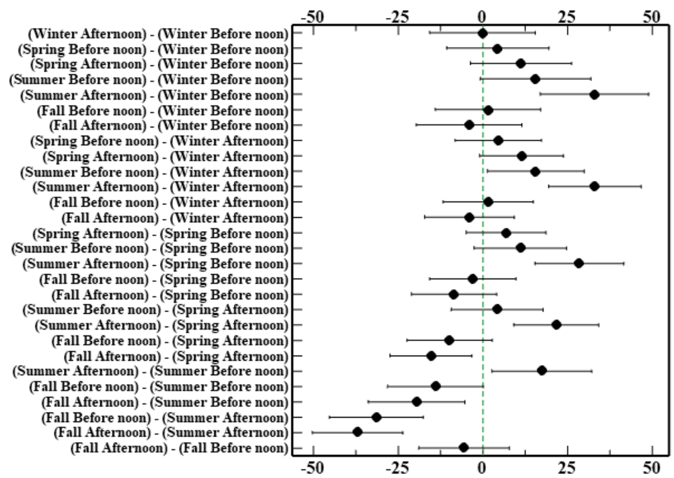
Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	20540	12.94%	20158	6719.5	25.52	0.000
Time	1	1010	0.64%	1031	1031.3	3.92	0.049
Maint. Cat.	2	77063	48.56%	73316	36658.2	139.22	0.000
Season*Time	3	3743	2.36%	3743	1247.5	4.74	**0.003**
Error	214	56350	35.51%	56350	263.3		
Lack-of-Fit	14	16188	10.20%	16188	1156.3	5.76	0.000
Pure Error	200	40163	25.31%	40163	200.8		
Total	223	158707	100.00%				

To further explain the summer LTE values, Figure 71(c) shows the 95% confidence interval of the pavement surface and air temperatures at the time of FWD measurements. There is a clear difference between the temperatures recorded between the before-noon and afternoon times while conducting FWD measurements. Thus, suggesting that elevated temperatures beyond 80°F should be avoided while conducting FWD testing on joints.

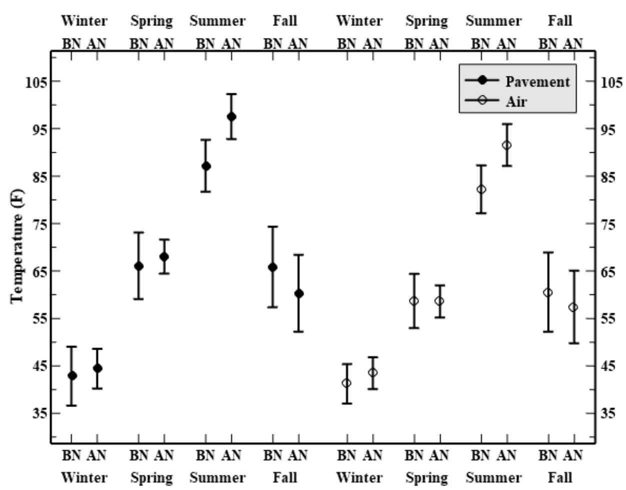
A similar ANOVA analysis for the DNF climatic region also reveals that the interaction of the two factors, that is, the FWD measurement season and time has an essential influence on the LTE values rather than the individual factors (see Table 51). The maintenance category is also a contributing factor influencing the LTE values; however, it is being used as a blocking factor. The interaction means do not show a significant difference between LTE values measured before noon and in the afternoon [see Figure 72(a)]. Also, the overall mean LTE values are higher than for DF climatic region. A possible explanation can be the higher range of measurement temperatures, i.e., around and over 75°F, which should be avoided while measuring LTE at joints [see Figure 72(b)].



(a) Interaction means plot



(b) Mean difference of LTE values with 95% confidence interval for season and time interaction



(c) Pavement surface and air temperatures during FWD measurements

Figure 71 ANOVA results - DF climatic region

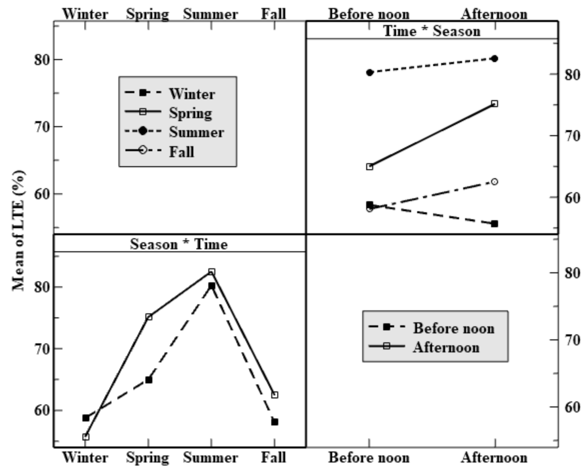
Table 51 ANOVA results for LTE values – DNF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	547985885	32.70%	520306982	173435661	56.42	0.000
Time	1	33623209	2.01%	17249536	17249536	5.61	0.018
Maint. Cat.	1	87039916	5.19%	94121166	94121166	30.62	0.000
Season*Time	3	32552731	1.94%	32552731	10850910	3.53	**0.015**
Error	317	974519223	58.16%	974519223	3074193		
Lack-of-Fit	6	179477449	10.71%	179477449	29912908	11.70	0.000
Pure Error	311	795041774	47.44%	795041774	2556404		
Total	325	1675720963	100.00%				

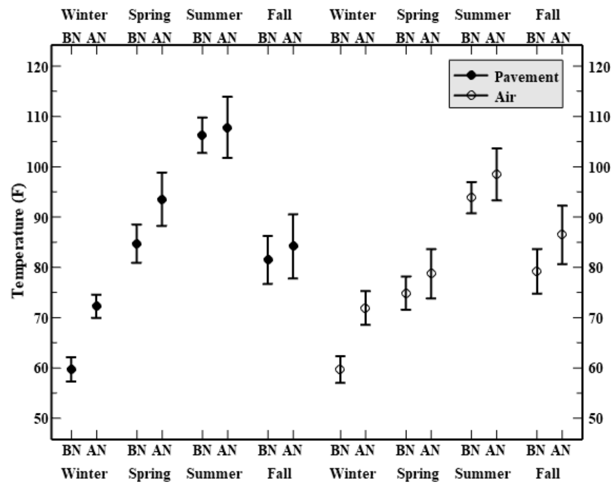
Table 52 ANOVA results for LTE values – WF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	756157660	13.11%	680113939	226704646	34.88	**0.000**
Time	1	154530676	2.68%	43189635	43189635	6.65	**0.010**
Maint. Cat.	2	1058360121	18.35%	1062049115	531024558	81.71	0.000
Season*Time	3	4293469	0.07%	4293469	1431156	0.22	0.882
Error	584	3795286065	65.79%	3795286065	6498778		
Lack-of-Fit	14	414978033	7.19%	414978033	29641288	5.00	0.000
Pure Error	570	3380308032	58.60%	3380308032	5930365		
Total	593	5768627991	100.00%				

The ANOVA analysis for wet regions shows that the main effects of the two factors, namely season and time, are significant contributors to the variations in LTE while their interaction is not (see Table 52 and Table 53). The maintenance category, used as a blocking factor, is also contributing to the variation of LTE values in the WF region. However, it is not a significant factor in the WNF region. The main effects plot in Figure 73(a) shows that the mean LTE value in summer is significantly higher than other seasons, while lowest in winter season in the WF climate region [also see Figure 73(c)]. While for the WNF climatic region, the LTE values are statistically different [see Figure 73(b) and Figure 73(d)] between all the seasons. However, the difference between winter and spring season LTE values (>15%) and summer and spring season LTE values (>20%) can be termed as practically different only.



(a) Interaction means plot



(b) Pavement surface and air temperatures during FWD measurements

Figure 72 ANOVA results - DNF climatic region

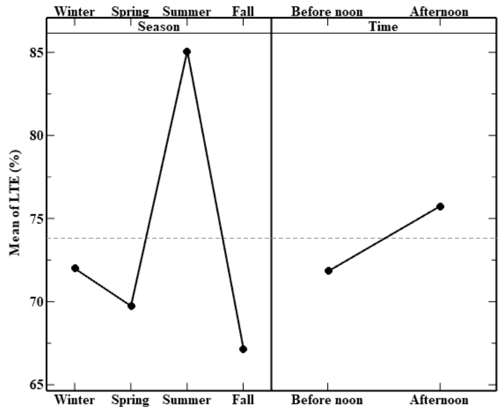
As discussed earlier, the higher LTE values in the summer season in the WF climatic region is explained based on the temperature range during the FWD measurements. The temperature range in summer for the WF climatic region is between 80-84°F, which causes an increase in LTE values [see Figure 74(a)]. Similarly, the difference between the seasonal LTE values in the WNF climate is also evident from the temperature ranges during FWD testing [see Figure 74(b)].

Table 53 ANOVA results for LTE values – WNF climatic region

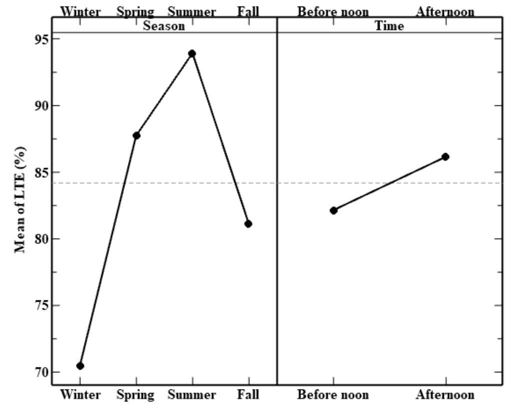
Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	47986	33.88%	49449.3	16483.1	86.60	**0.000**
Time	1	3256	2.30%	3217.5	3217.5	16.91	**0.000**
Maint. Cat.	1	352	0.25%	342.5	342.5	1.80	0.180
Season*Time	3	1161	0.82%	1160.7	386.9	2.03	0.108
Error	467	88882	62.75%	88882.4	190.3		
Total	475	141637	100.00%				

Observing the diurnal trends in both the WF and WNF climates, in Figure 73(a) and Figure 73(b), it is found that before noon measurements result in a lower LTE value as compared to an afternoon measurement. Figure 74(c) and Figure 74(d) shows the diurnal temperature ranges between the wet climates. In the WF region, the before-noon air temperatures are not very different from the afternoon temperatures; however, there is a significant difference between the corresponding pavement surface temperature ranges. Such temperature difference of the pavement surface causes the LTE values measured before-noon to be lower than the afternoon LTE values. The difference in the diurnal temperature ranges, in the WNF climatic region, explains the lower before-noon LTE values as opposed to afternoon LTE values.

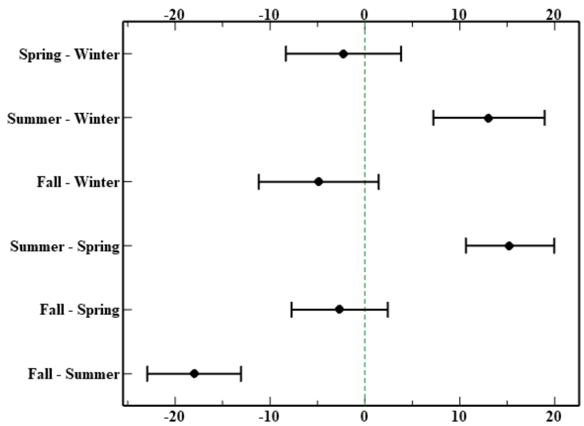
Generally, FWD measurements conducted before noon result in lower LTE values as compared to those measured in the afternoon, irrespective of the climatic region. Therefore, it is beneficial to perform deflection measurements on joints for LTE determination before noon when slabs are flatter. Also, Figure 75 shows the histogram of the temperature gradients data available in the SMP database for the JPCP sections. Ideally, a zero or near-zero temperature gradient would be ideal for measuring deflections at joints and, ultimately LTE, as such LTE values will depict the actual load transfer capacity of the joint. Around 50 measurements were found in the data where the temperature gradient was between -1 to 1. The time range of these measurements was found to be ranging from 8 am to around 1 pm. Hence, the available data also suggests that diurnally before noon measurements are ideal to see a zero gradient temperature condition, which can help to identify joints condition accurately.



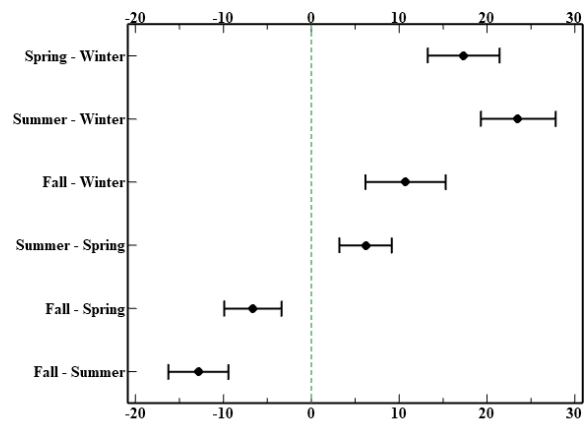
(a) Main effects plot for LTE - WF climatic region



(b) Main effects plot for LTE - WNF climatic region

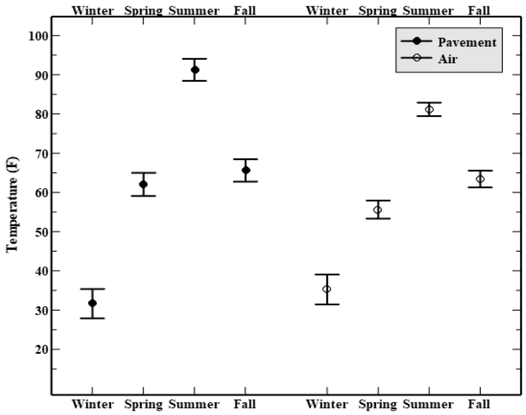


(c) The seasonal mean difference of LTE values with 95% confidence – WF climatic region

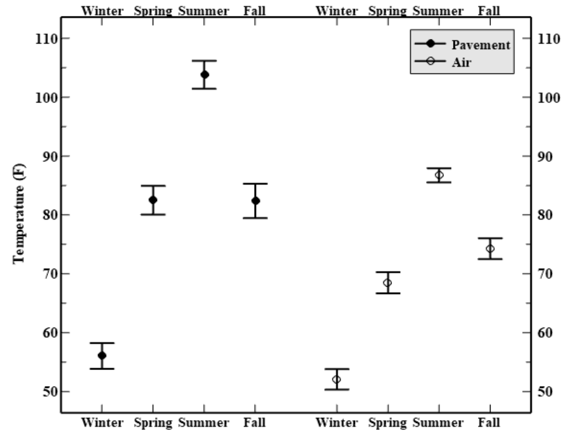


(d) The seasonal mean difference of LTE values with 95% confidence – WF climatic region

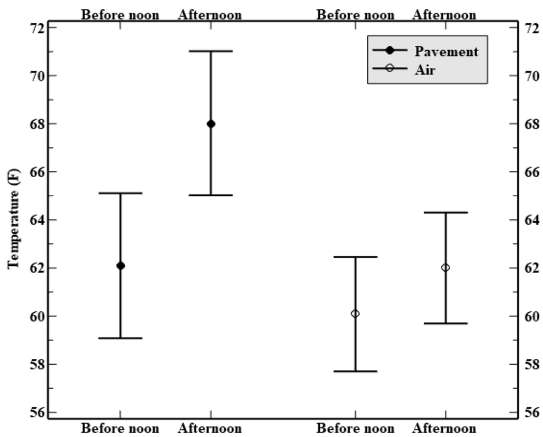
Figure 73 ANOVA results – WF and WNF climatic regions



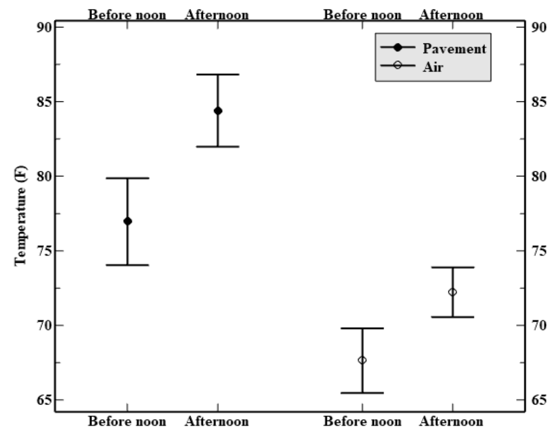
(a) WF climatic region



(b) WNF climatic region



(c) WF climatic region



(d) WNF climatic region

Figure 74 Seasonal and diurnal pavement surface and air temperatures

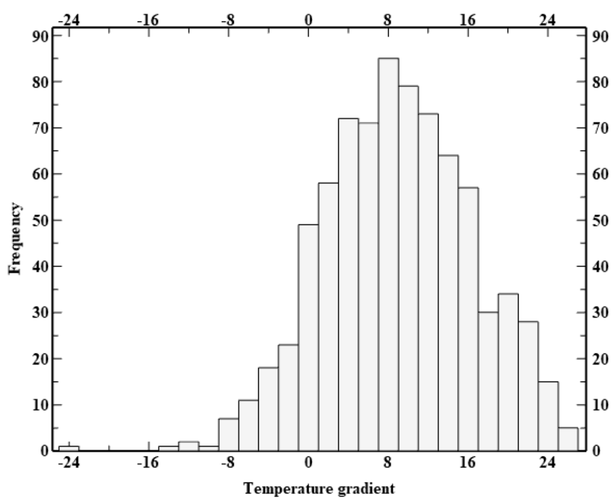
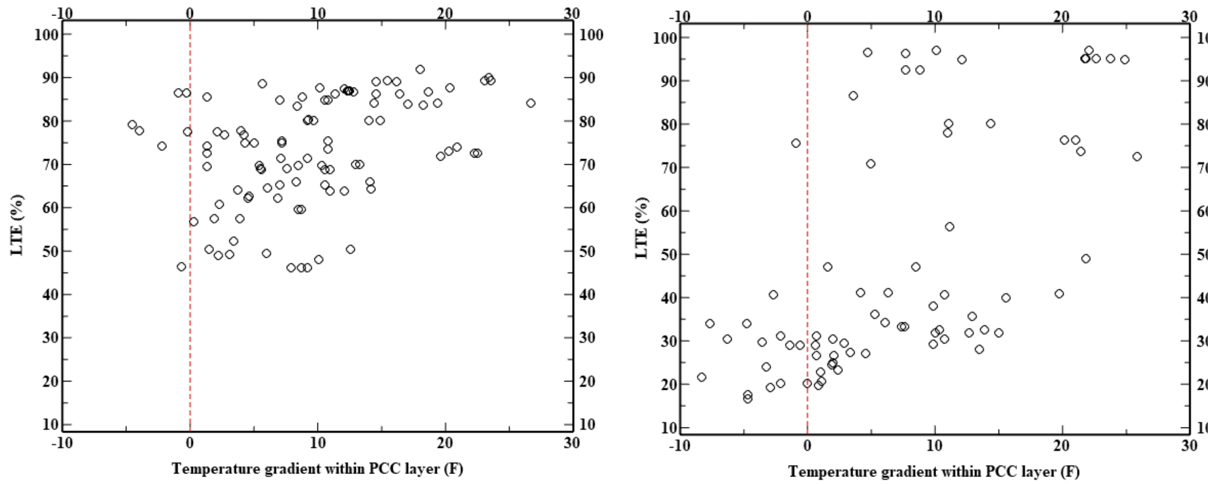


Figure 75 Histogram of the available temperature gradients data for LTE values – SMP JPCP sections



(a) Arizona section ID 4-0215 – DF climatic region

(b) Nebraska section ID 31-3018 – WF climatic region

Figure 76 Variation in LTE with temperature gradient - JPCP sections

Figure 76 displays examples of LTE for two JPCP sections, each in the DF and WF climatic regions. The plots display the increasing trend of LTE as the temperature gradient within the PCC layer shifts from negative to positive within a day (i.e., before noon to afternoon). The displayed LTE values were determined on different days in multiple years. The shift of the PCC slab shape from curled up to curled down causes the LTE to increase as the day passes.

4.2.2 Longitudinal Profile Measurements (IRI) – JPCP Pavements

The functional performance of new or existing pavements is assessed in terms of smoothness, which is estimated using longitudinal profile measurements. However, the longitudinal profiles of Jointed Concrete Pavements (JCP) are affected significantly by temporal (seasonal and diurnal) variations in temperature and moisture. These temporal variations translate into influencing the curling and warping of the concrete slabs of JPCP. Therefore, it is essential to consider such effects for accurately assessing the pavement condition.

The longitudinal profile measurements are commonly summarized by the International Roughness Index (IRI) that reduces the thousands of elevation values into a single value [38, 39]. However, no matter which index is calculated from a longitudinal profile, the quality of the information is only as good as the profile measurement [2]. Thus, there is a need to evaluate the impacts of temporal (seasonal temperature/moisture and daily temperature) variations on longitudinal profile measurements, especially for JCPs.

The steps involved in the analysis are enumerated as follows:

1. The pavement structure details, IRI values, profile measurement dates and timings, maintenance history, pavement surface temperature, and air temperature were some of the variables identified to perform the analysis.
2. The investigation required an analysis involving the available JPCP sections in the LTPP SMP database.
3. The available JPCP pavement sections were identified in the SMP LTPP database with their climatic region. Note that the climatic regions are defined based on temperature (i.e., freeze/no freeze), and moisture (i.e., wet/dry).
4. Obtained slab thicknesses for each JPCP sections.
5. The IRI values, along with the date and time of profile measurements, the air and pavement surface temperatures were obtained. Also, the maintenance history details for the section were extracted from the database (i.e., construction no. and type of treatment) and categorized.
6. Five profile measurements (runs) per visit are the LTPP standard [44]; the analysis used each of the calculated IRI values.
7. All the required data elements were arranged in a relational database.

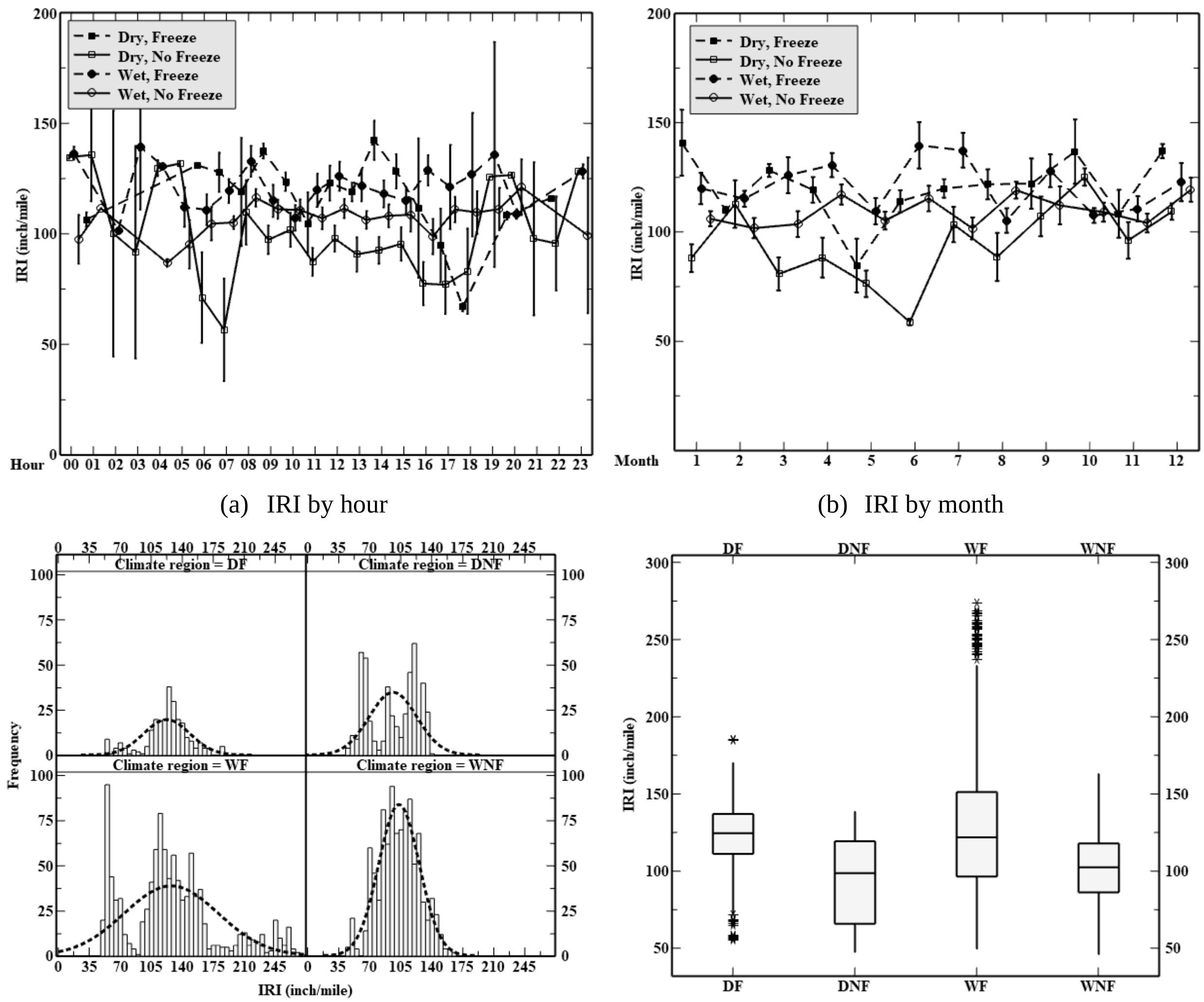
8. The data were inspected using a histogram and boxplot to identify outliers.
9. Two factors were used in this analysis; (a) measurement month discretized into four seasons (i.e., levels) to look at the seasonal effects, (b) measurement time with two levels (before noon and afternoon) for the diurnal effects. Besides, the maintenance category was used as a blocking factor.
10. Analysis of Variance (ANOVA) was conducted for JPCP sections within each climatic region to investigate the temporal effects on the joint LTE values.

Figure 77 shows the overall variations in the mean IRI values by the hour and month of profile measurements within different climatic regions. The IRI values show a significant hourly influence, i.e., the IRI values are different in each hour among the different climatic regions [see Figure 77(a)]. Also, significant variations can be seen in the IRI values among different months, with higher values in the freeze regions [see Figure 77(b)]. Figure 77(c) and (d) show the histogram and box-plot, while Table 54 displays the descriptive statistics of the data within each climatic region. There is generally higher variability in the IRI values within different climates, with the highest in the WF climatic region. The variation in the WF climatic region may be due to IRI values over 250 inch/mile. Such higher values can potentially mask the results of ANOVA. The IRI analysis presented in this study uses values between 70-170 inch/mile.

Table 54 Descriptive statistics IRI values—SMP JPCP pavement sections

Climatic region	N	Mean	Std.	Minimum	Q1	Median	Q3	Maximum
DF	258	122.1	26.1	54.8	110.9	124.4	136.9	185.3
DNF	474	95.7	27.1	47.1	65.6	98.5	119.2	138.5
WF	1038	127.2	53.2	49.1	96.4	121.8	151.1	274
WNF	969	102.4	23	45.6	86	102.3	117.8	163

Note: IRI values shown are in inch/mile units.



(a) IRI by hour

(b) IRI by month

(c) Histogram - Available IRI data

(d) Box-plot - Available IRI data

Figure 77 Assessing available IRI data – SMP JPCP pavement sections

Figure 78 shows the normality of the data used for the IRI analysis of the DF climatic region after a suitable transformation. As mentioned earlier, the satisfaction of the normality assumptions is critical to draw a meaningful conclusion from an ANOVA. Similar to the DF climatic region, data for all other climatic regions were transformed to ensure the satisfaction of the normality assumptions.

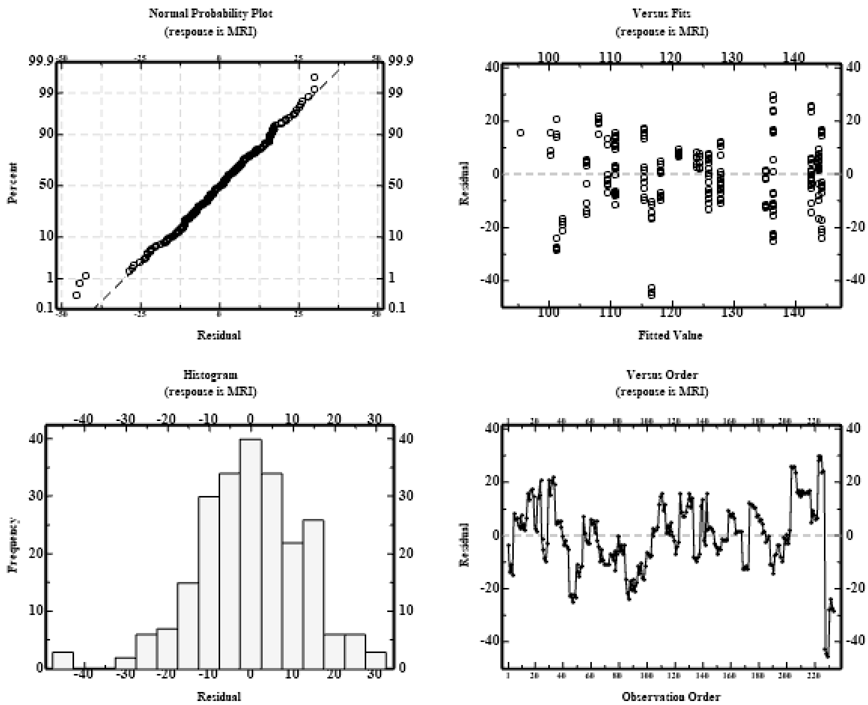


Figure 78 Evaluating normality of the IRI data - DF climatic region

Table 55 shows the ANOVA results for IRI analysis of the DF climatic region. Results reveal that profile measurement season and time influence the IRI values in the DF climatic region. The main effects plot in Figure 79(a) shows a noticeable difference in IRI values between the different seasons. Multiple mean comparisons plot reveals that there is no significant mean difference between fall and winter and summer and spring seasons [see Figure 79(b)]. It also shows that a mean difference higher than 12 inches/mile exists between the other season combinations (i.e., spring and winter, summer and winter, fall and spring, and fall and summer). Although statistically significant, the difference between IRI obtained from profile measurements before-noon and afternoon is not practically noticeable (< 6 inches/mile).

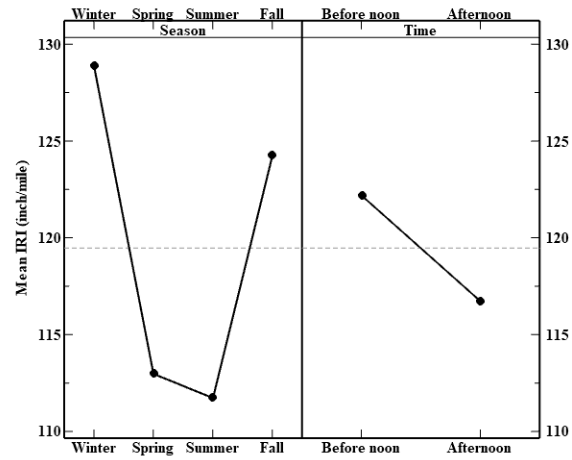
For an explanation of the effects seen in the DF climatic region, it is essential to know the ambient and surface PCC temperature at the time of the profile measurements. Figure 80(a) shows the ambient temperature range between different seasons during profile measurements.

Pavement surface temperature data were available for the spring season only. Low temperatures (below 40°F) explain higher IRI observed in the winter season. The increase in IRI could be due to the curling up of the pavement's slab at such temperatures. Whereas, downward curling of the JPCP slab at elevated temperatures (i.e., around 80°F) results in low IRI. The drop in IRI in the spring season can be related to the corresponding high pavement surface temperature causing the slab to curl down.

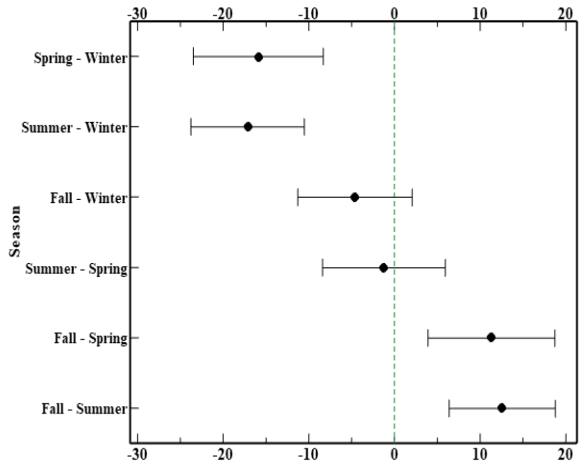
On the other hand, the practically insignificant difference between before-noon and afternoon IRI is because the temperature ranges do not vary between these timings [see Figure 80(b)]. Based on the discussion and Figure 80, profile measurements at an ambient temperature range of 55 – 65°F recorded in the spring and fall seasons are suggested in the DF climatic region. Also, considering the diurnal trends, the pavement profiles are better to measure in the afternoon.

Table 55 ANOVA results for IRI values – DF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	10364	12.27%	10687	3562.5	20.30	**0.000**
Time	1	2360	2.79%	1472	1472.4	8.39	**0.004**
Maint. Cat.	2	31102	36.82%	29127	14563.3	82.97	0.000
Season*Time	3	1325	1.57%	1325	441.7	2.52	0.059
Error	224	39318	46.55%	39318	175.5		
Lack-of-Fit	12	13392	15.85%	13392	1116.0	9.13	0.000
Pure Error	212	25926	30.69%	25926	122.3		
Total	233	84469	100.00%				



(a) Main effects plot

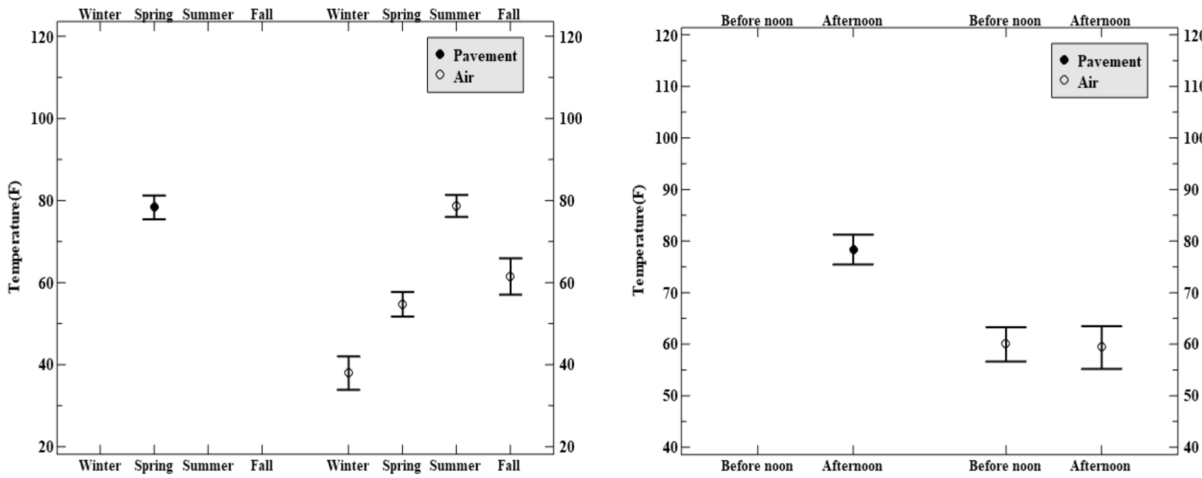


(b) Seasonal mean IRI differences

Figure 79 ANOVA plots for IRI data - DF climatic region

Table 56 ANOVA results for IRI values – DNF climatic region

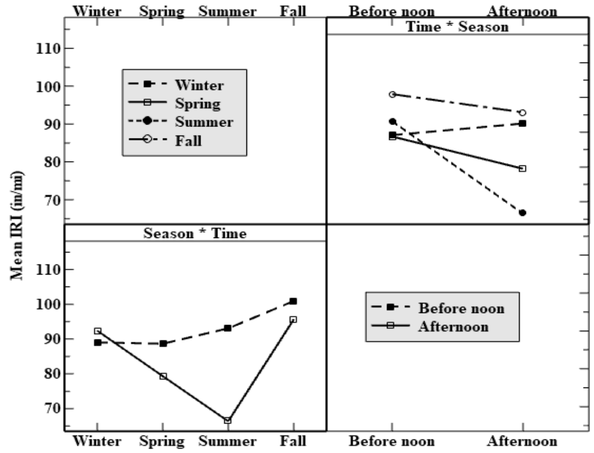
Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	2091.2	2.43%	8148	2715.8	15.93	0.000
Time	1	37.5	0.04%	3639	3638.9	21.35	0.000
Maint. Cat.	1	25864.0	29.99%	24336	24336.4	142.76	0.000
Season*Time	3	4535.3	5.26%	4535	1511.8	8.87	**0.000**
Error	315	53699.8	62.28%	53700	170.5		
Lack-of-Fit	1	1012.6	1.17%	1013	1012.6	6.03	0.015
Pure Error	314	52687.2	61.10%	52687	167.8		
Total	323	86227.7	100.00%				



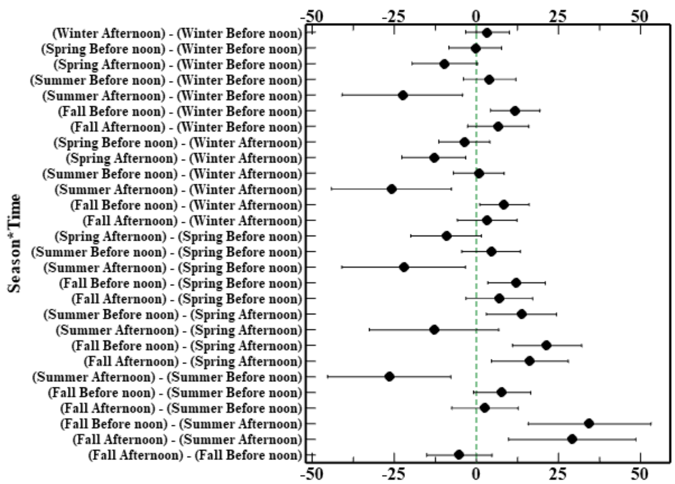
(a) Seasonal temperature ranges (b) Diurnal temperature ranges

Figure 80 Pavement surface and air temperatures during profile measurements - DF climatic region

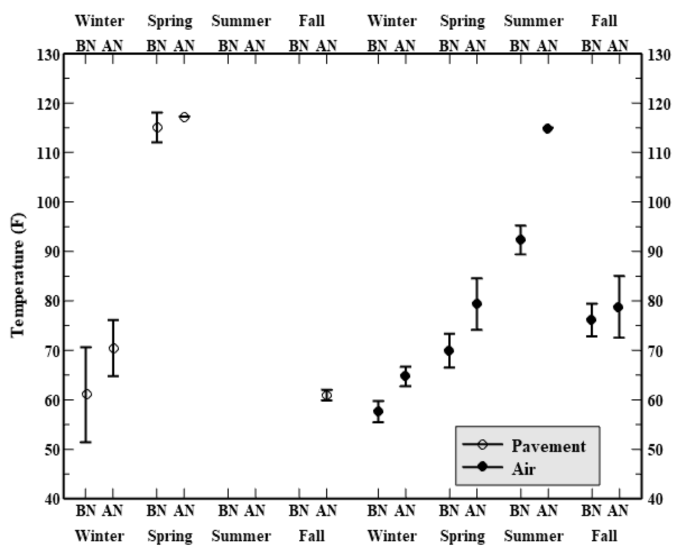
ANOVA results for the DNF climatic region shows that the interaction between profile measurement season and time is a pivotal contributor to the variations in IRI values (see Table 56). The interaction means plot illustrates a significant difference between IRI obtained from profile measurements conducted before-noon and the afternoon in spring and summer seasons [see Figure 81(a)]. Also, before-noon IRI values are higher than the afternoon ones for all seasons except winter, which displays almost similar IRI values irrespective of the time. Figure 81(b) shows that there is no significant difference between before-noon and afternoon IRI values in winter and fall seasons. However, there is a considerable difference (> 25 inches/mile) between the IRI values obtained before-noon and afternoon in the summer season.



(a) Interaction means plot



(b) Mean IRI difference with 95% confidence interval for season and time interaction



(c) Pavement surface and air temperatures

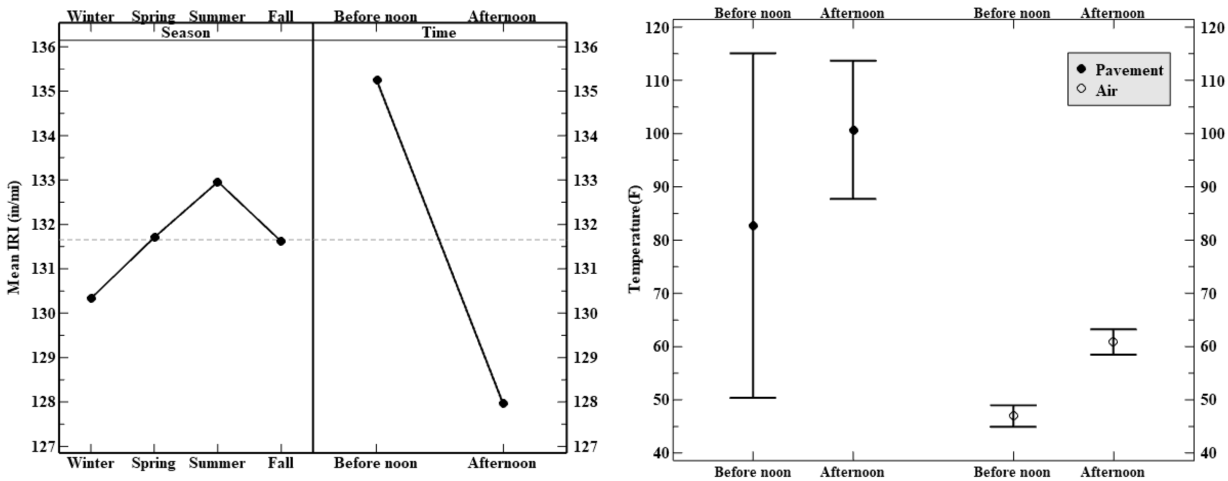
Figure 81 ANOVA results for IRI - DNF climatic region

The pavement surface temperature ranges for before-noon and afternoon timings in the winter season does not vary; hence, the similar IRI values [see Figure 81(c)]. The driving factor for the substantial IRI difference in the summer season is the clear distinction between the ambient temperatures in the season (pavement surface temperatures are unavailable in the data). Such a significant temperature difference could affect the level of the slab curling; thus, changes the IRI substantially between the two times (i.e., before-noon and the afternoon). Also, the IRI difference observed during the spring season (around 10 inches/mile) seen in Figure 81(b) is also explained by the noticeable difference between the ambient and pavement surface temperatures. Basing on the discussion and Figure 81(c) suggests profile measurements at ambient temperatures of 60 – 70^{o}F occurring in the winter and fall seasons in the DNF climatic region. Additionally, the afternoon pavement profile appears beneficial, considering the overall diurnal trends.

Table 57 ANOVA results for IRI values – WF climatic region

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	120876738	0.58%	36801493	12267164	0.59	0.624
Time	1	623684726	2.99%	599793853	599793853	28.67	**0.000**
Maint. Cat.	2	6130412326	29.37%	6129409617	3064704809	146.51	0.000
Season*Time	3	48800265	0.23%	48800265	16266755	0.78	0.507
Error	667	13952259180	66.83%	13952259180	20917930		
Lack-of-Fit	14	1293556633	6.20%	1293556633	92396902	4.77	0.000
Pure Error	653	12658702547	60.64%	12658702547	19385456		
Total	676	20876033235	100.00%				

Table 57 shows that the time of the profile measurement within a day influences the IRI of pavement sections in the WF climatic region. However, the statistically significant difference (less than 8 inches/mile) is not practical [see Figure 82(a)]. Although there is a definite difference in ambient temperatures between before-noon and afternoon times, however, the pavement surface temperatures are not very different (larger error bars are due to insufficient availability of pavement surface temperatures data). Thus, the corresponding difference in IRI values is not practically significant. The discussion on the ANOVA results along with temperature ranges shown in Figure 82(b) suggests profile measurements within the ambient temperature range of 50 - 65°F; conducted in the afternoon in the WF climatic region



(a) Main effects plot (b) Pavement surface and air temperatures

Figure 82 ANOVA results for IRI data - WF climatic region

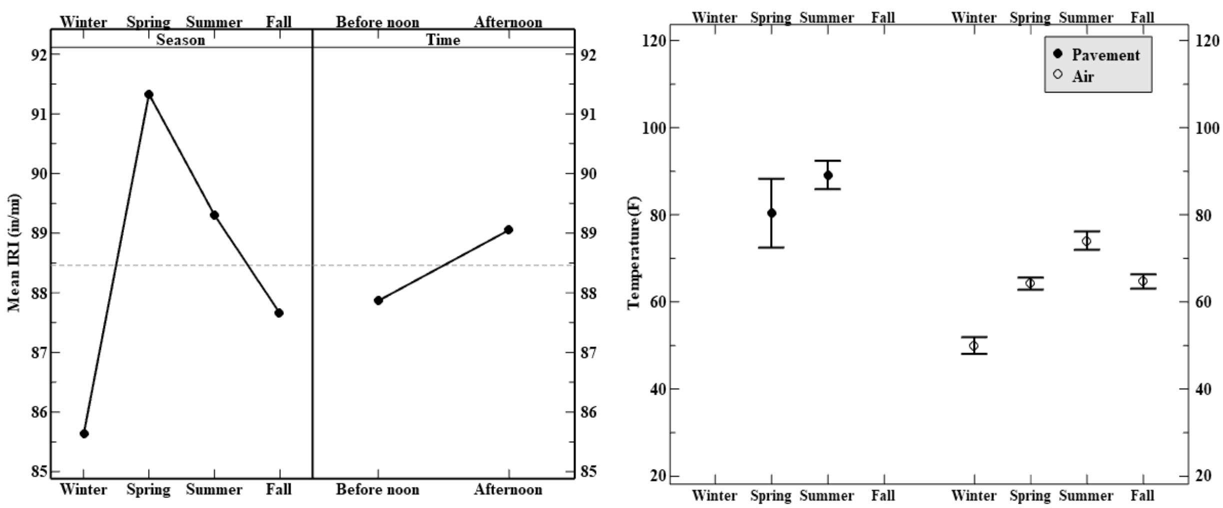
ANOVA results for the WNF climatic region are almost similar to the WF climatic region, with the only difference that the profile measurement season is the significant factor influencing the pavement's IRI (see Table 58). However, the mean difference between any two seasons is not practically noteworthy (i.e., less than 6 inches/mile), which is explained by the similar ambient and pavement surface temperature ranges observed during the profile measurements [see Figure 83(a) and (b)].

Table 58 ANOVA results for IRI values – WNF climatic region

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	*F*-value	*p*-value
Season	3	0.4160	1.29%	0.5137	0.17125	4.85	**0.002**
Time	1	0.0244	0.08%	0.0393	0.03926	1.11	0.292
Maint. Cat.	1	0.4832	1.49%	0.5154	0.51542	14.58	0.000
Season*Time	3	0.1949	0.60%	0.1949	0.06498	1.84	0.139
Error	883	31.2090	96.54%	31.2090	0.03534		
Total	891	32.3276	100.00%				

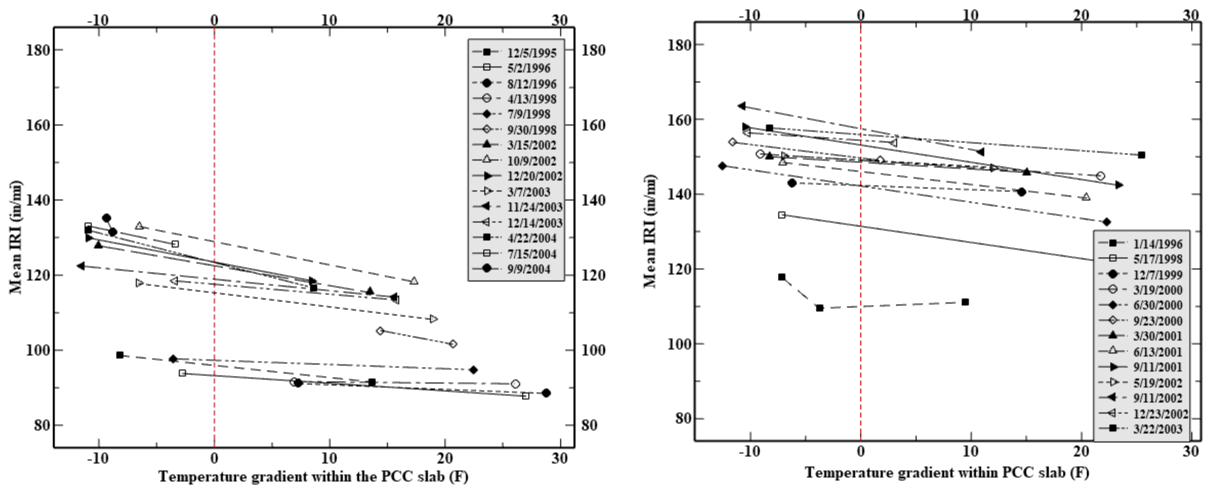
An interesting finding from the ANOVA results is that in the WNF climatic region, IRI values in the winter season are the lowest while those in the spring are the highest. Such effects are possibly due to relatively moderate winter temperatures, while the pavement surface temperatures corresponding to the spring season are much high. The high pavement temperatures coupled with moisture could be a possible explanation of the IRI effects observed in the spring season.

The main effects plot shows that the mean IRI values do not differ between the different seasons within the WNF climatic region. Thus, suggesting that the ambient temperature ranges within these seasons could be better for profile measurements. Observing the temperature ranges in Figure 83(b) indicates that the ambient temperature range between 50 - 65^{o}F could be better to measure profile that could generate near actual IRI values. Additionally, suggested time for profile measurements is in the morning (i.e., before noon) within this climatic region.



(a) Main effects plot (b) Pavement surface and air temperatures

Figure 83 ANOVA results for IRI data - WNF climatic region



(a) Arizona section ID 4-0215 – DF climatic region

(b) Nebraska section ID 31-3018 – WF climatic region

Figure 84 Variation in IRI with temperature gradients – JPCP sections

Figure 84 shows an example of two JPCP sections in the DF and WF climatic regions. These examples display the effect of a temperature gradient within the PCC layer on the pavement's IRI. It shows that as the temperature gradient shifts from negative to positive (i.e., from morning to afternoon) within a day, the IRI of the pavement decreases displaying the diurnal effects. Also, the figure displays the growth of IRI with age.

4.3 Summary

This section presented the ANOVA analysis of the available data arranged in a relational database for each of the identified elements. The factors used in the analysis mainly consist of FWD and profile measurement season and time of the day. For flexible pavement sections, the HMA layer thickness classified into two levels based on the original SMP experiment was also an additional factor. Besides, the maintenance category was used as a blocking factor to increase precision in the analysis by reducing the experimental error.

The analysis revealed an essential impact of the season and time of the day on the HMA layer moduli. However, it is less critical owing to the temperature correction procedures for AC layer moduli. The Asphalt Institute temperature correction equation performed well in correcting the HMA layer moduli values. Nevertheless, since a single FWD deflection measurement helps estimate the base and subgrade layer moduli, the seasonal variation effects become more critical for the unbound layers. The ANOVA results displayed the impact of the FWD measurement season to be significant on the unbound layer moduli.

The analysis of the available data for JPCP sections also showed that FWD measurement season and time of the day influence the PCC slab, thus changes the estimated moduli and *k*-values. The temperature differential within a day between the top and bottom of the PCC slab displayed an essential impact on the load transfer capacity of the JPCP joints as well. However, some of the results from the ANOVA for the JPCP pavements were not very clear due to the data limitation within the SMP experiment database.

The season and time of the profile measurements also showed an influence on the IRI of both pavement types based on the ANOVA results. While for the flexible pavement sections, the interaction between the season and time of profile measurements had a pronounced influence, their main effects were dominant over the IRI for the rigid pavements. Also, the shift of temperature gradient from negative to positive displayed a decrease in the IRI of JPCP pavements.

The section also related the measurement temperatures of the FWD and profile measurements with the parameters determined from them. Ambient temperature ranges are suggested for each climatic region to conduct FWD and profile measurements in anticipation of getting the moduli and IRI values that accurately represent the actual pavement conditions.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Evaluating the structural capacity of a pavement involves measuring and assessing deflections obtained from FWD testing. Longitudinal profile measurements are used to determine the functional performance of pavement in terms of smoothness. However, temporal changes influence these measurements. Assessing and quantifying the effects of temporal variations can assist in a better understanding of the pavement parameters obtained using these measurements, such as backcalculated layer moduli and IRI.

The data from the LTPP SMP database was extracted, arranged in different data tables, and analyzed using ANOVA. Data analysis for each element identified involved ANOVA on the climatic region basis. The effects observed and the ambient temperatures recorded at the time of FWD and profile measurements were related to formulating general guidelines for these measurements.

Analyses of the backcalculated layer moduli for flexible pavements revealed an essential effect of seasonal and diurnal changes. The HMA layer moduli showed minimal variation in the spring and fall seasons in every climatic region. Also, the HMA layer moduli were consistently higher, involving deflections measured before noon. However, temperature correction, generally applied to HMA layer moduli, renders the season, time, and temperature of the FWD measurements irrelevant. However, the base and subgrade layer moduli are backcalculated from the same measured deflections using the FWD test conducted on the surface. This practice makes the FWD measurement season, time, and temperatures critical in terms of the moduli values obtained for the unbound layers. Any guidelines concerning FWD testing should, therefore, take into account this fact.

Generally speaking, the base and subgrade moduli showed minimal variation within the temperature ranges occurring in the spring and fall seasons, which lead to concluding that such temperature within each climate region may potentially result in these layer moduli values that are close to their in-field condition. Also, the unbound layer showed no effect of time within a day, suggesting no limits for FWD measurements with regards to a better time for conducting these tests.

The PCC layer moduli, *k*-values, and LTE also exhibit meaningful effects of both the FWD measurement season and time. Interestingly, the temperature ranges within spring and fall seasons appear to have less variation within the PCC layer moduli and LTE values, which are more critical in the case of rigid pavements concerning seasonal and diurnal variations. Therefore, the suggested ambient temperatures for FWD measurements over rigid pavements are those recorded in the spring and fall seasons. Moreover, FWD testing conducted before noon has a better chance of finding a zero or near-zero temperature gradients, hence recommended.

Profile measurements on flexible pavements do not show a particular trend while dealing with pavement sections on the climatic region basis. However, in general, the effects show that temperature ranges occurring in the fall and spring seasons could result in less variable IRI values. While in the WF climatic region, summer season ambient temperatures also displayed little to no variation in determined IRI of the pavement sections. Diurnally, results showed no specific trend in the IRI values within different seasons.

Profile measurements on rigid pavements illustrated various trends based on the ANOVA within different climatic regions. The DF region IRI values showed less variation advocating temperature ranges within spring and fall seasons. The results for the DNF climatic region showed lower variability in the determined IRI values within the winter and fall seasons. In contrast, the IRI values in the wet regions did not show any particular trend seasonally. As far as diurnal patterns, afternoon time is better for profile measurements suggested based on the results for all seasons except the WNF climatic region.

5.2 Recommendations for FWD and Profile Measurements

The temperature correction of HMA layer moduli makes the backcalculated unbound layer moduli critical in defining the general guidelines for FWD testing on flexible pavements. The recommended general guidelines for FWD deflection testing based on the data analysis presented in this study are as follow:

- The recommended ambient temperature range for FWD testing on flexible pavements in the freeze (i.e., DF and WF) climatic regions is between 55 – 70^{o}F.
- In the non-freeze (i.e., DNF and WNF) climates, the recommended ambient temperature range to conduct FWD testing on flexible pavements is between 65 – 75^{o}F; however, in the DNF climatic region, the upper limit might be around 80^{o}F.
- The study recommends no restriction for the FWD testing time during a day. However, the spring and fall seasons are preferable for FWD deflection measurements on flexible pavements.

For the rigid pavements, the recommended general guidelines for conducting FWD deflection measurements are as follows:

- The recommended ambient temperature range for FWD testing on rigid pavements in the freeze (i.e., both the DF and WF) climatic regions is between 55 – 70^{o}F.

- In the non-freeze (i.e., DNF and WNF) climates, the recommended ambient temperature range to conduct FWD testing on rigid pavements is between 60 – 75^{o}F.
- The recommended time for FWD testing on rigid pavements is before-noon, preferably between 8 am to noon in the spring and fall seasons.

The general recommended guidelines for the profile measurements based on the available IRI data are as follows:

- The recommended temperature range suitable to measure flexible pavement profile is between 50 - 75^{o}F irrespective of the climatic region, season, and time of the day.
- The recommended temperature range for profile measurement on rigid pavements in freeze (i.e., DF and WF) regions is between 50 - 65^{o}F; while for the non-freeze (i.e., DNF and WNF) climatic regions, profile measurement is suitable between 50 - 70^{o}F.
- The study recommends spring and fall seasons for DF, winter and fall seasons for DNF, and no season limitation for the WF and WNF climatic regions for profile measurements on rigid pavements.
- This study recommends afternoon time to be better for profile measurements on rigid pavements except for the WNF climate region where before noon measurements are beneficial.

5.3 Recommended Future Work

- Agencies use LTE to determine the load transfer of the joints on a JPCP pavement. However, given the shortcomings of the LTE approach, the use of differential deflections instead of LTE can reveal the actual joint conditions better. Therefore, ANOVA on differential deflections can be performed in a future study.

- Utilization of the available moisture data within the unbound layers and the correlation between the number of wet days and subsurface moisture before the measurements in the LTPP database are recommended to be incorporated in the data analysis to enhance the moisture-related impacts on the unbound layers moduli.

APPENDIX

Table 59 Hourly data distribution of backcalculated parameters - SMP AC sections

Climate region	State	State code & section ID	Hour of the day																								Total
			00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
DF	Colorado	8_1053										11	21	22	22	15	14	9	3	1							118
DF	Idaho	16_1010										10	26	11	22	6	9	8	4								96
DF	Montana	30_0114									2	17	14	11	17	22	6	2									91
DF	Montana	30_8129										10	23	24	26	15	16	8	4								126
DF	Nevada	32_0101								1	9	28	19	25	22	18	5										127
DF	Saskatchewan	90_6405									4	21	15	13	13	12	5	4									87
DF	South Dakota	46_0804									5	20	29	29	28	15	10	1									137
DF	South Dakota	46_9187									4	12	12	12	12	10	9	2	1								74
DF	Wyoming	56_1007									1	13	20	19	21	10	9	4	4								101
DNF	Arizona	4_0113									6	26	22	32	30	21	7	3	1								148
DNF	Arizona	4_0114									2	24	26	28	24	21	12	5	1								143
DNF	Arizona	4_1017									1	3	2		2	2											10
DNF	Arizona	4_1018										1	2	2		1											6
DNF	Arizona	4_1024								1	6	15	20	12	14	8	4	1									81
DNF	New Mexico	35_1112									14	10	18	10	18	10	18	5									103
DNF	Utah	49_1001									2	11	13	18	20	10	8	5	3	1							91
WF	Connecticut	9_1803								1	9	21	23	26	15	14	4										113
WF	Maine	23_1026								2	7	22	19	19	14	18	3										104
WF	Manitoba	83_1801									3	24	29	29	18	16	7	7									133
WF	Manitoba	83_3802											1	1													2
WF	Massachusetts	25_1002									1	24	19	23	21	18	4										110
WF	Minnesota	27_1018								1	3	16	14	18	10	15	14	4									95
WF	Minnesota	27_1028									4	13	19	14	12	10	8	2									82
WF	Minnesota	27_6251								2	9	32	33	30	28	17	17	1									169
WF	Nebraska	31_0114									4	14	17	23	21	14	3	1									97
WF	New Hampshire	33_1001										17	18	23	17	20											95
WF	New Jersey	34_0501											1	2	1	2			1	1	4	1		1			14
WF	New Jersey	34_0502											1	4	4	3	1								1		14
WF	New Jersey	34_0503								1	2	3	2	3	4	1	1							1			18
WF	New Jersey	34_0504	1							1			2		2	1	2	1	2	2	1	1					16
WF	New Jersey	34_0505										2	1	3		1		3	1	2	1			1			15
WF	New Jersey	34_0506										3	2	3	3	1	2				2	1		1			18
WF	New Jersey	34_0507									4	4	3	3	1		1			1	1					1	19
WF	New Jersey	34_0508										1	4	4	3	3	1									1	17
WF	New Jersey	34_0509	1										2	3	2	4	3		1	1							17
WF	New Jersey	34_0559										1	1	1	1	3	3	2	1								13
WF	New Jersey	34_0560									1	1		1	3	4	2	2			1						15
WF	New Jersey	34_0901							1	3		1		3	1		1										10
WF	New Jersey	34_0902						1				2	1	3		1	1				1						10

Table 59 (cont'd)

Climate region	State	State code & section ID	Hour of the day																								Total
			00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
WF	New Jersey	34_0903								1	2		2			1	2						1				9
WF	New Jersey	34_0960								1			2	2	2			1	1								9
WF	New Jersey	34_0961						1					2	2	3			1		2							11
WF	New Jersey	34_0962								1		1		2	1	5	2										12
WF	New York	36_0801								1	2	11	27	31	36	28	11	1									148
WF	Ohio	39_0901	1	1	1	1	1	1	1	1	6	17	25	30	22	12	7	4	1	1		1	1	1	1	1	138
WF	Ontario	87_1622										7	18	12	10	11	7	2									67
WF	Pennsylvania	42_1606												1													1
WF	Quebec	89_3015											1	3													4
WF	Vermont	50_1002									2	5	41	29	34	29	4										144
WNF	Alabama	1_0101								2	8	8	12	13	11	8	15	6	6	2							91
WNF	Alabama	1_0102								3	8	11	12	7	15	5	7	8	3	2	1						82
WNF	Delaware	10_0102										13	8	11	8	12	5		1								58
WNF	Georgia	13_1005									13	15	3	13	10	5	10	3	3	1							76
WNF	Georgia	13_1031								1	8	23	12	11	17	11	11	6	7								107
WNF	Maryland	24_1634							1	8	4	7	17	26	6	10			1								80
WNF	Mississippi	28_1016								4	8	3	1	11	2	4	5	8	1	3							50
WNF	Mississippi	28_1802								3	8	15	9	11	9	6	9	4	4	1							79
WNF	North Carolina	37_1028									2	15	13	21	15	11	3										80
WNF	Oklahoma	40_4165									1	13	16	11	11	7	9	4									72
WNF	Texas	48_1060								9	8	14	11	14	11	8	10	7	3								95
WNF	Texas	48_1068								11	8	19	10	16	10	4	8	8		2							96
WNF	Texas	48_1077								8	11	13	17	7	16	4	11	8	8	3							106
WNF	Texas	48_1122								10	9	19	19	16	15	17	12	14	2	3							136
WNF	Texas	48_3739								8	8	12	19	15	14	13	8	11	1								109
WNF	Virginia	51_0113										17	15	20	17	10	7	2		1		1					90
WNF	Virginia	51_0114									1	14	26	24	26	20	8	1	1								121
WNF	Washington	53_3813													1												1

Table 60 Monthly distribution of IRI visit data - SMP AC sections

Climate region	State	State code & section ID	Month												Total
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	
DF	Colorado	8_1053	1	1	1	4	3		3	3	3	6	3	1	29
DF	Idaho	16_1010	1	1	2		2		4		3	2		2	17
DF	Montana	30_0114	3	2	1	5	1	2	9	6	4	3	2	2	40
DF	Montana	30_8129	1	1	1	4	1	5	4	3	3	4	3	1	31
DF	Nevada	32_0101	2	2	3	4		5	1	4	2	3	2	3	31
DF	Saskatchewan	90_6405	2	1		3	2	4	4	2	1	3	1		23
DF	South Dakota	46_0804	1		4	1	5	3	2	2	6	3		3	30
DF	South Dakota	46_9187	1			1	1	2	2	1	1	1	1		11
DF	Wyoming	56_1007	1	1	1	2	1		3	1	2	8	1	1	22
DNF	Arizona	4_0113	4	2	6	4			2	2	1	2	3	6	32
DNF	Arizona	4_0114	4	2	6	4			2	2	1	2	3	6	32
DNF	Arizona	4_1017	2	3	2								5	7	19
DNF	Arizona	4_1018	1	3	2								4	7	17
DNF	Arizona	4_1024	3	4	3	2	2	1	1	1		1	1	3	22
DNF	New Mexico	35_1112	3	4		2	1	3	2	1		6	1		23
DNF	Utah	49_1001	1	1	1	3	3		3	3	1	3	3	1	23
WF	Connecticut	9_1803	3	3		4	4	5	5	5		4	2		35
WF	Maine	23_1026	2	3		3	2	1	2	5	2	3	1		24
WF	Manitoba	83_1801	2	1	4	3	3	3	4	3	4	1	1	4	33
WF	Massachusetts	25_1002	3	4		4	1	4	3	2	5	3	1		30
WF	Minnesota	27_1018	2			2	1	3	4	2	1	2	1		18
WF	Minnesota	27_1028	2	1		3	1	1	3	1	2	2	2		18
WF	Minnesota	27_6251	2	1	4	5	3	3	4	3	4	2	2	3	36
WF	Nebraska	31_0114	1	2	2	3	4		1	1	2	1	3	2	22
WF	New Hampshire	33_1001	2	4		6	2	2	3	3	2	4	1		29
WF	New Jersey	34_0501	2	1	1		1	4		1	1	4		2	17
WF	New Jersey	34_0502	2	1	2	1	1	6		2	1	4		2	22
WF	New Jersey	34_0503	2	1	2	1	1	5		2	1	4		2	21
WF	New Jersey	34_0504	2	1	2	1	1	5		2	1	4		2	21
WF	New Jersey	34_0505	2	1	2	1	1	5		2	1	4		2	21
WF	New Jersey	34_0506	2	1	2	1	1	3		2	1	4		2	19
WF	New Jersey	34_0507	2	1	2	1	1	5		2	1	4		2	21
WF	New Jersey	34_0508	2	1	2	1	1	6		2	1	4		2	22
WF	New Jersey	34_0509	2	1	2	1	1	5		2	1	4		2	21
WF	New Jersey	34_0559	2	1	2	1	1	3		2	1	4		2	19
WF	New Jersey	34_0560	2	1	2	1	1	3		2	1	4		2	19
WF	New Jersey	34_0901	1	1	2	1		1		1	1	3		2	13
WF	New Jersey	34_0902	1	1	2	1		1		1	1	3		2	13
WF	New Jersey	34_0903	1	1	2	1		1		1	1	3		2	13
WF	New Jersey	34_0960	1	1	2	1		1		1	1	3		2	13
WF	New Jersey	34_0961	1	1	2	1		1		1	1	3		2	13
WF	New Jersey	34_0962	1	1	2	1		1		1	1	3		2	13
WF	New York	36_0801	4	2	3	3	5	3	2	2	3	3	1		31
WF	Ohio	39_0901		1	6	1	4	6	2	5	2	3	2	5	37
WF	Ontario	87_1622	1	3	1	3	4	1	5	4	4	5	2		33
WF	Vermont	50_1002	4	5	2	3	5	5	5	2	2	4	3		40
WNF	Alabama	1_0101	3		2	3	1		1	2	1	3		1	17
WNF	Alabama	1_0102	3		2	3	1		1	3	1	3		1	18
WNF	Delaware	10_0102	1	2		1	1	2	2	2	1		2	2	16
WNF	Georgia	13_1005	3			2	3		2	2		3	1	1	17
WNF	Georgia	13_1031	4	1	1	3	4	1	2	5		3		1	25
WNF	Maryland	24_1634	1	3	3	2	1	7	1	1	2	1		4	26
WNF	Mississippi	28_1016	3	1	1	1				3		4	1		14
WNF	Mississippi	28_1802	3		2	2	1	1	1	5		4		1	20
WNF	North Carolina	37_1028	3	1	3	3	1	2	1		1	2	2	6	25
WNF	Oklahoma	40_4165	3	1	2	3		2	1	2	1	3	2		20
WNF	Texas	48_1060	3			5		1	2	1		2		1	15
WNF	Texas	48_1068	2		1	5	2	1	1	2		3	3	1	21
WNF	Texas	48_1077	3			4	1	1	1	1		2	1		14
WNF	Texas	48_1122	2	2	1	6	2	1	4	1	2	3		3	27
WNF	Texas	48_3739	2	2	3	5	2	1	3	2	1	3	1	1	26
WNF	Virginia	51_0113	2	1	1	1	2		3			2	1	2	15
WNF	Virginia	51_0114	4	1	2	1	6	1	4	2	1	4	4	4	34

Table 61 Hourly distribution of IRI visit data - SMP AC sections

Climate region	State	State code & section ID	Hour of the day																								Total
			00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
DF	Colorado	8_1053					1	1					5	5	1	2	6	3	1	2	2						29
DF	Idaho	16_1010					1		1		1		1	1	1	2	4	1		2		2					17
DF	Montana	30_0114							1	1	1		2	6	8	2	4	5	2		2	2		2	2		40
DF	Montana	30_8129				1		1				1	4	1	5	5	1	3	1	6	1	1					31
DF	Nevada	32_0101								1	1	4	1	3	4	6	2	2	6		1						31
DF	Saskatchewan	90_6405			2						1		3	5	2	1	3	3		1		1	1				23
DF	South Dakota	46_0804	1								4	4	4	1	2	3	3	4	2	1	1						30
DF	South Dakota	46_9187										2	1	3	2	1		1	1								11
DF	Wyoming	56_1007		2							2	3	2	2	2	2	4		1	2							22
DNF	Arizona	4_0113			1						1	3	2	2	5	2	5	5	3	1					1	1	32
DNF	Arizona	4_0114			1							3	2	3	6	3	3	5	4					1	1		32
DNF	Arizona	4_1017										1		2	5	2	2	1			2	1	1			2	19
DNF	Arizona	4_1018	1								1	1	3	2			2	1	1				3	2			17
DNF	Arizona	4_1024				1				1			3	1	3	3	4	3	1		1	1					22
DNF	New Mexico	35_1112								1		3	2	4	2	3	2	2	2				2				23
DNF	Utah	49_1001					1				2	2	1	4	1	1	1	2	6			1	1				23
WF	Connecticut	9_1803									5	3	4	1	4	4	2	8		3		1					35
WF	Maine	23_1026										3	1	5	3	5	1	3	1	2							24
WF	Manitoba	83_1801				1	1				1		3	2	6	3	4	5	3	3		1					33
WF	Massachusetts	25_1002									2	7	7	6	1	2	1		1	1	1	1					30
WF	Minnesota	27_1018									2	2	2	1	3	1		4			1	2					18
WF	Minnesota	27_1028					1			1	1		2	2	2	3		1	1	2	2						18
WF	Minnesota	27_6251	1						3	1	1	5	4		2	3	6	7		2					1		36
WF	Nebraska	31_0114								1	3	5	1	3	1	1	3	2	1		1						22
WF	New Hampshire	33_1001									3	4	5		2	4	2	4		2	1	1		1			29
WF	New Jersey	34_0501									1	1	2	4	3	2	1	2						1			17
WF	New Jersey	34_0502									1	2	3	2	5	3	2	2	1					1			22
WF	New Jersey	34_0503									1	1	3	2	4	3	3	2	1					1			21
WF	New Jersey	34_0504									1	1	3	3	4	3	2	2	1					1			21
WF	New Jersey	34_0505									1	1	3	3	4	3	3	1	1					1			21
WF	New Jersey	34_0506									1	1	1	2	4	4	2	2	1					1			19
WF	New Jersey	34_0507									1	2	1	2	6	2	3	2	1					1			21
WF	New Jersey	34_0508									1	2	3	3	4	3	2	2	1					1			22
WF	New Jersey	34_0509									1	1	2	4	4	3	3	1	1					1			21
WF	New Jersey	34_0559									1	1	2	2	4	2	3	2	1					1			19
WF	New Jersey	34_0560									1	1	2	1	4	2	5	1	1					1			19
WF	New Jersey	34_0901											1		4	2	1	2	2					1			13
WF	New Jersey	34_0902										1	1		3	2	1	1	3					1			13
WF	New Jersey	34_0903										1			3	3	1	1	3					1			13
WF	New Jersey	34_0960										1		1	3	2	1	1	3					1			13
WF	New Jersey	34_0961										1	1		3	2	1	1	3					1			13

Table 61 (cont'd)

Climate region	State	State code & section ID	Hour of the day																								Total
			00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
WF	New Jersey	34_0962										1		1	3	2	1	1	3					1			13
WF	New York	36_0801								1		2	4	2	2	1	2	9		5	2				1		31
WF	Ohio	39_0901					1		2	2	5	2	5	2	2	3	5	2		1	3	1	1				37
WF	Ontario	87_1622								3	1	2	2	2	4	4	2	4	4	4	1						33
WF	Vermont	50_1002								1	2	2	5	6	2	5	8		3	2	1	3					40
WNF	Alabama	1_0101								2	1	2	1	2	4		2		3								17
WNF	Alabama	1_0102								1		1	4	2	3	1	1	2	2	1							18
WNF	Delaware	10_0102									1	2	1	1	2	2	3	1	2	1							16
WNF	Georgia	13_1005							1	1	4	1	1	2		1	3	1	2								17
WNF	Georgia	13_1031								1	2		3	2	2	2	1	4	6		2						25
WNF	Maryland	24_1634				1		1			2	3	2	3	4	4	3	1		1	1						26
WNF	Mississippi	28_1016								1	4	1	1	2	1	1		2	1								14
WNF	Mississippi	28_1802								1	2	3	3	2	1	1	3	1	1	1	1						20
WNF	North Carolina	37_1028									2	2	2	3	2	2	3	4	4	1							25
WNF	Oklahoma	40_4165									2	4	1	3	4		2	1				1	1			1	20
WNF	Texas	48_1060								1	4	2	2	1		2	1	1					1				15
WNF	Texas	48_1068				1					2	1	3	3	2	2	4	2	1								21
WNF	Texas	48_1077							1		3	1	1	1	2	1	1	1	1			1					14
WNF	Texas	48_1122						1			1	2	2	3	6	5	3	2				1	1				27
WNF	Texas	48_3739	1	1							5	4	3	2	3	1		1	2			2	1				26
WNF	Virginia	51_0113									1	2		4	1	2	4						1				15
WNF	Virginia	51_0114									1	3	1	7	3	5	6	1	1	4		1	1				34

Table 62 Monthly distribution of IRI visit data - SMP PCC sections

Climate region	State	State code & section ID	Month												Total
			1	2	3	4	5	6	7	8	9	10	11	12	
DF	Nevada	32_0204			2	1		4	1	3	2	1	1	3	18
DF	Utah	49_3011	2	1	2	3	5		2	3	5	5	4	4	36
DNF	Arizona	4_0215	7	5	5	4	3		6	3	5	3	5	17	63
DNF	California	6_3042	4	1	8	3	6	1	2	2	2		4	2	35
WF	Indiana	18_3002	1	2	1	5	3		3	4	2	6	2	2	31
WF	Kansas	20_4054	2	3	5	7	4			2	2	3	4		32
WF	Manitoba	83_3802	3	1	1	6	3	5	5	2	3	1	1		31
WF	Minnesota	27_4040	3	1		7		4	4	1	5	3	1		29
WF	Nebraska	31_3018	3	2	9	2	6	4		4	7		5	8	50
WF	New York	36_4018	2	3	1	10		1	3	4		4	1		29
WF	Ohio	39_0204		1	5	1	3	4		5		1	3	3	26
WF	Pennsylvania	42_1606	6	4	4	3	9	2	6	3	5	14	1	1	58
WF	Quebec	89_3015	2	6	3	3	7	6	5	5	7	5	3		52
WF	South Dakota	46_3010					4	1	3	5	1	4	1		19
WNF	Georgia	13_3019	5	3	3	5	5		1	8		6	2	2	40
WNF	North Carolina	37_0201	10	5	3	1	6	2	6	2	2	5	4	2	48
WNF	North Carolina	37_0205	2	2	2		4	1	2		1	3	3		20
WNF	North Carolina	37_0208	2	2	3	2	3	6	2		1	2	6	1	30
WNF	North Carolina	37_0212	2	2	4	2	5	6	2		1	2	6	1	33
WNF	Texas	48_4142	4	2	1	5		1	1	4		4		3	25
WNF	Texas	48_4143	3	1		6		1	1	4		4	1	3	24
WNF	Washington	53_3813	4		2	2	7	3		2	2		3		25

Table 63 Hourly distribution of IRI visit data - SMP PCC sections

Climate region	State	State code & section ID	Hour of the day																								Total
			00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
DF	Nevada	32_0204								1	1	1	3	1	3	6		2									18
DF	Utah	49_3011		1						3	3	3	1	2	6	1	7	3	2	2	1			1			36
DNF	Arizona	4_0215	1		1		3	2	1		3	10	5	4	7	4	9	6	1	1	1		2		2		63
DNF	California	6_3042			1				1	1		6	2	3	2	4	4	2	3	2	2				2		35
WF	Indiana	18_3002							1	3	4		1	4	3	2	4	3	3	2	1						31
WF	Kansas	20_4054						1	4	2	4	1	4	2	3	2	2	5	1		1						32
WF	Manitoba	83_3802				1			1		4	2	1	4	3	4	1	3	3	1	2		1				31
WF	Minnesota	27_4040	1			2		1		2	3	1		4	5		1	1	8								29
WF	Nebraska	31_3018					1	1	7	7	3	3	2	1	4	6	4	10			1						50
WF	New York	36_4018						1		1	5	3	6	1	1	1	5	1	2	1		1					29
WF	Ohio	39_0204				1			5	1	2	2	2	1	3	1	3	5									26
WF	Pennsylvania	42_1606			1				8	6	3	7	3	5	6	7	5	4		1	2						58
WF	Quebec	89_3015							2	2	8	2	2	7	3	9	9	4	3		1						52
WF	South Dakota	46_3010							1		4	1	4	1		1		3	2	2							19
WNF	Georgia	13_3019							1	3	3	6	5	3	5	8	1	1	3	1							40
WNF	North Carolina	37_0201					1	1	6	7	5	4	2	4	1	7	4	2	1	1	2						48
WNF	North Carolina	37_0205						1	1	1	1	2	2	2	3	1	1	1	3		1						20
WNF	North Carolina	37_0208						1	2		1	3	1	1	2	2	5	2	3	3	2	1	1				30
WNF	North Carolina	37_0212						1	2		2	3	2	3	2	2	5	1	3	4	1	1	1				33
WNF	Texas	48_4142								3	4	2	1	5	4	2	1			2			1				25
WNF	Texas	48_4143									6	1	2	2	4	2	3	2	1			1					24
WNF	Washington	53_3813									1	6	2	1		3	1	3	4	1	2	1					25

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