DEVELOPMENT OF A COMPREHENSIVE BACKCALCULATION PROCEDURE FOR RIGID PAVEMENT DESIGN PARAMETERS USING SLAB-EDGE DEFLECTION BASINS

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Samuel Dean Paitich

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Dr. Lev Khazanovich

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DEDICATION

This thesis is dedicated first and foremost to my hardworking parents, Dean and Bridget Paitich. Together, they instilled a strong work ethic and high expectations in me, which have enabled me to achieve my lengthiest of goals. For the imprint they continue to leave on me, along with the support they constantly provide, I am forever grateful. Next, this thesis is dedicated to my younger brother Maximilian Paitich, for never letting me win without a fight during the endless stickball games, ping-pong matches, and ice rink battles, where my grittiness flourished. This thesis is also dedicated to my late, older brother George Paitich, who perished just months before the completion of this thesis. George inspired me to live and work passionately, to persevere (#forthekids), and to have a lot of fun in the process. Lastly, I dedicate a piece of this thesis to every member of my extended Paitich and Greeninger families, of which I'm lucky and thankful to be a part of. I am proud to be the first member of either extended family to attain a Master of Science degree, and with that, I hope to inspire my family members, as well as those beyond my family, to "reach for the stars."

ABSTRACT

Backcalculation of structural parameters for rigid pavements is commonly conducted with falling weight deflectometer (FWD) deflection basins measured at the center of slabs. Although a number of established techniques exist to backcalculate pavement parameters for the slab-center location, a reliable technique to backcalculate such parameters at the neighboring slab-edge location does not exist. The slab-edge location is critical to the design and management of rigid, concrete pavements because high stress levels and early signs of degradation originate at the slab edge.

An edge backcalculation procedure accounting for the load transfer efficiency (LTE) of inter-slab joints is developed in this study. The proposed procedure is based on finite element modeling and dimensional analysis. Testing and validation of the edge backcalculation procedure is performed using FWD basins measured at the slab-edge location of in-situ pavements, along with measured LTEs, via the Long Term Pavement Performance (LTPP) program. Some prospective applications of the new procedure, in conjunction with the LTPP database, are presented. It is shown that the new edge backcalculation procedure is robust and satisfactory, particularly for pavements in good structural condition.

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1 INTRODUCTION

Backcalculation is an inverse analysis procedure used to characterize pavement layer properties of in-situ pavement based on the measured response, or deflection basin, of the pavement to a specified load. This nondestructive evaluation (NDE) technique is well-regarded among researchers, and it enables individuals that design and manage pavement systems to make more prudent decisions in the assessment of pavement conditions for the present and future. For instance, the standard backcalculation output values are used as direct inputs in common pavement design procedures such as the Mechanistic-Empirical Pavement Design Guide (MEPDG) and the American Association of State Highway and Transportation Officials 1993 (AASHTO 93) procedures (NCHRP 2004, AASHTO 2008).

Backcalculation has been in use for over 40 years; however, it is still limited to interpreting only deflection basins recorded at the slab-center location, where the effects of inter-slab joints, slab size, and local edge phenomena like curling are traditionally neglected. The longitudinal, slab-edge location is particularly significant in regards to assessing rigid pavements because pavement degradation typically originates near the edge of the slab where stresses are the highest for standard pavement loading.

Figure 1.1 shows two arbitrarily-selected deflection basins recorded on the same date and within the same slab of a concrete pavement test section in Delaware.

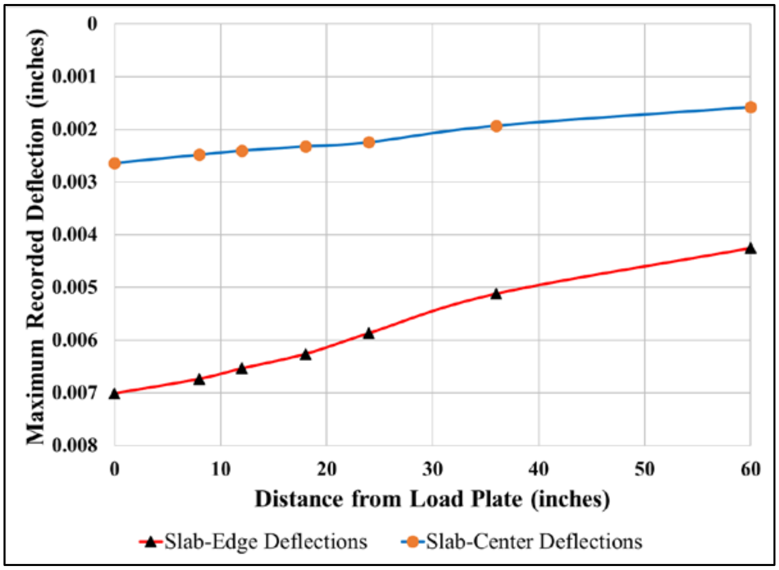

Figure 1.1 - Slab-Edge vs. Slab-Center Deflection Basins from a Pavement Test Section in Delaware (InfoPave™)

One basin was recorded at the traditional slab-center location, and the other was recorded at the slab edge. The same nominal load was applied at each location, but the deflection basins are not similar based on Figure 1.1. Not only do the shapes of the basins vary, but the magnitude of some deflections nearly doubles between the two basins at some locations. Unsurprisingly, the backcalculation results/outputs are equally dissimilar for each case when the conventional backcalculation procedure is applied.

Part of the challenge to conventional backcalculation techniques is that pavement section properties are generally not consistent across the width of the pavement, and the other part of the challenge is that the structural model of existing backcalculation procedures is generally based on an infinitely sized slab with no nearby joints or slab-size effects accounted for. Thanks to the finite element method (FEM), such shortfalls in the existing backcalculation procedure can be overcome. The goal of this study is to improve the prevailing backcalculation procedure by developing a backcalculation procedure for slab-edge deflection basins measured on rigid (concrete) pavements.

The general methodology for developing the new procedure goes as follows: First, using a realistic finite element model, a comprehensive ‘training’ database of artificial, slab-edge deflection basins is created using an FEM modeling software (ISLAB2005). Then, using that database as a reference, an advanced version of the conventional backcalculation interpolation scheme is trained to develop recognition of the correlation between the artificial deflection basins and their associated pavement model properties. Next, the predictive abilities of the trained interpolation scheme are verified using artificial deflection basins that are generated with slight variations of the pavement model properties used in the production of the training database. When a reasonable success rate is achieved upon verifying and troubleshooting the new interpolation scheme, the development of the slab-edge backcalculation procedure is complete.

Further evaluations and analyses are conducted thereafter for this project using real deflection basins from the Long Term Pavement Performance (LTPP) database.
Also for this project, a similar process was completed for deflection basins at the slab-center location in order to compare the backcalculation results between the two locations of interest within the same pavement.

2 LITERATURE REVIEW

Background information presented in this chapter provides context for the development of the rest of the thesis. First, an introduction of the basic tools and concepts required for backcalculation methods is provided. Then, a background on existing backcalculation methodology is presented. After that, more contemporary pavement technology is reviewed before a final review of recent research in the area of slab-edge backcalculation is reviewed.

2.1 TRADITIONAL BACKCALCULATION ANALYSIS TOOLS AND CONCEPTS

The falling weight deflectometer and Westergaard's theory are the fundamental tools used to perform all rigid pavement backcalculations. Background on each of these backcalculation tools is introduced for a general understanding.

2.1.1 FALLING WEIGHT DEFLECTOMETER

A falling weight deflectometer, or FWD, is a device designed to simulate the impact of a truck tire moving at an average highway velocity across a single point on the pavement surface. The impact is imparted on the pavement surface by a circular, steel weight, dropped from a specified height, onto an 11.8-inch (300-millimeter) diameter loading plate. Research tests by Hoffman and Thompson (1982) showed that the FWD is the best available device for simulating the response of pavements to a moving load. The response of each slab is measured by deflectometers (typically geophones) that are placed at pre-designed radial offsets from the center of the loading plate. The deflectometers measure surface deflections over the entire time of loading, but typically, and in this study, only the maximum deflections are considered for backcalculation analyses. The load magnitude, measured by a calibrated spring attached to the loading plate is also recorded for each drop. The maximum deflections measured at each sensor location (termed collectively as the deflection basin), along with the measured load magnitude, for any given drop, are used as the primary inputs for backcalculation. Refer to Figure 1.1 in the introduction for an example of a deflection basin recorded by a falling weight deflectometer.

2.1.2 RIGID PAVEMENT ANALYSIS - WESTERGAARD'S THEORY

The success of a backcalculation program rests on the selection of an appropriate structural model to characterize the pavement. In most instances, the pavement model that is favored by the engineer for forward analyses is the same model chosen for backcalculation. For rigid pavements, the most common choice among researchers is the slab-on-grade, or Westergaard model (Westergaard 1926), illustrated in Figure 2.1.

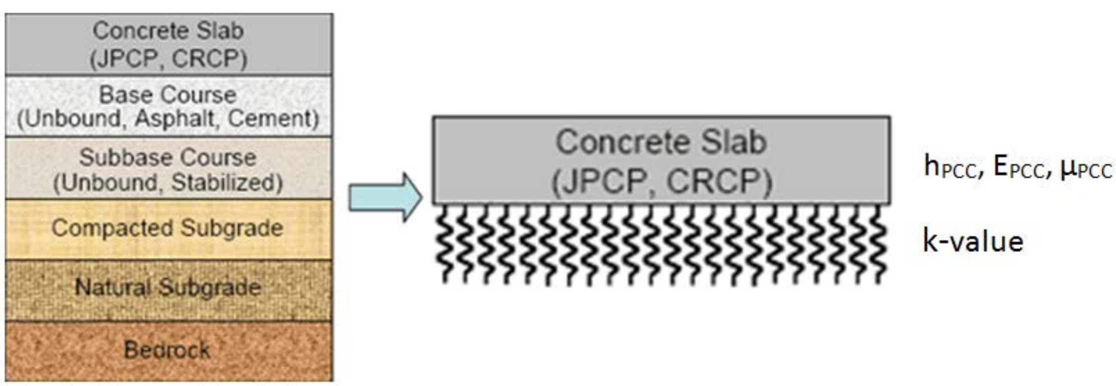

Figure 2.1 - Idealized Westergaard Model for a Conventional Rigid Pavement (Barry, Schwartz and Boudreau 2006)

Note: JPCP denotes Jointed Plain Concrete Pavement

CRCP denotes Continuously Reinforced Concrete Pavement

Both JPCP and CRCP are rigid pavement types, but this study will focus solely on the most common rigid pavement type: JPCP.

This slab-on-grade model condenses ordinary, multi-layered rigid pavements into a slab-on-grade system that consists of only two layers: the surface slab and the underlying foundation layer (see Figure 2.1). The surface slab, which generally represents the Portland Cement Concrete, or PCC, layer is modeled as a homogeneous and linear elastic thin plate in the slab-on-grade model and is characterized by its thickness, h_{PCC}, elastic modulus, E_{PCC}, and Poisson's ratio, μ_{PCC}. Beneath the top layer, the underlying subgrade layer is typically modeled as a Winkler foundation. This layer is characterized by the modulus of subgrade reaction, k. It is important to note that the k-value is not an intrinsic soil property in this model, but rather a pavement system characteristic that defines the stiffness of the effective subgrade layer. Also, the foundation layer can be characterized as either an elastic solid (ES) or a dense liquid (DL) depending on conditions evaluated and the discretion of the engineer.

In almost all instances, real pavements behave in a manner that is between an ES foundation model and a DL foundation model; however, the primary focus of this study is the edge of pavements, so the DL foundation is the most reasonable choice for the purposes of this study. However, like any idealized model, the Westergaard model is limited in its ability to fully characterize real rigid pavements.

Detailed discussions on the limitations of the Westergaard model and suggestions for improvement are available in Ioannides paper (Ioannides 2006). The most noteworthy limitations are that the Westergaard model only considers a single layer above the foundation layer and that it does not account for edge effects from joints, finite slab sizes, or warping effects due to temperature and moisture differentials within the pavement. In spite of wide-ranging efforts to overcome these limitations, there is still not one single approach that successfully integrates all of the shortcoming of the conventional Westergaard model. Westergaard's model is still widely accepted as the most reasonable analysis tool for rigid pavements (Ioannides 2006).

2.2 ESTABLISHED BACKCALCULATION METHODS

The AREA method and the Best-Fit method are the two most prominent methods established to backcalculate deflection basins using analytical equations. A brief background on both methods is presented in this section to provide bases for the selection of the scheme to be used for this research. Lastly, a background on pavement joints is presented.

2.2.1 AREA METHOD

Hoffman and Thompson (1981) proposed the deflection basin "area" concept which combines all of the measured deflections in the basin to compute a basin "area" which is unique to each deflection basin (herein referred to as AREA). The AREA of a deflection basin is the computation of the area under the deflection basin on a vertical plane through the radial axis of the deflection sensors. The AREA is computed by using Simpson's rule and by normalizing all of the deflections with respect to D_0, the deflection measured directly beneath the loading plate, to eliminate the effects of load magnitude. Therefore, the AREA function is dependent on sensor location. In general, the stiffer the pavement, the larger the AREA value. A schematic representing one example of the AREA parameter is shown in Figure 2.2.

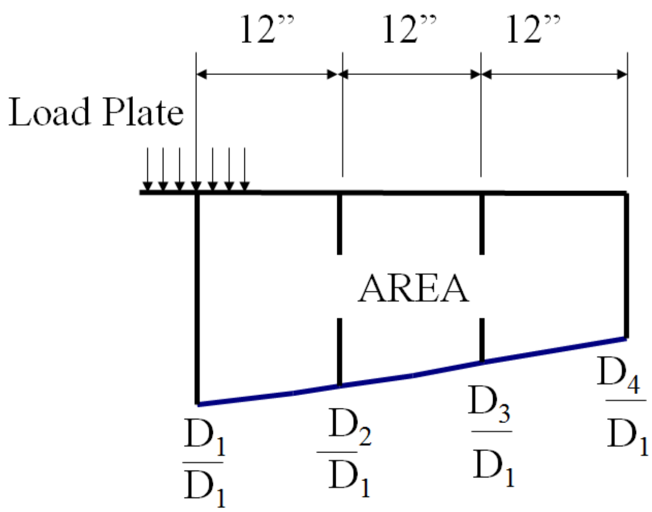

Figure 2.2 - Four-Sensor AREA Parameter Schematic

$$AREA_4\ (inches) = 6 + 12\left(\frac{D_2}{D_1}\right) + 12\left(\frac{D_3}{D_1}\right) + 6\left(\frac{D_4}{D_1}\right) \tag{1}$$

where: 'D_i' is the deflection at the 'i^{th}' sensor location numbered sequentially from the center of the loading plate; and

'$AREA_4$' is the AREA for a basin consisting of 4 total sensors in units of inches.

Figure 2.2 and Equation (1) exhibit an AREA computation for a four-sensor apparatus with uniform sensor spacing.

Hoffman and Thompson (1981) developed the AREA method specifically for flexible pavements. Later research extended the capability of the AREA method to rigid pavements. Ioannides (1990) and Barenberg and Petros (1991) developed closed-form equations to calculate k and E_{PCC} based on the AREA of a deflection basin for rigid pavements. Ioannides (1990) described that for a given value of ‘a/ℓ’, “a unique dimensionless deflection profile is predicted by plate theory,” where ‘a’ is the radius of the loaded area and ‘ℓ’ is the radius of relative stiffness of the slab-subgrade system—a key parameter that characterizes the stiffness of the slab relative to that of the foundation. From this theory, Ioannides proposed that there is a unique relationship between the AREA of a deflection basin of a loaded pavement system and such pavement’s radius of relative stiffness, as long as the radius of the loading plate remains constant. Based on pavement deflection equations developed by Losberg (1961), Ioannides (1990) then developed theoretical deflection equations for interior loading of infinitely-sized concrete pavements with a circular load.

Deflections at any radial distance from the center of the load could be calculated as a function of ‘a/ℓ’ with the newly developed equations. Curve-fitting was used to develop regression equations for the deflection curve of any sensor location to create AREA vs. ℓ charts for a constant circular loading radius. An example is shown in Figure 2.3, where a constant load plate radius of 5.91 inches (150 millimeters) was used for both DL and ES foundation types.

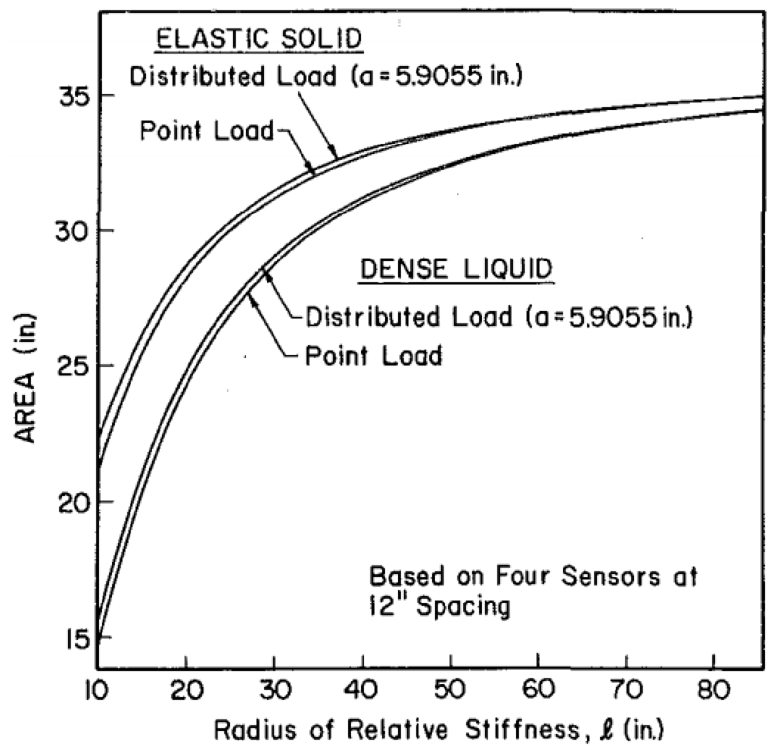

Figure 2.3 - Variation of AREA with ℓ (Ioannides 1990)

The radius of relative stiffness is represented in Equation (2) below:

$$\ell = \sqrt[4]{\frac{D}{k}} \tag{2}$$

where: D is the flexural stiffness of the PCC layer, and
k is the modulus of subgrade reaction.

Using Figure 2.3, the radius of relative stiffness, ℓ, can be determined from the $AREA_4$ parameter. If the radius of relative stiffness is known, then the coefficient of subgrade reaction, k, can be calculated using Westergaard's solution for the maximum deflection under interior loading (Westergaard 1926). Then, using Equation (2), the flexural stiffness, D, of the PCC layer, is computed. For a single-layered slab-on-grade system, D represents the flexural stiffness of the PCC plate and is a function of the Poisson's ratio, thickness, and elastic modulus of the PCC layer as shown in Equation (3).

$$D = \frac{E_{PCC} h_{PCC}^3}{12(1 - \mu_{PCC}^2)} \quad (3)$$

where: E_{PCC} is the elastic modulus of the PCC layer,
h_{PCC} is the thickness of the PCC layer, and
μ_{PCC} is Poisson's ratio of the PCC layer.

If two of the three variables in Equation (3) are known, or estimated, the third unknown variable can be backcalculated. Typically, E_{PCC} is backcalculated because the concrete slab thickness of in-service pavements can be determined from cores and Poisson's ratio of the PCC layer is commonly assumed to equal 0.15.

In an idealized setting, backcalculation requires knowledge of only two deflections to compute ℓ and D. After some experiments, however, Ioannides (1990) concluded that more sensors provide independent verification of the results and fewer potential effects of measurement errors resulting from the FWD test. Also, combining all of the measured deflections minimizes the effect of possible sensor malfunctions, but most importantly, the AREA parameter makes it possible to characterize multi-layered models compared to earlier, single-deflection backcalculation schemes (Hoffman and Thompson 1981). Overall, the AREA procedure yields reasonable results, but the process of using the 'AREA vs. ℓ' charts by hand can be tedious for more than a few deflection basins.

Therefore, Hall (1991) later derived closed-form equations that relate the computed AREA directly to the dense liquid radius of relative stiffness, ℓ, using a nonlinear regression tool. The equations were derived for the interior loading case of Westergaard's solutions and a constant radius of the loading plate.

While the AREA and D_0 values may not be able to fully characterize the complex pavement-subgrade structural behavior for real pavements, the AREA method is a practical backcalculation tool for two-layered theoretical models because of its programmability and reasonable reliability. The AREA method also takes into account multiple deflections, which are easy to measure, and it accommodates the variability present in real pavement systems. In addition, the AREA concept is easily extended to seven-deflection basins to comply with standard FWD practices used today in the United States, especially for Strategic Highway Research Program (SHRP) studies where seven, and more recently nine, different sensors are used to record the pavement response. Albeit, compared to a more recent method, to be described next, the AREA method is relatively restrictive.

2.2.2 BEST-FIT METHOD

The Best-fit method was first introduced by Khazanovich, Tayabji, and Darter (2001). The objective of the Best-fit method is to determine the combination of E_{PCC} and k for which the shape of the calculated deflection basin most closely matches that of the measured, or actual, deflection basin.

The problem is presented first as a minimization of the error function, F, which is the sum of the weighted square difference between the calculated deflections at each sensor position, $w(r_i)$, and the measured surface deflections, W_i, of a given pavement (see Equation (4)).

$$F(E_{PCC}, k) = \sum_{i=0}^{n} a_i (w(r_i) - W_i)^2 \qquad (4)$$

The weighting factors, α_i, can be set to any numbers at the discretion of the user. Often they are set between 0 and 1, or sometimes to $1/W_i^2$. The calculated deflection for every i^{th} sensor in the Best-fit method is generally calculated using Westergaard's solutions (Westergaard 1926), but more sophisticated deflection prediction equations may be used for $w(r_i)$ depending on the desired efficiency of the algorithm and accuracy of the end results.

Equation (5) shows the general form of Westergaard's solution for interior loading, where f_i represents the function of the deflection for offset 'i'. Based on this solution, the deflection at any given sensor is linearly dependent on the magnitude of the drop load (assuming a constant load radius) and the modulus of subgrade reaction. As noted in section 2.2.1, the deflections are also a function of the nondimensional ratios $(\frac{a}{\ell})$ and $(\frac{r_i}{\ell})$.

$$w(r_i) = \frac{p}{k} f_i\left(\frac{a}{\ell}, \frac{r_i}{\ell}\right) \qquad (5)$$

The Westergaard solution for a given load radius and constant configuration of the deflection sensors can be reduced to the form shown in Equation (6), based on nondimensional principles developed by Ioannides (1990). The deflection equation is then solely dependent on the radius of relative stiffness of the slab-subgrade system.

$$w(r_i) = \frac{p}{k} f_i(\ell) \tag{6}$$

Now, the error function shown in Equation (4) can be re-formulated to the form in Equation (7):

$$F(E_{PCC}, k) = F(\ell, k) = \sum_{i=0}^{n} a_i \left(\frac{p}{k} f_i(\ell) - W_i \right)^2 \tag{7}$$

The error function is solved by minimizing the difference between the calculated and measured deflections at each offset, as a whole. In order to calculate the ℓ- and k-values that minimize the error function in Equation (7), the following partial derivatives must be satisfied:

$$\frac{dF}{d\ell} \tag{8}$$

$$\frac{dF}{dk} \tag{9}$$

Plugging Equation (7) into Equations (8) and (9) results in the following independent solutions for the radius of relative stiffness, ℓ and the modulus of subgrade reaction, k, respectively:

$$\frac{\sum_{i=0}^{n} a_i\, f_i(\ell) f_i'(\ell)}{\sum_{i=0}^{n} a_i\, (f_i(\ell))^2} = \frac{\sum_{i=0}^{n} a_i\ \ W_i\, f_i'(\ell)}{\sum_{i=0}^{n} a_i\ \ W_i\, f_i(\ell)} \tag{10}$$

$$k = p\, \frac{\sum_{i=0}^{n} a_i \big(f_i(\ell)\big)^2}{\sum_{i=0}^{n} a_i\ \ W_i\, f_i(\ell)} \tag{11}$$

First, the non-linear equation for ℓ (Equation (10)) is solved. Once ℓ is known, the k-value can be calculated using the closed-form equation shown in Equation (11). After solving for ℓ and k, the elastic modulus of the pavement can be calculated using Equation (3), which is re-written in the following form:

$$E_{PCC} = \frac{\ell^4 k (1 - \mu_{PCC}^2) 12}{h_{PCC}^3} \tag{12}$$

An analysis of the difference in results of backcalculation on real pavement section basins using the AREA and Best-fit methods was performed by Khazanovich, Tayabji, and Darter (2001). The Best-fit procedure is preferred for backcalculation of rigid pavement model parameters with dense liquid foundations and interior loading because it is less sensitive to random measurement errors and has better correspondence between measured and calculated deflection basins. Other advanced methods—such as the database approach first used by Uzan et al. in 1989 (Uzan, Lytton and Germann 1989), the generic approach by Lee et al. in 1998 (Lee, Lee and Bair 1998), and the neural network approach by Ceylan and Gopalakrishnan (2014) — use the same fundamental structural models in their approach, but are better suited to incorporate the effects of finite slab sizes and edges, as is the approach of this project.

The Best-fit method and the AREA method are both based on Westergaard's solutions for interior loading of a PCC slab on a dense liquid foundation. For the sake of this study, the Best-fit method is the most reasonable algorithm to use.

2.3 CONTEMPORARY PAVEMENT ANALYSIS TOOLS AND RESOURCES

A state-of-the-art pavement modeling software and the LTPP database are presented to introduce the reader to relevant tools that were strongly depended on for the research conducted in this study. First and foremost, a description and background on the characterization of pavement joints is provided.

2.3.1 PAVEMENT JOINTS

An actual rigid pavement is not infinite in both horizontal directions; rather it is bounded by contraction joints spaced along the length of the pavement. The contraction, or transverse, joints are typically sawed on the surface of the pavement to a depth of one-fourth to one-third of the PCC thickness. These joints are intended to regulate cracking and alleviate residual stresses caused by expansion and contraction due to surface temperature variations. The spacing of the joints is selected based on the expected thermal expansion of the pavement and the possible resonance effect on vehicles. One of the most important properties of a pavement joint is its ability to transfer load from the loaded slab to the adjacent slab.

Figure 2.4 depicts a general slab layout for concrete pavements, where the lower row of slabs is typically the slab of interest for backcalculation because most truck traffic occurs on this lane.

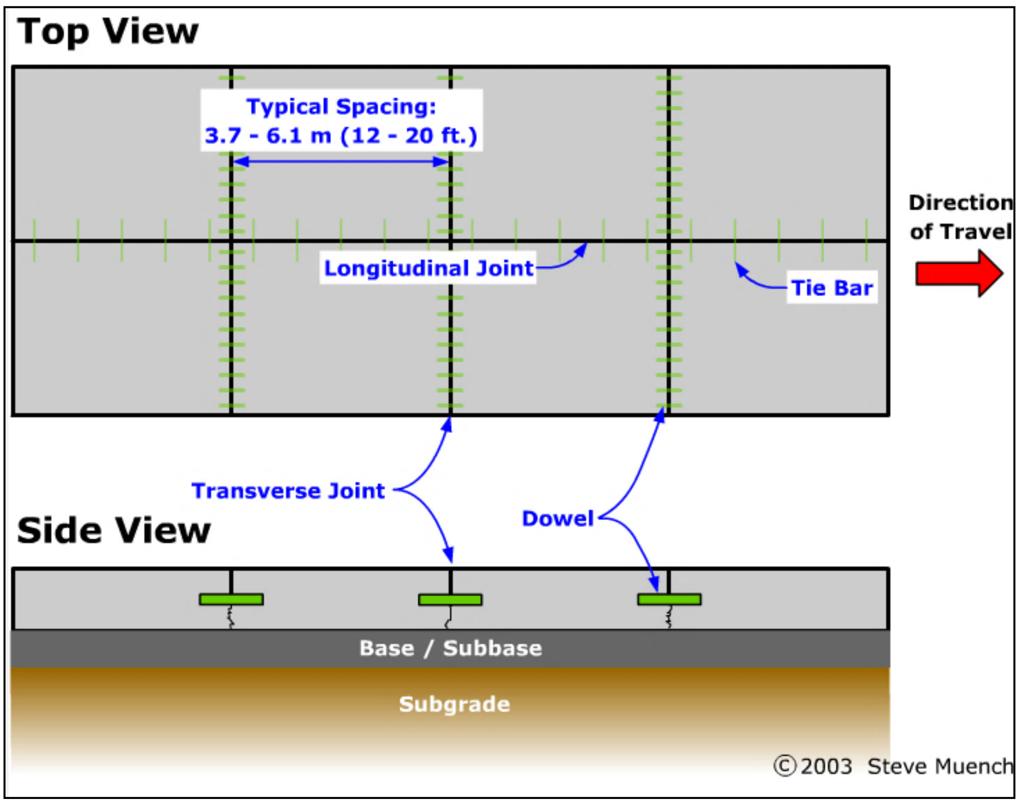

Figure 2.4 - General Layout of a Jointed Plain Concrete (Rigid) Pavement

Joint load transfer efficiency, or LTE, can be measured using a FWD on in-service pavements where the loading plate is typically placed tangent to the edge of the pavement, halfway between the longitudinal joints. The maximum deflection beneath the loading plate represents the loaded-slab deflection and the maximum deflection measured on the adjacent slab the same distance away from the joint represents the unloaded-slab deflection. The amount that the unloaded slab deflects compared to the loaded slab is a direct measurement of the load transfer efficiency of the joint, as shown in Equation (13):

$$LTE\ (\%) = \frac{\delta_u}{\delta_l} * 100 \tag{13}$$

where: δ_u = the deflection of the unloaded slab, and
δ_l = the deflection of the loaded slab.

If a joint is performing well, the unloaded slab deflection is expected to match the loaded slab deflection and the LTE is close to 100%. If a joint is damaged or poorly constructed, the unloaded slab would be expected to deflect much less than the loaded slab and, consequently, the LTE would be lower.

Load transfer efficiency measured along the length of the joint is generally consistent as shown by Foxworthy and Darter (1986). However, in some cases, the LTE falls off dramatically near the corners due to loss of base support and/or curling of the concrete slab, which occurs when there are temperature differentials between the top and bottom of the PCC slab (Foxworthy and Darter 1986). Changes in temperature can also cause steep drops and rises in LTE along a joint due to the contraction and expansion of the pavement slabs. In such a case, the effect of temperature could be significant when predicting or measuring load transfer across a contraction joint. More subtle influences include the base type, saw depth, and age of the joint, but such matters are outside of the scope of this study.

The LTE measurement is considered in this study because it has a profound effect on rigid pavement performance. In particular, the level of load transfer efficiency of the surrounding joints of a slab can affect the shape of the deflection basin depending on where the load is located. This parameter has not been fully incorporated by past edge backcalculation studies. For this study, temperature effects will not be accounted for and the LTE will be assumed constant across the length of the joint, an assumption driven primarily by the capabilities of the pavement analysis software used in this study. The software and its capabilities are described next.

2.3.2 ISLAB2005

The finite element pavement analysis program chosen for this study is ISLAB2005 (Khazanovich, Shats, et al. 2005), which provides invaluable accuracy in negligible amounts of time and is fully capable of modeling the pavement as the preferred Westergaard model of a slab-on-grade pavement system.

In ISLAB2005, the foundation layer is idealized as the Winkler finite element foundation with an equivalent stiffness matrix to account for the mesh of springs in between the two ends of the slabs, or nodes. The equivalent stiffness matrix is visually represented by the vertical and rotational springs shown at the nodes in Figure 2.5.

Figure 2.5 - ISLAB2005 Winkler Foundation Schematic

“The stiffness of these springs is defined based on the equality of potential energy of their deformation and deformation of the original DL model,” as described by the authors of the computer program (Khazanovich, Shats, et al. 2005). The foundation layer is characterized in ISLAB2005 by one variable: the k-value, as was introduced earlier in this chapter. Likewise, the surface PCC layer is also modeled using the basic parameters discussed in the introduction.

One reason ISLAB2005 is advantageous in this study is because the program is capable of incorporating the LTE parameter. LTE can be input directly in ISLAB2005 in any value between 0% and 100%, so that sensitivity analyses for the LTE can be conducted or field measurements can be input directly. Although it can only incorporate LTE as a constant value across the entire length of the joint, ISLAB2005’s assimilation of LTE extends the capabilities of forward calculations and, subsequently, backcalculations. ISLAB2005 is also advantageous due to its high level of accuracy, speed, and robustness compared to traditional methods.

The program does have some limitations. First, ISLAB2005 is only capable of applying static loads to the surface of the pavement. Khazanovich (2000) performed a study to determine the effects of a dynamic FWD load modeled as a static load in analysis programs. Khazanovich found some potentially significant effects, but for the sake of this study, those effects will not be considered because of the complex nature of modeling dynamic loads in ISLAB2005 or any available rigid pavement analysis program.

There are additional limitations of ISLAB2005. It is limited to joints with zero skew. In real pavements, designers sometimes choose to angle the joint from perpendicular to the direction of traffic to a slight skew. ISLAB2005 is only capable of modeling joints that are parallel (longitudinal joints) and perpendicular (perpendicular joints) to the direction of traffic. This is a potential shortcoming for the backcalculation of non-conventional pavements with skewed joints. Also, ISLAB2005 cannot account for pavement cracking, which is common in aged rigid pavements. This, too, may limit the backcalculation of real pavements to those without major defects. Lastly, the loading surface shape in ISLAB2005 analyses is square, to represent the circular FWD loading plate; however, the effects of using a square shape, with a surface area equal to the corresponding circular load, are negligible for the sake of rigid pavement analysis (Timoshenko and Woinowsky-Krieger 1959).

2.3.3 LTPP DATABASE

The Long Term Pavement Performance (LTPP) program is a large research project sponsored by the Federal Highway Administration that includes various studies to investigate specific pavement related details that are critical to pavement performance (Federal Highway Administration 2015). In recent years, access to the database has been extended to internet users around the world through LTPP InfoPave™. As it pertains to this thesis, LTPP InfoPave™ provides data on deflection basins from pavement test sections located throughout the U.S. and Canada. To ensure that the quality of the deflection basins is sufficient, this study focuses mainly on the Specific Pavement Studies (SPS) experiments for FWD results, specifically the SPS-2 experiment.

The SPS-2 experiment, titled 'Strategic Study of Structural Factors for Rigid Pavements' is described per the LTPP website (Federal Highway Administration 2015) as follows:

SPS-2 examines the effects of climatic region, subgrade soil (fine- and coarse-grained), and traffic rate (as a covariate) on doweled jointed plain concrete pavement (JPCP) sections incorporating different levels of structural factors. These factors include drainage (presence or lack of it), concrete thickness (203 mm and 279 mm), base type (dense-graded aggregate and lean concrete), concrete flexural strength (3.79 and 6.21 MPa at 14 days), and lane width (3.9 m and 4.6 m). The study requires that all test sections be constructed with perpendicular joints at 4.9 m spacing and stipulate a traffic load level in the lane in excess of 200,000 ESALs per year.

The quality control and quality assurance associated with SPS experiments are comparatively higher than that of other experiments; therefore, the deflection basins used for this study are considered to be particularly reliable. There are multiple SPS-2 test sections located in 14 different states in the U.S., and each section has a FWD test performed on it in regular intervals throughout the year. Also, each pavement section is unique in structure and is identified by a Strategic Highway Research Program (SHRP) number and state code. The standard LTPP FWD testing plan is illustrated in Figure 2.6 and described next.

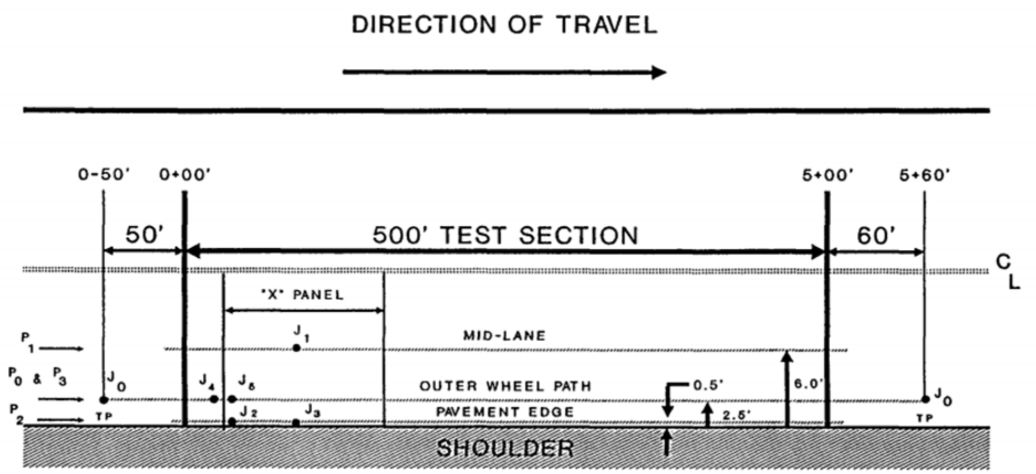

Figure 2.6 - Schematic of Typical LTPP FWD Testing Locations (Shmalzer 2006)

Figure 2.6 shows the testing points for a typical ‘X’ panel, or slab, from the LTPP FWD manual (Shmalzer 2006). The J1 position (on the Mid-lane line) shown in the schematic represents the slab-center loading position, and the J3 position (on the Pavement Edge line) represents the slab-edge loading position. It is the J4 and J5 positions, which are tested on every test slab, that return the pertinent LTE values for this process. The SPS-2 test provides copious amounts of data for both the slab-center and slab-edge locations. This thesis makes use of data from the SPS-2 test.

2.4 RELATED RESEARCH

Previous studies conducted to determine the structural model parameters at the edge of pavements are summarized in this section. As of the time of this study, the majority of research in this area has been focused on determining the most accurate backcalculation method. Recently, some research has been directed towards extending the capabilities of specific backcalculation methods with respect to locations other than the center of the pavement.

2.4.1 WESTERGAARD FREE-EDGE LOADING BACKCALCULATION

A study by Uzan et al. (Uzan, Briggs and Scullion 1992) was the first of its kind because it was the first time that deflection basins measured at the edge of the pavement were considered for backcalculation. In their study, Uzan et al. adapted a previously developed program called MODULUS (Scullion and Michalak 1991) to backcalculate the E_{PCC} and k-values for the center and free-edge loading conditions.

The MODULUS program uses a two-step process. In the first step, a linear elastic program is run for varying values of layer moduli and resulting deflections are stored in a deflection database. In the second step, a pattern search and interpolation scheme is used to provide analytical solutions in order to minimize the error between measured and predicted deflection basins. The linear elastic program used to predict deflection basins was based on Westergaard's "free-edge" solutions integrated over a circular loading area, which is described by Uzan and Sides (1987) in a previous study for a semi-infinite slab resting on a dense liquid foundation. The "free-edge" condition does not consider the effects of adjacent slabs, cracks or slab shape. Therefore, the effect of load transfer characteristics was not included in the evaluation because "the problem becomes too complicated for standard backcalculation procedures" (Uzan and Sides 1987).

A 10x10 factorial of ℓ- and k-values ranging from 10-140 inches and 25-1,500 psi/in., respectively, was used to build the deflection database to represent the extent of practical values seen in rigid pavements. To evaluate the backcalculation procedure, FWD deflection data from the Strategic Highway Research Program (SHRP) were processed on five study sections in Texas with varying thickness, base types, and joint spacing.

Results from the in-service pavement analyses show that for the Westergaard model, the backcalculated modulus of subgrade reaction at the edge is two to four times higher than that obtained from the center slab deflection basins. The results also showed that the average error per sensor between computed and measured deflections at the edge varied from 2-5% for the Westergaard model, which was higher than error percentages obtained from the slab-center deflection basin evaluations.

At the time, the backcalculation approach used by Uzan et al. in this study was one-of-a-kind in terms of the factorial used to create the deflection database (100 basins) and because they were the first to attempt to match measured field deflections at the edge to predicted deflections at the edge. This concept was also first of its kind because it was the first to incorporate edge conditions. However, the reliability of the results was low due to the lack of a sophisticated pavement model to incorporate the real behavior of a pavement near adjacent slabs and joints. Also, four out of the five test sections analyzed had stabilized base layers. Non-stabilized base layers are expected to yield more accurate backcalculation results due to the inherent characteristics of the slab-on-grade model, which assumes the slab is much stiffer than the subgrade layer. The study (Uzan, Briggs and Scullion 1992) was sound but limited by the lack of computer processing power at the time of the study.

2.4.2 INCORPORATING EDGE EFFECTS WITH ILLI-SLAB

James Crovetti was a pioneer in regards to incorporating edge effects into the backcalculation of pavement properties at the slab-edge location. Crovetti's initial approach was limited to the determination of only the foundation support parameter, k (Crovetti 1994). In that study, he proposed one deflection measurement, the maximum edge deflection under the center of a tangentially loaded plate, to be the only input for backcalculating the k-value at the edge of the pavement (k_e).

Crovetti used Westergaard's equations from 1948 to calculate the maximum edge deflection expected directly under a circular loading plate tangential to the "free edge" of the pavement (Westergaard 1948). To determine the k-value for the slab-edge location (k_e) based on such conditions and for a chosen load plate radius, Crovetti used empirical principles. Later on, Crovetti also proposed correction factors in his paper to address slab size effects for rectangular slabs of typical field dimensions. The correction factors were a function of 'L/ℓ' where L represents the slab length ratio. In summary, his study addressed the backcalculation of the foundation parameter k_e by using one measured deflection and assuming the slab stiffness at the interior was the same at the edge. In reality, the thickness of the PCC layer, which directly affects pavement stiffness, may vary noticeably from the interior location to the edge location.

In a later study, Crovetti extended his original work with edge deflections and slab size correction factors to additionally incorporate the effect of joint characteristics based on field-measured joint parameters (Crovetti 2002). The field parameter that was measured for this study is a sum of the unloaded- to loaded-slab deflections across a joint, named the total edge deflection.

Based on separate analyses using a pavement analysis program called ILLI-SLAB, Crovetti determined that the total edge deflection essentially remains constant and equal to actual edge deflections for variable levels of load transfer across joints. Crovetti suggests using the total edge deflection parameter in place of the actual edge deflection in his 1994 paper; however, he suggested the use of a correction factor (developed from regression analyses) to adjust the total edge deflection value before using it to calculate an adjusted k_e-value. The correction factor is a function of the ratio of the effective slab length to the radius of relative stiffness. The calculation for the adjusted k-value at the pavement edge, k_{e-adj}, was reduced to a single equation by Crovetti.

These concepts were applied to field pavements, but because the primary purpose of testing was to determine the uniformity of support beneath the slab at three different locations, the accuracy of the proposed formulations, in terms of expected or measured field results, was never widely validated.

The results of research on total edge deflection values by Crovetti suggest that the deflection of the unloaded slab across a joint is relatively small in most cases because he described that the total edge deflection is constant and equal to the edge deflection of the loaded slab. This would mean that the ability of the joint to transfer load across the joint is not effective. This is contrary to real pavements which typically contain joints that effectively transfer loads from one adjacent slab to the other.

Regardless, Crovetti made a reasonable effort to recognize the joint as an important component of edge backcalculation using the total edge deflection measurements as an input. His method, like Uzan's still relied on regression analyses and the assumption of equivalent slab bending stiffness for interior and edge, however. The concepts presented in Crovetti's paper are principally based on Westergaard's solutions from 1948, as well. In summary, Crovetti used one slab-center deflection to predict slab-edge properties and eventually advanced his methodology to account for load transfer characteristics at the slab-edge.

More recent efforts were made by Liu and Fwa (2007) to develop closed-form deflection equations for the edge of the pavement with more realistic slab groupings and joint effects; however, such equations became obsolete over time due to the robust, numerical solutions provided by the advent of finite element (FE) analysis tools.

3 DEVELOPMENT METHODOLOGY

Based on the review of past studies, it is evident that there is a lack of analytically-derived, closed-form equations to predict edge deflections that account for the variable conditions present in pavement slabs such as slab size, slab shapes and grouping, and load transfer characteristics of joints. Most of these properties have not been considered in the past due to the lack of research and relative insufficient computing capacity. A new edge backcalculation procedure is developed.

3.1 ASSEMBLING THE ARTIFICIAL DEFLECTION BASIN (TRAINING) DATABASE

The first step in developing the edge backcalculation procedure was assembling a robust directory or database of artificial deflection basins to 'train' the pattern search and interpolation scheme. A robust database is one that contains enough deflection basins to envelop all of the reasonable deflection basins that could be recorded in the field. Additionally, it should not be too dense as to clutter the efficiency of the mathematical process involved. Through dimensional analysis, a reasonable factorial of training cases (as opposed to an immense, full factorial) was designed and subsequently implemented using the finite element program ISLAB2005.

3.1.1 ESTABLISH TRAINING CASE CONSTANTS IN ISLAB2005

In this sub-step, the non-variable design parameters for the finite element model were selected for the formation of the training database. The goal of this step was to create a base model in ISLAB2005 that simulated the most common pavement configurations and

FWD testing specifications through the selection of slab configuration parameters, loading conditions, and standard FEM modeling practice.

3.1.1.1 Pavement Slab Plan Configuration

The base training case model for ISLAB2005 was designed with multiple slabs to simulate realistic pavement conditions consistent with those from a typical two-lane highway with a shoulder. The base model consists of nine slabs with transverse and longitudinal joints between the slabs at defined intervals of spacing. The slab of interest for this research is the middle slab in the outside lane where heavy truck traffic is usually present and where normal FWD testing is completed. Each driving lane is a standard twelve feet in width and the shoulder is eight feet in width, both standard widths. All of the transverse joints are assigned one LTE value, LTE_y, and the all of the longitudinal joints are assigned one LTE value, LTE_x, across the entire model. The LTE parameter is a variable in each training case; therefore, selection of a constant value was not necessary for the base model. Refer to Figure 3.1 below for an illustration of the base model configuration.

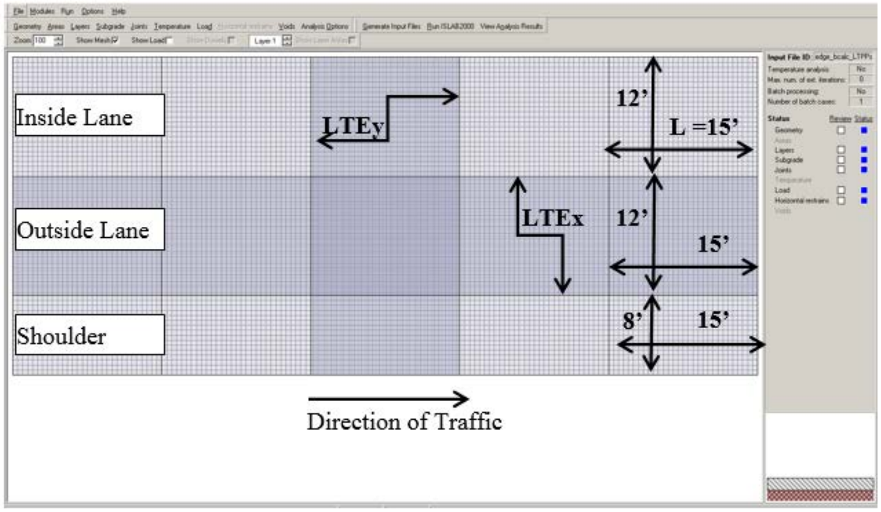

Figure 3.1 - ISLAB2005 Base Model Plan Configuration

3.1.1.2 Pavement Slab Cross-Section Configuration

First, the surface layer was modeled as a PCC layer with plate elements and a constant thickness and Poisson's ratio of ten inches and 0.15, respectively. All other ISLAB2005 defaults were not changed in regards to the unit weight of the slab or the coefficient of thermal expansion because these values are within reason for typical concrete pavements and represent the values chosen after credible research to develop ISLAB2005 (Khazanovich, Shats, et al. 2005). The elastic modulus of the model slab is another variable factor used to establish the training factorial, as will be described in sub-section 3.1.2. The k-value, for the semi-infinitely modeled foundation layer, is constant at 100 psi/in. for the base model.

3.1.1.3 Loading Configuration and Positioning

The static load was modeled as a square shape of constant dimensions for all training cases. The side length of the load shape, a, was 10.47 inches (26.6 cm) which makes the loading surface area equal to 109.56 in.^{2} (706.64 cm^2) which is equivalent to the 30-inch diameter FWD loading plate used in FWD field testing. ISLAB2005 requires users to set the square area by choosing a “tire” or contact pressure, and load magnitude. A load magnitude of 9,000 pounds was chosen because that is one of three standard load magnitudes used in FWD testing. The ‘tire pressure’ input was adjusted accordingly in ISLAB2005 to simulate this load magnitude for the adjusted loading surface area.

The center slab, or slab of interest is the only slab that is subjected to the simulated FWD load. The load location within the slab for edge testing was selected based on the common procedure that is used for the Long Term Pavement Performance program. The center of the loading apparatus is typically placed six inches from the longitudinal shoulder joint towards the centerline of the pavement, halfway between the adjacent transverse joints. Ideally, the edge of the loading apparatus is tangent to the longitudinal edge of the pavement.

Figure 3.2 shows a plan view of the edge loading configuration for with seven dots extending radially from the square loading area to represent the FWD, seven-sensor apparatus.

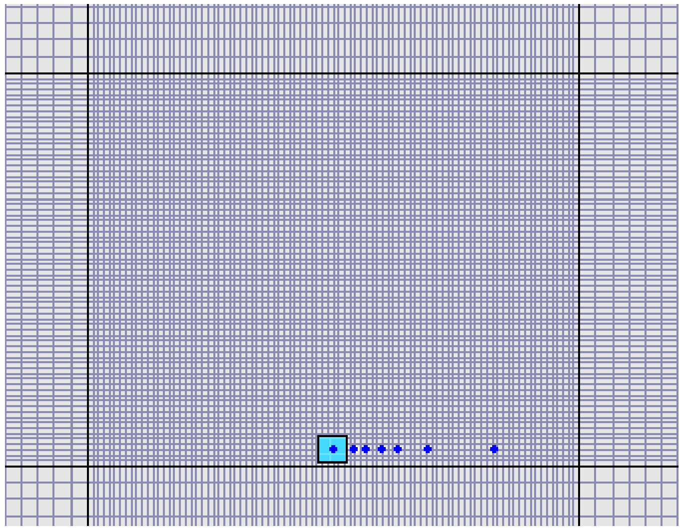

Figure 3.2 - Central Slab Close-Up for Edge Loading Position and Deflection Sensor Offsets

3.1.1.4 Establishing Deflection Basin Node Locations

The small dots in Figure 3.2 represent the location on the surface for each point at which the deflection value is extracted from the output for the training cases. There are seven different 'sensor' offsets in total and each sensor is named sequentially as D_1, D_2, D_3, D_4, D_5, D_6, and D_7, starting from the first sensor located directly beneath the center of the loading plate. The offsets are constant starting at 0 inches for D_1, and extending to 8, 12 18, 24, 36, and 60 inches, respectively. These sensor offsets were chosen based on the typical offsets that are used in the Long Term Pavement Performance program procedure for FWD testing.

Simulating the Long Term Pavement Performance's procedures allows the training cases to be compatible with in-service pavement testing. The locations of the sensors in the nine-sensor arrangement are a repeat of the locations from the seven-sensor configuration except it has two additional sensors at new locations. A seven-sensor configuration was chosen over the relatively new nine-sensor configuration because incorporating the two, new sensor locations would limit the user to vast amounts of data recorded with the conventional seven-sensor apparatus. The finite element mesh size is addressed next to wrap up the base model description section.

3.1.1.5 Finite Element Mesh Sensitivity Test

The finite element mesh size varies across the entire array of pavement slabs. The size of the finite element mesh was chosen based on preliminary analyses conducted on the time-to-accuracy ratio for the central slab deflections. For sensitivity analyses, the program produced deflection outputs near a center-slab load of FWD proportions for a mesh size of one, two, and four inches square, nominally. The deflections measured at pre-determined distances from the load center for the one- and two-inch mesh matched while the four-inch mesh produced results that varied from the smaller nominal mesh sizes. From this outcome, it was determined that a square, two-inch nominal mesh size would be used over the central slab of interest. This allows sufficient accuracy in a reasonable analysis time and it allows the extraction of output deflections from every two inches from the center of the load, which is sufficient for the deflection layout prescribed in the last sub-section.

The central slab of interest has the darkest tone, as depicted in Figure 3.1, because of the overlapping two-inch mesh coordinates from the central row and column. A nominal, square mesh size of six inches was selected for all slabs outside of the central row and column to save computational time for the response of less critical slabs. With that, the creation of the training case base model was complete.

3.1.2 DESIGN FACTORIAL FOR THE ARTIFICIAL DEFLECTION BASIN DATABASE

In order to stock the reference database of artificial deflections, a set of forward calculations, or simulations, had to be prescribed and produced in ISLAB2005. In this section, the design variables and factorial used to create each unique deflection basin in the database are described and justified.

3.1.2.1 Independent Design Factors

In this study, the principles of dimensional analysis was used to reduce the size of the factorial for the training cases and therefore reduce the amount of training cases that need to be simulated in ISLAB2005 to develop the desired regression equations. As Ioannides pointed out in his 1990 paper, pavement deflection is solely a function of the radius of relative stiffness of the slab-subgrade system so long as the location of the deflection, the radius of the load, and the length of the pavement remain constant (Ioannides 1990). The same concepts will be applied in this study; however, the deflection at a given point will not only be a function of the radius of relative stiffness in this study, but of the LTE of the transverse and longitudinal joints as well, which are independent of one another. Therefore, the three independent factors of design are the radius of relative stiffness of the entire pavement system, ℓ, LTE_x, and LTE_y.

The elastic modulus of the PCC layer can be used as the primary variable input to vary ℓ across the desired factorial range based on the relationship between E_{PCC} and ℓ as long as the thickness of the PCC layer is constant throughout all training cases. This relationship is derived from Equations (2) and (3) and shown in Equation (14):

$$\ell = \sqrt[4]{\frac{E_{PCC} h_{PCC}^3}{12(1 - \mu_{PCC}^2)k}} \tag{14}$$

where: E_{PCC} is the elastic modulus of the PCC layer,
h_{PCC} is the thickness of the PCC layer, and
μ_{PCC} is Poisson's ratio of the PCC layer.

3.1.2.2 Factorial Design

The goal of the factorial design is to reduce the number of runs from thousands, for a full factorial, to hundreds by incorporating dimensional analysis. For this study, a range of ℓ-values from 20 to 60 inches (50.8 to 127 cm) was chosen for the factorial design because this range represents a realistic range of stiffness values for typical rigid pavements. To produce this range, a range of E_{PCC} values from 150,000 to 16,000,000 psi (1,034,100 to 110,304,000 kPa) were used for individual simulations. The range of E_{PCC} values for this factorial does not represent the true range of concrete pavement stiffness values measured in the field, but as stated, the pavement response is strictly dependent on the radius of relative stiffness of the pavement. An array of E_{PCC} values were selected to complete the factorial with a uniform spread of ℓ-values for the training cases. Next, a factorial of LTE_x and LTE_y values was chosen.

Real data was researched to effectively account for the entire spectrum of LTE values typically associated with rigid pavements, Based on stored data in the MON_DEFL_LTE table from the LTPP database (InfoPave™), the range of LTE values for both the longitudinal and transverse joints was chosen as 10% to 90%. The LTE factorial for both joint types was distributed from 10 to 90% over 10% increments because the reliability of measured LTE values for real pavements is generally on the order of ten across an entire joint of a slab. In total, the training factorial consisted of thirty-one different values of E_{PCC}, nine different values of LTE_x, and nine different values of LTE_y. Combining these values results in 2,511 unique training cases. Such a factorial can be simulated all at once using the batch mode function incorporated into ISLAB2005. For a complete list of the E_{PCC}, LTE_x, and LTE_y values used for the training cases and the computed ℓ-value associated with each simulation, see Table 3.1 below, where ℓ_{calc} represents the ℓ-value computed using the model constants and each respective value of E_{PCC} in Equation (14).

Table 3.1 - List of Design Factorial Values for the Training Database

E_{PCC}	ℓ_{calc}	LTE_x	LTE_y
150,000	18.91	10	10
200,000	20.32	20	20
300,000	22.49	30	30
400,000	24.17	40	40
600,000	26.74	50	50
800,000	28.74	60	60
1,000,000	30.39	70	70
1,200,000	31.80	80	80
1,400,000	33.05	90	90
1,600,000	34.17		
1,800,000	35.20		
2,000,000	36.14		
2,250,000	37.22		
2,500,000	38.21		
2,750,000	39.13		
3,000,000	39.99		
3,500,000	41.56		
4,000,000	42.97		
4,500,000	44.26		
5,000,000	45.44		
6,000,000	47.56		
7,000,000	49.43		
8,000,000	51.10		
9,000,000	52.63		
10,000,000	54.04		
11,000,000	55.34		
12,000,000	56.55		
13,000,000	57.70		
14,000,000	58.78		
15,000,000	59.80		
16,000,000	60.77		
Total: 31		9	9

The deflection at each FWD deflectometer location is captured to record the deflection basin for each trial of the factorial and then these basins are stored in the artificial deflection basin database, each one defined by its unique set of independent factors.

3.2 DERIVING THE MODIFIED BEST-FIT METHOD

A modified Best-fit method was developed to determine which combination of ℓ_e and k_e minimizes the difference between measured and computed deflections at the edge of a pavement, where ℓ_e and k_e represent the radius of relative stiffness and coefficient of subgrade reaction for the edge of the pavement, respectively. Three additional nondimensional variables are considered to improve on previous Best-fit methods to backcalculate edge parameters. The traditional Best-fit method establishes an error function that is the sum of the weighted square errors between measured deflections, W_i, and computed deflections, $w(r_i)$, as described in the literature review (Section 2.2.2). The computed deflections at a given radial distance, r_i, from the center of the circular load plate were presented as a product of the ratio of supplied pressure to the coefficient of subgrade reaction to and the function of dimensionless variables shown in Equation (15):

$$w(r_i) = \frac{p}{k} f_i\left(\frac{a}{\ell}, \frac{r_i}{\ell}\right) \tag{15}$$

The deflection functions were typically developed by regression analyses of Westergaard's solutions, integration methods, or more recently, of numerical simulations for deflections. For the modified Best-fit method, only the function of dimensionless variables, f_i, is modified to account for three additional nondimensional variables. The new function, g_i, takes the form shown in the modified deflection equation (16):

$$w(r_i) = \frac{p}{k} g_i \left(\frac{a}{\ell}, \frac{r_i}{\ell}, \frac{\mathrm{L}}{\ell}, LTE_x, LTE_y \right) \tag{16}$$

where $LTE_x =$ the load transfer efficiency of the longitudinal joints surrounding the slab of interest;

$LTE_y =$ the load transfer efficiency of the transverse joints surrounding the slab of interest; and,

$L =$ slab length

No closed-form analytical solutions or reliable integration techniques are currently available to account for the additional slab size components or edge characteristics presented. Thanks to the finite element method, these parameters are much more easily accounted for.

The new function for a deflection at any given radial offset from the load center, $g(r_i)$, can be expressed as shown in Equation (17):

$$g(r_i) = \frac{kw_i(\ell, LTE_x, LTE_y)}{p} \tag{17}$$

With this function, the deflection basin for any set of loading conditions can be predicted based on numerical solutions without direct computation with ISLAB2005. Dividing the solution for one sensor location by the solution of another sensor location eliminates the effect of the k-value and the load surface pressure as shown in Equation 18:

$$\frac{g(r_i)}{g(r_j)} = \frac{w_i(\ell, LTE_x, LTE_y)}{w_j(\ell, LTE_x, LTE_y)} \quad (18)$$

The shape of the deflection basin is now a function of only the three parameters: ℓ, LTE_x, and LTE_y. The same steps from the original Best-fit method can be applied to the modified equations.

While the LTE_y (transverse) value is measured in the field during standard FWD test passes, the LTE_x value is backcalculated using the same minimization principles from the original Best-fit method. LTE_y is a fixed input, and the algorithm searches for an LTE_x value that minimizes the difference between the best fitting k_e- and ℓ_e-values that are backcalculated simultaneously. This addition to the backcalculation procedure adds some complexity, but makes the backcalculation solution more robust and adds negligible time to the computation.

To test the interpolation scheme used in this study, artificial data was created in ISLAB2005 using the same base model with different factorial values to create intermediate deflection basins.

3.3 BACKCALCULATION PROCEDURE

A new backcalculation computer program was developed using FORTRAN. The new program accepts the input deflection basin and FWD load along with LTE_y and the concrete layer parameters, h_{PCC} and μ_{PCC}. The program then returns the resultant k_e and l_e

values, the LTE_x (shoulder load transfer efficiency), and the ratio of the measured deflection at each node versus the calculated deflection for the given outputs. An effective error value is also returned, which is a measure of the difference between the measured deflections, as a whole, and the calculated deflections. Table 3.2 and Table 3.3 illustrate the inputs and outputs, respectively, of the FORTRAN program.

Table 3.2 - Slab-Edge Backcalculation Input Format

P	LTE_y	Measured Deflections (in.)						
(lbs.)	(%)	D1	D2	D3	D4	D5	D6	D7

Table 3.3 - Slab-Edge Backcalculation Output Format

Basin	ℓe	ke	LTE_x	Eff. Error	D_{calc}/D_{meas}						
(-)	(in.)	(psi/in.)		(-)	D1	D2	D3	D4	D5	D6	D7

The details of development of the slab-edge backcalculation have been presented thus far.

3.4 VERIFYING THE NEW ALGORITHM WITH ARTIFICIAL DEFLECTION BASINS

One of the most important steps in producing a reliable procedure is testing the procedure. Testing was done using ambiguous test cases built upon artificial deflection basins created in the same FEM program used to develop the program. The goal of testing the backcalculation algorithm with artificial data is to verify whether the interpolation scheme is working as expected under controlled conditions. Effectively, the same model that was used to develop the training basins was used to create the testing basins. No single testing case will exactly match the conditions of any training case.

3.4.1 METHODOLOGY

Verification of the newly developed procedure is completed through comparisons of the backcalculated E_{PCC} and k-values and the input E_{PCC} and k-values for artificially-created deflection basins created using ISLAB2005. Each artificially-created deflection basin is backcalculated per the procedure outlined in in the previous sub-section with the input LTE_y matching the value that was used to create each deflection basin. Troubleshooting is performed as necessary to resolve when the backcalculated properties of the artificial pavement are not closely matching the properties used to create each associated deflection basin with ISLAB2005. The new procedure is considered to be performing as expected when the results for each case are closely matching.

A new database of artificial deflection basins was created to verify the new procedure. The deflection basins created for the verification test cases are generated with almost identical pavement plan configuration and material properties, outside of the independent factors used in the factorial design for the training cases. The one exception is the thickness of the pavement. The thickness of the pavement is set to nine inches to evaluate the ability of the new procedure in backcalculating the correct results with a pavement thickness varying from that of the base training cases. There were two primary test cases conducted for this study. The other unique properties of each of the test cases are described in detail next.

3.4.1.1 Verification Test Case 1 Description

The purpose of Test Case 1 is to verify that the new procedure can correctly backcalculate E_{PCC} and the k-value of a controlled pavement system for deflection basins created using the same computer program with varying values of k and pre-determined values of LTE for both joints that are the same as the ones used in the training cases. The elastic modulus of the surface layer was chosen as 4,000,000 psi at random from the list of E_{PCC} used to create the training cases. The k-value, which was constant throughout the training cases at 100 psi/in., was varied across 17 different test cases from 100 to 500 psi/in. which is an expected range of k-values for real pavements. LTE_y and LTE_x were chosen as 50% and 30%, respectively, which also were used in creating the training case database. Table 3.4 summarizes each of the independent factors that were varied for this test and Figure 3.3 shows the distribution of the resulting deflection basins created from ISLAB2005. It should be noted that $'\ell_{result}'$ is the radius of stiffness of the pavement that is pre-calculated (see Equation (14)) prior to backcalculation to verify that the range of radius of stiffness values still falls within the expected range seen in in-service pavements. Said range is verified in Table 3.4.

Table 3.4 - Inputs and Outputs for ISLAB2005 Test Case 1

Test Case No.	Inputs				
	E_{PCC} (psi)	k-value (psi/in.)	ℓ_{result} (in.)	LTEy (%)	LTEx (%)
1	4,000,000	100	39.71	50	30
2	4,000,000	125	37.55	50	30
3	4,000,000	150	35.88	50	30
4	4,000,000	175	34.52	50	30
5	4,000,000	200	33.39	50	30
6	4,000,000	225	32.42	50	30
7	4,000,000	250	31.58	50	30
8	4,000,000	275	30.83	50	30
9	4,000,000	300	30.17	50	30
10	4,000,000	325	29.57	50	30
11	4,000,000	350	29.03	50	30
12	4,000,000	375	28.53	50	30
13	4,000,000	400	28.08	50	30
14	4,000,000	425	27.66	50	30
15	4,000,000	450	27.26	50	30
16	4,000,000	475	26.90	50	30
17	4,000,000	500	26.55	50	30

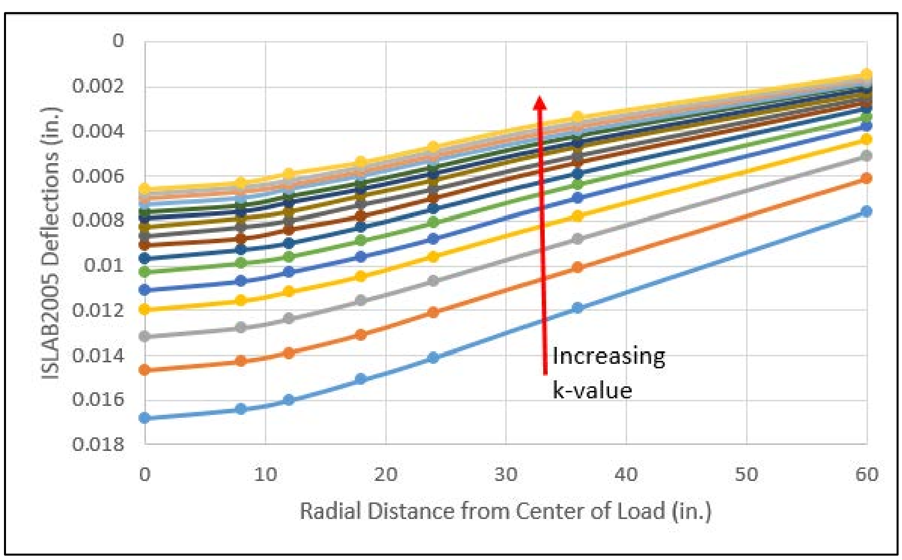

Figure 3.3 – Deflection Basins from ISLAB2005 for Test Case 1 Inputs

3.4.1.2 Verification Test Case 2 Description

The purpose of Test Case 2 is to verify that the new procedure can correctly backcalculate E_{PCC} and the k-value of a controlled pavement system for deflection basins created using the same computer program with varying values of E_{PCC} and arbitrarily-chosen values of LTE for both joints that are different from the ones used in the training cases. The elastic modulus values for this test were varied from the lower end of the training case values to the upper end values. The values were chosen to be in between those from the training case to present the most challenging scenario for the algorithm. Opposite of Test Case 1, the k-value remained constant for each deflection basin computation at the same value used for all training cases. Also opposite from Test Case 1, the LTE values were chosen arbitrarily for each unique deflection basin to test whether the new procedure could effectively backcalculate the LTE at the shoulder given input LTEs that were not used in the training cases. Table 3.5 summarizes each of the independent factors that were varied for this test and Figure 3.4 shows the deflection basins created from ISLAB2005.

Table 3.5 - Inputs and Outputs for ISLAB2005 Test Case 2

Test Case No.	Inputs				
	E_{PCC} (psi)	k-value (psi/in.)	ℓ_{result} (in.)	LTEy (%)	LTEx (%)
1	185,000	100	19.93	85	55
2	520,000	100	25.80	65	15
3	900,000	100	29.60	45	25
4	1,560,000	100	33.96	55	25
5	2,560,000	100	38.44	75	75
6	3,640,000	100	41.97	35	75
7	4,500,000	100	44.26	55	65
8	6,660,000	100	48.81	15	55
9	7,540,000	100	50.35	85	15
10	8,500,000	100	51.88	85	45
11	9,560,000	100	53.43	45	45
12	10,420,000	100	54.59	15	45
13	11,540,000	100	56.01	25	15
14	12,490,000	100	57.12	25	35
15	15,480,000	100	60.27	75	85

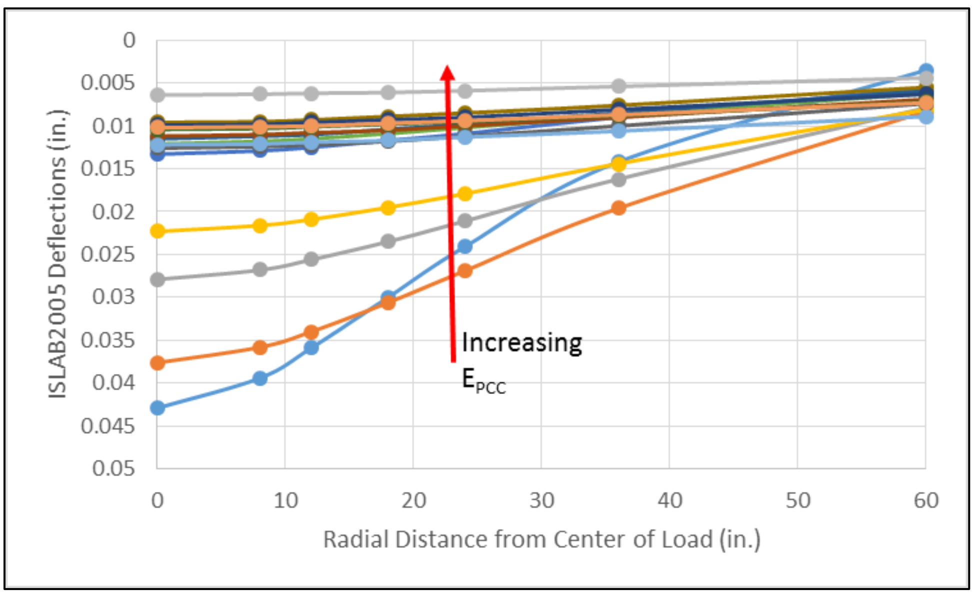

Figure 3.4 - Deflection Basins from ISLAB2005 for Test Case 2 Inputs

3.4.2 RESULTS

The results from the artificial data proved that the backcalculation interpolation scheme is accurate as intended and that the edge backcalculation procedure is robust. Per Figure 3.5 below, the backcalculated values match nearly one-to-one with their input counterparts.

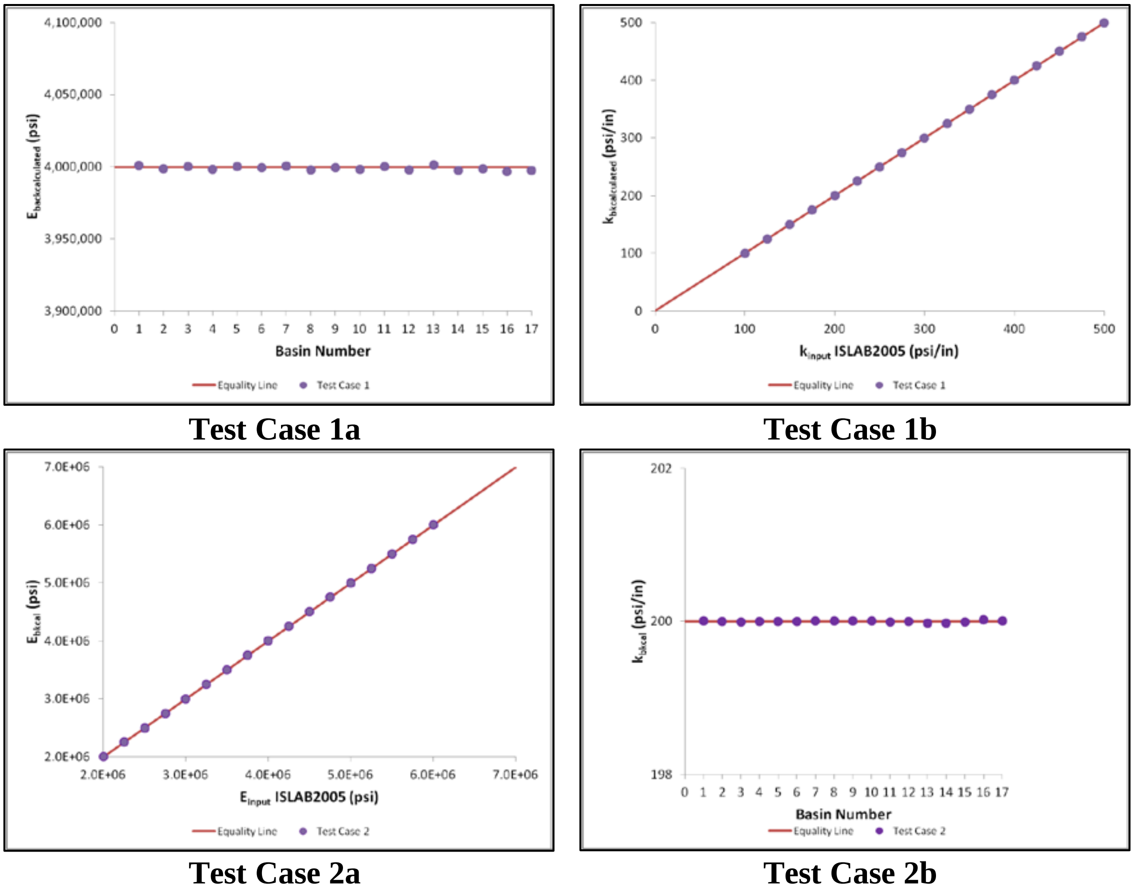

Figure 3.5 – Verification Test Results by Test Case: a) Backcalculated Surface Layer Elastic Moduli; b) Backcalculated k-Values

Even when values were chosen more arbitrarily (Test Case 2), the new procedure performed well in recovering the pavement properties used in the creation of each deflection basin. Although not shown in the results, the backcalculated LTE_x values matched directly one-to-one with their input counterparts, and all effective errors for each test case are effectively zero. With that, the development of the new edge backcalculation method is complete. Further validation of the procedure in its entirety with LTPP test section data is reported in Section 4.

4 VALIDATION OF THE EDGE BACKCALCULATION PROCEDURE

In Section 3, the new slab-edge backcalculation procedure was verified to be effective in backcalculating artificially-created deflection basins. However, artificially-created deflections do not contain random errors commonly associated with in-service pavement FWD tests. Therefore, the new procedure was subjected to validation tests with real deflection basins to ensure that the procedure is not impacted by the random error and the real behavior of in-service pavement deflection basins.

4.1 TEST 1: RANDOM LTPP TEST SECTION TEST

The new edge backcalculation procedure provides users with an effective error value and the calculated (or predicted) deflections at each sensor. The effective error value is a sum-of-the-square error for each deflection location. This value is an indicator of backcalculation performance in terms of how well the pavement deflection conforms to the model on which the new procedure was trained. In other words, a high error would mean that the deflection basin does not conform to the concrete pavement model established for this procedure. A low effective error would represent a deflection basin that conforms to the concrete pavement model. These statements must be validated by testing that the resultant effective error value for each deflection basin is an actual indicator of the level of conformance between the tested deflection basin and the model chosen. An example of the validation process is provided here.

FWD deflection data collected for the LTPP section 32-0201 were used in this validation example. Test section 32-0201 is located in Arizona, which is within the “dry, non-freeze” LTPP-designated climate region. The original construction date of the test section was August 1st, 1995, and the date of testing for this experiment was June 3rd, 1997. No photographs exist of the pavement surface at the testing location before the date of testing; however, an ADS (Automatic Distress Survey) photograph from the LTPP inventory illustrates the shape and layout of a similar pavement in good condition (see Figure 4.1).

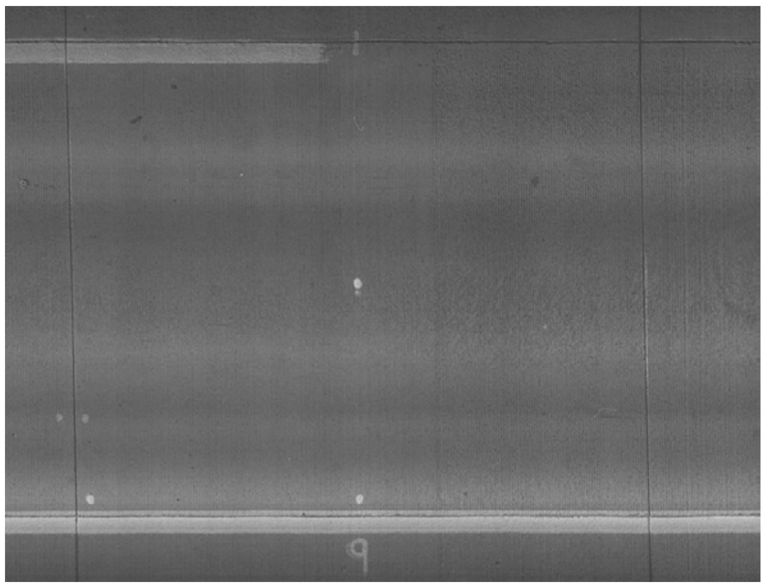

Figure 4.1 - Automatic Distress Survey Photograph of Pavement Section 32-0201, Slab 9 from the LTPP Database

The white dots mark the locations of the FWD testing points for the J1 and J3 locations at mid-panel. The white line at the bottom of the photograph indicates the lane marker for the right edge of the outside driving lane and the shoulder when facing in the driving direction. Based on this photo, there are no visible defects in this slab at the time of testing.

According to the LTPP database, the measured PCC thickness of section 32-0201, was 9.2 inches. The base layer was 5.9 inches of crushed gravel. The FWD test time for this experiment on section 32-0201 was 02:31 pm. The load position was J3, and the test location was +45.4 meters, or slab 4. The recorded drop load was 8,835 pounds. The measured transverse LTE across the pavement slab that day was 84% on average on both sides of the slab. The shoulder type for this section was granular. Also, the transverse joint spacing was 15 feet, which is the same as the ISLAB2005 base case used for training.

Test 1 verified the accuracy of the resultant effective error value by comparing the predicted deflections (which were calculated using the error ratios for each sensor in a backcalculated deflection basin) to the deflections that were re-calculated using ISLAB2005, with the model inputs set to the backcalculated properties of the associated section. The measured FWD deflections and other backcalculation input parameters are shown in Table 4.1. Table 4.2 shows the results of the backcalculation.

Table 4.1 - Backcalculation Input for LTPP Test Section 32-0201

P	LTE_y	Measured Deflections (in)						
(lbs)	(%)	D1	D2	D3	D4	D5	D6	D7
8835	84	0.0100	0.0093	0.0087	0.0078	0.0069	0.0049	0.00224

Table 4.2 - Backcalculation Output for LTPP Test Section 32-0201

Basin No.	ℓ	k	LTE_X	Eff. Error *10^4	Dcalc/Dmeas						
(-)	(in.)	(psi/in.)		(-)	D1	D2	D3	D4	D5	D6	D7
1	25.5	236.1	90	2.73	1.01	0.99	0.99	1.00	1.01	0.99	1.02

An analysis of ISLAB2005 was conducted to validate that the reported calculated deflections are similar to the deflections produced by ISLAB2005 for the pavement model with the backcalculated pavement properties. The same ISLAB2005 model parameters described in Section 3.1 were used, but the following changes were made:

- The applied load was set to 8,835 pounds to 9,000 pounds (tire pressure was adjusted to reflect the same area of loading as the 11.81 inch diameter FWD plate)
- The k-value was set to 236.08 psi/in
- The elastic modulus of the PCC layer, E_{PCC} was set to 1,170,994.1 psi, based on backcalculated k-value and radius of relative stiffness (see Equation 19) and constant thickness, h_{pcc} = 10 inches:

$$E_{pcc} = \frac{(25.5in)^4(1-(0.15)^2)12(236.1\frac{psi}{in})}{(10in)^3} = 1{,}170{,}994\ psi \tag{19}$$

- The LTE_y value was set to 84% and the LTE_x value was set to 90%

The seven deflections at each sensor offset were extracted from the output file after generating output for this case in ISLAB2005. Figure 4.2 shows the actual deflections recorded in the field versus the deflections obtained from the output file of the ISLAB2005 experiment.

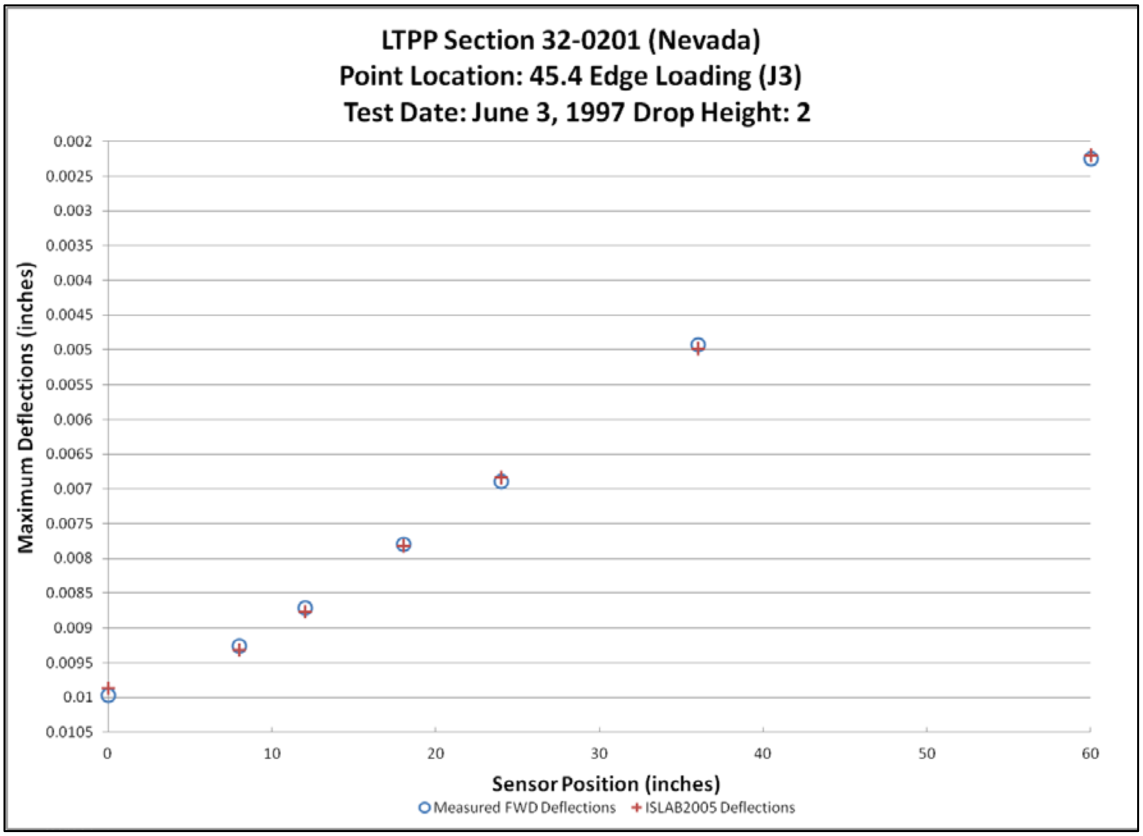

Figure 4.2 - Measured Deflections vs. ISLAB2005 Deflections for LTPP Test Case

The ratios between the measured and ISLAB2005 deflections correspond well with the ratio of $w_{measured}/w_{calculated}$ output from the new, edge backcalculation procedure (listed in Table 4.2).

This experiment verified that the backcalculation algorithm can predict pavement deflections based on the training data provided to it without the direct use of ISLAB2005. This experiment also validated the reliability of the resultant effective error value. With this verification, the new procedure is expected to produce reliable results for thousands of deflection basins in under a minute.

4.2 TEST 2: LTE SENSITIVITY TESTING

An assumed or measured value for the transverse joint LTE, LTE_y specifically, is necessary for each deflection basin evaluated in order to backcalculate the structural parameters of the pavement slab of interest. Then the longitudinal LTE value (LTE_x) can be backcalculated by minimizing the difference between predicted and measured deflections, using a set value of LTE_y and iterative values of LTE_x, while k and ℓ are independently solved for simultaneously. Ideally, the measured value would be constant across the whole length of both transverse joints surrounding the slab of interest. However, matching the correct LTE_y value with the slab of interest can be a tedious process, especially when matching more than one batch of measured deflection basins.

It was proposed that the average of all measured LTE_y values from the J4 and J5 testing positions across an entire LTPP pavement section, on a given date, be used as the input LTE_y value for all deflection basins recorded across the same section on the same date. The proposed technique for establishing input LTE_y values simplified the time and detail required to assign the measured value of LTE_y to the deflection basin measured on the adjacent slab for each basin. LTE sensitivity test cases with real LTPP data were set up to examine the effects of the simplification and used to decide whether such a simplification was reasonable before the backcalculation results from hundreds of different sections were analyzed.

Sections 04-0215 and 04-0219 were chosen for these tests. Both sections are part of the LTPP SPS-2 program and part of the same stretch of highway in Arizona. Both sections have twelve-foot wide lanes with fifteen-foot contraction spacing and no skewed joints. The FWD tests were conducted four days apart for each section, but the time of day during testing was generally the same. The main difference between the two sections is the constructed base type. The base type for section 04-0215 is granular, and the base type for section 04-0219 is lean concrete. The purpose was to verify the results from two different base-type sections independently.

LTE sensitivity cases were conducted for one date of testing on each section. The backcalculated k- and ℓ-values were plotted against the station number associated with each FWD test and variation was observed in the backcalculated values based on varying values of the LTE_y input. In particular, the minimum, maximum, average, and actual LTE_y values were used as inputs. The backcalculated results from each input value represented four separate curves to clearly distinguish the results of each case. Each case was then compared to the average-LTE_y-value case and the effect of the simplifying assumption was evaluated. The results from the LTE sensitivity analysis are presented next along with a discussion on whether the simplified LTE_y input extraction and input technique used for this study is appropriate and reasonable.

Four separate charts (Figures 4.3 through 4.6) are introduced to illustrate the effects of the input LTE_y value on the edge backcalculation parameters ℓ and k for two different test sections. Additional charts were developed to show the effect of the input LTE value on the backcalculated LTE_x value, but the difference was negligible in almost all reasonable cases because the LTE output values are limited to a number between ten and ninety in increments of ten; therefore, those charts are not included in this thesis.

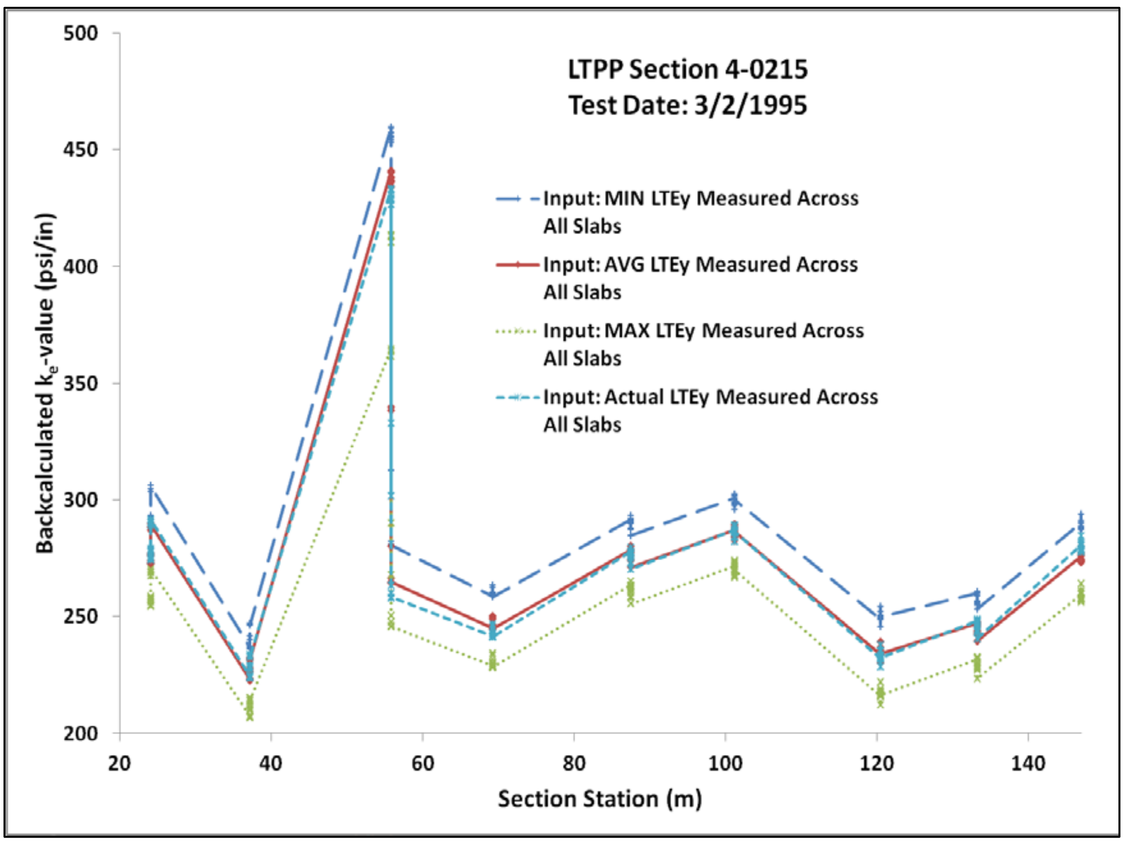

Figure 4.3 - Backcalculated k_e-Values for Section 04-0215 with Varying LTE_y Values

Figure 4.3 shows backcalculated moduli of subgrade reaction for section 04-2015. The backcalculated values for the minimum and maximum LTE_y input values represent the bounds of the effects of the LTE_y input value on backcalculated results. The fluctuation of k_e-values across the length of the pavement is considered a natural fluctuation due to varying characteristics inherent in pavement construction. Only one station, between 40 and 60 m, had inconsistent results. This station appears to be an anomaly and will not be considered in the discussion of the results.

The difference between the minimum and maximum bounds is noticeably less than the natural variation of the subgrade parameter along the length of the section, which means the LTE_y approximation has a small effect, but it is not a significant effect at any particular point along the pavement. More importantly, when the actual LTE_y-input results are compared to the average LTE_y-input results, the variation between the two is negligible. This means that using the average measured LTE_y value across the entire section on any given day could be a reasonable simplification at the cost of negligible to small error.

Figure 4.4 below shows generally the same results for another LTPP pavement section, 04-2019. It can be observed that the effect of LTE_y selection is even less pronounced for this section.

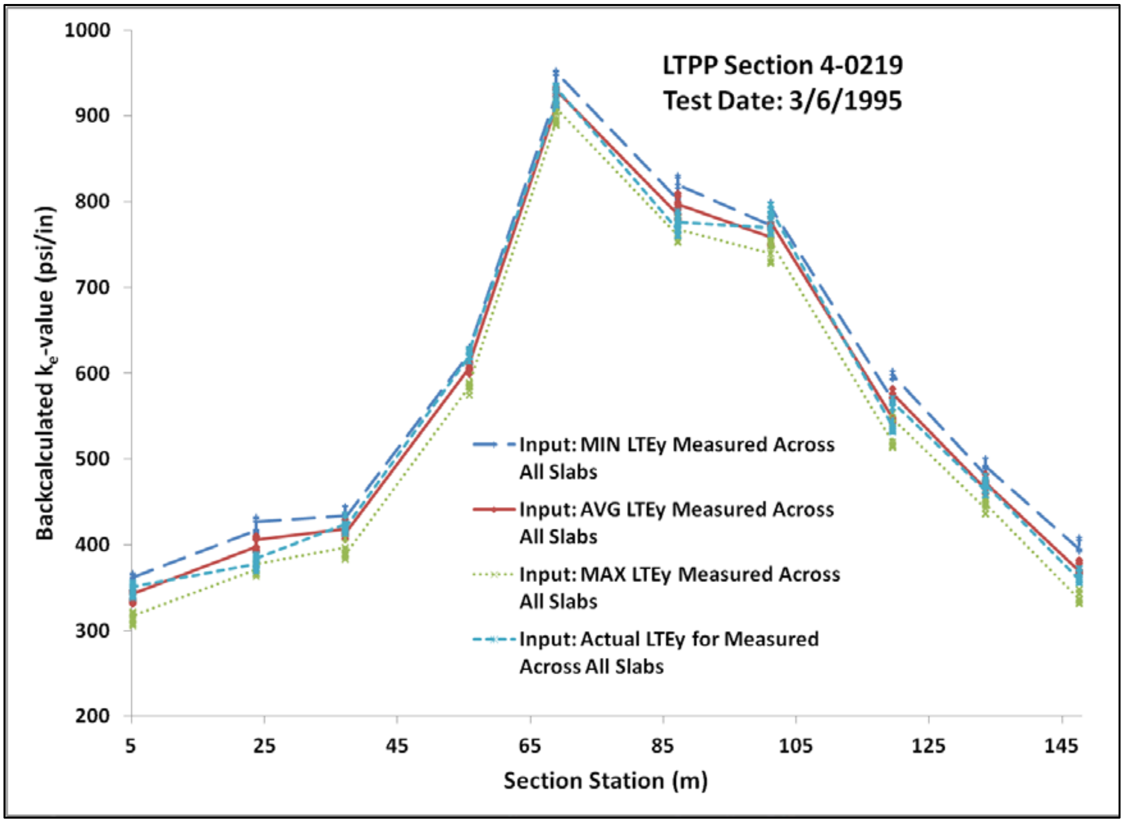

Figure 4.4 - Backcalculated k_e-values for Section 04-0219 with Varying LTE_y Values

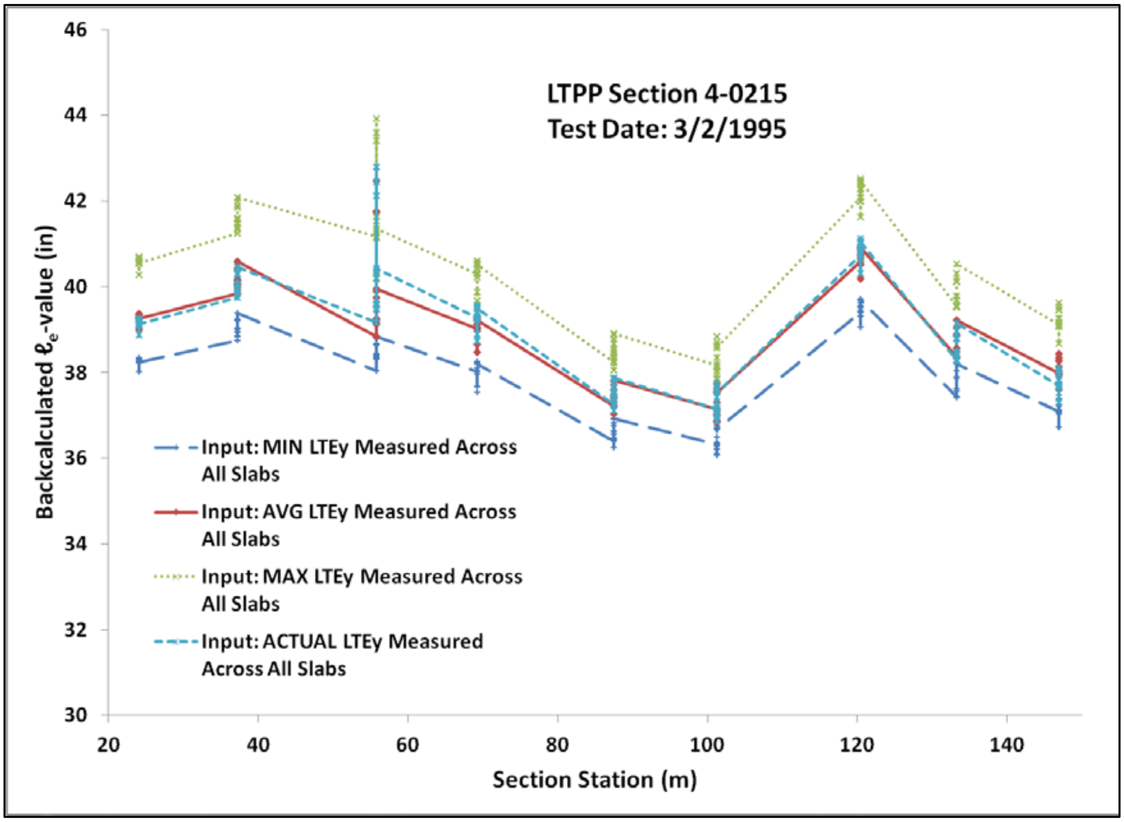

Figure 4.5 - Backcalculated ℓ_e-values for Section 04-0215 with Varying LTE_y Values

Figure 4.5 represents the same pavement section used for Figure 4.3 except the backcalculated radii of relative stiffness are compared along the length of this section. The same result can be stated for this parameter as was stated for the k-values in previous figures: the variation caused by the input LTEy value is not nearly as significant as the variation caused by natural variance in the pavement structure along the length of the pavement section.

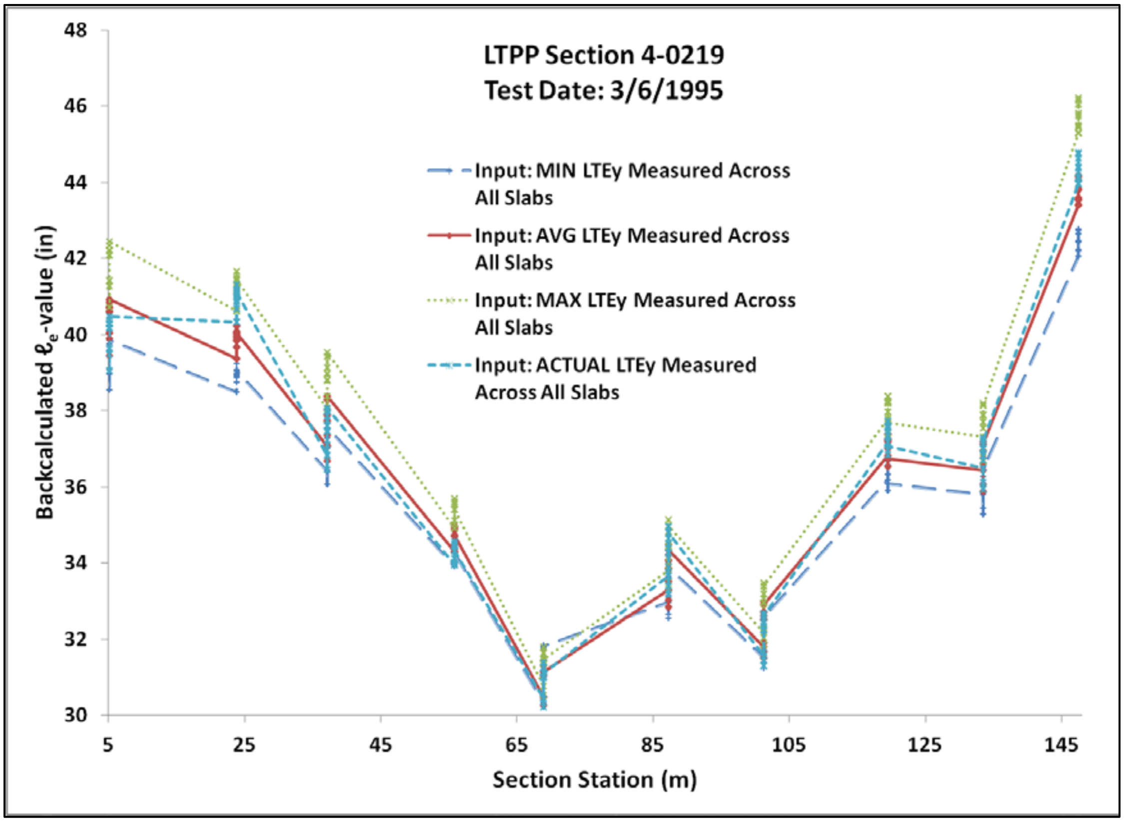

Figure 4.6 - Backcalculated ℓ_e-values for Section 04-0219 with Varying LTE_y Values

This observation is even more valid for section 04-2019 as could be observed from Figure 4.6. Again, the results match well with the results from the proposed procedural results using the average LTE_y value from across the section in place of the actual measured LTE_y.

In conclusion, it is sufficient to use the average LTE_y-value measured on any given date for the input LTE_y-value on a given deflection basin measured on a slab within the same section on the same date. This process was used for examining hundreds of thousands of pavement section deflection basins recorded from the time the LTPP database was created until present time. Some of the results of those tests are examined next.

5 EXAMPLES OF EDGE BACKCALCULATION USING LTPP DATA

Preliminary tests were performed in this portion of the study on real deflection basins to illustrate potential applications of the new tool and its improvements and limitations compared to past techniques. Backcalculations were performed on all JPCP test section basins included in the current LTPP database using the average transverse LTE (LTE_y) value recorded at all joints in a given test section on a given test date. Further refining of the results was conducted as necessary for the ensuing tests and evaluations. First, an in-depth evaluation of the backcalculated error-of-fit values is performed, followed by a discussion on its implications for later analyses. Then, an evaluation of the FWD load-level effects is discussed to further validate the correctness of the new backcalculation tool. Lastly, an evaluation of specific parameters backcalculated at the slab-edge versus the slab-center location is described and the results compared on a test section-to-section basis.

5.1 STUDY 1: ERROR OF FIT ANALYSES

The error of fit is a calculated, non-dimensional value that quantifies the level of agreement between a real deflection basin and its backcalculated counterpart. In this study, error of fit defines a normalized, sum-of-square errors equation (see Equation (20) below) that is implemented into the backcalculation program and reported for every backcalculation.

An error of fit equal to 0.0 represents an exact match between all seven of the measured deflections and deflection basins computed with ISLAB2005 using the backcalculated modulus of elasticity and the coefficient of subgrade reaction. Relatively higher values of error indicate relatively higher levels of disagreement between the measured and computed deflection basins. The purpose of this part of the study is to evaluate the relationship between the computed error and the degree of misfit for a representative sample of the backcalculated basins from the entire set of JPCP test sections in the LTPP database.

$$\left[\sum_{i=1}^{7}\left(\frac{w_{m,i} - w_{c,i}}{w_{m,1}}\right)^2\right] \cdot 10^4 \qquad (20)$$

Note: w_m represents measured deflections, w_c represents calculated deflections, and *i* denotes each sensor.

To perform the evaluation, seven individual deflection basins, along with their backcalculated results, are chosen based on their backcalculated error of fit values which range from the minimum observed error of fit to the maximum observed error of fit. For each selected test case, a simulated deflection basin is generated using ISLAB2005 with the backcalculated design parameters as design inputs in the base training model. The simulated deflection basins are then visually compared to the real deflections for evaluation. LTPP test identifiers for the seven representative backcalculation basins used specifically in this study are provided in Table 5.1 below. Observations of the resulting plots and relevant discussion are provided in the subsequent figures and final conclusions are reported on the error of fit.

Table 5.1 – List of LTPP Test Sections Used in Effective Error Study

LTPP State Code	SHRP ID	Test Date	Test Location (m)	Backcalculated Error of Fit
1	0606	2/9/1998	80.2	0.55
1	0604	2/10/1998	81.4	1.35
46	0602	8/10/1995	284.7	5.24
1	0605	11/15/2001	278.6	28.87
13	3019	3/6/1989	98.5	48.98
89	3015	12/17/1996	51.5	618.14
39	0209	8/7/2012	63.7	1102.27

Figures 5.1, 5.2, and 5.3 show charts that illustrate the difference between the real and simulated deflections for relatively low, intermediate, and high calculated error-of-fit values found in Table 5.1, respectively. Referring to the charts in Figure 5.1 below, the actual deflections essentially overlap the predicted deflections for the lowest tier of error values (closest to 0.0). These are examples of well-conforming pavement slabs.

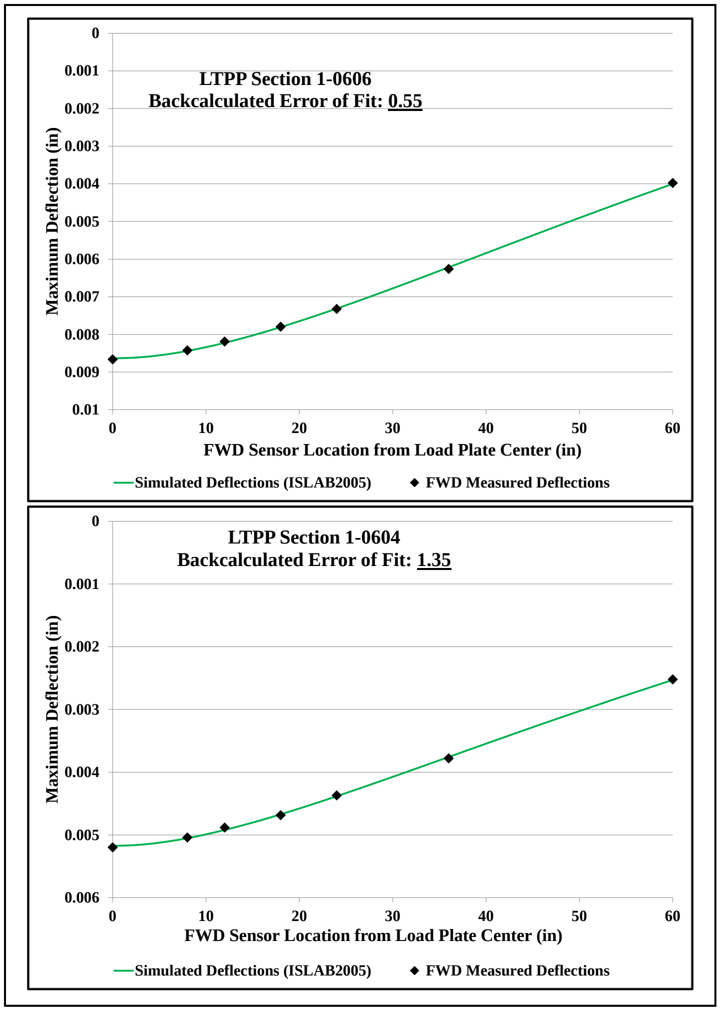

Figure 5.1 - Measured vs. Simulated Deflection Basins with Lowest Errors of Fit

Even for mid-range errors of fit near 10.0 (refer to Figure 5.2), the majority of actual deflections overlap with the predicted deflection curve as well; however, some (two to three) of the actual deflections are distinctly offset from their backcalculated counterparts.

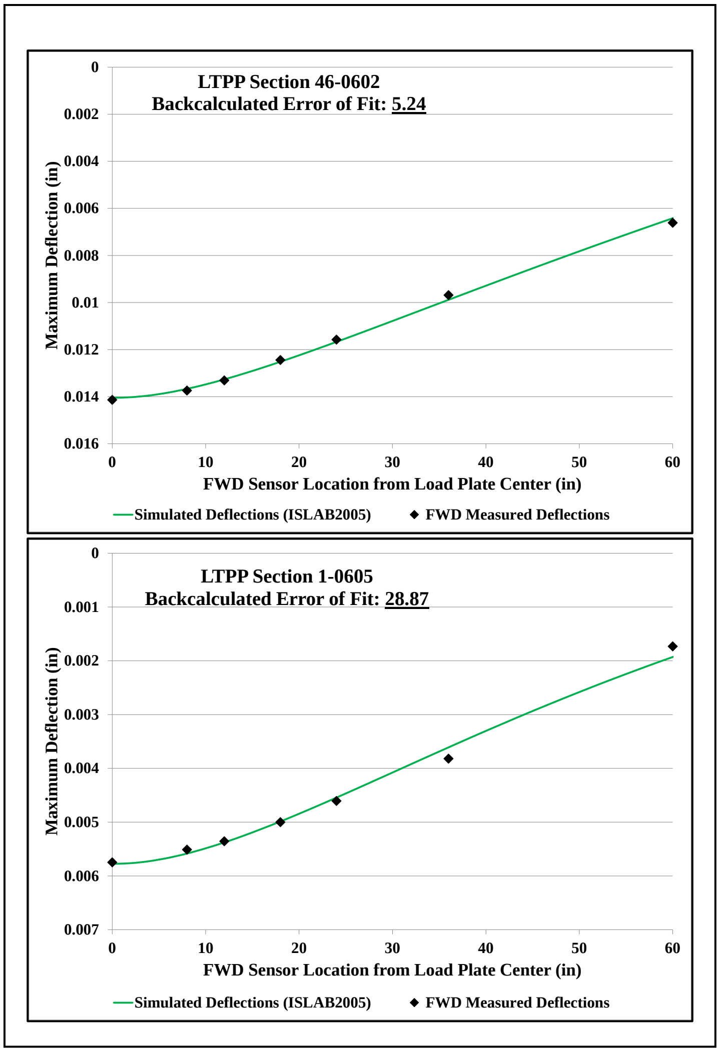

Figure 5.2 - Measured vs. Simulated Deflection Basins with Intermediate Errors of Fit

From both previous figures, charts representing LTPP sections 46-0602 and 1-0605 show, in particular, that the measured deflections furthest from the load plate contributed mainly to the higher errors, if any.

The last two charts in Figure 5.3 represent deflection basins backcalculated with errors nearing 100.0 and 1,000.0, respectively. For the case of an error of fit nearing 100.0, it is observed that the shape of the real deflection basin is similar to its simulated counterpart, but some deflections are again offset in no particular order. When the same plot is observed for the case of error nearing 1,000.0, it is observed that there is no distinct correlation between the measured deflection and the backcalculated deflections. An error of this magnitude represents a poor fit between the backcalculated and measured deflections.

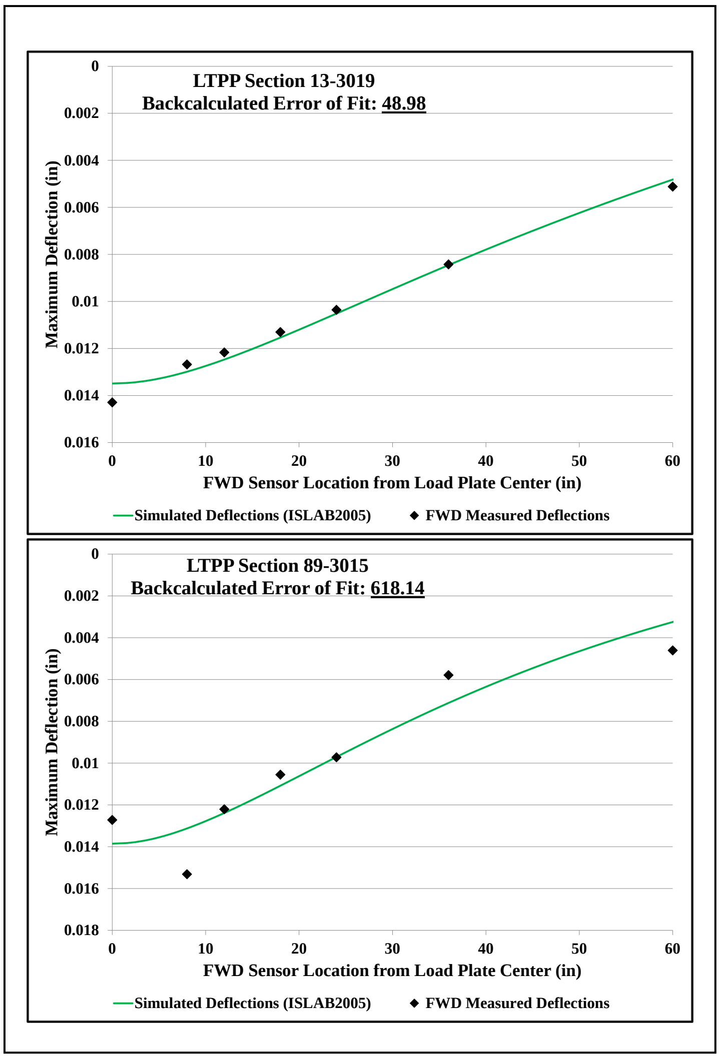

Figure 5.3 - Measured vs. Simulated Deflection Basins with Higher Errors of Fit

Lastly, Figure 5.4 is presented to illustrate the same deflection basin comparisons, this time for a case of extremely high backcalculation error in LTPP section 39-0209, listed in Table 5.1. For this case, the measured deflections increase linearly from the loading plate to the second-to-last deflection, but the last deflection is completely discontinuous with its predecessors. This configuration is not compatible with the pavement model used in the new backcalculation program; therefore, this pavement slab is considered non-conforming.

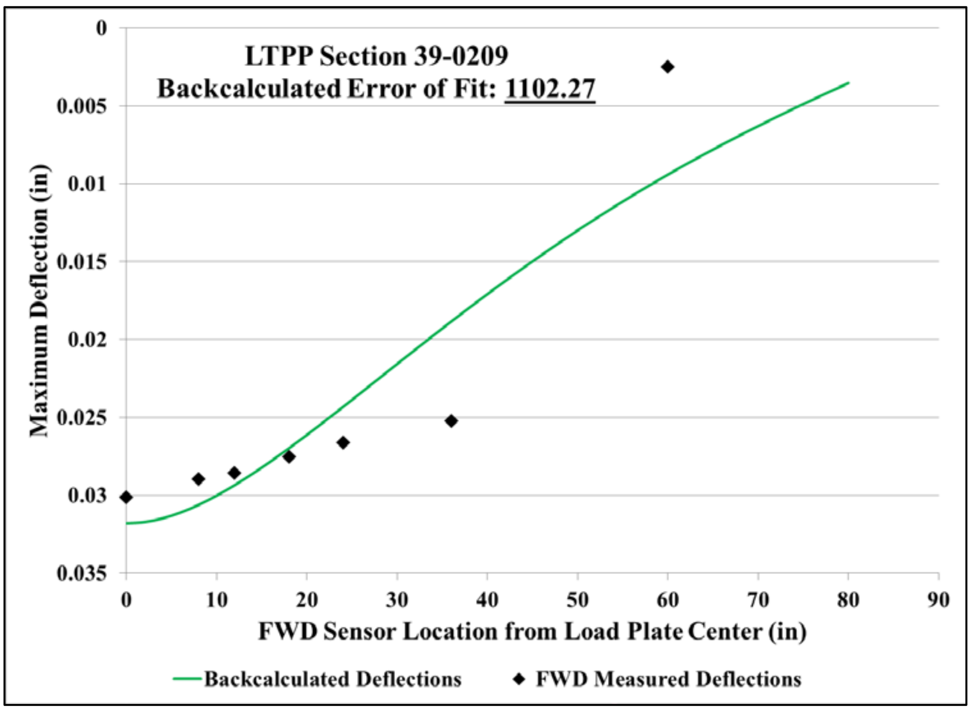

Figure 5.4 - Measured vs. Backcalculated Deflections for Cracked LTPP Test Section 39-0209

In general, it is concluded that a higher error of fit is directly related to a higher discrepancy between the actual deflections and their associated backcalculated deflections. For errors of fit under 10.0, the pavement slab tested is considered well-conforming. Subsequently, the reliability of the resulting backcalculated pavements is considered lower, but acceptable. There are no apparent indications of cause for some of the offset deflections observed for test cases with errors nearing 10.0, but the offsets are relatively small in such cases so the error is attributed to combinations of natural, random error associated with FWD testing and an imperfect pavement model on which the backcalculation program is created with.

For errors above 100.0, there are more apparent indications that either more drastic measurement errors or non-conforming and cracked pavement slabs caused the high error. For instance, in regards to section 89-3015 in Figure 5.3, the measured deflections are not representative of a standard concrete pavement profile tested with a FWD. This is considered a testing error and cases like these should not be considered when examining the backcalculated parameters. Refer to Figure 5.5 below for additional evidence of problematic testing.

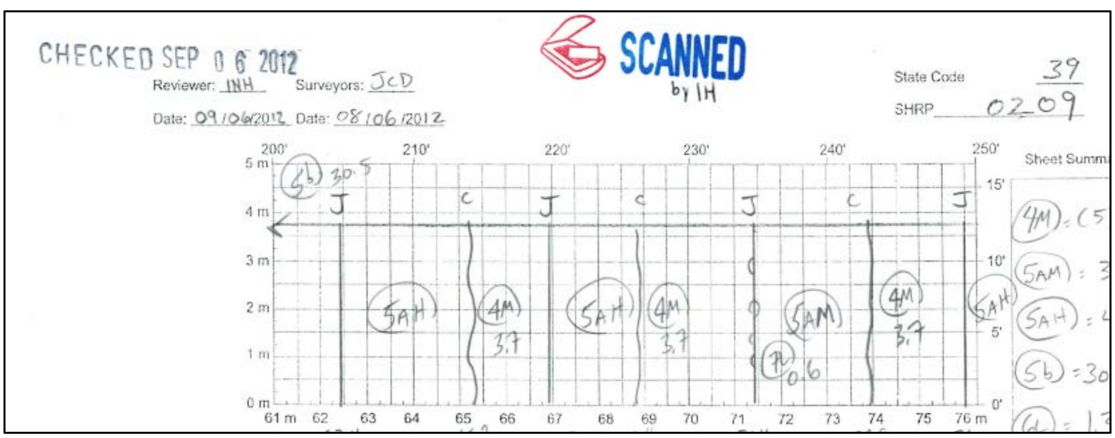

Figure 5.5 - Manual Distress Survey of Cracked LTPP Test Section (InfoPave™)

Figure 5.5 is the manual distress survey map recorded on the date of testing and for the particular slab location represented in Figure 5.4. The survey indicates a crack existed at the time of testing on this particular slab. The existence of this crack is clearly reflected in the measured deflections plotted in Figure 5.4 where the deflection furthest away from the loading plate 'jumps' away from the rest of the measured deflections. Such instances of problematic testing can be captured by evaluating the error of fit, which eliminates the necessity of inspecting visual distress maps for problematic sections like this one.

Implications from this study are that the backcalculated error may be used to pre-qualify backcalculated results and as a general indicator of pavement conformance with the new edge-backcalculation program. It is also concluded that relatively high error values may be attributed to testing error such as faulty deflection sensors, cracked pavements and/or natural, random error, in general, and not by the fault of the backcalculation program. For supplementary analysis of the backcalculated error-of-fit values in a more holistic sense, see Section 5.3.

5.2 STUDY 2: LOAD-LEVEL EFFECTS

For each LTPP test section, there are twelve FWD drop tests conducted at the slab-edge location for three different drop loads, as described in the literature review. The three different drop loads are nominally 9,000, 12,000, and 16,000 pounds. This drop load is scalable in the artificial, linear system used to create the backcalculation program for this study (ISLAB2005); therefore, if the real, tested pavement behaves the way it has been modeled in this study, the backcalculated, slab-edge parameters should be load-independent. A random set of the LTPP, SPS-2 test sections were selected and tested for load-dependency to determine if there is load dependency in the backcalculated parameters because apparent load dependency could be an indication of undesirable programmatic errors. More details on the test sections and methodology for this evaluation are provided next.

Three separate levels of evaluation are conducted for the load-level assessment. The first evaluation is performed to illustrate the variance of the backcalculated k-value across each of the twelve drops at a single location along the test section for each section. The k-value is chosen for this evaluation, in particular, because it is commonly an evaluated parameter in studies similar to this one. In the next part of the assessment, a pair of deflection profiles for different drop loads on the same test slab are plotted against their backcalculated counterparts to examine potential causes for any load variation discovered in the first evaluation of this section. Lastly, the ratios of slab-edge k-values backcalculated for the highest drop load to the lowest drop load are plotted for all tests on an entire LTPP test section and a given test date for the LTPP sections examined in the first portion of the assessment.

Results and observations for each part of the assessment are presented next before the final conclusions. Before the results are discussed, a brief summary of the test sections used in this part of the study is presented.

Three pavement test sections from the LTPP, SPS-2 database are randomly selected for conducting this evaluation. The section IDs along with the main properties of the three test sections randomly selected for this assessment are provided below in Table 5.2.

Table 5.2 - LTPP Pavement Section Summaries

Section ID	**10-0205**	**32-0259**	**10-0203**
Location	Delaware	Nevada	Delaware
Climate Category	Wet, Non-Freeze	Dry, Freeze	Wet, Non-Freeze
Date of Testing	7-May-96	26-Mar-96	1-Jul-97
Surface Layer (1):	PC Concrete (9.20")	PC Concrete (10.80")	PC Concrete (11.70")
Layer 2:	Lean Concrete Base (5.50")	Aggregate Base (1.50")	Asphalt Treated Base (6.10")
Layer 3:	Granular Subbase (30")	Granular Subbase (8")	Granular Subbase (14")
Layer 4:	Untreated Subgrade	Treated Subbase (12")	Untreated Subgrade
Layer 5:	-	Untreated Subgrade	-
Shoulder Type	Asphalt Concrete (4")	Concrete (10.5")	Asphalt Concrete (4")
Shoulder Base Type	Dense Graded, Hot-Laid Central Plant Mix (3")	Dense Graded, Hot-Laid Central Plant Mix (1.5")	Dense Graded, Hot-Laid Central Plant Mix (3")

The similarities and differences between the test sections chosen are summarized below:

- the two Delaware sections are almost identical, outside of the base type;
- the Nevada test section is in a different climate and has a different shoulder and base type;
- dates of testing are very close across all three sections; and
- all three sections have a unique base type.

Figure 5.6 below is a compilation of three charts representing results from the three test sections listed in Table 5.2.

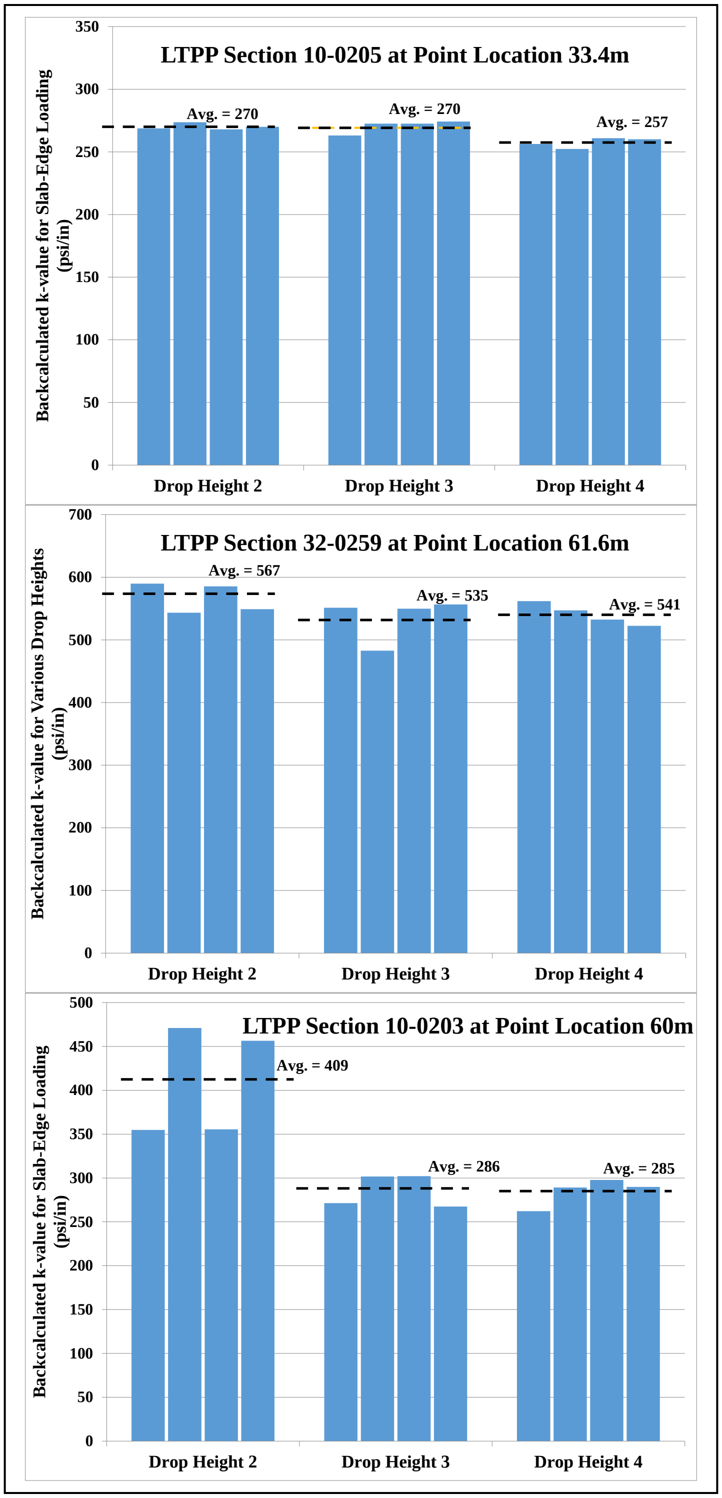

Figure 5.6 - Chart of Backcalculated k_e Values by Drop Height for Three LTPP Test Sections

Each chart in Figure 5.6 displays the k-values backcalculated for each of the twelve drop loads (separated by nominal load level) that comprise a complete FWD test for a representative test location within each of the three test sections. The average k-value for each nominal load level is also provided on the charts for illustrative purposes. Such plots demonstrate whether or not a trend is apparent for the load dependency of the backcalculated parameters across a larger sample size of data.

In the first of three charts, the backcalculated k-value is nominally constant as the load is repeated within each nominal drop load level; however, some variance is noted from drop heights 2 and 3 to drop height 4 for this test location. In the second chart, for section 32-0259, there is much more variability between sequential drops at each nominal drop load level, as well as between each of the drop load levels; however, there is no indicative trend in the backcalculated k-value increasing or decreasing with increasing drop load. The k-value appears to vary inconsistently across different drop heights at this test location. In the 3rd and final chart of Figure 5.6, there is significant variance in the backcalculated k-value from drop height 2 to drop height 3 and 4 and there is even higher variance within drop height 2 than in any of the other test locations or drop heights. A closer look at the fluctuating backcalculated k-values for sections 32-0259 and 10-0203 is taken next to investigate the variance when FWD drop heights are the same.

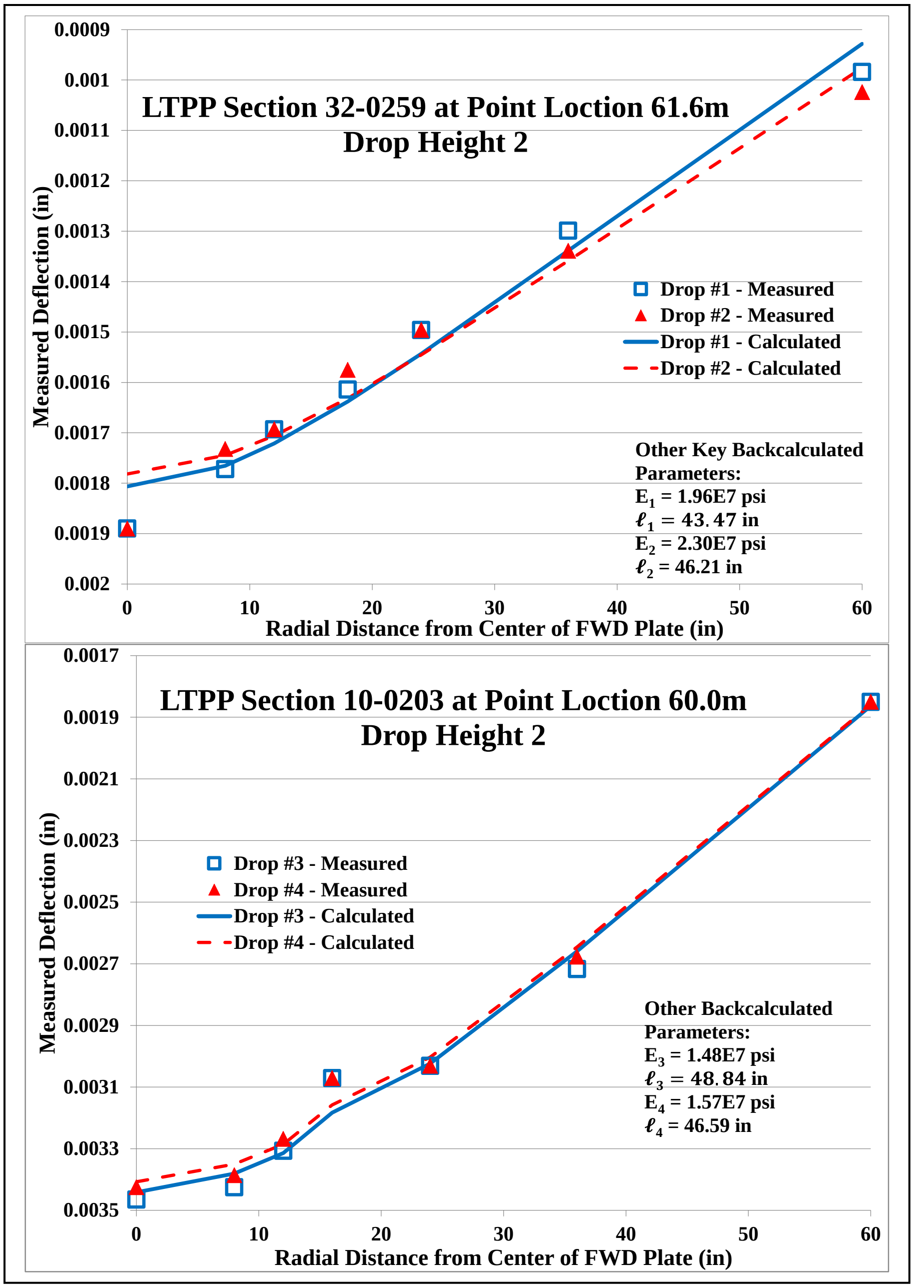

Figure 5.7 – Measured Deflections vs. Calculated Deflections for Separate Drop Heights

Two charts in Figure 5.7 compare the measured and calculated (by the backcalculation algorithm) deflections at each standard sensor location that were recorded for two distinct FWD drops tests within the same nominal load level for two of the three sections used in the previous assessment. In particular, the top chart represents drops number one and two for drop height 2 at 61.6m, with drop number increasing sequentially from left to right, starting at one for each nominal load level plotted in Figure 5.6. Per the LTPP database, the recorded loads for these FWD tests were exactly the same: 9,469 lbs. The deflection beneath the loading plate for both drops are the same per Figure 5.7, but much higher than the rest of the deflections recorded on the other sensors. The other measured deflections vary randomly by drop number for the rest of the sensor locations.

This variance in deflection magnitude(s) causes a difference in the calculated deflections which subsequently causes the backcalculated k-values to vary as shown in Figure 5.7. Measurement error is the main contributor to the backcalculation variance in this case due to the deflection differences from drop to drop. It is not expected that the backcalculated parameters would be the same for such different deflection basins. This is evident in the other backcalculated parameters shown in the top chart in Figure 5.7 as well.

For the bottom chart in Figure 5.7, similar circumstances are evident, but this time for LTPP section 10-0203. The measured and predicted deflection profiles are representative of drops three and four from drop height 2, as reflected in Figure 5.6. Again, there is a variance between the backcalculated k-values. Other key parameters, for each unique drop and the drop loads, again, were exactly the same this time at 9,421 lbs. In this case, for unknown reasons, the deflection beneath the plate varied from drop number three to drop number four. Typically, if the load is the same, the deflection beneath the plate is expected to be the same from drop to drop. That is not the case in this instance. Again, the variance between the actual deflection basins recorded for each test attribute variance in the backcalculated parameters; not an erroneous backcalculation scheme.

It is concluded from these select cases that inaccurate measurements from faulty sensors or faulty pavements are the main contributors to and variable backcalculated parameters for FWD tests conducted on the same test slab with even the exact same load, and not the backcalculation program itself.

Next, the ratio of backcalculated k-values for drop load height four to drop load height two is computed for each successive drop within a nominal load level series and for each section location within the three previously evaluated test sections. The resulting ratios are then plotted against a unity line for a broader evaluation of the load-level effects. Refer to Figure 5.8 below for a compilation of the resulting plots.

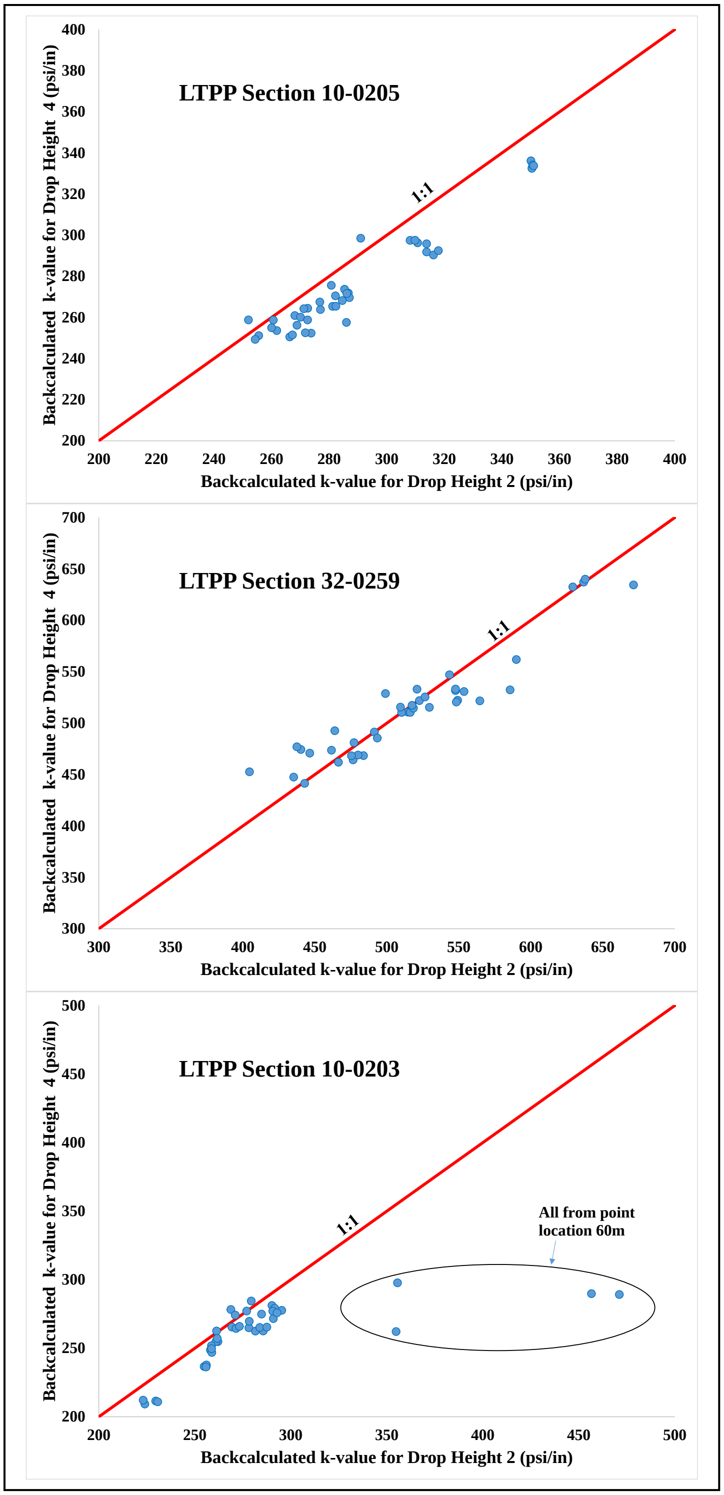

Figure 5.8 – Backcalculated Slab-Edge k-values of Drop Height 4 vs. Drop Height 2

For section 10-0205, represented at the top of Figure 5.8, it is evident that a slight trend exists in which the backcalculated k-value for drop height 4 is consistently less than the k-value backcalculated for FWD tests conducted at drop height 2. This trend is not evident in the other two charts representing sections 32-0259 and 10-0203. For the second chart, section 32-0259, there is a wide range of backcalculated k-values throughout the entire section, but generally, the backcalculated k-values for FWD tests conducted at drop height 4 are not consistently greater than or less than the k-values backcalculated for drop height 2 tests. This is a sign of load-independence. In the third plot, representing section 10-0203, there is a much narrower band of k-values backcalculated across the entire set of test slabs along the section. For the average k-value calculated across the entire section, the ratio of backcalculated k-values for drop height 4 to drop height 2 is close to 1:1.

Four data points have been circled for additional comments related to the chart representing section 10-0203 in Figure 5.8. This group of points represents a portion of the third chart in Figure 5.6 where the backcalculated k-values for a drop height of 4 are much more than for a drop height of 2. This represents an anomaly and such cases should not be considered for further backcalculation analysis.

In conclusion, small variations in backcalculated k-values are attributed to random variations in the measured deflection profiles, be it measurement error or random variation, but not attributed to a flaw in the design of the backcalculation procedure. In this assessment, it was determined that for the same test location on the same date, it is reasonable to average the k-value across all twelve tests unless there is relatively significant variation between the backcalculated k-values at certain drop heights. For the purposes of this study, averaging the k-values improves the ability to analyze the backcalculated parameters from section-to-section, as opposed to within each section. Test sections with a variance of backcalculated k-values for all twelve tests more than 5% are eliminated using a post-analysis filtering technique to be discussed.

Before post-analysis filtering is conducted, one last evaluation is completed to demonstrate the reasonability of comparing backcalculated k-values averaged across the entire LTPP section for each test date in order to facilitate a more broad, section-to-section analysis of the backcalculated results. To perform the evaluation, the same three LTPP test sections are enlisted. For each section, the backcalculated k-values are averaged across all 12 drops at each location and reduced to one data point for the slab-center location and one data point for the slab-edge location. These data points are then plotted against one another on the same chart, by section location, to illustrate the variance of the backcalculated k-values for each slab location across an entire section.

Figure 5.9 contains results for all three of the same LTPP test sections used for evaluations previously completed in this section.

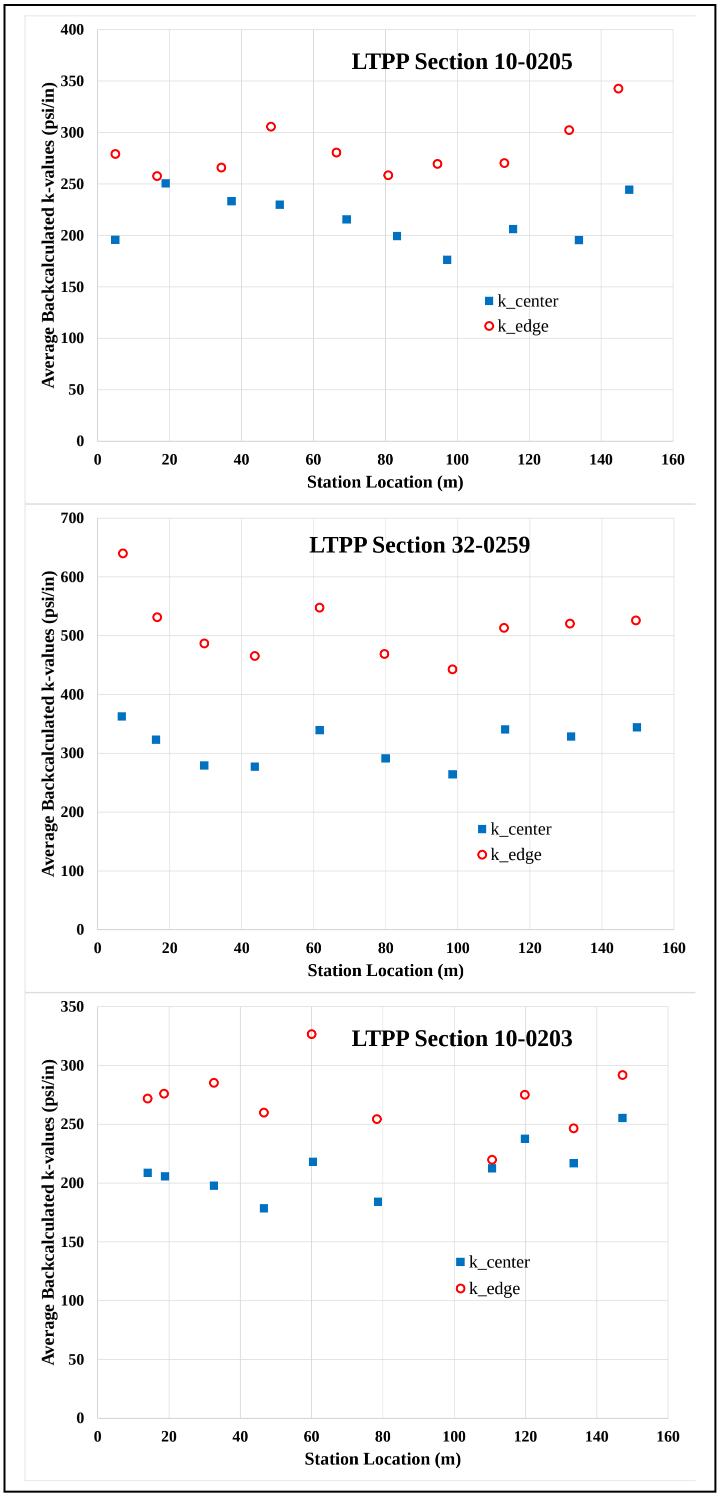

Figure 5.9 – Average Backcalculated k_{edge} and k_{center} for All LTPP Test Section Locations

For LTPP sections 10-0205 and 32-0259 in Figure 5.9, it is observed that the backcalculated k-values do not match one-to-one from slab-center to slab-edge tests along the entire section; however, it is generally observed that the backcalculated k-value for the slab-edge varies along the pavement length in a manner similar to variation in backcalculated k-value for the center of the slab. In other words, as the average, backcalculated slab-center k-value increases or decreases from one test location to another test location along the section, so does the average, backcalculated slab-edge k-value, for most cases. For section 10-0203, the difference between the backcalculated slab-center k-value and the corresponding slab-edge value varies much more across the LTTP section.

In summary, it is generally reasonable to compare the average of the average backcalculated, slab-center k-values for each test location across a given LTPP test section against its slab-edge counterpart, based on the observations discussed in this portion of the study.

5.3 STUDY 3: SLAB-EDGE OUTPUTS VS. SLAB-CENTER OUTPUTS

A final evaluation is conducted in the next section to evaluate the ratio of the backcalculated slab-edge k-value to the slab-center k-value for qualifying sections. In order to be considered a qualifying section, each test section must meet the filtering criteria justified in previous sections and implemented in the next section of this study.

Before filtering begins, there are 120,284 slab-edge deflection basins recorded across LTPP test sections in fourteen different states in the U.S. that fall in the SPS-2 category described in the literature review.

The first basins eliminated were those with FWD test loads falling under 8,000 pound because these represent faulty tests. That leaves 119,454 basins, meaning less than 1% of the basins were eliminated based on this criteria. Next, the backcalculated k-value was averaged in a database for each unique slab on each unique test date for every qualifying test slab. As a result, there were 9,493 records existing, in total.

The database was then further refined by eliminating the existing records, by test slab, or test location, that had a k-value variance of more than 5.00% across the twelve test drops allotted to each slab (as discussed in Section 5.2 of this study). This criteria resulted in an elimination of nearly 20% of the existing records, leaving the total count at 7,675 unique records remaining. With the remaining, qualified test records, the data was queried to compile the average backcalculation results by test section and test date. This resulted in 954 unique records for the J3 test location amongst all SPS-2 in the LTPP database.

This new set of records was further refined by eliminating those test sections that have 14- and 13-foot wide slabs, reducing the count of records to 524. Pavements with 13- and 14-foot wide slabs are not considered in this study because the backcalculation algorithm was not trained for such sections as that was not within the scope of this study.

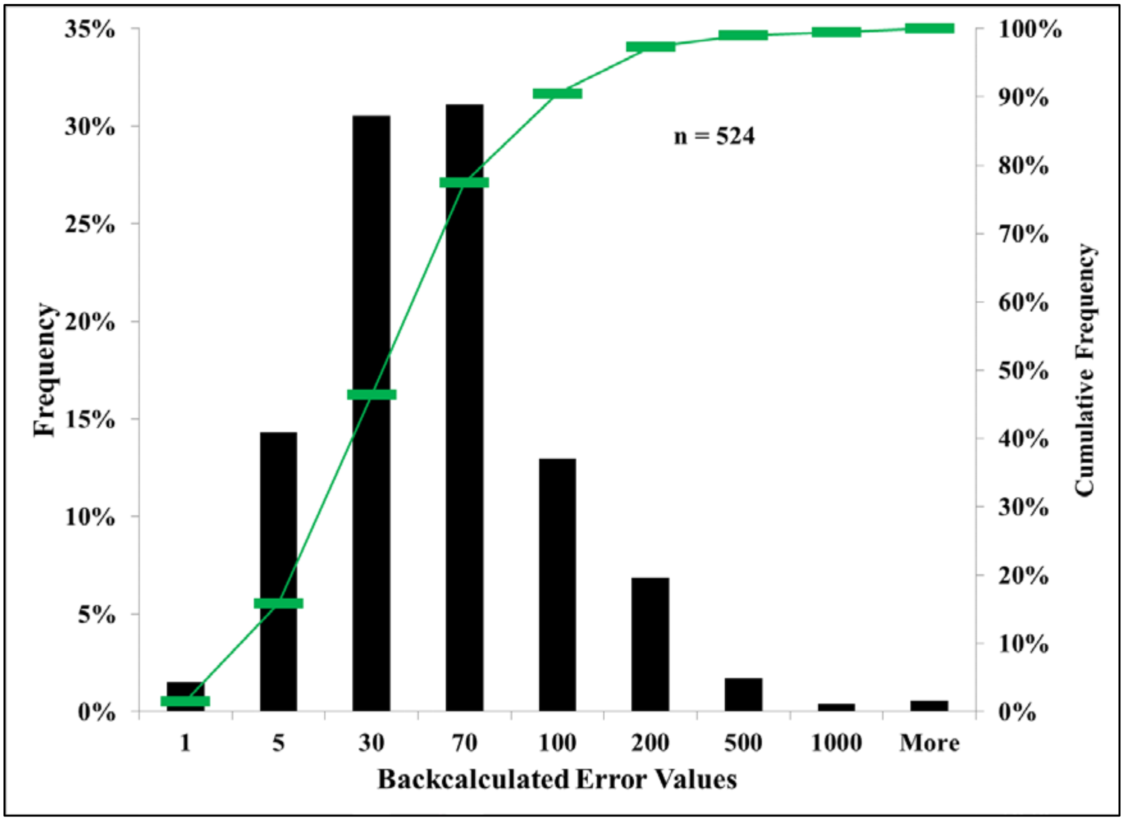

Figure 5.10 – J3 Backcalculation Error-of-Fit Distribution for Qualifying SPS-2 Sections

Figure 5.10 illustrates the distribution of error values for the collection of the final J3 records by section average. It is observed that around 90% of the sections have an error-of-fit of less than 100.0. It was determined that the remaining 10% of sections with average error-of-fit values exceeding 100.0 contained erroneous measurements and were not fit for this analysis. Therefore, the final count of qualifying sections was reduced to 474 unique records for results from the slab-edge location.

By the same extensive filtering process, the slab-center records were reduced to 574 unique records. Finally, the remaining records for the slab-center and slab-edge location were linked across the combination of unique identifiers, test section ID and test date.

This query led to a 395 unique test records that are used for comparing the backcalculated results across all pavement types for the slab-edge versus slab-center test position. In this study, the backcalculated k-values are averaged by section and test date and then plotted against each other by base type along with the average of the ratio of k_e/k_i. Results are divided up by base type and shown in Figure 5.11 and Figure 5.12.

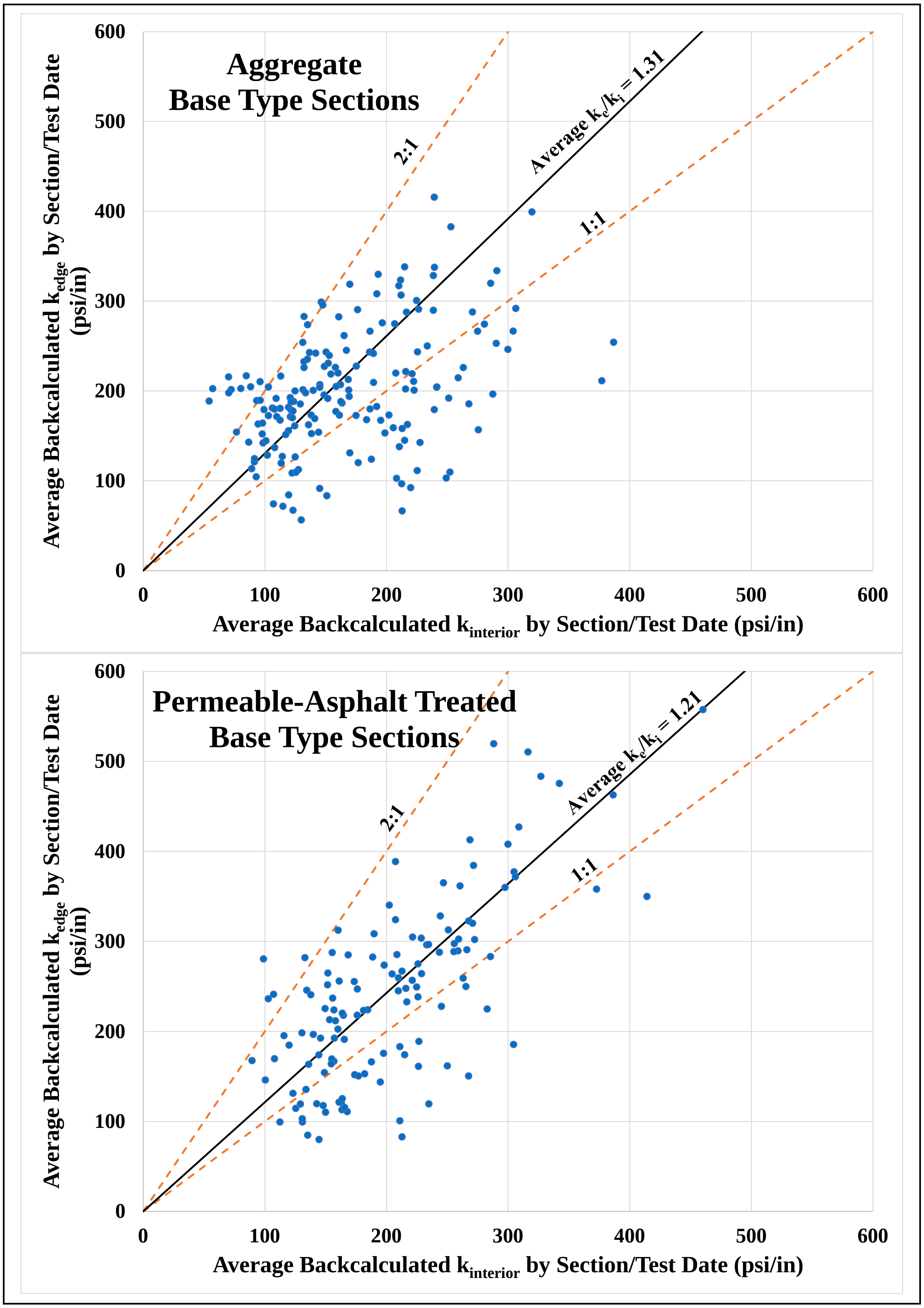

Figure 5.11 – Backcalculated k_e/k_i for LTPP Data Sections for Two Base Types

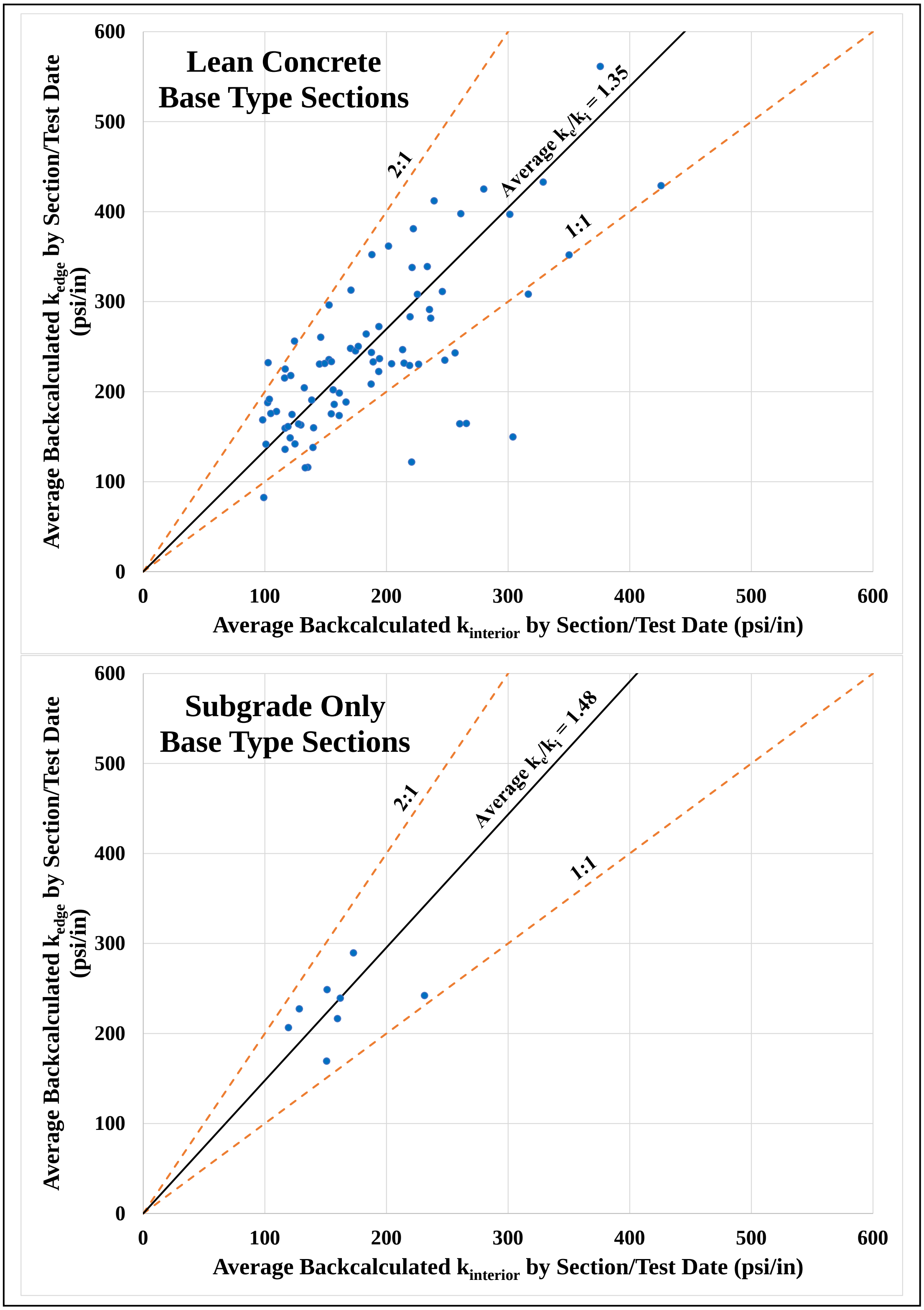

Figure 5.12 - Backcalculated k_e/k_i for LTPP Data Sections for Two Base Types

There is no significant difference in the results observed across base types based on Figure 5.11 and Figure 5.12; however, the results are different from Uzan's results in which the k_e/k_i values ranged from 2 to 4, in general (Uzan 1992). Instead, our data shows an average ranging generally from 0.75 to 2.0, in general, across all base types. It should be noted that the results found differ from the results of previous studies conducted using now less modern technology.

6 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

In this study, a modified, edge backcalculation procedure was developed, verified, and validated. The new procedure accounts for the effects of edge loading, presence of joints, and finite slab sizes in rigid pavements using a finite element analysis program (ISLAB2005). In addition, the new procedure was tested to compare the pavement parameters backcalculated using slab-edge deflection basins to those parameters calculated using slab-center deflection basins.

A comprehensive field study was performed using data on numerous, specially selected deflection basins extracted from the LTPP database (InfoPave™). In particular, under-utilized FWD measurements recorded at the pavement edge (J3 location) and joints (J4 and J5 locations) were backcalculated. The results of the study revealed that the ratio of the edge-to-center coefficient of subgrade reaction varies from 1.0 to 2.0, in most cases, regardless of the base type. This analysis demonstrated the applicability of the newly developed procedure for characterizing in-service rigid pavements. It also validated that pavement properties are not constant within individual slabs, let alone across an entire section.

The new edge backcalculation method developed in this study was successful for controlled, artificial data tests, and it was proven to perform well as a tool to investigate properties of in-service pavements. Overall, the new method is robust and reliable for interpreting edge FWD deflection basins near the middle edge of PCC pavements, a value that has traditionally been difficult to interpret. This backcalculation tool is valuable for the assessment of pavement life and future research related to prolonging the life of PCC pavements.

For future research, it is recommended that the edge backcalculation method be improved to account for a variety of pavement geometries. In addition, other slab sizes should be considered and multi-layered pavements should be accounted for by incorporating the interfacial bond between the surface layer and base layers.

In previous attempts to account for variable slab geometries, Crovetti suggested effective length factors but his progress was limited by a lack of computer power. But now with faster computer power, the effective length factors can be replaced by theoretically-based solutions, such as FEM. If such steps are taken, the sensitivity of the pavement geometry on the backcalculation results should be analyzed.

In regard to accounting for multi-layered pavements, the number of layers in the base model could be increased to three layers to represent the majority of real pavements in the field. Although a three-layered pavement structure may add complexity to the analysis method, it would be preferable to replace the effective subgrade stiffness value with two explicit values such as E_{base} and a k-value for the subgrade only.

Lastly, an in-depth evaluation of the interfacial bond between the PCC layer and the base layer could be performed with a three-layered base model by using an additional friction coefficient to improve the capabilities of the newly developed model. Currently, the new edge backcalculation method only considers a full-slip surface between the PCC layer and the effective subgrade layer. This friction-based modification would enable a long-term and short-term structural analysis based on the bond interaction between the surface and base layers over time.

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