

Prediction of Longitudinal Fatigue Cracking in Rigid Pavements using *RadiCAL*

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Abstract

The capability of the software program *RadiCAL* to predict longitudinal fatigue cracking in jointed plain concrete pavements (JPCP) was studied to assess several sections in multiple climatic regions in California. *RadiCAL* fatigue cracking predictions were compared against measured distresses using the Caltrans' pavement management system. Using this approach, *RadiCAL* was able to correctly predict zero or near-zero longitudinal cracking in newer JPCPs. The predictive performance for older JPCPs was variable and dependent upon defining proper input variables, including built-in curl and the concrete's flexural strength. Issues such as random joint spacing and skewed joints complicated analyses for some sections as well. The challenges and solutions to using an existing pavement management system database for verification and eventual calibration are also described. This design verification stage of *RadiCAL* will help develop future versions of the software, as transfer functions between stress, damage, and cracking will be further enhanced to align with measured distresses in the state.

Introduction

The pavement design methods used in California and most of the U.S. for the past fifty years have been empirical in nature. While these empirical methods have generally served pavement designs well, they are severely limited in their ability to effectively consider increased traffic volumes, increased, axle weights, different axle configurations, climatic influences, and the development of new pavement materials.

As part of the ongoing development of mechanistic-empirical design procedures for the state of California, the California Department of Transportation (Caltrans) has evaluated the Mechanistic-Empirical Pavement Design Guide (*MEPDG*) (*MEPDG* 2007) jointed plain concrete pavement (JPCP) design program and is using California-specific data to validate the results it produces to calibrate where necessary. One important capability that the *MEPDG* currently lacks is the ability to predict longitudinal cracking in JPCP pavements. Longitudinal cracking is common in California and other western states, while it is less prevalent in much of the rest of the United States. Climate is the

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primary reason for this difference. Western states have climates that are arid during the hottest times of the year in comparison with mid-western and eastern states that are more humid during this season. Even within California, the same JPCP designs will perform differently depending on the climatic region in which they are constructed. In some areas of California, the extent of longitudinal cracking is similar to that of transverse cracking (Harvey et al. 2000). However, some studies have shown that while longitudinal cracking exists, transverse cracking is predominant in the state (Smith et al. 1998). Anecdotal, it also appears that longitudinal cracking may appear before transverse cracking in dry regions of California (most of the state). Therefore, it is important to have the capability to model and predict the effects of design and construction practices on longitudinal cracking performance of JPCPs. This capability also provides information for prediction of future maintenance needs for the state's pavement management system (PMS).

The University of Illinois, with partial funding from Caltrans through the University of California Pavement Research Center (UCPRC), developed a mechanistic-empirical analysis model to help researchers and designers understand the particular material, environmental, construction, traffic, and design factors causing longitudinal cracking in JPCP. The model was based in part on Caltrans-funded original research at the UCPRC (Heath et al. 2003). The model was incorporated into a software program called *RadiCAL* (*Rigid Pavement Analysis for Design in California*) (Hiller and Roesler 2005) to predict longitudinal and transverse fatigue cracking in JPCP under a variety of design features, environmental, and loading conditions.

To provide data necessary for the calibration of *MEPDG* and the field verification of *RadiCAL*, as well as to better understand the current condition of the rigid pavements in California, materials samples and structural data on JPCP and crack, seat, and asphalt overlay (CSOL) sections throughout California were collected. A total of 50 concrete sections and 43 CSOL sections were sampled. Additionally, the UCPRC extracted and analyzed cracking performance data to combine with the field data for the validation/calibration exercise.

The field verification process required measurement, collection or estimation of the following data for each of the existing sections: joint spacing, slab thickness, climate region, coefficient of thermal expansion, percent slabs cracked, load spectra, truck configurations, and slab flexural strength. Once these data were collected, it was used with *RadiCAL* to compare between the predicted fatigue damage and the cracking data from the PMS. Correlations were then developed relating damage to actual field performance. Details of this process are presented in (Signore et al. 2008). This process was also used for calibration of the *MEPDG* rigid pavement models for transverse fatigue cracking and faulting as described in (Kannekanti and Harvey 2007a).

This paper will briefly discuss the longitudinal cracking mechanism in JPCP and the use of *RadiCAL* to verify measured field performance. *RadiCAL*'s capabilities to predict longitudinal cracking in JPCP and specifically how *RadiCAL* can predict varying longitudinal cracking performance under multiple environmental conditions will also be presented.

Longitudinal fatigue cracking mechanism

The mechanics of longitudinal fatigue cracking of JPCPs, specific to the western United States and other dry climates, have eluded pavement engineering researchers and practitioners for many years. Longitudinal cracking is caused by a combination of environmental, material, and traffic factors in conjunction with geometry and restraint of slabs. As a JPCP slab's top surface becomes warmer or wetter than its lower surface it expands and slab corners bend downwards. Conversely, as the JPCP slab's top surface cools or becomes drier than its lower surface, it contracts, bending the slab corners upwards. This bending is commonly called warping if due to changes in slab moisture and curling if due to changes in slab temperature.

A JPCP slab possesses considerable self-weight that counteracts these curling/warping tendencies, which results in bending stresses within the slab. When a slab curls/warps downward, its center is unsupported, creating tensile stresses at the bottom center of the slab where its weight pulls downward. When a slab curls/warps upward, tensile stresses occur at the top of the slab as the weight of the slab edges pull down. This stress-reversal process continues throughout the life of a slab as it is exposed to cycles of temperature and moisture change.

After placement, JPCP slabs start to dry and shrink due to the environment and the formation of cementing products that are of smaller volume than their constituent parts (autogenous shrinkage), affecting the entire slab thickness.

As shrinkage causes slabs to crack at their respective joint-relief cuts, they become freer to curl and warp. Due to this phenomenon, undowelled slabs are freer to move than those restrained by dowels. Asymmetric bending can occur if one transverse edge of a slab is more restrained than another. This can be due to late cracking at one saw joint compared to another or to different levels of joint restraint from load transfer devices or aggregate interlock.

The magnitude of total curl varies with cyclical temperature and moisture gradients in the slab, but a certain level of permanent built-in curl always remains (Hiller 2007). The hot dry summer conditions in the arid western states cause greater shrinkage on the top of JPCP slabs than on the bottom, which results in upward curling of the slab corners. Irreversible shrinkage in the top 50-100mm of the concrete slab, as well as the built-in temperature gradients during the setting of concrete, causes a majority of pavements to curl permanently upward regardless of the cyclical temperature gradient (Hiller 2007).

The degree of permanent upward slab curl caused by differential drying shrinkage, built-in construction curl, and other factors can be described in terms of an equivalent temperature differential (top to bottom) that would cause a plane/flat slab to curl to the same extent; hence the term effective built-in temperature differential (EBITD). The more negative the EBITD value, the greater the permanent upward curl at the corners of the slabs, and hence the greater surface temperature increase required to flatten the slab.

Backcalculations from full-scale test results from the desert climate of Palmdale, California suggest that the levels of permanent curl in terms of a linear EBITD can exceed -22°C for undoweled slabs (Rao and Roesler 2005a), although those values are an extreme case. During the course of a day, curling stresses working in a typical slab force its corners to curl both upward and downward. However, in some environments and for slabs with highly negative EBITD values (corners curled up as if the slab's top is colder

than its bottom), downward curling never occurs, leaving these slabs with permanent upward curl. Interaction between EBITD and a number of other factors, including slab thickness, traffic load spectra, environment, joint load transfer, and other variables, can lead to longitudinal cracking. Slabs in these upward curled conditions or slabs with shorter joint spacing are more prone to longitudinal cracking and corner cracking (Hiller 2007) due to the unsupported corners and reduced bending stress at the mid-slab edge location.

The traditional mechanics model (Westergaard 1948) states that the underside of the longitudinal mid-slab edge has the highest stresses due to wheel loading with the wheel at the mid-slab edge and daytime temperature gradients (warmer on top than bottom). While this model is correct for mid-slab edge loading situations, it is *incomplete*, particularly for slabs that possess a degree of residual curling. It thus becomes difficult to determine the exact location of highest slab stress (Hiller 2007). The highest-stress location is highly dependent upon axle configuration and degree of slab curvature, which contribute to the presence of significant longitudinal cracking in dry environments. The mid-slab, bottom-up cracking model must be supplemented by additional factors that account for slab curling and various axle load configurations, which lead to multiple high stress locations on a JPCP slab. For slabs with upward curled corners that are unsupported, a corner wheel loading may be the highest stress location, thereby causing top-down longitudinal fatigue cracking between loaded areas of an axle.

Overview of RadiCAL. *RadiCAL* was developed as a response to the current understanding that concrete fatigue failure is a far more complex process than that described by the classic Westergaard cracking mechanism. In developing *RadiCAL*, Hiller and Roesler (Hiller and Roesler 2008b) first computed stresses in JPCP using finite element analysis (FEA) ISLAB2000 (ERES-Consultants 1999) using a wide range of physical, environmental, and loading conditions typically found in California and other western states. *RadiCAL* uses these FEA solutions in conjunction with statistical distributions of inputs such as traffic classifications, load spectra, axle spacing distributions, and climatic influences as well as direct design parameters such as traffic counts, built-in curl level, slab geometry, load transfer level, etc., to determine fatigue damage for numerous locations within the concrete slab. *RadiCAL* also has the ability to analyze pavements using several fatigue transfer functions with linear or multiple non-linear temperature profile options.

RadiCAL is programmed to simulate the movement of a vehicle's wheels as it travels across a slab for a given axle load or combination of axle loads, while performing a series of static calculations for each load location (or *node*) along the slab. Damage is computed for up to 89 nodes along each slab edge, with the spacing between nodes dependent on the geometry of the slab. A typical output from *RadiCAL* is shown in Figure 1 showing predicted damage accumulated along the transverse joint. Critical damage locations are indicated by the maximum damage levels along either the transverse joint (indicating longitudinal cracking potential) or the longitudinal edge of a slab (indicating transverse cracking) for both top-down and bottom-up fatigue cracking mechanisms. By examining the level and location of these critical stresses, the likelihood of longitudinal and transverse fatigue cracking can be determined at locations and by causes not predicted using traditional theories involving mid-slab edge/bottom-up fatigue.

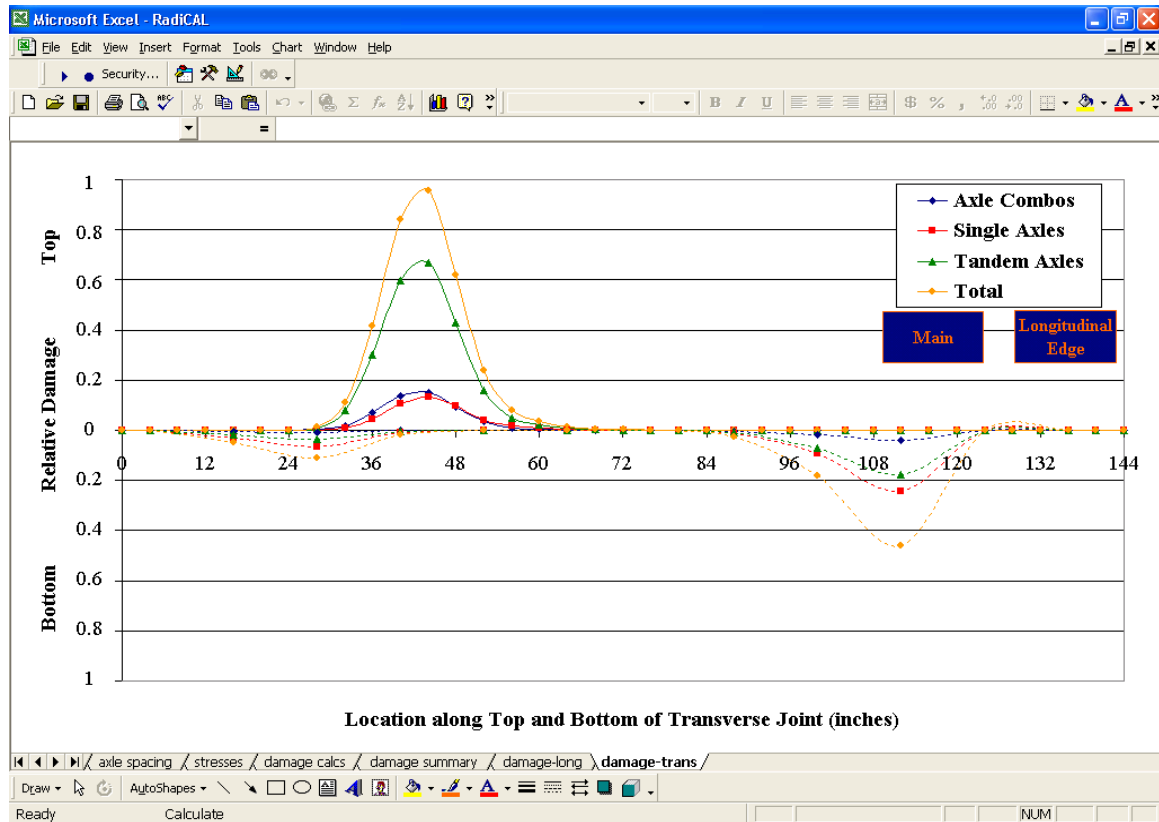


Figure 1. *RadiCAL* output screen showing relative damage values and locations (1 inch = 2.54cm).

EBITD is a primary input parameter to *RadiCAL*, although it is important to note that EBITD for a given JPCP slab cannot be known with certainty in advance by a designer. Instead, it must be estimated based on information from previously constructed pavements using deflection tests with a falling-weight deflectometer. Deflection tests can be performed to backcalculate EBITD, determine joint load transfer and estimate layer stiffnesses for an existing pavement slab or series of slabs using the process developed by Rao and Roesler (2005b). In the EBITD backcalculation process, the pavement structure is modeled with a FEA using the load transfer efficiencies and moduli backcalculated previously as inputs. Comparisons are made between the measured slab deflections and those calculated by FEA at various temperatures for a number of assumed EBITD values. The EBITD value for a given pavement is the one that produces the best fit to field slab deflections, as measured by residual sum of squares analysis.

Once appropriate EBITD values are determined, the user can run *RadiCAL* for various structural sections and input parameters to calculate damage. The calculated damage is used with fatigue cracking transfer functions to estimate the performance of JPCP design sections. In this paper, fatigue cracking factors using cracking densities/percentages from field surveys will be compared to damage values predicted from *RadiCAL*.

Data Collection and Preparation

For this study, all of the California JPCP sections were undoweled as was typical for past designs in the state. Slab and base thicknesses and concrete compressive strengths were determined from cores taken on the sections, which had been in service for many years. Flexural strengths were estimated from the compressive strengths using American Concrete Institute correlations (ACI-318 2008).

The coefficient of thermal expansion (CTE) was measured on the cores following a modified AASHTO TP 60 procedure (AASHTO 2005). Truck traffic data was taken from Caltrans databases, including truck counts and in some cases Weigh-In-Motion (WIM) data. Slab lengths were measured in the field for concrete sections or estimated from historical data for sections that had been overlaid. Details regarding field data collection are documented in (Kannekanti and Harvey 2007b).

Deflections were measured on many sections. However, lack of sufficient measurements at different temperatures and uncertainty with regard to the location of joints under overlaid sections made backcalculation of stiffness and EBITD difficult. Concrete slab stiffnesses were estimated from compressive strengths, and EBITD values were assumed for the sections included in this study. Joint load transfer efficiencies were evaluated using collected deflection data.

Cracking performance data was extracted from historical Caltrans PMS data and verified by field observations for the sections that had not been overlaid. Specific information regarding how this data was extracted from the PMS appears in (Kannekanti et al. 2007).

Within the Caltrans PMS, slab cracking is reported as a percentage of cracked slabs for the following three types of cracks:

- *First-stage cracks* (FSC) are transverse, longitudinal, or diagonal cracks that do not intersect and which divide the slab into two or more large pieces.
- *Third-stage cracks* (TSC) are interconnected cracks that divide the slab into three or more large pieces. Fragmented slabs are characterized by interconnected, irregular multiple cracks and breaks. By definition first-stage cracking and third-stage cracking cannot exist in the same slab.

To utilize Caltrans PMS historic performance data for this study, the FSC and TSC cracking data had to be converted to longitudinal cracking. By definition, an FSC can be either transverse crack (TC) or longitudinal crack (LC), but cannot be both. Therefore, there can be two possible scenarios:

- *Scenario 1: All FSCs are longitudinal cracks.* TSC by definition has both transverse and longitudinal cracks and therefore is added to FSC to get the percentage of longitudinal cracks. In this case, total longitudinal cracking is equal to the sum of FSC and TSC.
- *Scenario 2: All FSCs are transverse cracks.* In this case, total longitudinal cracking is equal to TSC only.

Scenario 1 gives the maximum possible longitudinal cracking ($LC_{\max} = \text{FSC} + \text{TSC}$) and Scenario 2 gives the minimum possible longitudinal cracking ($LC_{\min} = \text{TSC}$).

In reality, FSC will be a combination of some slabs with transverse cracks and some slabs with longitudinal cracks. Therefore, the true percentage of slabs with longitudinal cracking that occurred on the section will always be between this maximum and minimum. For many sections that had been overlaid, this was the best way to estimate the previous amount of longitudinal cracking as this value is not expressly recorded in the Caltrans PMS. Consequently, many of the following figures show both minimum and maximum cracking measured to demonstrate the target range of longitudinal cracking.

RadiCAL Field Verification

The field verification process consisted of comparing and correlating measured field performance to damage values calculated by *RadiCAL*. *RadiCAL* calculates both top down (TD) and bottom up (BU) damage at numerous locations. A transfer function was required to correlate the longitudinal damage calculated by *RadiCAL* to the percent slabs cracked in a pavement section. Equation (1) has been taken from the *MEPDG* (MEPDG 2007), which converts “damage” into a cracking factor (CRK) using the same FEA program as *RadiCAL* for development of its stress prediction algorithm. Two CRK values are computed, one based on top-down (TD) and one on bottom-up (BU) damage. Equation (2), also from the *MEPDG* (MEPDG 2007), converts the TD and BU cracking factors into percent slabs cracked. These formulas were used in this study to determine percent slabs cracked based on *RadiCAL* damage calculations, which utilized the same fatigue transfer function (equation 3) and Miner’s Hypothesis (Miner 1945) for fatigue damage accumulation as the *MEPDG* for this analysis. The damage values, DI_F , computed by *RadiCAL* vary depending on pavement dimensions, traffic, environment, and other input parameters for each pavement test section included in this study.

$$CRK = \frac{1}{1 + DI_F^{-1.98}} \quad (1)$$

Where: CRK = Predicted amount of bottom-up or top-down slab cracking (fraction)
 DI_F = Fatigue damage level after design period using Miner’s Hypothesis for linear fatigue damage accumulation

$$CRACK = CRK_{BU} + CRK_{TD} - CRK_{BU} \times CRK_{TD} \quad (2)$$

Where: CRACK = Total amount of transverse or longitudinal cracking (%)
 CRK_{BU} = Predicted amount of bottom-up cracking (fraction)
 CRK_{TD} = Predicted amount of top-down cracking (fraction)

$$\text{Log}(N) = 2.0 \left(\frac{MOR}{\sigma} \right)^{1.22} \quad (3)$$

Where: N = Number of repetitions to failure
MOR = Modulus of rupture of the concrete
 σ = Applied maximum stress level at particular node

Longitudinal cracking prediction and analysis

While eight different JPCP sections were analyzed with *RadiCAL* for this project, the results from four pavements in three different climate regions are presented.

1. Interstate 80 through Solano County in the central valley climate region
2. Highway 101 through Santa Barbara County in the south coast climate region
3. Highway 58 through Kern County in the central valley climate region
4. Highway 86 through Imperial County in the desert climate region

The basic experimental design and number of *RadiCAL* runs for each pavement in addition to *RadiCAL* input parameter limitations are shown in Table 1. A consistent process was used to predict longitudinal cracking for each pavement. Input parameters were selected, *RadiCAL* was run and the results compared to measured field performance. *RadiCAL* currently offers eight different options for fatigue analysis. The results presented here were obtained using the *MEPDG* fatigue function with non-linear temperature profiles using the Non-linear area (NOLA) method (Hiller and Roesler 2008a; Hiller and Roesler 2009). Analysis was performed assuming a constant EBITD value of -6°C.

Table 1. *RadiCAL* input parameters.

Input Parameter	Options		Value selected for analysis
(1) Pavement life (age at time of analysis)	0, 5, 10, 20, 30, 40 years or yearly		As appropriate for age at analysis
(2) Two-way Year 1 AADTT	Value depends on analysis period		Depends on analysis period
(3) Climate region	Bay Area Central Valley High Desert	Desert Low Mountain North Coast South Coast	As appropriate
(4) PCC thickness	20, 25, or 30 cm		As appropriate, or interpolated if different thickness
(5) Lane width	3.8 m		3.8 m
(6) Joint spacing	3.8 m, 4.8 m		If not 3.8 m or 4.8 m., closest value to actual is selected or interpolated with multiple runs
(7) Shoulder type	Tied PCC or Asphalt Concrete (AC)		AC
(8) Modulus of rupture (MOR)	As measured		As measured/adjusted for time period of interest
(9) Transverse joint load transfer (LTE)	20, 50, 70, or 90%		20% or 50% due to lack of dowel bars for load transfer
(10) EBITD	-22°C to 0°C		-11°C, -6°C, -3°C, -0°C

Due to several issues, Caltrans now promotes the use of dowel bars and less rigid bases, which will help reduce the level of EBITD in their JPCPs. While many of the pavement structures analyzed in this study are no longer constructed by Caltrans, the use of *RadiCAL* to verify the longitudinal cracking mechanisms from these sections helps validate the software as a mechanistic tool for all types of fatigue cracking.

I-80 Solano. Interstate 80 (I-80) was constructed in 1965 with 20 to 25cm JPCP slabs over a 10cm CTB base. Two-way AADTT varied from approximately 3,500 at 10 years to 8,000 at 40 years. PCC flexural strength was consistently calculated between 1.45 to 5.0MPa, with one section at 3.52MPa. Joint spacing varies from 4.2m continuous to 5.2m/3.6m alternating. For the *RadiCAL* analysis, 4.5m joint spacing was used. It should be noted that joint spacing has a significant non-linear effect on the predicted fatigue damage for both transverse and longitudinal cracking. While 4.5m is a good representation of the average joint spacing, smaller (or larger) individual slabs may perform differently than the average slab dimension.

Figure 2 shows yearly predicted and measured longitudinal percent-cracked-slab-levels versus pavement age for Sections 248 and 255, two of nine examined. There are two measured cracking values, which were taken from the Caltrans database. Due to uncertainty about the actual percentage of cracked slabs in the field, minimum and maximum longitudinal cracking estimates are shown as described previously. Based on the damage-to-cracking transfer functions (Equations [1] and [2]), for five sections *RadiCAL* predicted reasonable percent-slabs-cracked estimates. For the remaining four sections, an uncalibrated *RadiCAL* program tended to underpredict longitudinal cracking.

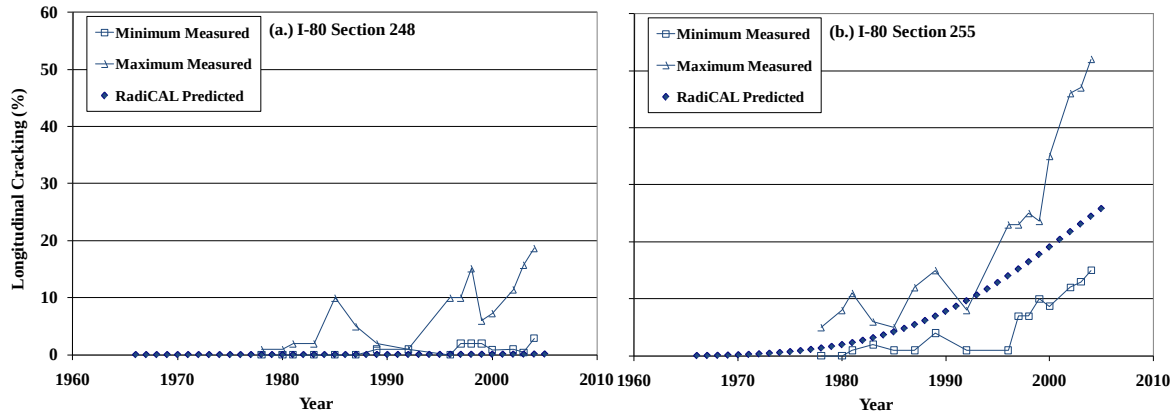


Figure 2. Predicted and actual longitudinal percent cracked slabs versus year for (a.) I-80 Section 248 and (b.) I-80 Section 255.

US-101 Santa Barbara. US-101 through Santa Barbara was constructed in 1958 and originally consisted of 20 to 22cm JPCP slabs with 4.6m joint spacing. In 1993, this pavement was cracked, sealed, and overlaid with 10 to 13cm of asphalt concrete. The initial two-way AADTT was approximately 1800 for two sections examined and 900 for the remaining four sections. Flexural strengths ranged from 4.14 to 4.83MPa. Coefficient of thermal expansion of the PCC ranged from 10.55 to $10.87 \times 10^{-6}/^{\circ}\text{C}$.

Figure 3 presents annual predicted and measured longitudinal percent cracked slabs versus pavement age for sections 300 and 303. *RadiCAL* significantly

overpredicted percent cracked slabs for section 300 due to the reduced flexural strength found from concrete samples in those sections, while correctly predicting cracking for section 303. *RadiCAL* predicted distress consistent with the varying estimated flexural strength of the sections. The remaining sections generally showed overprediction in percent cracked slabs when lower flexural strength correlations were used. Better accuracy of the predictions would be expected using higher strengths in the *RadiCAL* program.

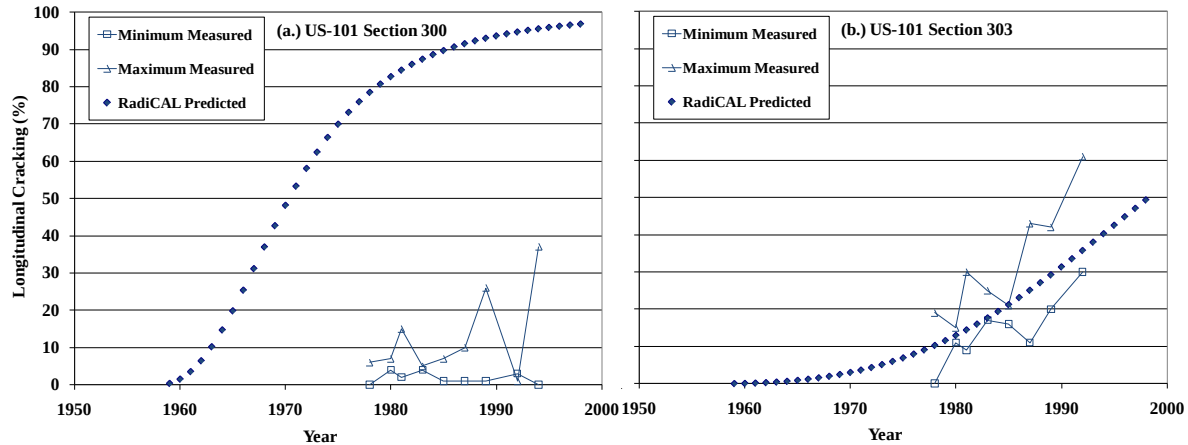


Figure 3. Predicted and actual longitudinal cracking versus year for (a.) US-101 Section 300 and (b.) US-101 Section 303.

SH-58 Kern. State Highway 58 (SH-58) through Kern County was constructed in 1961 as 21cm thick JPCP slabs with 4.5m joint spacing. It was overlaid with 6cm asphalt concrete after cracking and seating in 1992, therefore cracking data only exists until this time. Two-way AADTT ranged from approximately 2600 at ten years to 4700 at thirty years. Flexural strength calculated from compressive strengths of field cores ranged from 4.0MPa to 4.55MPa.

Figure 4 presents the predicted and measured longitudinal percent slabs cracked versus pavement age for sections 423 and 427 on SH-58. While *RadiCAL* predicts longitudinal cracking within the maximum/minimum band from the available PMS data, the program overpredicts the amount of longitudinal cracking seen in Section 427 for a lower flexural strength section. Another major factor that may lead to this overprediction is the lack of a site-specific EBITD value, which is very sensitive to fatigue cracking prediction (Hiller and Roesler 2008b).

Figure 5 shows the predicted versus measured percent longitudinal slabs cracked for all sections analyzed over time. *RadiCAL* accurately predicted the slab cracking for Sections 423, 424, and 425 (MOR ranging from 5.24 to 5.34MPa), while overpredicting fatigue cracking for Sections 426 and 427 (MOR ranging from 4.70 to 5.03MPa). In general, the *RadiCAL* program predicted longitudinal cracking well for the sections with higher measured flexural strength in most cases. Further confirmation of concrete flexural strengths in addition to calibration of the fatigue cracking prediction model may help remedy these differences between predicted and actual cracking performance.

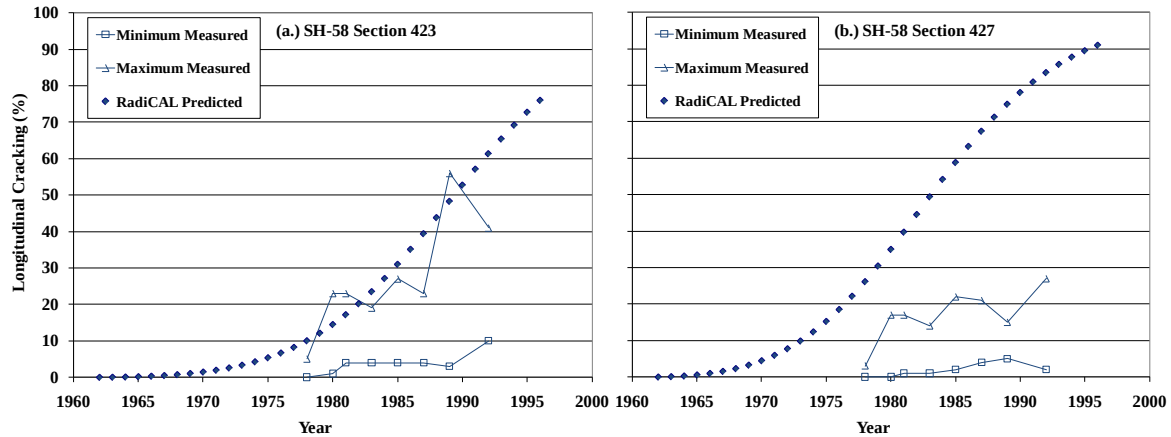


Figure 4. Predicted and actual longitudinal cracking versus year for (a.) SH-58 Section 423 and (b.) SH-58 Section 427.

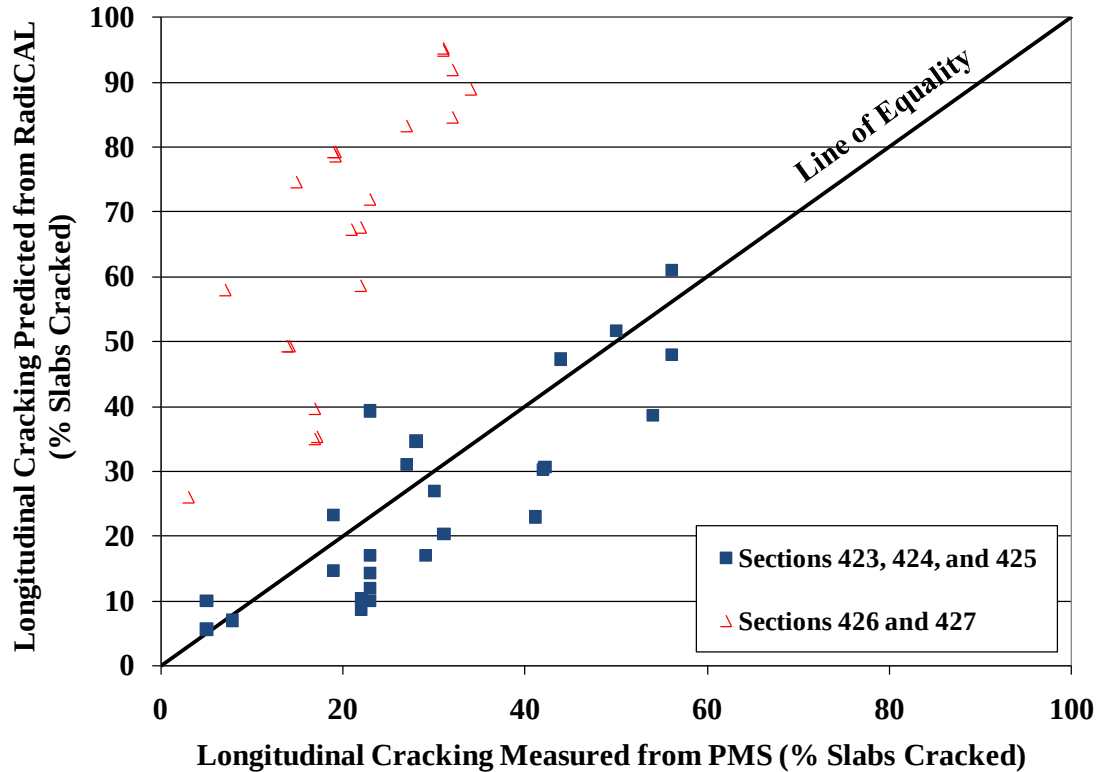


Figure 5. Predicted versus actual longitudinal cracking for all SH-58 sections.

SH-86 Imperial. State Highway 86 (SH-86) through Imperial County was constructed in 1994. It consists of 20 to 25 cm thick JPCP slabs with a joint spacing of 4.2m, and a 10 to 15cm asphalt concrete base. Joint spacing of 4.5m was used as an input in *RadiCAL*. Initial two-way AADTT was 1750. PCC modulus of rupture calculated from compressive strengths on field cores varied from 4.0 to 4.4MPa.

Figure 6 presents the predicted versus measured longitudinal percent cracked slabs versus pavement age and various EBITD levels. The upper of the pairs of points represents 20 percent load transfer, the lower point represents 50 percent as these pavement were undoweled and typically had low load transfer efficiencies. For lower EBITD values, *RadiCAL* correctly predicted the level of longitudinal slabs cracked, while larger EBITD values lead to poorer predicted values for this section.

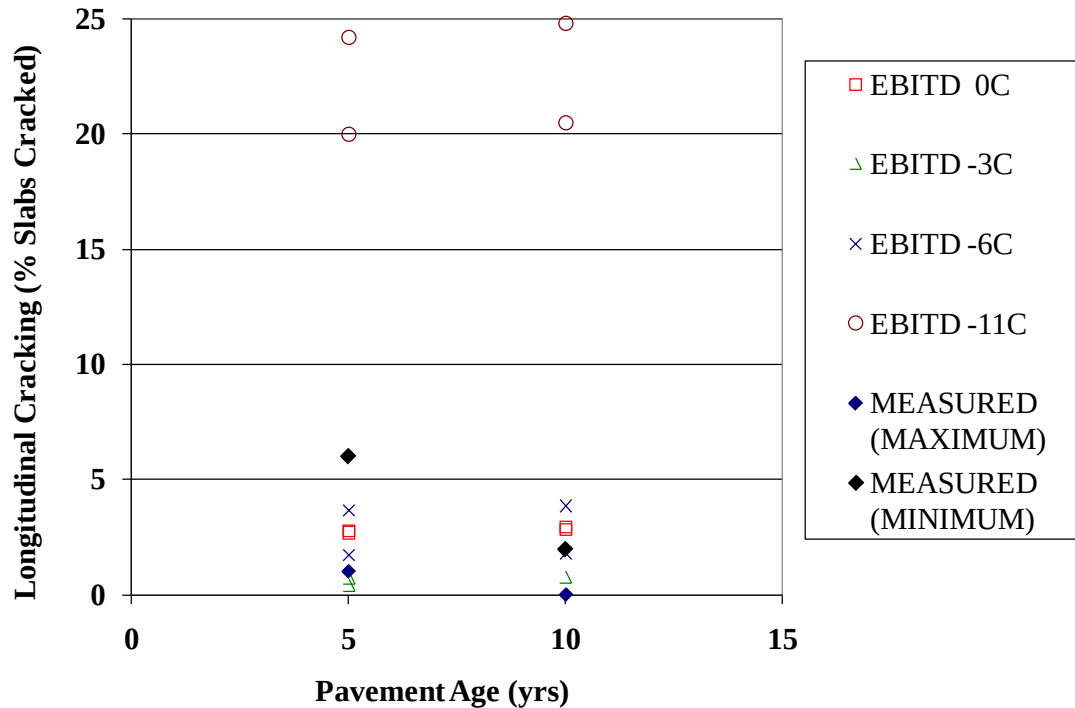


Figure 6. Sensitivity analysis of predicted and actual longitudinal cracking versus age for SH-86 Section 636.

Network-Level EBITD Value

Similar comparisons of measured and calculated cracking performance for different assumed values of EBITD for other sections were included in (Signore et al. 2008). Due to variation in predictive performance among the sections studied, it was therefore intuitive to combine all the data from this study into one group to determine an “optimum” EBITD value for designers to assume for JPCP pavements in California. Two issues were readily apparent: (1) in general, *RadiCAL* tended to overpredict the amount of longitudinal slab cracking; and (2) the accuracy of the prediction is highly dependent upon the value of EBITD used for analysis. It must be noted that this consistent overprediction may in part be due to the fact that these comparisons have been made against visual field measurements and that no records or account of slab replacement due to slab cracking were available. Therefore the levels of overprediction may be overstated and could be rectified through a calibration process of the transfer function in *RadiCAL*.

A sum-of-squares analysis was performed to determine the EBITD value for use with *RadiCAL* that produces longitudinal cracking performance estimates that most closely match measured performance, Figure 7 shows a box-and-whisker plot of the

difference between predicted and measured longitudinal cracking versus EBITD value used for analysis. The top and bottom of the solid bar represent the 75th and 25th percentile measurements respectively. Therefore, in general, the larger the solid bar, the greater the variation in prediction of the middle half of the data. The white bar in the center of the solid bar is the median (50th percentile) measurement. Therefore, the closer the center of the solid line is to zero, the more accurate the prediction. The lines above and below the solid bars, the “whiskers,” represent the extreme values determined from the data. Based on a review of these four sets of data, it is evident that an EBITD value of -3°C produced the most accurate prediction of percentage of longitudinal slab cracking over the course of the pavement lives for these sections studied under the current set of transfer functions in place in *RadiCAL*.

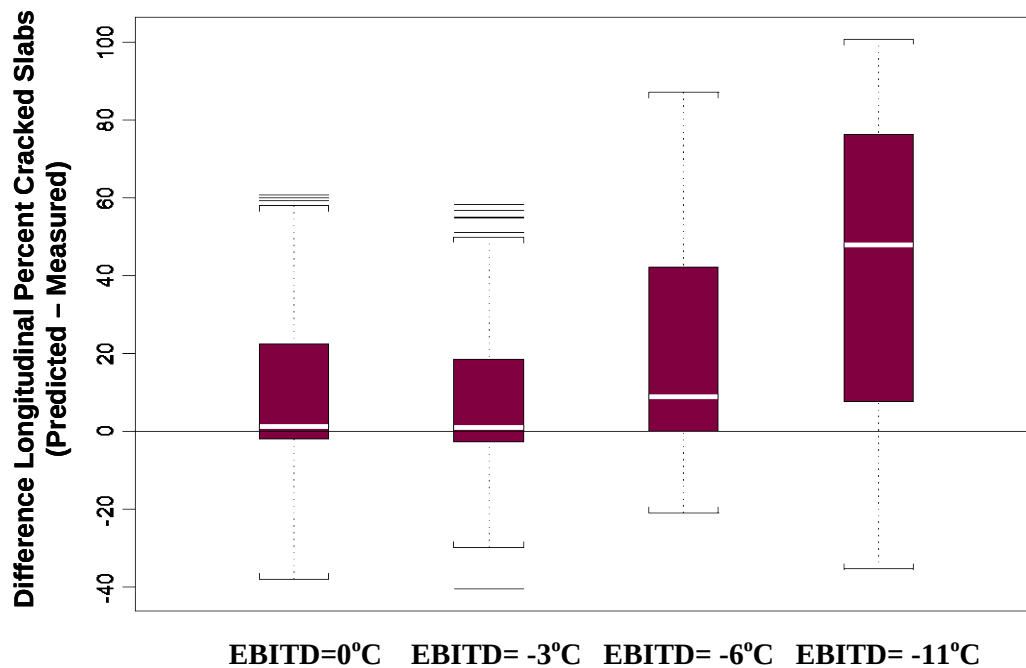


Figure 7. Box plot of accuracy of *RadiCAL* prediction of longitudinal cracking percentages versus EBITD.

While this network-level approach may provide a ballpark number for design, the effects of specific climates, geometries, restraint, curing conditions, and other factors should be considered when designing a joint concrete pavement for a specific project.

Initial Fatigue Cracking Verification

Using the four JPCP routes noted in the previous sections, the fatigue damage predicted by *RadiCAL* was paired with the maximum and minimum longitudinal cracking from the Caltrans PMS as shown in Figure 8. These data points were compared with the MEPDG damage to cracking model presented in equation (1) as shown in the black line of Figure 8. While the plotted data demonstrates a great deal of scatter, a clear trend of increasing longitudinal cracking with damage predicted by *RadiCAL* can be observed that matches the sigmoidal curve from equation (1). This initial verification helps start a more in-

depth look at calibration of the fatigue model and damage-to-cracking model utilized in *RadiCAL* for more accurate predictions of longitudinal fatigue cracking in JPCPs.

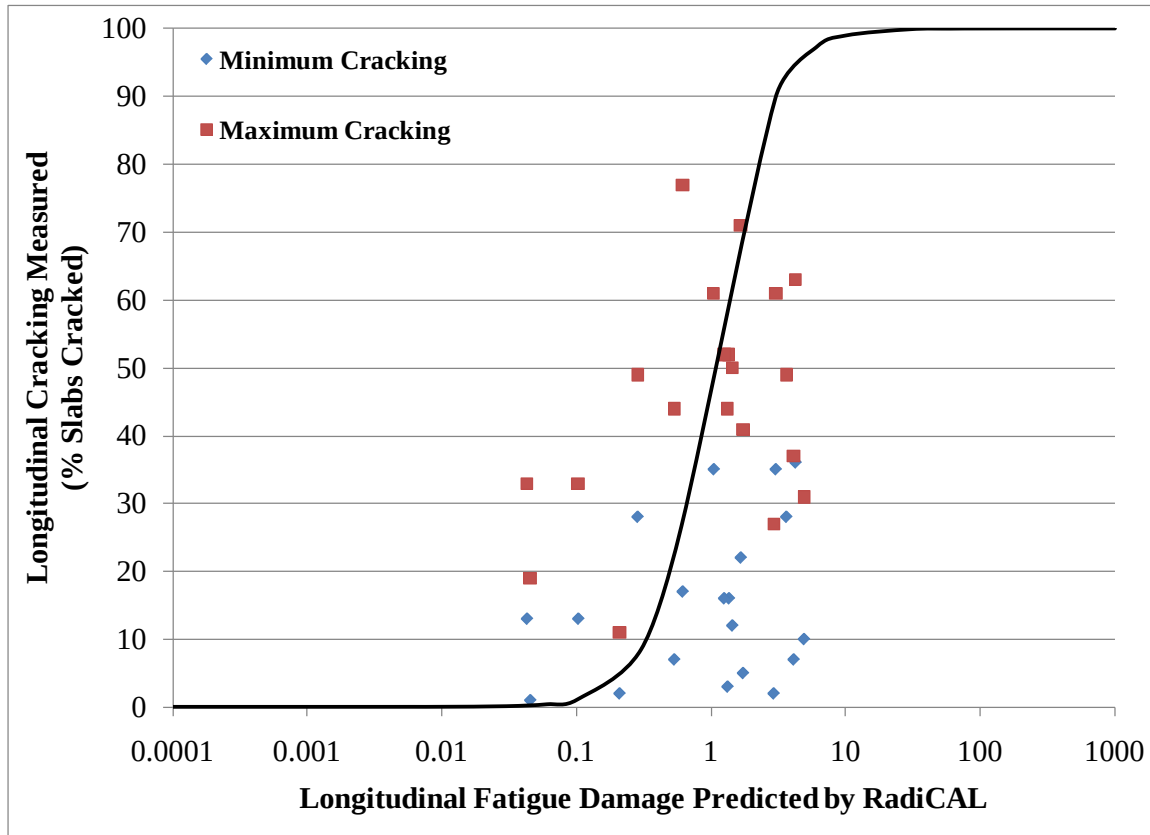


Figure 8. California longitudinal cracking data fitted with MEPDG fatigue calibration function.

Conclusions and Recommendations

A study was undertaken to assess the capability of *RadiCAL* to predict longitudinal cracking in JPCP structures in different climate regions. Over 3,000 *RadiCAL* runs were performed on over forty pavement sections within eight stretches of California highways. Analysis of the pavement sections presented here has shown that the longitudinal cracking predictive capabilities of *RadiCAL* can be accurate. However, the predicted cracking levels are dependent upon a number of critical input factors. *RadiCAL* was able to correctly predict zero or near-zero longitudinal cracking in newer pavements as seen in Highway 86. With the most accurate EBITD values selected, *RadiCAL* was able to predict consistently accurate levels of cracking for periods up to thirty years on I-80, US-101, and SH-58. The accuracy of the *RadiCAL* predictions was also improved for sections with higher concrete flexural strengths, generally above 5MPa. Issues such as random joint spacing, non site-specific EBITD values, and a PMS that does not clearly identify cracking by transverse or longitudinal cracking further complicated this effort.

While *RadiCAL* assesses a broad range of concrete pavement performance parameters, enhancements to future versions should include capabilities to account for localized differences in soils, paving times, slab lengths, and coefficients of thermal expansion. These refinements could address the above mentioned pavement variability

issue and provide insight into the differences in field performance they create. Further calibration and refinement of the program could then be made to enhance its usefulness for predicting longitudinal cracking.

Finally, the authors believe that *RadiCAL* can be used in its present form to supplement designs based upon MEPDG. The latter could be run to find a design that does not fail in transverse cracking and/or faulting, while *RadiCAL* can then be used to check the design's longitudinal cracking performance. A sensitivity analysis for thicknesses and load transfer efficiencies surrounding the expected design values could be performed to see if longitudinal cracking is limited to a maximum value, for example, of ten percent at 30 years. Further calibration of *RadiCAL* will enhance its ability to serve as an independent JPCP design program in the future.

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