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Development of Thin HMA Overlay Crack Initiation and Progression Probabilistic Models

Authors:
Frank Farshidi and John T. Harvey

Work Conducted as part of Partnered Pavement Research Center Strategic Plan Element No. 3.2.5: "Documentation of Pavement Performance Data for Pavement Preservation Strategies and Evaluation of Cost-effectiveness of Such Strategies."

PREPARED FOR:

California Department of Transportation
Division of Research and Innovation

PREPARED BY:

University of California
Pavement Research Center
UC Davis and Berkeley

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Abstract:

This report presents the results of a study to evaluate fatigue cracking performance models for hot-mix asphalt (HMA) overlays placed on existing HMA pavements. Previously, data from the Washington State Department of Transportation (WSDOT) pavement management system (PMS) were used to develop separate models for crack initiation and progression. Later, these two models were combined into a combined model for the entire cracking process. The study presented in this report evaluates the combined model using the limited California PMS data available. This was done to assess the model's ability to predict the performance of HMA overlays of cracked asphalt pavement in California.

An earlier study identified that data in the WSDOT PMS primarily reflects the performance of overlays of 0.15 ft (45 mm) on pavement with low levels of existing cracking. However, a sensitivity analysis performed in this study indicates that the performance trends for California overlays predicted by the model are reasonable.

In a performance comparison of crack initiation between Washington State and California using PMS data from each state, the model underpredicted the performance of California overlays of similar thickness. Although there was insufficient data available to validate the model for crack progression, comparison results indicated that the model likely overpredicts the performance of California overlays for crack progression because of differences in pavement preservation practices conducted by Caltrans and the WSDOT in the late 1990s and early 2000s. As a result, this study recommends performance of a recalibration of the variable coefficients once better California PMS data is available. Revised coefficients would reflect differences in WSDOT and Caltrans practice and conditions, including the use of thicker overlays in California and the historic Caltrans practice of placing overlays at more advanced states of cracking in the existing pavement, California's more benign climate conditions (less rain and fewer freeze-thaw cycles), and possible differences in scheduling of pavement preservation activities. To accomplish these changes, it is recommended that the Caltrans PMS database be populated with information collected over consistently segmented sections, and with accurate information regarding overlay material types and thicknesses of overlays and existing pavement structures.

Keywords:

Performance models, pavement preservation, fatigue cracking, Alligator A cracking, Alligator B cracking

Proposals for implementation:

No recommendation for implementation until model is recalibrated using more complete California PMS data.

Related documents:

- *Development of Empirical-Mechanistic Pavement Performance Models Using Data from the Washington State PMS Database,* by S. Madanat, Z. Nakat, F. Farshidi, N. Sathaye, and J. Harvey. (October 2005). Research report: UCPRC-RR-2005-05
- *Development of an Empirical-Mechanistic Model of Overlay Crack Progression Using Data from the Washington State PMS Database,* by Z. Nakat, S. Madanat, F. Farshidi, and J. Harvey. (December 2006). Research report: UCPRC-RR-2006-15
- *Pavement Performance Data Extraction from the Caltrans PMS,* by V. Kannekanti, C. Lee, L. Popescu, J. Harvey, and W. Nokes. (November 2007). Technical memorandum: UCPRC-TM-2007-06.
- *Alligator Cracking Performance and Life-Cycle Cost Analysis of Pavement Preservation Treatments,* by C. Lee, W. Nokes, and J. Harvey (November 2007, Rev. October 2008). Technical memorandum: UCPRC-TM-2007-08.

Signatures:

Frank Farshidi **First Author**	John T. Harvey **Technical Review**	David Spinner **Editor**	John T. Harvey **Principal Investigator**	T. Joseph Holland **Caltrans Contract Manager**

DISCLAIMER

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The authors are grateful to the Washington State DOT for providing their PMS database. The assistance of Linda Pierce and Joseph Mahoney with understanding of the traffic variables in the WSDOT PMS database is gratefully acknowledged. The authors would also like to acknowledge the help of Samer Madanant, Shadi Anani, and Tim Du Lac, who helped with understanding of the model spreadsheet, and the Caltrans Division of Maintenance Office of Pavement Preservation, under the direction of Shakir Shatnawi, and Office of Roadway Rehabilitation, under the direction of Susan Massey, who have provided continued guidance and assistance on this project.

PROJECT OBJECTIVES

This report was completed as part of Partnered Pavement Research Center (PPRC) Strategic Plan Element 3.2.5, titled "Documentation of pavement performance data for pavement preservation strategies and evaluation of cost-effectiveness of such strategies." The main objective of this project was to develop Empirical-Mechanistic (E-M) performance models using data from Washington State's PMS databases and to evaluate their usefulness for performance prediction for use in the California Department of Transportation pavement management system (PMS).

EXECUTIVE SUMMARY

The work presented in this report was performed for the California Department of Transportation (Caltrans) by the University of California Pavement Research Center (UCPRC) as part of Partnered Pavement Research Center Strategic Plan Element 3.2.5 (PPRC SPE 3.2.5), titled "Documentation of Pavement Performance Data for Pavement Preservation Strategies and Evaluation of Cost-effectiveness of Such Strategies." Work on PPRC SPE 3.2.5 began in 2006. When the work commenced the Pavement Standards Team (PST) technical lead for PPRC SPE 3.2.5 was Shakir Shatnawi of the Division of Maintenance, Office of Pavement Preservation, which has become part of the Division of Pavement Management.

UCPRC used WSDOT data to create models for the initiation and progression of alligator cracking of HMA overlays on asphalt pavements; as part of the investigation of cracking behavior, the two models were combined into a single one; however, as the models were made using data from the Washington State PMS it was unknown whether the combined model would work (i.e., accurately predict crack initiation and propagation) with data on California roads based on data from the Caltrans PMS; in order to find out whether it would, a sensitivity analysis was undertaken to discover whether the combined model could be used for predictions of pavement performance using data in the Caltrans PMS. These steps were followed to accomplish the objectives:

1. Perform a general sensitivity analysis with the WSDOT model to identify the effect of different input variables on the overall model predictions, and to determine which variables have the largest effect on predicted performance. The reasonableness of the model predictions was checked by varying key input variables, including previous Alligator A cracking, previous Alligator B cracking, overlay thickness, precipitation, minimum temperature, maximum temperature, freeze-thaw cycles, traffic volume, structural base thickness and base type. A spreadsheet calculator for the models was run for all combinations of these key input variables and the results from cases were compared.
2. Based on the sensitivity analysis, evaluate the reasonableness of the WSDOT model for use in California and identify problems the model has for making predictions about California pavements.
3. Using the limited amount of California PMS data available, develop an initiation model and compare it with the one developed with data from WSDOT PMS database.

Note that the Caltrans PMS database contained insufficient data to calibrate the crack propagation model.

A sensitivity analysis helps to check the reasonableness of a model's predictions, to identify software problems, and to reveal the level of difficulty in obtaining the inputs. The reasonableness of the model was checked by varying key variables, including previous Alligator A cracking, previous Alligator B cracking, overlay thickness, precipitation, minimum temperature, maximum temperature, freeze-thaw cycles, truck traffic volume (in terms of Equivalent Single Axle Loads [ESALs]), structural base thickness, and base type. The factorial resulted in 384 simulations. The software outputs were the probability of crack initiation (defined as five percent of the wheelpath with cracking) in each year after placement of the overlay and then the probability of progression of cracking (in terms of percent of the wheelpath cracked in subsequent years).

Results from all the sensitivity analysis showed that all of the cases produce correct trends with respect to the climate and overlay thickness input variables, but that both crack initiation and progression appear to be overly sensitive to overlay thickness, climate region, and traffic volumes. The sensitivity analyses also indicated that the crack progression model shows that cracking tends to never exceed about 10 percent of the wheelpath with Alligator B cracking; this is unreasonable when compared with levels of crack progression found in the historical Caltrans PMS database, which shows progression up to 50 percent of the wheelpath with Alligator B cracking. This is likely caused by the fact that historical WSDOT pavement preservation practice resulted in nearly all of the sections in the database being overlaid before they reached 10 percent wheelpath cracking.

The comparison of the WSDOT survival model with a limited crack initiation model developed from HM-1 pavement preservation data from the Caltrans PMS showed that the WSDOT overlay sections have a higher probability of survival at early stages. This might be due to the difference between maintenance practices of the Washington State DOT and Caltrans. WSDOT places overlays at early stages (usually when Alligator B cracking is less than 10 percent). Moreover, WSDOT generally places thicker overlays (45 mm) compared to the Caltrans HM-1 overlay sections (25 to 35 mm). A similar analysis was attempted for rubberized gap-graded mixes, however only 75 observations were available which is an insufficient sample for creating a hazard function.

Conclusions from this research can be summarized as follows:

1. The combined performance model developed for crack initiation and progression in HMA overlays on asphalt pavements is rich in relevant explanatory variables and produces reasonable trends. However, the combined model appears to be overly sensitive to overlay thickness and climate variables and it produces unreasonable results when applied to California climate regions and thicker overlays. This is likely because the WSDOT PMS database used to calibrate the the

WSDOT initiation and progression models does not include the more benign California climates and because historical WSDOT practice results in placement of overlays when there is little or no cracking, whereas historical California practice in the late 1990s and early 2000s typically resulted in placement of overlays on pavement with higher levels of cracking.

2. The following explanatory variables were found to be the most sensitive variables in the combined models:
    - The thickness of the overlay
    - The annual traffic loading in ESALs
    - The average daily minimum temperature during the coldest month (December) and the average daily maximum temperature during the hottest month (July)
    - The annual precipitation
    - The number of freeze-thaw cycles in one year

The main recommendations contained in the report are:

1. Recalibrate the combined HMA pavement performance models with California PMS data. The Caltrans PMS database needs to be populated with information collected over consistently segmented sections and include information regarding existing pavement and overlay thickness and type before it can be used to recalibrate the models. Because of differences in the historical maintenance policies of WSDOT and Caltrans, and the more benign climate regions in many parts of California, it is expected that the model's parameters will be changed.
2. Recalibration does not necessarily mean that all parameters will need to be re-estimated. The sensitivity analysis revealed that the coefficients that will need recalibration include the *coefficient for overlay thickness,* because Washington State DOT generally uses thinner overlays than Caltrans, and the *coefficient for existing cracking before overlay,* because of the maintenance policy differences between WSDOT and Caltrans, i.e., historically WSDOT practices have included more pavement preservation and less rehabilitation than Caltrans. The climate variable coefficients will also need to be recalibrated to reflect the more benign climate regions in California
3. As illustrated in Chapter 5 of this report, survival estimates of the WSDOT initiation model could be updated for California's use with a limited number of input variables while Caltrans populates its PMS database. Recalibration of the progression model will also be required. Once enough data has been recorded and measured, the two WSDOT models with all the significant input variables can be implemented as a decision-support tool to aid Caltrans in planning Maintenance, Rehabilitation, and Reconstruction (MR&R) activities at both project level and network level.

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1 INTRODUCTION

1.1 Background

The work presented in this report was performed for the California Department of Transportation (Caltrans) by the University of California Pavement Research Center (UCPRC) as part of Partnered Pavement Research Center Strategic Plan Element 3.2.5 (PPRC SPE 3.2.5), titled “Documentation of pavement performance data for pavement preservation strategies and evaluation of cost-effectiveness of such strategies.” The work of PPRC SPE 3.2.5 built upon the results of an earlier project, PPRC SPE 4.5.

In the earlier project, PPRC SPE 4.5, the UCPRC developed two performance models, one for the initiation of fatigue cracking in the wheelpath (also referred to as alligator cracking) of flexible pavements and one for performance trend changes of International Roughness Index (IRI). (1) Both models were developed using data from the Washington State Department of Transportation (WSDOT) pavement management system (PMS) database. As part of PPRC SPE 3.2.5, the UCPRC developed a second model to be used in combination with the crack initiation model for predicting the progression of Alligator B cracking beyond crack initiation (2), which the first model defined as five percent of the wheelpath cracked with either Alligator A or Alligator B cracks, whichever developed more rapidly.

In an earlier project, PPRC SPE 4.5, the UCPRC developed performance models using the pavement management system (PMS) database of the Washington State Department of Transportation (WSDOT) for flexible pavement for the initiation of fatigue cracking in the wheelpath (also referred to as alligator cracking) and performance trends for change of International Roughness Index (IRI) (1). Crack initiation was defined as five percent of the wheelpath cracked with either Alligator A or Alligator B cracking, whichever comes first. As part of this PPRC SPE 3.2.5 the UCPRC developed a second model, to be used with the first model, for predicting the progression of Alligator B cracking beyond crack initiation (2).

Although the goal of this project was to develop cracking models applicable to California pavements, the models developed from the WSDOT data were calibrated with performance and explanatory variable data from Washington State. This was done because the existing Caltrans PMS database (1) lacked key data pertaining to the pavement structure prior to placement of the overlay and the thickness and type of the overlay and (2) over the years the condition survey data was collected using segments with different boundaries, complicating development of a time series. WSDOT database was divided into two portions, one portion of the WSDOT database was used to calibrate the initiation and progression models and another portion for validating them. The validation results showed that the models were calibrated well with the WSDOT data. Subsequently, a spreadsheet solution was developed for the combined initiation and progression models. The WSDOT cracking models were calibrated with performance and explanatory variable data from Washington State. The California PMS database was not used to develop the models because it does not include any data regarding the pavement structure prior to placement of the overlay and the thickness and type of the overlay, and because the condition survey data was collected using segments with different boundaries in each year which made development of time series very difficult. A portion of the WSDOT database was not used for calibration and was used to validate that the models were well calibrated. The validation showed a good calibration with the WSDOT data. A spreadsheet solution was developed for the combined initiation and progression models.

However, the question remained as to whether the models as calibrated with WSDOT data required recalibration for California conditions. In the process of evaluating the models, an error in interpretation of the WSDOT traffic data was found and both the initiation and progression models were corrected. To correct for this error, both models were regenerated using the correct traffic data.

1.2 Overview of WSDOT Database

The WSDOT PMS database includes existing pavement structure, overlay thickness and type, truck traffic, climate data, and observed percent of the wheelpath cracked as recorded in annual condition surveys for the years 1983 through 1999. The initiation and progression models were combined in a spreadsheet calculator that was used in this study to perform a sensitivity analysis to the input variables. WSDOT and Caltrans define reflection crack types differently and reconciling them was necessary to validate and calibrate the models for California data. Unlike the Caltrans PMS, the WSDOT PMS divides fatigue cracking into two categories in its measurements and records: longitudinal cracking and alligator cracking.

- In the WSDOT definition, longitudinal cracks run roughly parallel to the roadway centerline in the wheelpath; Caltrans defines this as Type A alligator cracking.
- The WSDOT PMS defines alligator cracking as several discontinuous longitudinal cracks that have begun to interconnect, relates their extent to the length of the wheelpaths, and measures and records them as a percentage of wheelpath length. The Caltrans defines the equivalent of WSDOT alligator cracking as either Type B or Type C alligator cracking.

Washington State's historical maintenance strategy has been to perform pavement preservation mainly with conventional overlays (not polymer-modified or asphalt rubber) averaging approximately 0.15 ft (45 mm) thickness, and to place few thicker rehabilitation overlays. However, the agency almost always places overlays on Alligator B cracking before it exceeds 10 percent of the wheelpath and typically places overlays at about 5 percent of the wheelpath cracked (Figure 1 and Figure 2). These practices create a bias in the WSDOT database that results in the crack propagation model being unable to predict cracking extents of more than about 10 percent of the wheelpath. This bias does not exist in the Caltrans PMS data because the California department follows a different set of practices.

Another limitation of the initiation and progression models is the approximately 7,500,000 cumulative ESALs maximum in the WSDOT database. This limit renders the crack propagation model unable to predict beyond than that traffic level.

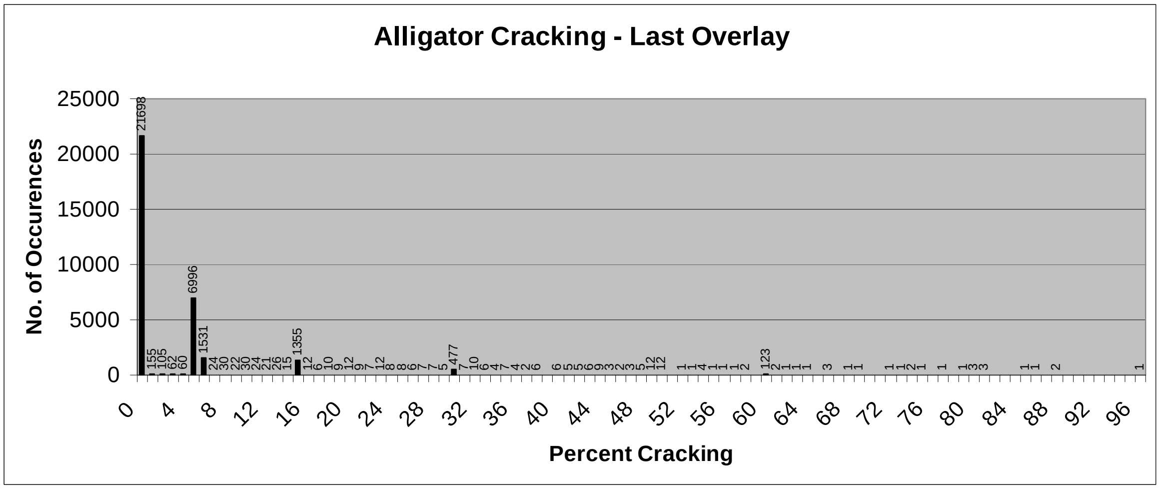

Figure 1: Histogram of percent Alligator B cracking in the wheelpaths of current overlay at last year of survey (WSDOT PMS Data).

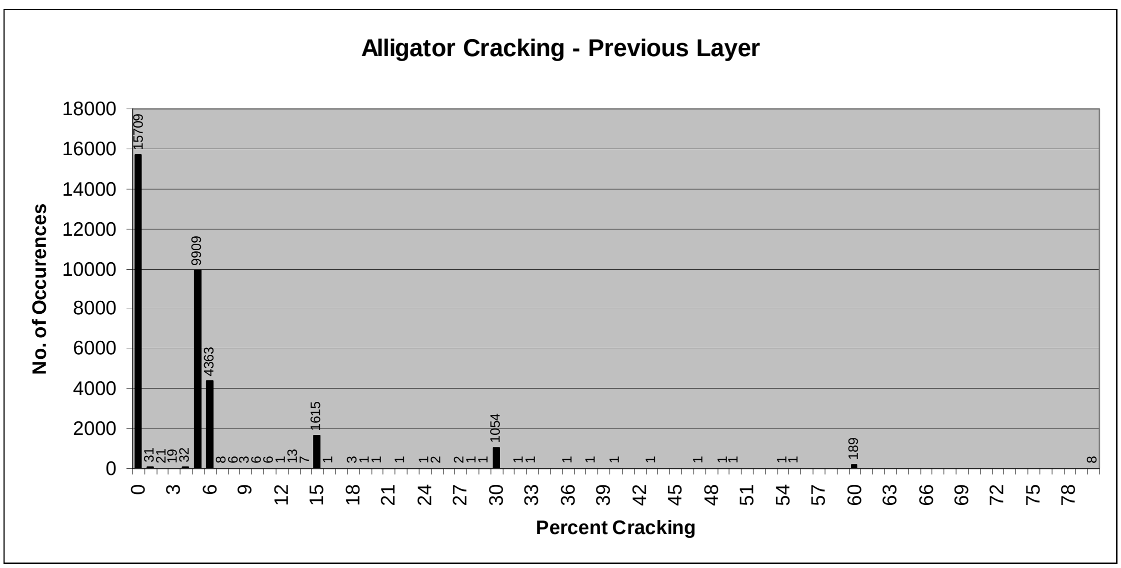

Figure 2: Histogram of percent Alligator B cracking in the wheelpaths in the underlying pavement at the time of placement of most recent overlay (WSDOT PMS Data).

1.3 Research Objectives and Scope of Work Covered in This Report

The goal of the work described in this report is to evaluate the combined model "suite" using the WSDOT PMS database by comparing predictions with California PMS performance data to determine whether the models can be used as is, or whether they need recalibration with California data. The cracking model developed from WSDOT PMS data is able to provide predictions of the deterioration of flexible pavements through performance predictions of crack initiation and the extent of progression during the life of the pavement. The model was developed for use as a decision-support tool to aid the Department in planning Maintenance, Rehabilitation, and Reconstruction (MR&R) activities.

The specific objectives of the investigation described in this report are as follows:

1. Perform a general sensitivity analysis with the WSDOT model suite to identify the effects of different input variables on the overall model predictions, and determine which variables have the largest effect on predicted performance.
2. Based on the sensitivity analysis, evaluate the reasonableness of the WSDOT model for use in California and identify any problems with the model.
3. Develop an initiation model with the limited amount of California PMS data and compare the model with the one developed with data from the WSDOT PMS database.

The first step to complete these objectives was performance of a sensitivity analysis of the WSDOT model, the results of which are presented in this report. The sensitivity analysis made use of a spreadsheet solution for the combined cracking initiation and progression model developed for this project. Key input variables were varied in the sensitivity analysis, including previous Alligator A and Alligator B cracking, overlay thickness, precipitation, minimum temperature, maximum temperature, freeze-thaw cycles, traffic volume, structural base thickness, and base type. The spreadsheet calculator was run for all combinations of these key input variables and the results from the cases were compared. The climate data was typical of different California climate regions, and other input variables were selected to reflect California practice. To evaluate the reasonableness of the model for its original calibration data, a similar sensitivity analysis was performed using the mean and the mean plus and minus standard deviation values for each key variable in the WSDOT database.

The second step was to create a new crack initiation model with a very limited data set extracted from the Caltrans PMS database for HM-1 pavement preservation projects (3). This model is referred to as the HM-1 model, and its results were compared with those from the initiation model based on the WSDOT data.

Recommendations were then made for further work, once better data is available from the Caltrans PMS.

1.4 Presentation of Prediction Results in the Spreadsheet

The model developed using the WSDOT data is probabilistic. It uses Monte Carlo simulation and probabilistic analysis for the crack propagation module. The WSDOT model spreadsheet creates a graph that shows the cracking paths resulting from 1,000 Monte Carlo–simulated experiments, employing a technique that converts uncertainties in a model's input variables into probability distributions. By combining the distributions and randomly selecting values from them, it recalculates the simulated model many times and experimentally provides an estimate of the probability of the output.

Figure 3 shows an example of an output graph. The x-axis is the year after construction, the right y-axis is the number of crack initiations in a given year (5 percent of the wheelpath with Alligator A or B cracking, whichever comes first) out of 1,000 probabilistic simulations, and the left y-axis is the percentage of Alligator B cracking in the wheelpath progressing from the initiations in each year. As shown in Figure 3, each year has a bar with a number of crack initiations on top of it (initiation model) and a curve associated with the progression pattern (progression model). The model assumes an analysis period of 20 years and shows the results for 20 years. Any initiations after 20 years do not appear on the plot. In the example shown in Figure 3, there are 941 experiments out of 1,000 in the one simulation that have crack initiation in Year 6, and their crack progression is represented by the lowest curve. Similarly, there are 15 experiments out of 1,000 that started cracking in Year 3, and so forth. The crack progression pattern is illustrated by the upper curve for each year that crack initiations exist. In the example shown in Figure 3, all of the progression curves show approximately nine percent of the wheelpath with Alligator B cracking after Year 19.

1.5 Scope of This Report

Chapter 2 contains an explanation of the experimental design used for the sensitivity analysis, a discussion of the inputs used to run the sensitivity analysis, and the source of these inputs.

Chapter 3 discusses the results of the sensitivity analysis. Plots summarizing the effects of different variables on crack initiation and crack progression are presented in this chapter.

Chapter 4 presents the results of sensitivity analysis with regard to the effect of input variables on the life of the overlay, using the WSDOT PMS data values.

Chapter 5 discusses the results obtained from a crack initiation model developed using limited Caltrans HM-1 data and a comparison with the original WSDOT model.

Chapter 6 discusses the conclusions from this study and provides recommendations concerning use of the WSDOT model as is and ways to update it for Caltrans use after better PMS data is available.

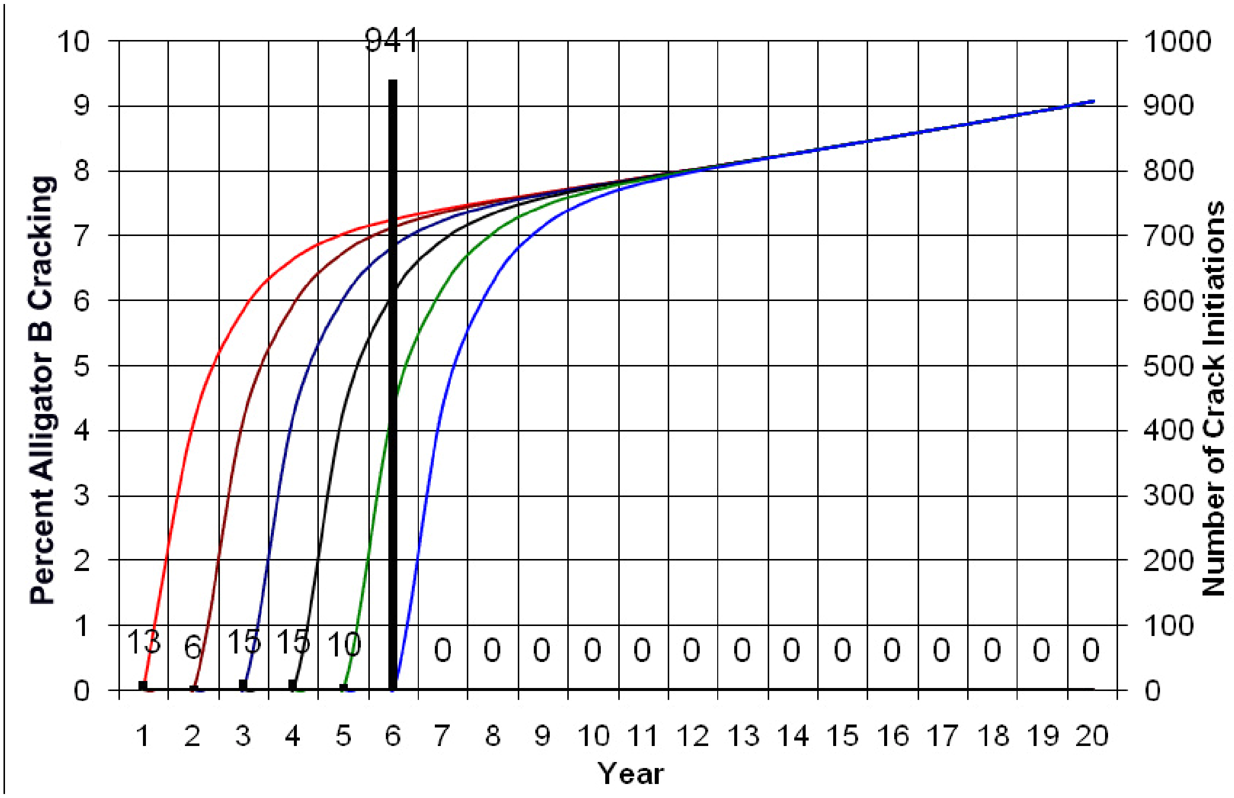

Figure 3: Graphical representation of sample crack initiation and progression output.

2 SENSITIVITY ANALYSIS EXPERIMENT DESIGN

2.1 Introduction

Input variables that affect the model suite predictions were selected and the combined model (crack initiation and progression) was run for several factor levels for each of the selected variables, which are shown in Table 1. To the extent possible, the variables and factor levels were chosen to represent Caltrans practices and California conditions. The full factorial was run, totaling 384 cases.

Table 1: Factorial for Sensitivity Analysis

	Variable (Factor Levels)	Factor Levels	
1	**Existing Cracking (4)**	Alligator A Cracking %	Alligator B Cracking %
		15	20
		10	10
		10	5
		20	30
2	**Overlay Thickness (4)**	0.15 ft (45 mm)	
		0.2 ft (60 mm)	
		0.35 ft (106 mm)	
		0.5 ft (127 mm)	
3	**Climate Region (4)**	South Coast (Los Angeles)	
		Valley (Sacramento)	
		North Coast (Arcata)	
		Mountain/High Desert (Reno)	
4	**Traffic(ESAL/yr/lane) (3)**	25,000	
		100,000	
		400,000	
5	**Underlying Pavement Structure (2)**	**Pavement Structure 1** 0.16 ft (50 mm) underlying AC 0.33 ft (100 mm) asphalt concrete base (old asphalt layers) 1 ft (305 mm) aggregate base	**Pavement Structure 2** 0.33 ft (102 mm) underlying AC 0.66 ft (305 mm) cement-treated base

2.2 Traffic Inputs

Traffic inputs for this study were based on the range of traffic experienced on the California network. Three traffic inputs were chosen for this study. Traffic growth rate was set at 2 percent annually for all the simulations linearly. Table 2 shows a summary of traffic inputs used in this study.

Table 2: Traffic Inputs

Traffic Input Scenario	ESALs/yr/lane
Low	25,000
Medium	100,000
High	400,000

2.3 Climate Data

Weather data for representative cities in each climate region were obtained using the software program *Climatic Database for Integrated Model (CDIM,) version 1.0.* The weather data variables obtained were average minimum temperature during the coldest month, average maximum temperature during the hottest month, average annual number of freeze-thaw cycles, and average total yearly precipitation. The average values were taken from 30 years of data. The four climate regions and the representative city for each used for the sensitivity analysis were:

- South Coast (Los Angeles)
- North Coast (Arcata)
- Valley (Sacramento)
- Mountain/High Desert (Reno)

Table 3 shows the difference in temperature and precipitation for the four climate regions. These values were obtained from the *CDIM* software , which is based on daily and hourly weather data in the western half of the United States.

Table 3: Annual Average Climate Data for the Representative Cities for the Four Selected Climate Regions

Weather Data/Climate Region	Los Angeles	Sacramento	Arcata	Reno
Average lowest temperature in the coldest month (ºF)	37.4 (3°C)	26 (-3.3°C)	29 (-1.6°C)	12.5 (-10.8°C)
Average highest temperature in the hottest month (ºF)	97 (36°C)	106 (41°C)	79 (26°C)	97 (36°C)
Average Freeze-Thaw Cycles	0	3	0	68
Average Total Yearly Precipitation (in.)	12.8 (325 mm)	17.3 (439.4 mm)	37.8 (960 mm)	64.9 (1,648 mm) *

* Total precipitation for Reno combines rain and snow, while data for other cities only includes rain.

2.4 Underlying Pavement Structure

For the purpose of this sensitivity analysis, two underlying pavement structures were used (see Table 1). It should be noted that the WSDOT database pavement structures include a single Asphalt Concrete Base (ACB) that varies from the predominant type of Caltrans structures, which are typically multiple layers of old asphalt concrete accumulated through years of repeated thin overlays. However, for the simulations it was assumed that the cumulative thickness of these old asphalt layers was the equivalent of ACB.

2.5 Existing Cracking Data

The WSDOT model uses both previous Alligator A cracking (referred to as "longitudinal cracking" in the WSDOT PMS) and Alligator B cracking as input variables. To evaluate the sensitivity of the model based on past Caltrans pavement preservation practices, four combinations of existing Alligator A and B cracking were chosen. Table 1 shows the cracking inputs used for this study.

2.6 Overlay Material and Thickness

The WSDOT model lets the user choose between two asphalt concrete (or hot-mix asphalt) material types: AA and BA. Comparison of WSDOT Type AA and BA specifications with those of Caltrans showed the following:

- Typical binder type is the same for both Caltrans and WSDOT prior to implementation of performance-graded (PG) binder grades: AR4000.
- Both WSDOT and Caltrans historically used the Hveem mix design procedure and Hveem aggregate gradations. The mix design specifications for WSDOT Type AA are very similar to those of Caltrans dense-graded asphalt concrete (DGAC) Type A. The only difference is in the largest aggregates in the gradation: WSDOT uses a maximum aggregate size of 5/8 in. (15.87 mm) instead of the 3/4 in. (19mm) or 1/2 in. (12.7 mm) typically used by Caltrans. WSDOT Type B mix falls between the Caltrans Type A and Type B mixes with regard to specification requirements. The main difference between the WSDOT Type B and the Caltrans Type B is that the former requires more fractured faces.

All 384 simulations were run with Type AA as overlay material type since the WSDOT Type AA mixes were concluded to be very similar to Caltrans DGAC Type A mixes.

Sensitivity of the model to overlay thickness was evaluated by choosing four different thicknesses (Table 1). Selection of these four values was based on studying Caltrans maintenance practices for HM-1, Capital Maintenance (CAPM), and rehabilitation projects. HM-1, CAPM, and rehabilitation are three pavement preservation strategies that Caltrans currently practices. The main difference between the strategies is in the thickness of the new overlay applied. For example, pavement sections that receive the HM-1 strategy have a thin overlay of approximately 0.15-ft (45-mm) thickness.

3 RESULTS OF SENSITIVITY ANALYSIS

All combinations of the factorial experiment described in Chapter 2 were run using the *Excel*™–based calculator and a macro written for the purpose of this study, which will be given to Caltrans with this report. The model was run in a batch mode for each of the 384 simulations and the results loaded into a database. The effect of the all the variables studied on crack initiation and crack progression as predicted by the model are discussed in this chapter, each section of which describes the effect of changing a particular variable while the others are held at a constant value, as shown in Table 4.

Table 4: Constant Values Assumed in Single Variable Sensitivity Analysis

Variable		Constant Factor Levels	
1	**Existing Cracking**	Alligator A Cracking %	Alligator B Cracking %
		10	10
2	**Overlay Thickness**	0.2 ft (60 mm)	
3	**Climate Region**	South Coast (Los Angeles)	
4	**Traffic(ESAL/yr/lane)**	100,000	
5	**Underlying Structure**	**Pavement Structure 1** 0.16 ft (50 mm) underlying AC 0.33 ft (100 mm) asphalt concrete base (old asphalt layers) 1 ft (305 mm) aggregate base	

3.1 Effect of Explanatory Variables

The effect of explanatory variables described in Table 1 will be analyzed in the following sections to identify the most sensitive variables of the model suite.

3.1.1 Effect of Climate

Figure 4 through Figure 7 show crack initiation and progression predictions for the four climate regions evaluated while all the other variables were held at the constant values shown in Table 4. Each figure shows the number of crack initiations as well as the crack progression pattern and percentage of Alligator B cracking in each year. Figure 4 shows that in some cases the total number of crack initiations does not add up to 1,000. The reason for this behavior is that based on the input variables for this particular scenario the model predicted fewer than 1,000 crack initiations in the 20-year analysis period. In other words, the initiation criteria of five percent cracking was not met for all the simulations during the analysis period, and therefore the number of crack initiations predicted by the model does not equal 1,000.

Model predictions for climate regions varied, with Reno showing (Figure 7) the highest number of crack initiations:

- The total number of crack initiations predicted up to Year 10 for Sacramento climate (Valley Region, Figure 4) was 45 out of 1,000 simulations.
- For Los Angeles (South Coast Region, Figure 5) the model predicted a total of 19 initiations out of 1,000 up to Year 10.
- For Arcata (North Coast Region, Figure 6), the model predicted 97 out of 1,000 crack initiations up to year Year 10.
- For Reno (Mountain/High Desert Region), which has relatively high precipitation (rain and snow), cold temperatures, and a large number of freeze-thaw cycles, the model predicted all 1,000 crack initiations in Year 1 (Figure 7).

All of these simulations are for the 60 mm overlay based on data primarily for mixes with AR4000 binder.

It is important to note that in all four cases the maximum percent wheelpath cracking values from the progression part of the model are low. The value ranges from 4 percent for Los Angeles to 6.2 percent for Reno. This behavior is probably due to the fact that the WSDOT PMS database reflects WSDOT's aggressive pavement preservation strategy, which results in overlays being placed before Alligator B cracking has exceeded 10 percent of the wheelpath.

In summary, results as shown in Figure 4 through Figure 7 seem reasonable with engineering judgment in terms of ranking, and show sensitivity of the model to environmental variables including the number of freeze-thaw cycles, the average lowest temperature of the coldest month and the highest temperature of the hottest month, and the average annual precipitation. The results seem particularly sensitive to the annual number of freeze-thaw cycles and the average lowest temperature with regard to prediction of crack initiation of new overlays. The results do not seem reasonable in terms of the extremely good performance of the more benign climates in California, and in terms of the slowing of predicted crack progression which seldom exceeds 5 to 10 percent Alligator B cracking.

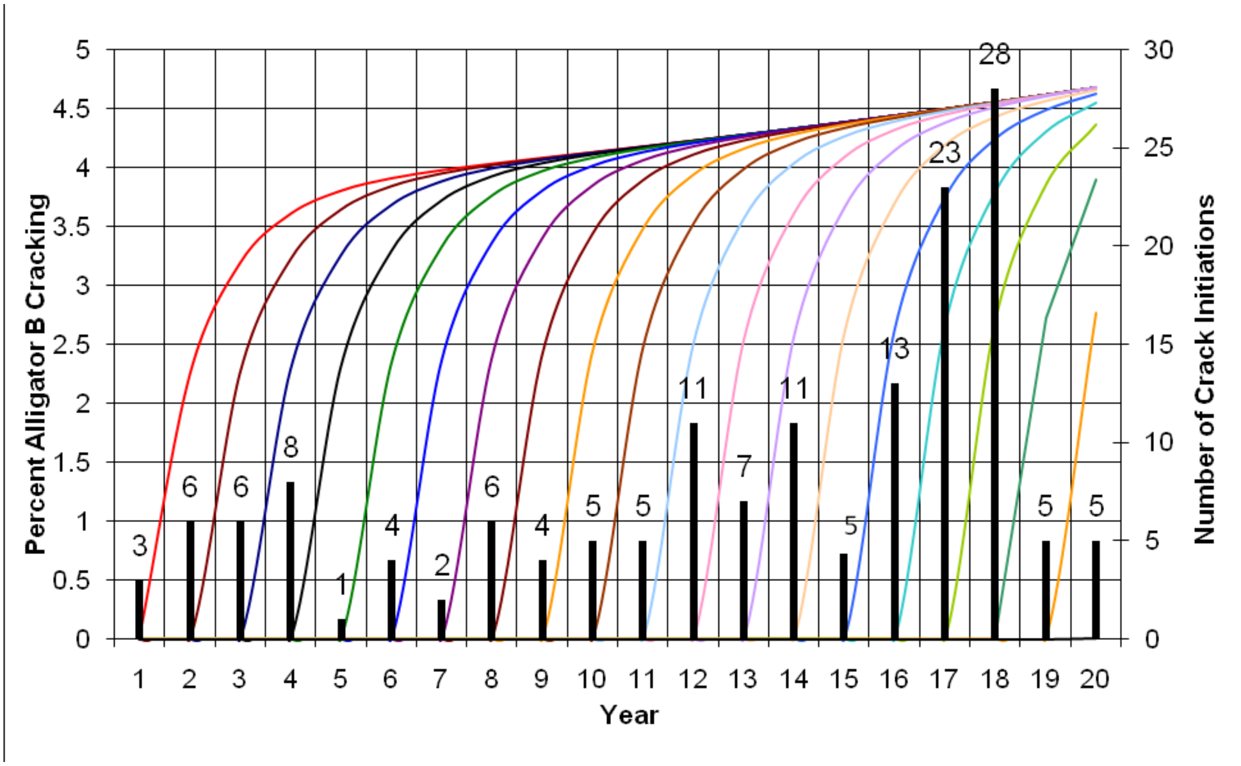

Figure 4: Climate zone:Valley (Sacramento); other variables constant.

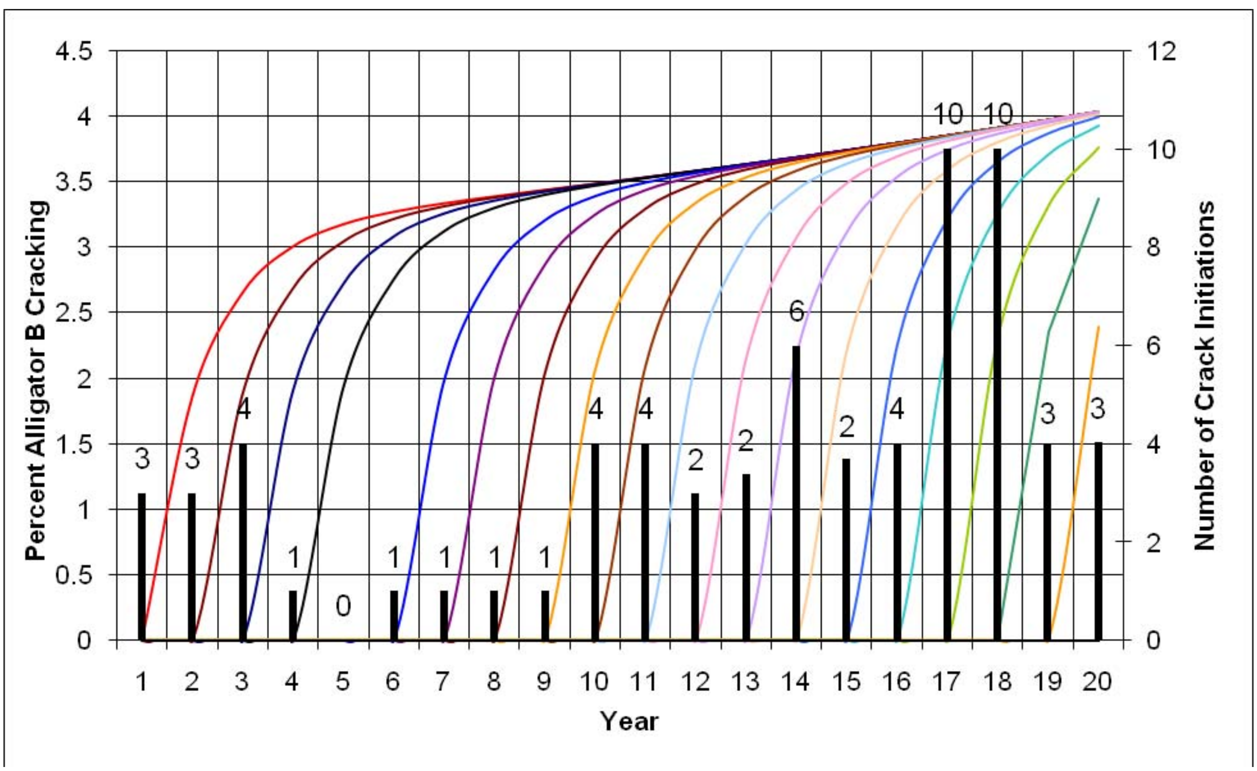

Figure 5: Climate zone: South Coast (Los Angeles); other variables constant.

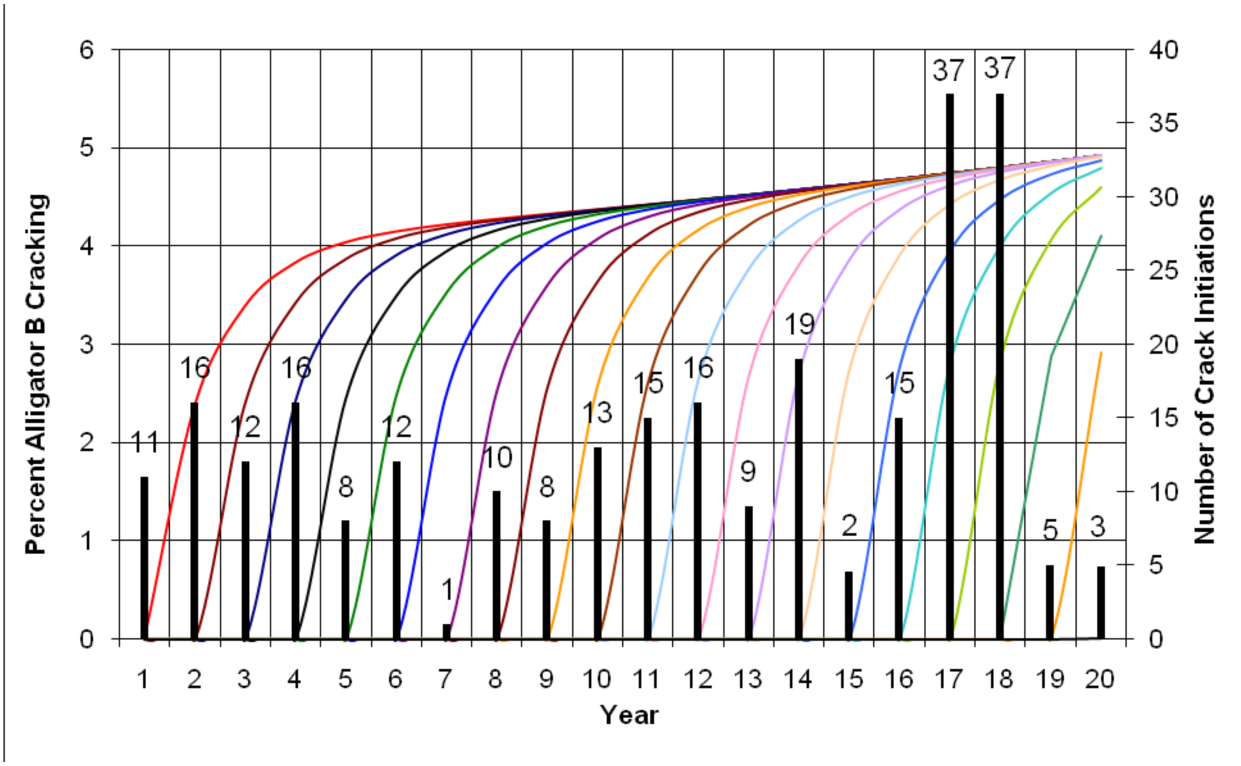

Figure 6: Climate zone: North Coast (Arcata); other variables constant.

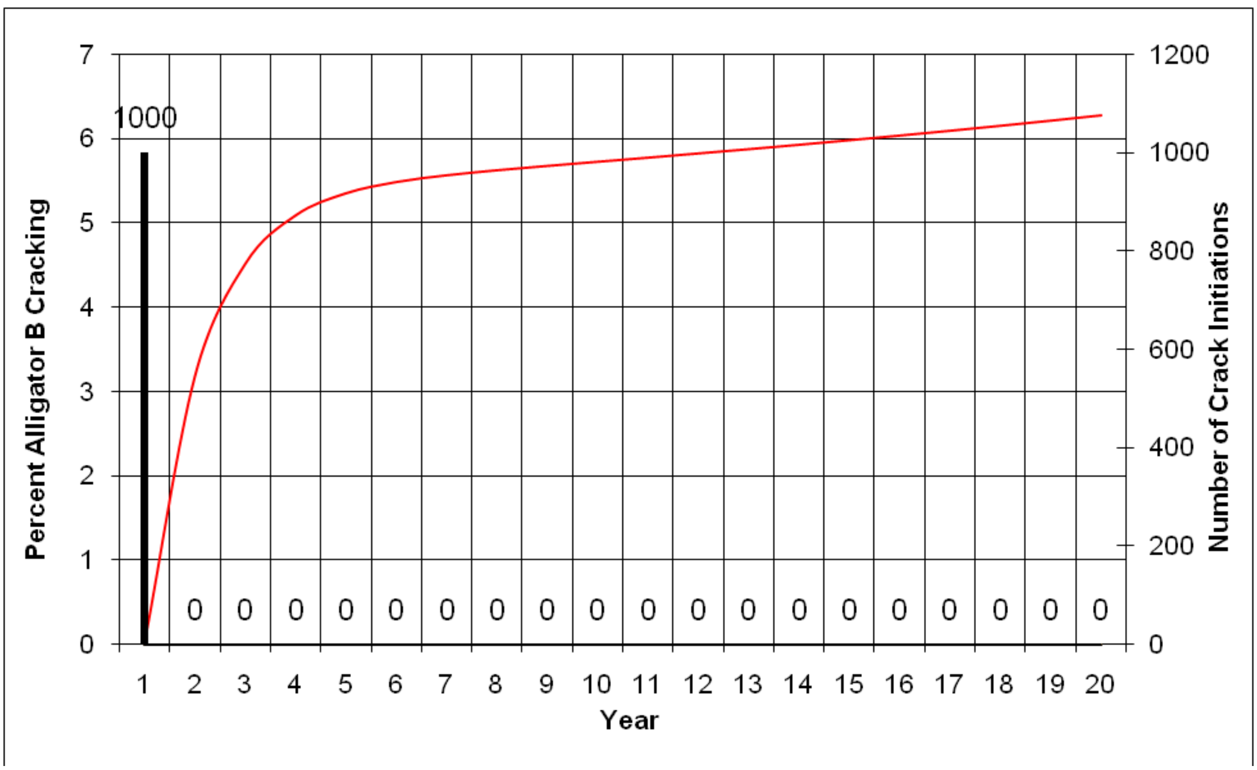

Figure 7: Climate zone: Mountain/High Desert (Reno); other variables constant.

3.1.2 Effect of Overlay Thickness

It should be remembered that results discussed in this section for the effect of overlay thickness assumes the following explanatory variables are constant: South Coast climate region (Los Angeles), 100,000 ESALs per year in the design lane, and 10 percent existing Alligator A and 10 percent existing Alligator B cracking.

The sensitivity analysis presented in this section shows that crack initiation (5 percent Alligator A or Alligator B cracking) is sensitive to overlay thickness. As shown in Figure 8 to Figure 11, the number of crack initiations decreases as overlay thickness increases. The total number of crack initiations predicted by Year 10 are 119, 27, zero, and zero out of 1,000 simulations for overlay thicknesses of 0.15 ft (45 mm), 0.2 ft (60 mm), 0.35 ft (106 mm) and 0.5 ft (127 mm), respectively.

Percent Alligator B cracking in the wheelpath after initiation also decreases as hot-mix asphalt (HMA) thickness increases. The thinnest overlay considered in this study 0.15 ft (45 mm, [1.8 in.]) has the highest total percent cracking (4.3 percent) compared with the lowest percent cracking (1.8 percent) for the thickest overlay of 0.5 ft (127 mm [6.0 in.]).

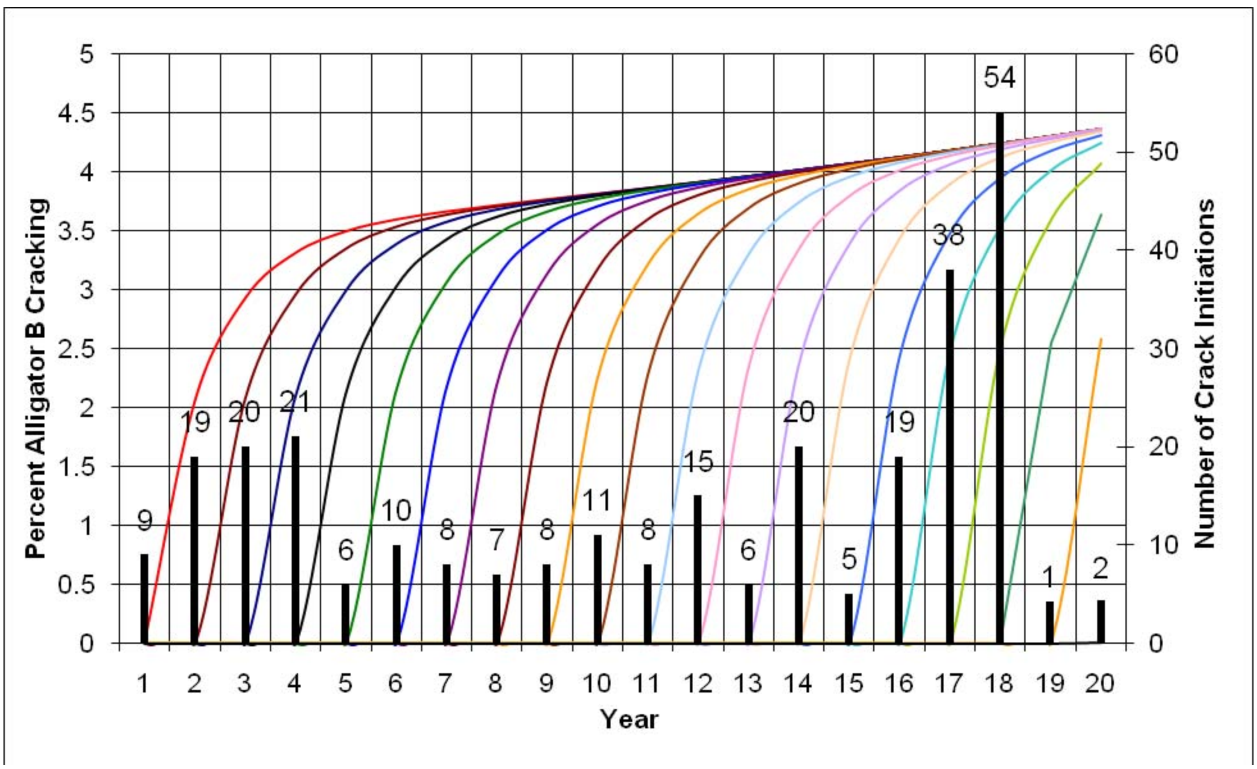

Figure 8: Overlay Thickness: 0.15 ft (45 mm [1.8 in.]); other variables constant.

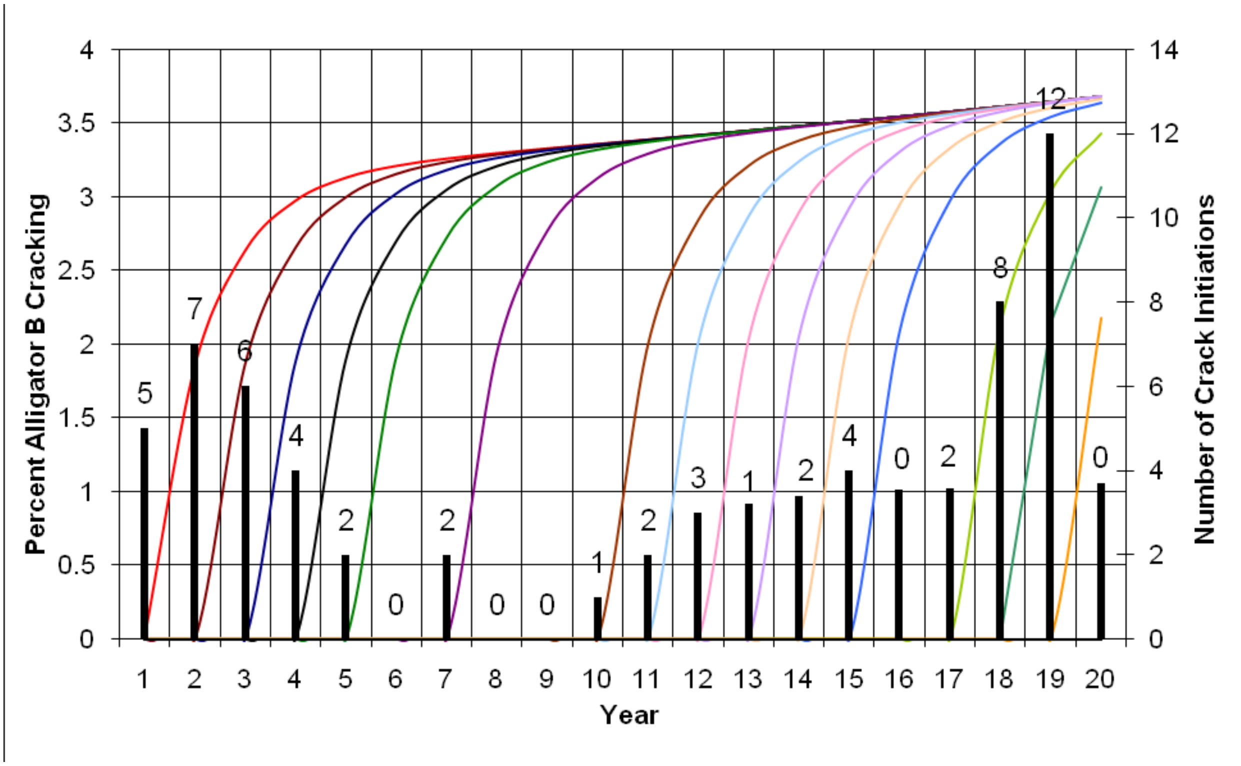

Figure 9: Overlay thickness: 0.2 ft (60 mm [2.4 in.]); other variables constant.

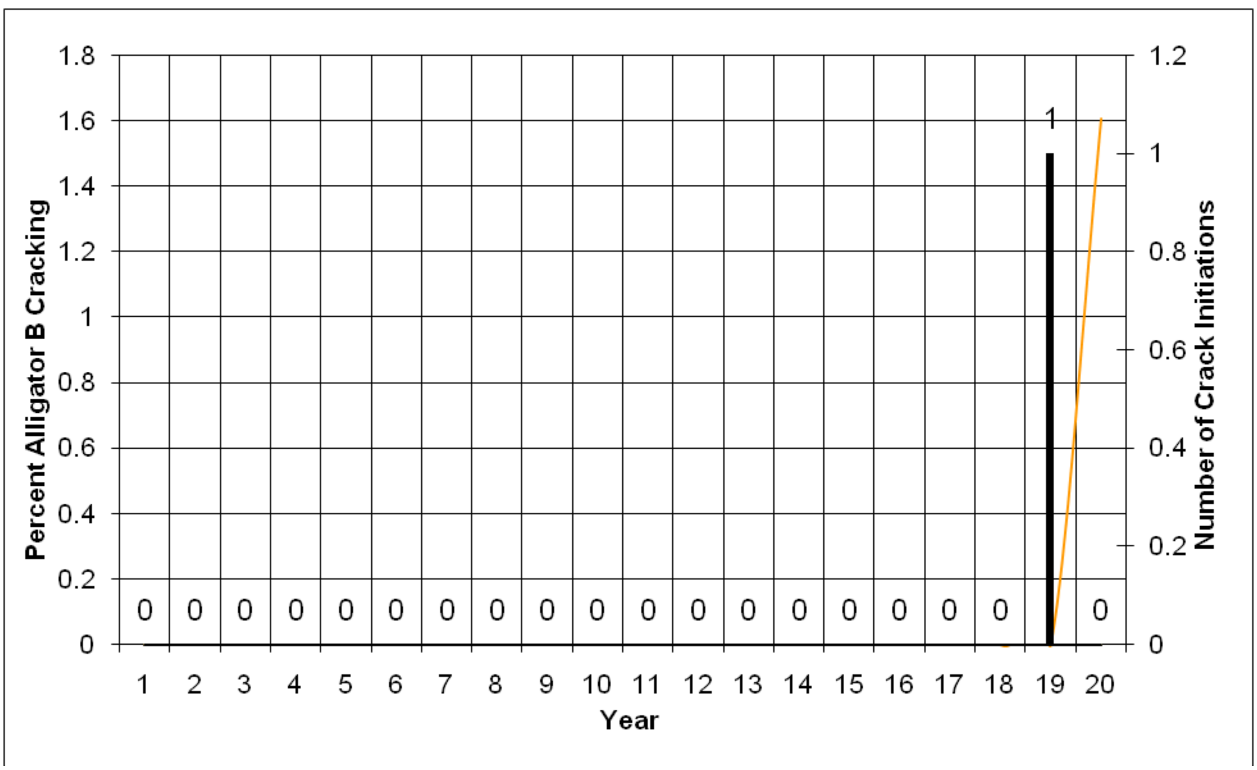

Figure 10: Overlay thickness: 0.35 ft (106 mm [4.2 in.]); other variables constant.

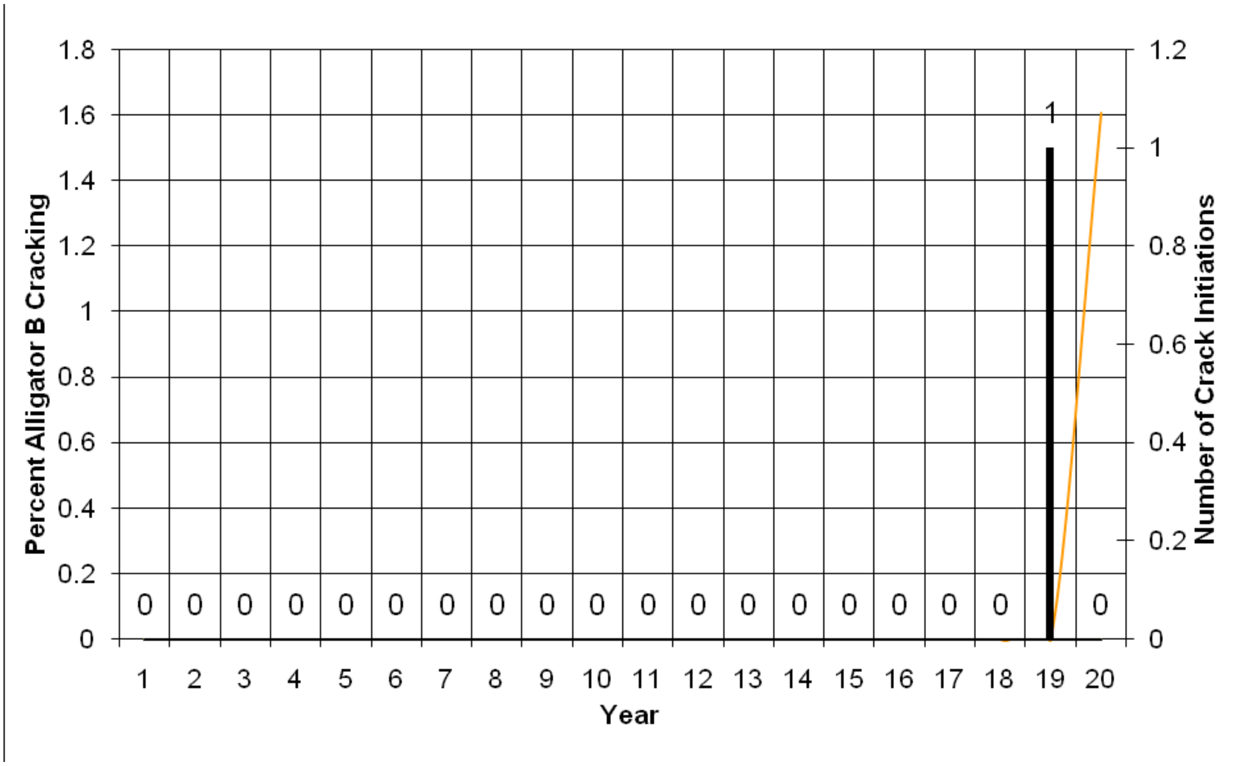

Figure 11: Overlay thickness: 0.5 ft (152 mm [6.0 in.]); other variables constant.

As shown in Figures 8 to 11, the overall performance prediction trends are reasonable for the overlay thicknesses, but the initiation model results suggest that it may be overly sensitive (it should be noted that overlays thicker than 0.2 ft (60 mm) were extremely rare in the WSDOT database, and predictions for the thicker overlays are therefore extrapolations). As will be the case for all of the sensitivity analysis results, the model appears to underestimate long-term crack propagation for the reasons already stated several times.

3.1.3 Effect of Traffic

Traffic volume has a significant effect on both crack initiation and progression. As traffic volume increases crack initiation occurs earlier and crack progression grows faster. Figure 12 through Figure 14 show the effect of traffic for the three traffic levels assumed in this study, while other variables were assumed to be constant. As expected, at very low traffic (Figure 12) the model does not predict many crack initiations. The model predicts a total of 16 crack initiations out of 1,000 simulations up to Year 10, compared with 100 crack initiations for medium-level traffic (100,000 ESALs/ln/yr [Figure 13]) and 301 crack initiations for high-level traffic (400,000 ESALs/ln/yr [Figure 14]).

Crack progression in terms of total percent Alligator B cracking shows a similar trend. As traffic volume increases, total percent cracking in the wheelpath also increases. As shown in Figure 12, at the lowest traffic volume assumed in this study, the overlay reaches 2.8 percent Alligator B cracking in Year 20. However at the highest traffic volume, Figure 14, Alligator B cracking reaches 9.5 percent in Year 20.

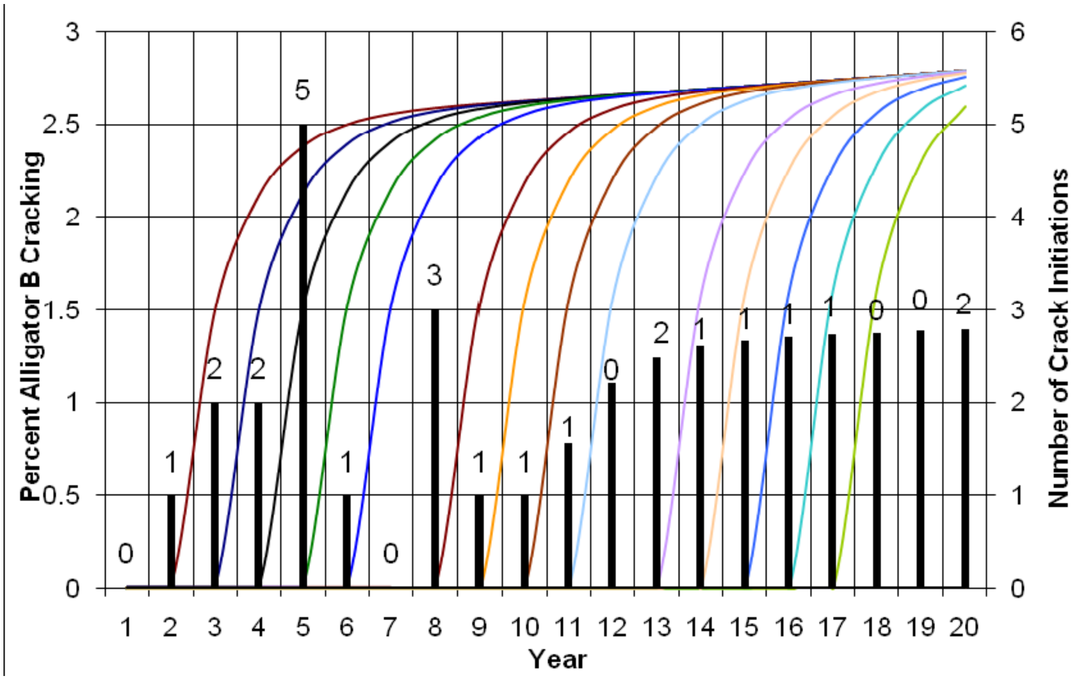

Figure 12: Traffic volume: 25,000 ESALs/lane/yr; other variables constant.

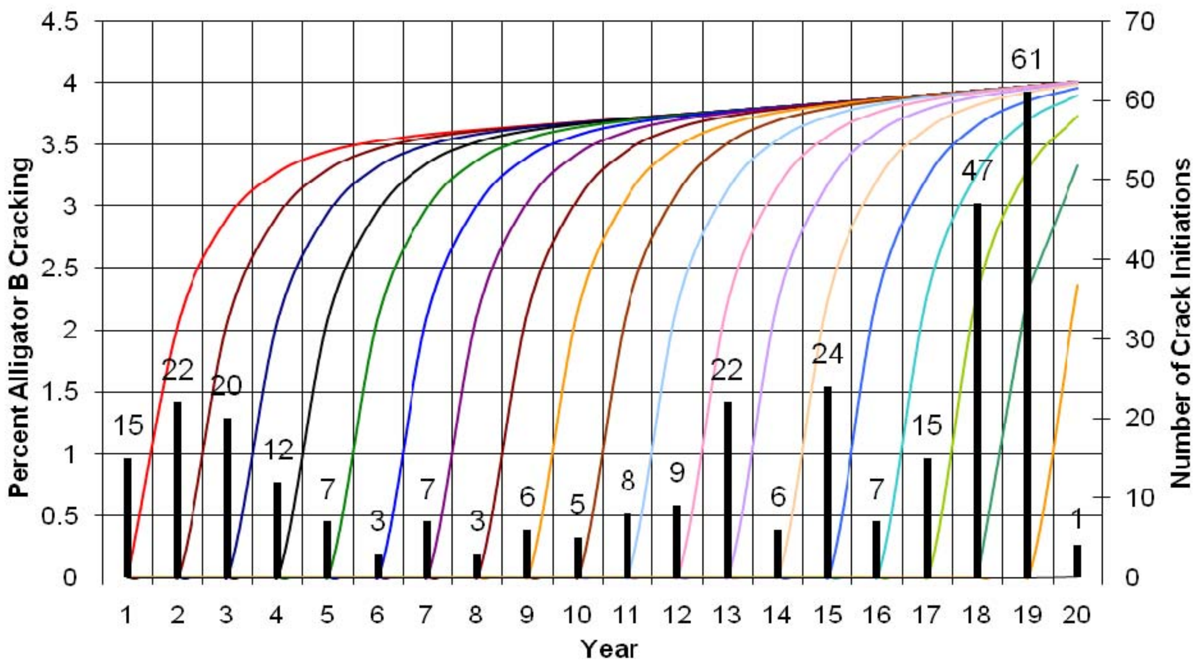

Figure 13: Traffic volume: 100,000 ESALs/lane/yr; other variables constant.

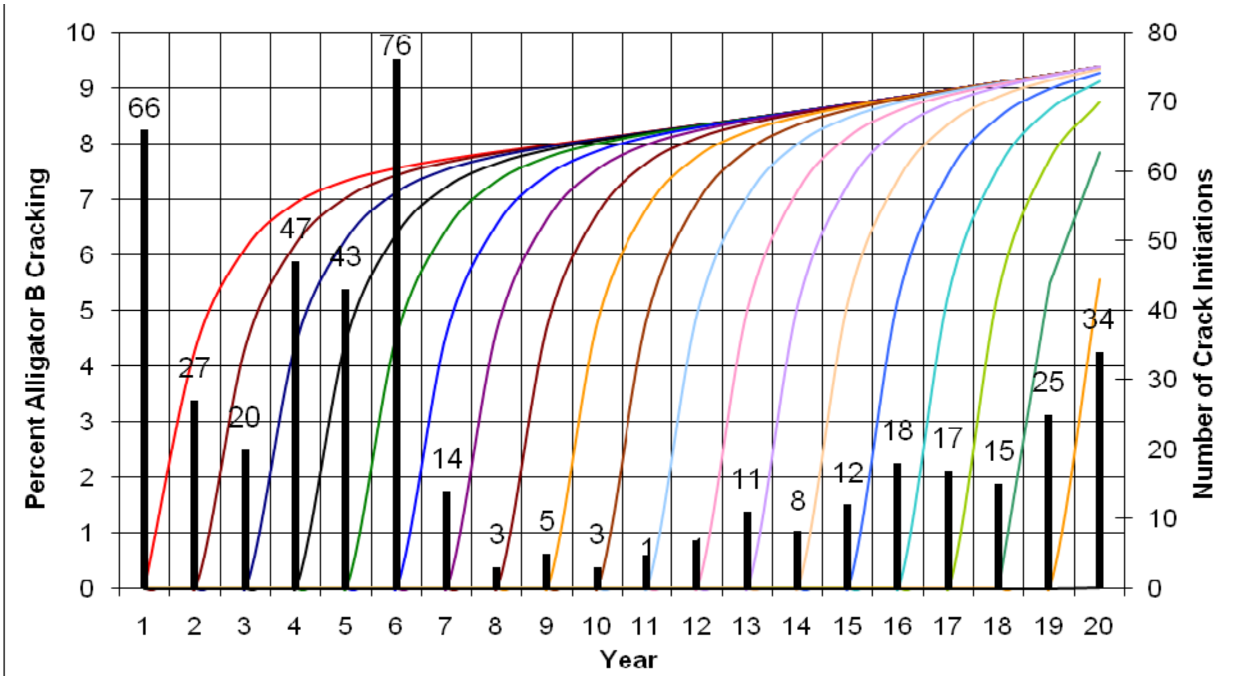

Figure 14: Traffic volume: 400,000 ESALs/lane/yr; other variables constant.

3.1.4 Effect of Underlying Pavement Structure

Results presented in Figure 15 and Figure 16 show that sections with Pavement Structure 1 (aggregate base/asphalt base layer) in Table 1 have a slightly greater probability of crack initiation than sections with Pavement Structure 2 (cement-treated base) layers. Crack progression shows a similar result for both pavement structures.

3.1.5 Effect of Previous Alligator Cracking

Figure 17 through Figure 20 show the sensitivity of model predictions to the extent of previous cracking at the time of overlay for both crack initiation and crack progression. As shown in the results, the model is not very sensitive to previous alligator cracking history. However, both crack initiation and progression model results are reasonable in terms of ranking according to engineering judgment. As previous cracking increases, the number of crack initiation simulations also increases. For instance, comparing Figure 19 and Figure 20 shows that the total number of crack initiations up to Year 10 for a section with 15 percent Alligator A cracking and 20 percent Alligator B cracking is 159 out of 1,000 simulations, while there are 189 out of 1,000 for 20 percent Alligator A and 30 percent Alligator B.

The total Alligator B cracking percentage also increases as previous alligator cracking in the existing surface increases. Again comparing Figure 19 and Figure 20, it can be seen that the pavement section with less previous cracking in Figure 19 (15 percent Alligator A, 20 percent Alligator B) reaches 5.2 percent Alligator B cracking by Year 19 versus 6.7 percent for the scenario shown in Figure 20 with higher previous cracking (20 percent Alligator A, 30 percent Alligator B).

In summary, these results strongly suggest that overlay cracking is primarily due to reflection cracking for asphalt overlays, and that the cracking predicted by the model is primarily reflection of the previous cracking. The very low levels of cracking predicted by the model are not reasonable for these California examples. However, as mentioned earlier in this report, since WSDOT has an aggressive pavement preservation strategy and overlays in the early stages of cracking (typically before they reach 10 percent Alligator B cracking in the wheelpath), the model is therefore not highly sensitive to previous Alligator A and Alligator B cracking. Once Caltrans populates its PMS database with enough data, Alligator A and Alligator B cracking coefficients in the model will need to be updated to account for the two states' different pavement preservation practices and strategies.

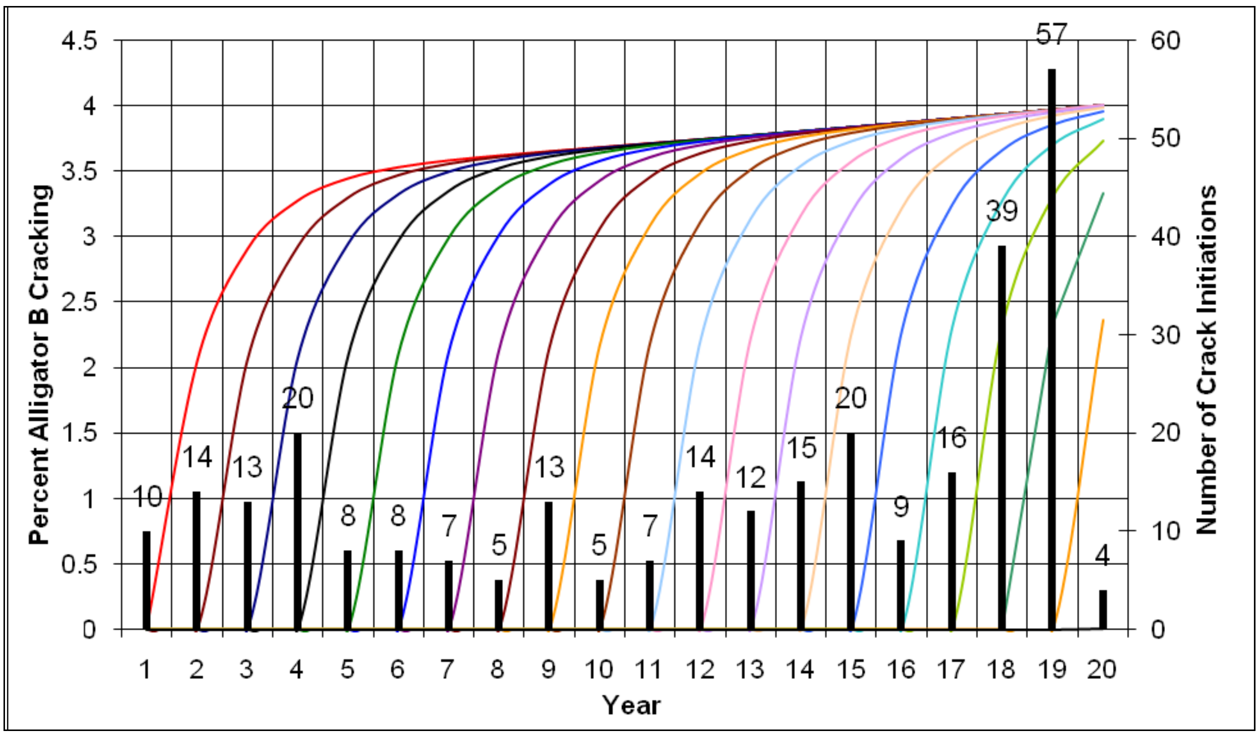

Figure 15: Asphalt concrete base; other variables constant.

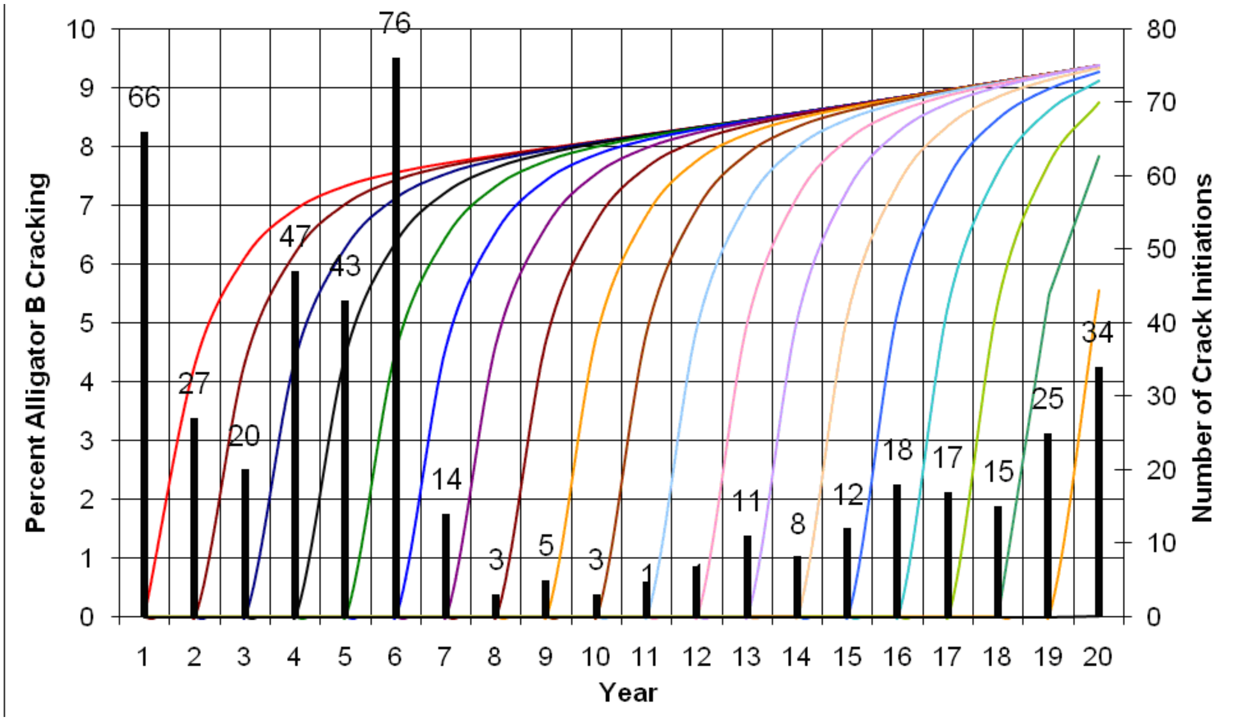

Figure 16: PCC base; other variables constant.

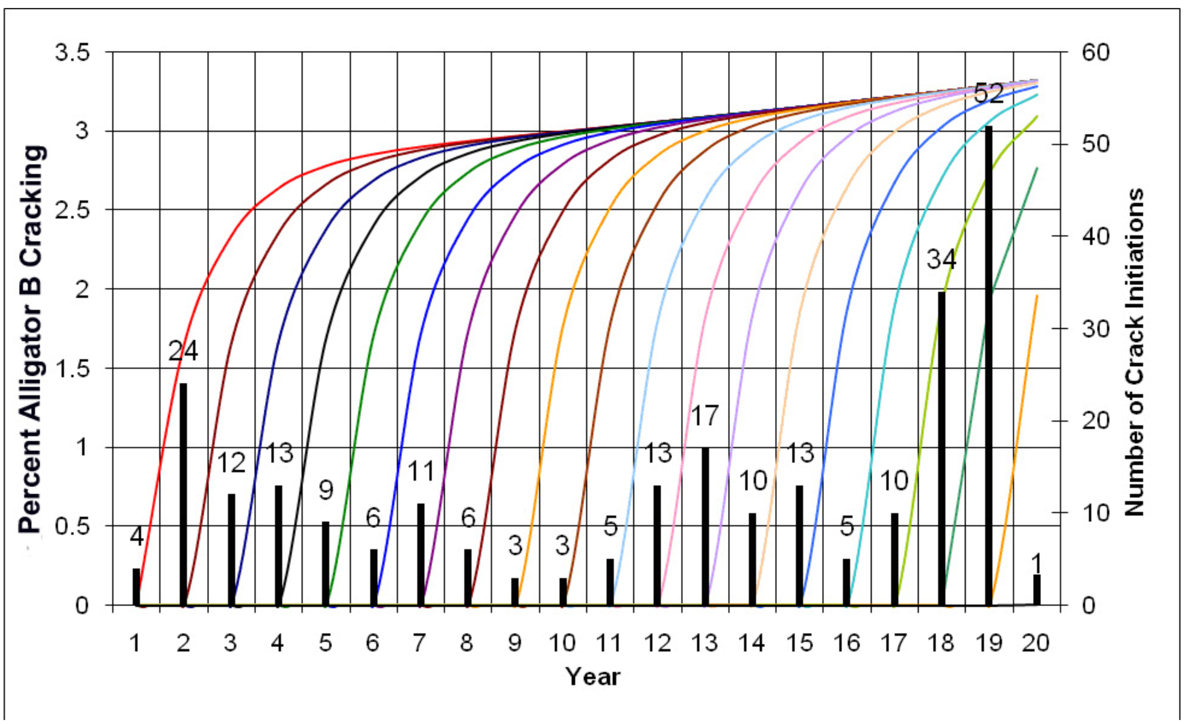

Figure 17: Alligator A cracking: 10 percent, Alligator B cracking: 5 percent; other variables constant.

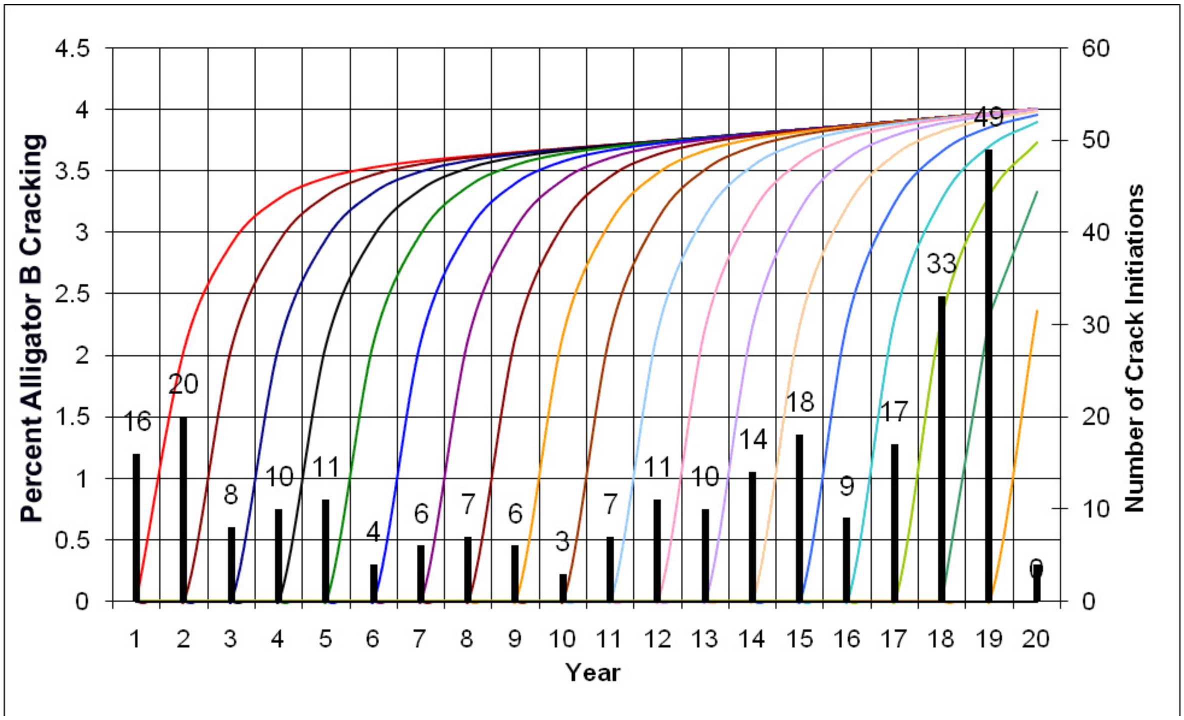

Figure 18: Alligator A cracking: 10 percent, Alligator B cracking: 10percent; other variables constant.

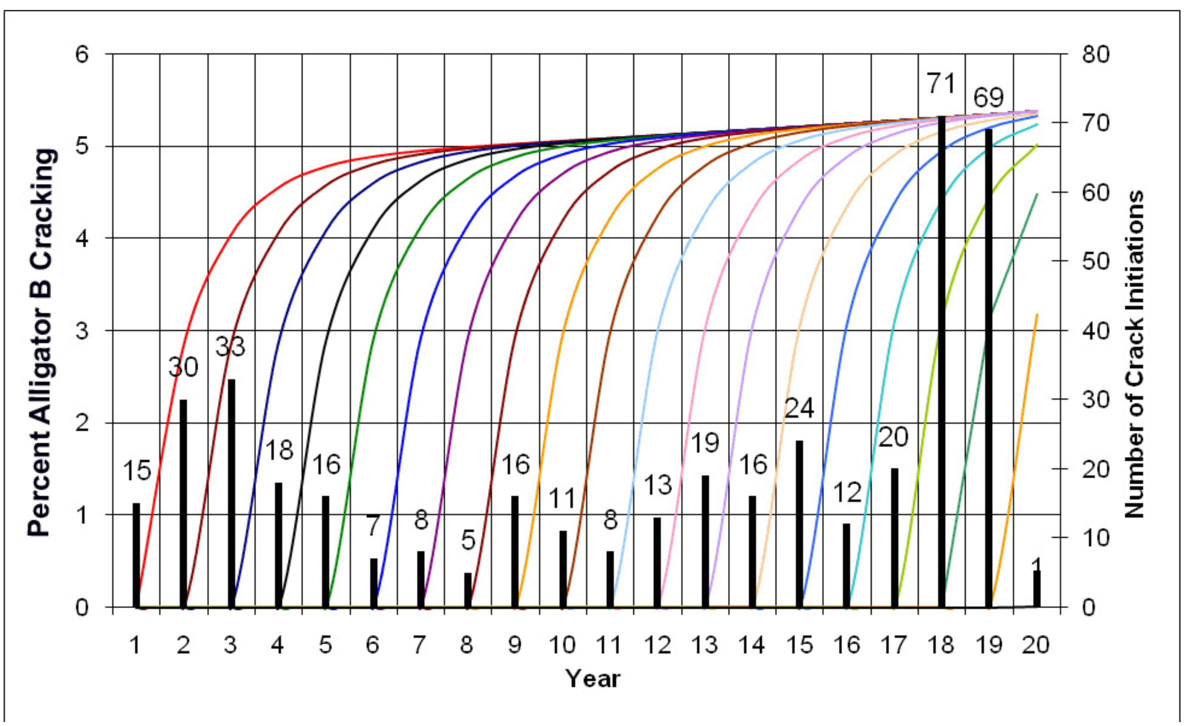

Figure 19: Alligator A cracking: 15 percent, Alligator B cracking: 20 percent; other variables constant.

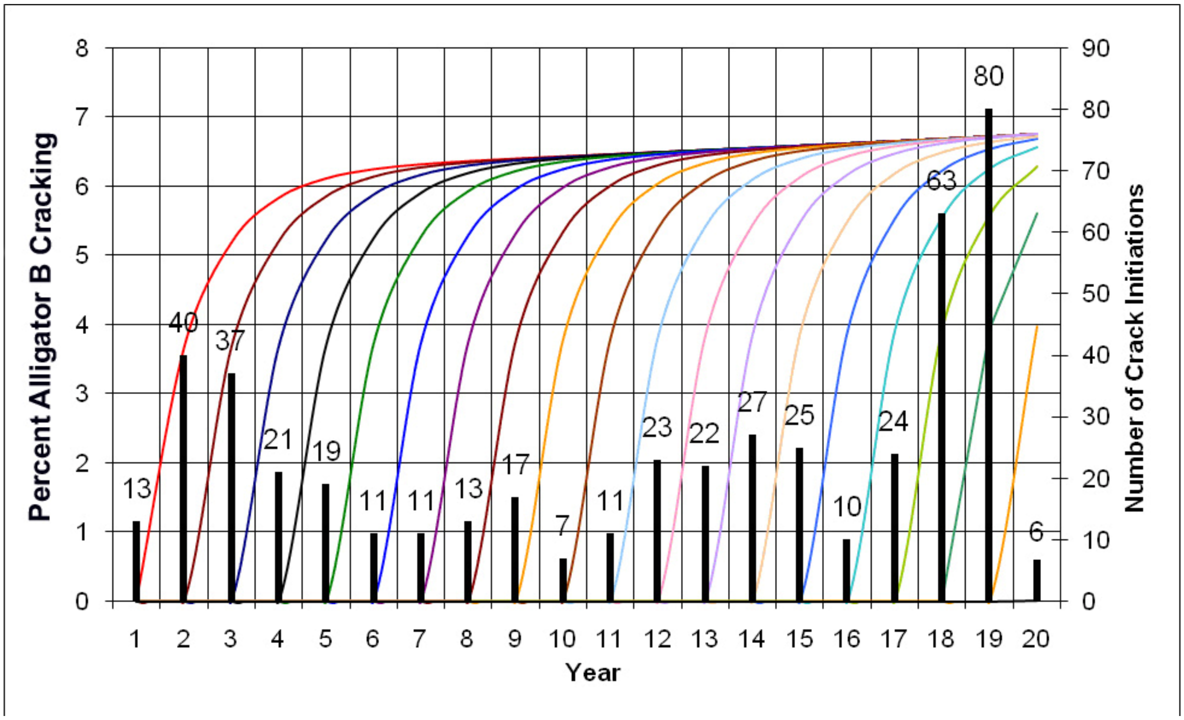

Figure 20: Alligator A cracking: 20 percent, Alligator B cracking: 30 percent; other variables constant.

4 SENSITIVITY ANALYSIS FOR WSDOT DATABASE INPUT VALUES

In this section, the effect of input variables of the WSDOT model on the life of the overlay is evaluated through sensitivity analysis using a range of values from the WSDOT PMS data originally used to calibrate the model.

The expected ESALs to 5 percent Alligator A or B cracking (whichever occurs first) for each variable at its mean value in the sample and mean +/- one standard deviation (S) (Table 5) are computed, while all other variables are kept fixed at their mean values. The results presented in Figure 21 show that the overlay thickness has the largest effect on the life of the overlay. The environmental variables including the average maximum temperature of the hottest month, the average minimum temperature of the coldest month, and the freeze-thaw cycles are also important in determining the life of the overlay, and they rank as the second most important variables. Existing Alligator A and Alligator B cracking seem to have a smaller effect on the life of the overlay. This behavior is probably due to the WSDOT's proactive approach to pavement preservation practices. The department almost always places overlays before cracking has exceeded 10 percent of the wheelpath with Alligator B cracking and typically overlays at about 5 percent of the wheelpath cracked. Therefore in the WSDOT PMS database, most of the sections have less than 10 percent existing cracking (Figure 1 and Figure 2).

The results shown in Figure 21 help one understand the behavior observed in Chapter 3, where the effects of input variables were analyzed for some California conditions. Overlay thickness seems to be the most sensitive variable both in the analysis with the WSDOT database as well as the scenarios studied with California data. However, as noted in Chapter 1, most of the data used to calibrate the model is from overlays of approximately 0.15 ft (about 45 mm). As can be seen in Table 5, the mean plus one standard deviation thickness is only 0.21 ft (about 65 mm). Therefore use of the model for thicker overlays is largely an extrapolation. It can also be seen that the thicknesses of existing asphalt layers is thinner than would be found on many Caltrans highways. Environmental variables are the next most sensitive variables in the WSDOT models.

Table 5: The Mean, and Mean +/-S of Each Explanatory Variable in the Sample

Variable	Description	Units	Mean-S	Mean	Mean+S
Alligator B	Existing Alligator B cracking	% of wheelpath	N/A	4.98	12.33
Alligator A	Existing Alligator A cracking	% of wheelpath	5.58	29.39	53.19
Actbthick	Thickness of AC base layer	ft	0.28	0.39	0.50
Pcctbthick	Thickness of cemented base layer	ft	0.47	0.50	0.52
untrthick	Thickness of untreated base layer	ft	0.40	0.80	1.20
Prev. AC thick	Thickness of previous AC overlay	ft	0.24	0.46	0.67
T max	Average high temperature in hottest month	°C	21.81	25.44	29.08
Tmin	Average low temperature in coldest month	°C	-4.73	-1.45	1.83
Ftprep	(Average annual freeze-thaw cycles) * (average annual rainfall)	(Cycles) * (mm)	N/A	22,192.30	45,277.68
Newoverlay	New overlay thickness	ft	0.09	0.15	0.21

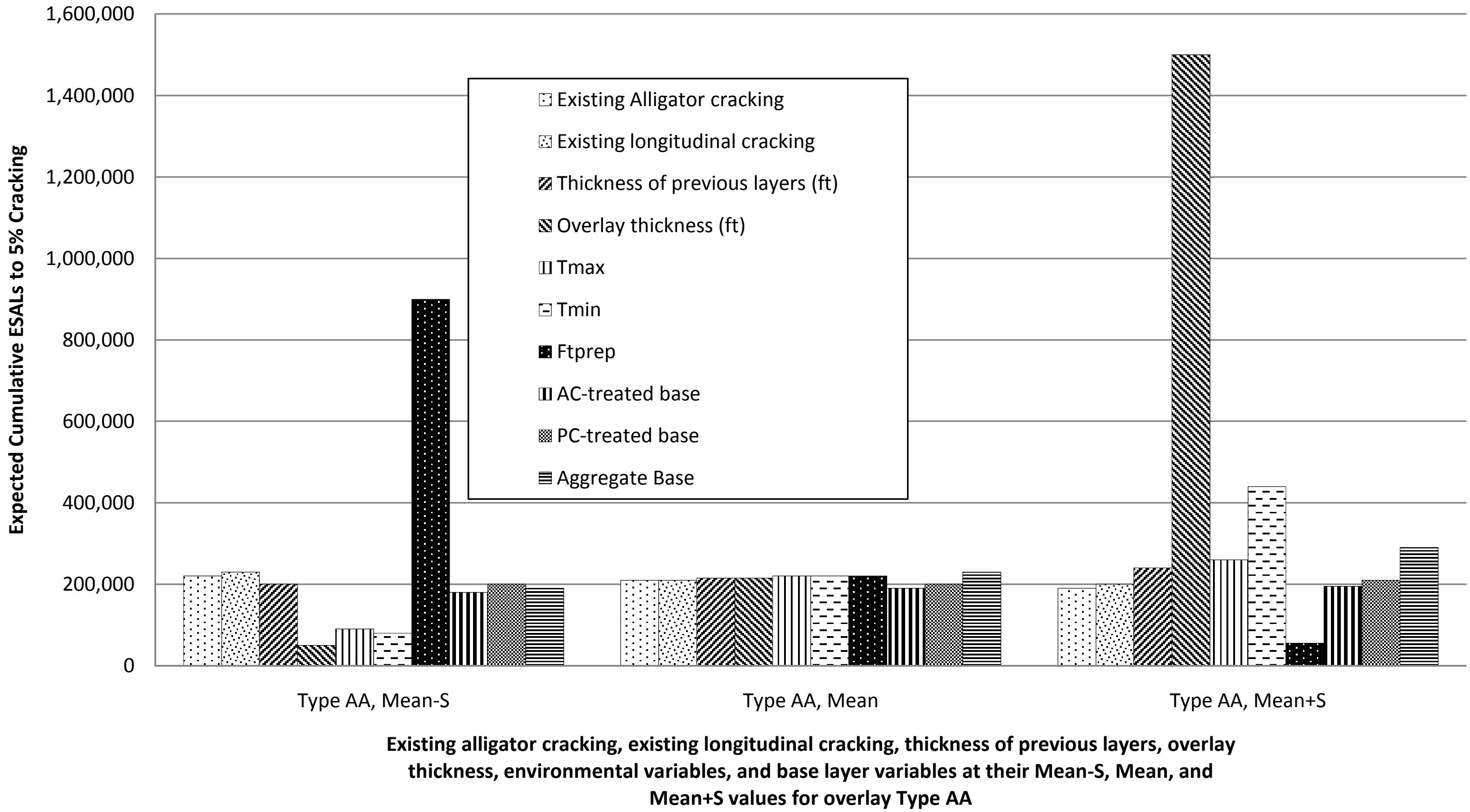

Figure 21: Comparison of the effect of input variables on the life of the overlay with WSDOT PMS data.

5 CRACK INITIATION MODEL DEVELOPMENT WITH AVAILABLE CALTRANS DATA

This section summarizes the results of an attempt to update the model—originally calibrated with WSDOT PMS data for crack initiation (defined as five percent of the wheelpath with either Alligator A or Alligator B cracking, whichever comes first)—with Alligator cracking performance data from the Caltrans PMS database. Data used for the comparison was gathered by University of California Pavement Research Center (UCPRC) staff (3) to estimate the performance of different pavement preservation strategies after extraction of performance data from the historical Caltrans PMS database. However, actual overlay thicknesses and underlying structures were not available in the Caltrans database, and had to be estimated based on the assumed typical overlay thicknesses defined in the overlay funding program—either Maintenance (HM-1), Capital Preventive Maintenance (CAPM), or Rehabilitation.

The crack initiation model developed here is based on limited HM-1 overlay performance (600 observations) available from the Caltrans PMS database. Almost all of the sections used are assumed to be thin overlays of 25 mm to 35 mm. Following is a description of the relevant variables found in the HM-1 data used in the model. A similar analysis was attempted for rubberized gap-graded mixes, however, only 75 observations were available which is an insufficient sample to create a hazard function.

The dependent variable is the number of cumulative ESALs to failure when failure is defined as 5 percent Alligator A cracking. The variables Mintemp, Exabc, and Ftavg used as explanatory variables are defined as follows:

- *Mintemp:* Average monthly minimum temperature in °C of the coldest month;
- *Exabc*: Existing Alligator B cracking in percentage;
- *Ftavg:* Average number of freeze-thaw cycles in a year; and
- *Cum-ESAL:* Cumulative ESALs to initiation. Cum-ESAL is the sum of the ESALs from the year of the last overlay to the year when crack initiation occurs. If cracking does not occur by the end of the experiment, then Cum-ESAL is the sum of the ESAL from the last overlay to the end of the experiment.

It is important to note that since this model was developed based on limited HM-1 data with thicknesses of 25 mm to 35 mm, overlay thickness could not be included as an explanatory variable. Therefore, application of the model is limited to predictions of overlay cracking with similar conditions (thin conventional type A DGAC overlays between 25 mm to 35 mm).

Table 6 shows the minimum, mean, and maximum values of each explanatory variable in the sample.

Table 6: The Minimum, Mean, Standard Deviation, and Maximum of Each Explanatory Variable in the Sample

Variable	Mean	Std. Dev.	Min	Max
Mintemp (°C)	12.17	7.94	-26.30	2.30
Exabc (%)	17.00	18.35	0.00	100.00
Ftavg	98.77	70.79	0.00	207.00

5.1 Model Specification

The initiation of pavement distress is highly variable because distress occurs at different times at various locations along a homogenous section of road. Therefore, time of failure should be represented by a probability density function rather than by a point estimate. Moreover, a robust pavement deterioration model should be able to predict future pavement condition on the basis of both present condition and a variety of external deterioration factors, such as traffic, climatic, and environmental parameters. For these reasons, duration models were used instead of regression models, which only provide point estimates. A new semiparametric duration model (Cox model) was developed to predict crack initiation for thin overlays. Details of the model's development are discussed in this section.

A new survival analysis using the Cox model was performed using the limited HM-1 data available in order to correct the crack initiation model predictions. A baseline survival function using Caltrans HM-1 data was developed and is presented here. It is important to note that since data used for the new model are only from HM-1 strategies, this model should be used in predictions for thin overlays (less than 0.2 ft [65 mm]). Once Caltrans populates its PMS with sufficient data, this model can be updated and used for other pavement preservation strategies as well.

A new Cox model was developed using approximately 600 observations from the HM-1 Caltrans data sources described earlier. The Cox model is the duration model used in this study. The hazard function is the primary focus of duration models. The hazard function can be regarded as the probability of occurrence of the event of interest within a short time interval, conditional on the pavement section having survived to the interval's start time and the influence of the relevant explanatory variables. For this study, the failure event is defined as crack initiation in new overlays (five percent Alligator A or B cracking). Time to cracking of a pavement (or cumulative ESALs to five percent cracking), denoted by T, is defined as a nonnegative random variable that takes values in the interval $(0, \infty)$. It has a cumulative distribution F(t) and a density function f(t). F(t) is given by:

$$F(t) = \int_0^t f(s)ds = \Pr ob(T \le t) \quad \textbf{(1)}$$

The probability that cracking occurs after time t is given by the survival function:

$$S(t) = 1 - F(t) = \Pr ob(T \ge t) \quad \textbf{(2)}$$

Define g(t) as the probability that a pavement cracks in the next small interval, Δt, given it lasts at least until time t:

$$g(t) = \Pr ob(t \le T < \mathrm{t} + \Delta \mathrm{t} \mid \mathrm{T} \ge \mathrm{t}) \quad \textbf{(3)}$$

The instantaneous rate of change of g(t), defined as the Hazard Rate Function, h(t), is given by:

$$h(t) = \lim_{\Delta t \to 0} \frac{g(t)}{\Delta t} \quad \textbf{(4)}$$

The hazard rate quantifies the instantaneous risk that the pavement sections crack at time t. To ensure modeling success, selection of hazard functions is of primary interest. As suggested by previous studies (7, 8), semiparametric models appear to be well suited for modeling the failure hazard of pavements due to their flexibility in modeling and the simpler function form. The Cox model is one of the most flexible and the most used models in the semiparametric family of models.

For nontime variant covariates, the Cox hazard function is given by:

$$h(t) = h_0(t)\Psi(x) \quad \textbf{(5)}$$

where $h_0(t)$ is an arbitrary unspecified baseline hazard function that will be estimated, and

$$\Psi(x) = e^{\underline{x}^T \underline{\beta}} \quad \textbf{(6)}$$

where $\underline{x}$ is a vector of explanatory variables observed with the duration data and $\underline{\beta}$ is a vector of parameters that will be estimated by maximum likelihood.

The cumulative distribution function, the density function, and the survival function are given by Equations 7, 8, and 9 respectively.

$$F(t) = 1 - [S_0(t)]^{\Psi(x)} \quad \textbf{(7)}$$

$$f(t) = f_0(t)\Psi(x)[S_0(t)]^{\Psi(x)-1} \quad \textbf{(8)}$$

$$S(t) = [S_0(t)]^{\Psi(x)} \quad \textbf{(9)}$$

where S_0 and f_0 are the baseline survival and density functions respectively, and are equal to S(t) and f(t) respectively when $\Psi(x) = 1, (\underline{x} = \underline{0})$

The baseline hazard function is related to the baseline survival and density functions:

$$h_0(t) = \frac{f_0(t)}{S_0(t)} \quad \textbf{(10)}$$

The function $\Psi(x) = e^{x^T \beta}$ that gives the best model using the limited number of explanatory variables available from HM-1 data is of the form:

$$\Psi(x) = \text{Exp}\ (\beta_0 + \beta_1 \text{mintemp} + \beta_2 \text{exabc} + \beta_3\ \text{ftavg}) \quad \textbf{(11)}$$

5.2 Model Results and Analysis

The model estimation results are shown in Table 7. It can be seen that all the parameters are significant (p-values are less than 0.05). This result suggests that all the variables—existing alligator B cracking, average number of freeze-thaw cycles, and the lowest minimum temperature of the coldest month—contribute significantly to the time of crack initiation (five percent Alligator A cracking). Furthermore, these results confirm the signs expected. It is important to note that positive coefficients indicate negative effect on the cumulative ESALs to five percent cracking.

Table 7: Estimation Results for the HM-1 Model

Variable	Symbols	Coef.	Z	P> |z|
Constant	β_0	-5.8832	-24.16	0.04
Mintemp	β_1	-0.1021	-3.82	0.00
Exabc	β_2	0.0009	1.08	0.003
Ftavg	β_3	-0.0061	-2.04	0.00

In order to compare the prediction results of the Cox model developed in this study with the model developed using WSDOT PMS database (1, 2) the estimated survival and hazard functions of both models were plotted on the same plot (Figure 22 and Figure 23, respectively). Figure 22 shows the difference between the survival function estimates of the Caltrans HM-1 overlays and the WSDOT sections. The figure shows that the WSDOT overlay sections have a higher probability of survival at early stages. For instance, around 30 percent of WSDOT overlay sections survive past 2,000,000 cumulative ESALs, whereas 10 percent of Caltrans HM-1 overlay sections survive past 2,000,000 cumulative ESALs. An explanation for this survival function's behavior is that WSDOT performs higher routine maintenance at early stages compared to Caltrans maintenance practice.

Figure 22 shows the Cox survival functions for both the Caltrans HM-1 and WSDOT sections after model estimations using a semiparametric Cox model. It can be seen that the WSDOT sections have a higher probability of survival compared to the Caltrans HM-1 sections. One explanation for this trend may be that the WSDOT sections generally have thicker overlays (45 mm) compared to the Caltrans overlays (25 to 35 mm). Moreover, WSDOT has an intensive maintenance strategy and usually places overlays before Alligator B cracking exceeds 10 percent of the wheelpath, which is quite different from Caltrans practice prior to 2003, which forms the bulk of the California observations.

Figure 23 shows the hazard functions both for Caltrans HM-1 overlays and WSDOT sections. Here it is seen that the hazard rate for both the Caltrans and WSDOT sections is initially high for the relatively low values of cumulative ESALs. This high rate of early failure is likely due to poor construction or badly cracked underlying sections . However, those sections that have survived early failure have low hazard rates and extended lives. This trend is observed both for Caltrans and WSDOT sections, as shown in Figure 23. It is important to note that routine maintenance practices among DOTs differ and hence the hazard rate behavior differs between the two states. In addition, hazard rate is controlled by climate, construction quality, and extent of cracking in the underlying section.

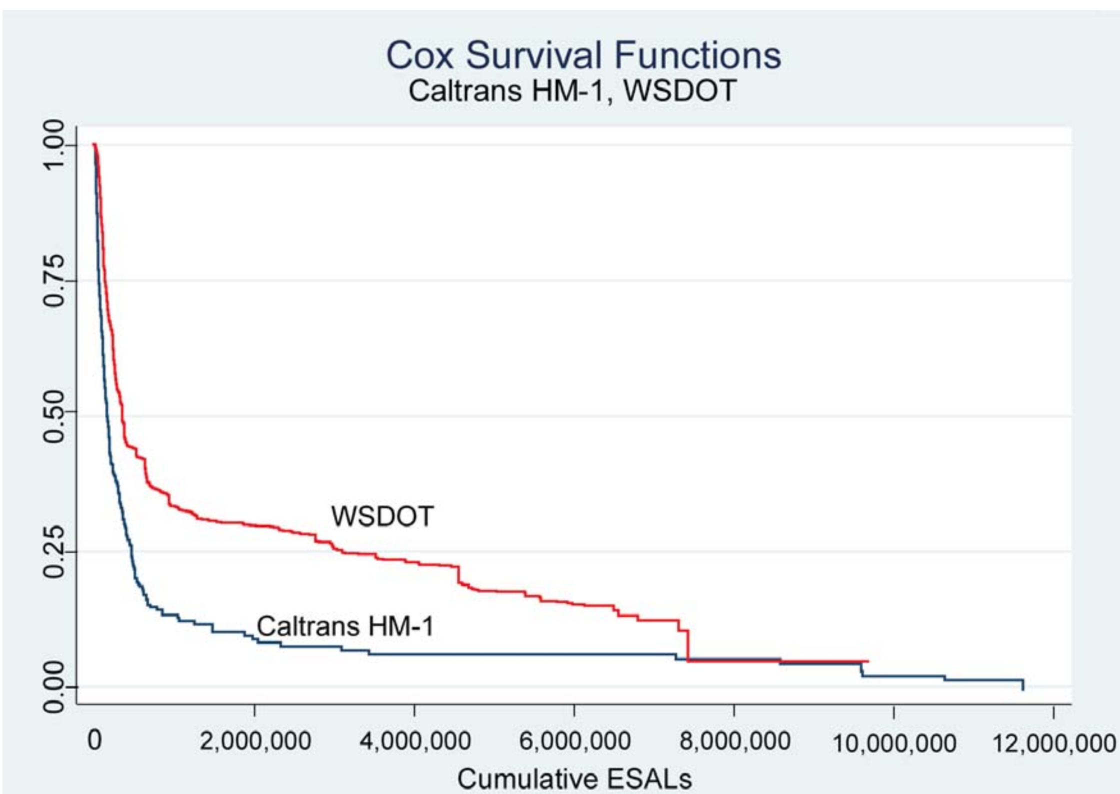

Figure 22: Combined survival functions for Caltrans HM-1 and WSDOT.

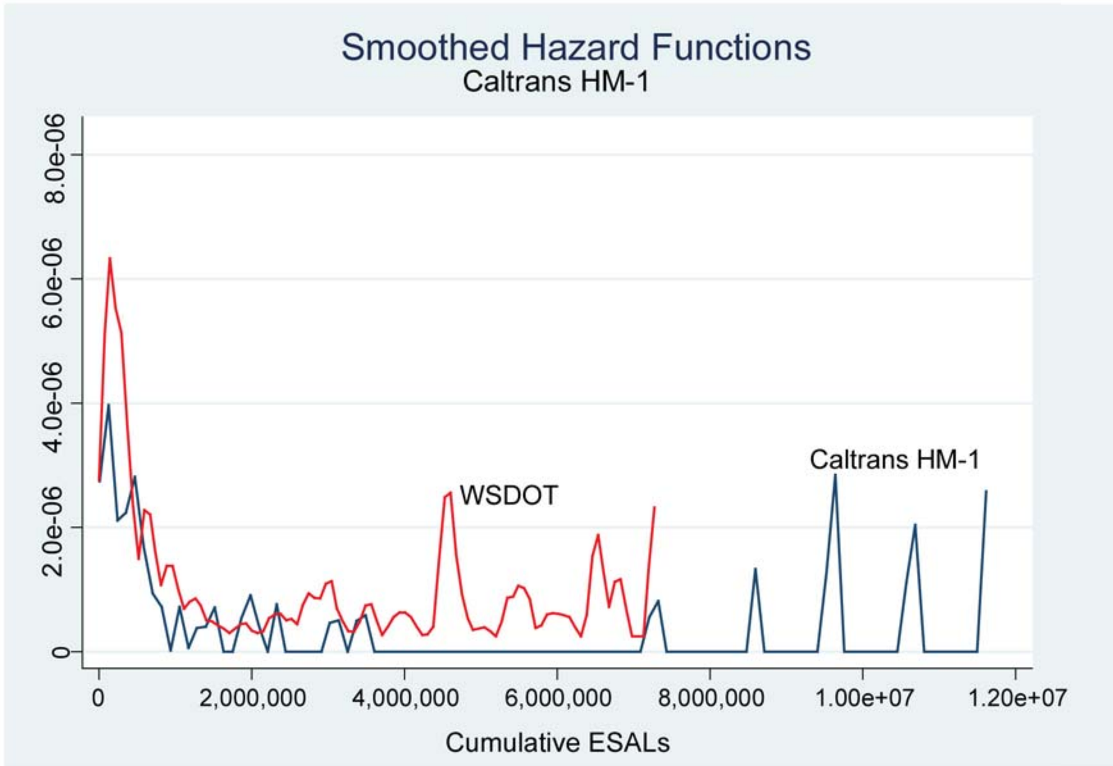

Figure 23: Plot of hazard functions for Caltrans HM-1 and WSDOT.

6 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are drawn from the results presented in this report.

Sensitivity analysis done as part of this study helped to identify the basic behavior of the initiation and progression models and to indentify their main design variables. The sensitivity analysis also identified the most sensitive input variables of the WSDOT models: overlay thickness and environmental variables. The reasonableness of the trends from the model was confirmed by varying the key variables and interpreting the results. However, both crack initiation and progression appear to be overly sensitivity to overlay thickness, climate region, and traffic volumes. The sensitivity analyses also indicated that the WSDOT crack progression model shows that cracking tends to never exceed about 10 percent of the wheelpath with Alligator B cracking, which is unreasonable when compared with levels of crack progression found in the historical Caltrans PMS database, which shows progression up to 50 percent of the wheelpath cracked. This is likely caused by the fact that historical WSDOT pavement preservation practice resulted in nearly all of the sections in the database being overlaid before they reached 10 percent wheelpath cracking.

Washington State's historical maintenance strategy has been to perform pavement preservation mainly with overlays averaging about 0.15 ft (45mm) thickness, and to place few thicker rehabilitation overlays. Data in the WSDOT PMS database indicates that the department has almost always placed thin overlays before cracking exceeds 10 percent of the wheelpath cracked, and typically overlays at about 5 percent of the wheelpath cracked. This results in biases in the coefficients for overlay thickness, Type A Alligator cracking, and Type B Alligator cracking in the WSDOT models. Consequently, Caltrans will need to recalibrate the models after it accumulates enough data in its PMS database. The coefficients of environmental variables—including number of freeze-thaw cycles, average lowest and highest temperatures, and average annual precipitation—will also need to be updated for good prediction of overlay performance in California.

The comparison of the WSDOT survival model with a limited crack initiation model developed from HM-1 pavement preservation data from the Caltrans PMS showed that the WSDOT overlay sections have a higher probability of survival at early stages. This might be due to the difference between maintenance practices of the Washington State DOT and Caltrans. WSDOT places overlays at early stages (usually when Alligator B cracking is less than 10 percent).Moreover, WSDOT generally places thicker overlays (45 mm) compared to the Caltrans HM-1 overlays (25 to 35 mm). A similar analysis was attempted for rubberized gap-graded mixes, however only 75 observations were available which is an insufficient sample to create a hazard function.

Review of the hazard rate functions both for Caltrans HM-1 overlays and WSDOT overlayss indicated that the shapes of the two hazard rates have a similar trend, rising initially due to poor construction or to badly cracked underlying sections, and then decreasing as the sections that survived early failure underwent routine maintenance. It is important to note that the shapes of these hazard rate functions lack a resemblance to any of the parametric functions such as the Weibull. This confirms that the Cox semiparametric model was the appropriate choice for modeling preservation overlays.

Based on these conclusions, the following recommendations are made:

- The HMA pavement performance model suite calibrated with WSDOT data needs to be recalibrated with California PMS data. However, before this can be done the Caltrans PMS database must be populated with information collected over consistently segmented sections and include information regarding existing pavement and overlay thickness and type. These changes in the Caltrans PMS database are scheduled to occur over the next three years (2009 to 2011). Because of the differences in historical maintenance policy between WSDOT and Caltrans, and the more benign climate regions in many parts of California, it is expected that the model parameters will change.
- Recalibration does not necessarily mean that all parameters will need to be re-estimated. As the sensitivity analysis revealed, the coefficients that will need recalibration include the *coefficient for overlay thickness*—because Washington State DOT generally uses thinner overlays than Caltrans—and the *coefficient for existing cracking before overlay*—because of the difference in maintenance policy between Washington State DOT and Caltrans. Historically, WSDOT's maintenance policy has leaned more toward pavement preservation than rehabilitation. The *climate variable coefficients* will also need to be recalibrated to reflect the more benign climate regions in California
- As illustrated in Chapter 5, survival estimates of the WSDOT initiation model could be updated for California's use with a limited number of input variables while Caltrans populates its PMS database. Recalibration of the progression model will also be required. Once enough data has been recorded and measured, the WSDOT model "suite" with all the significant input variables can be implemented as a decision-support tool to aid Caltrans in planning Maintenance, Rehabilitation, and Reconstruction (MR&R) activities at both the project and network levels.

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