Features of Mechanistic Empirical Asphalt Pavement Models for New Design and Rehabilitation in California

J. Harvey
University of California Pavement Research Center, Davis, California, USA

Q. Lu
University of California Pavement Research Center, Davis, California, USA

J. D. Lea
University of California Pavement Research Center, Davis, California, USA

P. Ullidtz
Dynatest Consulting Inc., Denmark

R. Wu
University of California Pavement Research Center, Davis, California, USA

I. Basheer
California Department of Transportation, Sacramento, California, USA

ABSTRACT:
In 2005, the California Department of Transportation (Caltrans) approved an issue memo titled "Adoption of Mechanistic-Empirical (ME) Pavement Design Method", which calls for the adoption of ME pavement design methodology to replace existing pavement design methods, which have been in place since the early 1960s. For design of new flexible pavements and for rehabilitation of existing concrete and asphalt pavements with asphalt, a number of Mechanistic Empirical models have been developed, tested, and collected into a design system known as CalME, which employs an incremental-recursive approach using the time hardening procedure and Weigh In Motion (WIM) load distribution data. The paper generally describes the system layout with an emphasis on the use of the models for rehabilitation design, as well as the final versions of the models included into CalME, highlighting models that differ from typical ME models, including MEPDG. In particular, the different methods of handling climate, traffic and materials variability are described, including definitions of failure tied to variability. Examples presented in the paper show the use of Monte Carlo simulation and consideration of maintenance or rehabilitation (M&R) actions over any desired evaluation time period. These M&R actions may consist of traditional overlays, preventive maintenance actions, mill and fill, or any recycling actions. The use of predicted performance from these simulations in the Pavement Management Systems (PMS) is discussed.

KEYWORDS: Mechanistic-empirical, asphalt, variability, monte carlo, climate, traffic, preservation.

1 INTRODUCTION

1.1 Background

The California Department of Transportation (Caltrans) has used the R-value empirical design method originally developed by Hveem for design of new and reconstructed asphalt pavement, last calibrated in the 1960s, and a deflection-reduction method for design of asphalt overlays since the 1970s. These current design methods are extremely limited in their ability to consider current issues of importance to Caltrans for design and analysis such as pavement preservation overlays; longer design lives for new pavement, reconstruction and rehabilitation; new materials; the variety of asphalt, cemented and granular materials in use; recycled materials (in-place and plant recycled asphalt, concrete and granular materials and rubberized asphalt); construction compaction; the variety and condition of existing pavement structures; reflection cracking in asphalt pavements; climate regions; increases in tire inflation pressures and axle loads; traffic speed; variability of materials and construction practices; and uncertainty regarding future traffic growth.

Realizing the ability of ME methods to help with addressing these limitations, Caltrans approved an issue memorandum in 2005 titled “Adoption of Mechanistic-Empirical (ME) Pavement Design Method”, which calls for the adoption of ME pavement design methodology to replace existing empirical methods. The issue memorandum has lead to local calibration and adoption of the MEPDG (NCHRP 2004) for jointed-plain concrete pavement design. Limitations of the MEPDG flexible models were identified during its development, and the opportunity was taken to produce, calibrate and implement an alternative set of design and analysis models for asphalt pavement incorporated in a software program called *CalME* to address the issues described above.

1.2 Goal and Objectives of ME Flexible Design and Analysis System

One of the goals of the project to develop a new ME design and analysis system for California is to produce a software package, databases, guidelines and test methods that will result in more cost-effective pavements. Cost efficiency is defined by Caltrans primarily in terms of life cycle cost (LCC), which considers relevant costs to the sponsoring agency, owner, facility operator, and roadway user that will occur throughout the life of an alternative. CalME is intended to support this goal. One of the objectives for CalME is that it can be calibrated using accelerated pavement test data, such as Heavy Vehicle Simulator (HVS) test section, as well as test track and field section data. The incremental-recursive approach used in CalME means that the entire damage process measured by HVS test section instruments can be used for calibration of response and damage models from the first load through the end of the project, with many data points in between. In contrast, the MEPDG and other ME methods using Miner’s Law (hypothesis of linear accumulation of damage) only use the initial undamaged responses of the pavement to temperature and load, and assumes the entire damage process to the end failure state. The incremental-recursive approach also permits use of deflection and other response data tracking the damage and aging processes on test tracks and field sections for calibration of the damage process, even when failure has not yet manifested itself on the pavement surface, provided that measurements are regularly taken after construction. In contrast, the MEPDG and other methods using Miner’s Law must use biased data sets for their calibration because sections that have been damaged but not yet manifested distress at their surface are essentially excluded from the calibration data set or must be considered as undamaged in the data set.

Additionally, in contrast to the MEPDG which is primarily focused on new pavement design, CalME is designed to maximize its utility for the work that Caltrans and consultant engineers will use it for by focusing on:

- Rehabilitation and pavement preservation
- New materials and in-place recycling
- Construction quality
- Integration with the improved PMS

Significant variables that are considered in CalME that are not considered in current empirical methods used in California include:

- Climate regions
- Changes in traffic axle load spectra, inflation pressures, wander and speed
- Variability of materials, construction, climate and traffic
- Properties of in-place pavement materials

2 FEATURES OF CALME

2.1 Traffic Characterization

CalME uses the axle load spectrum approach for truck traffic inputs. Caltrans has made a major investment in establishing more than 110 permanent weigh-in-motion (WIM) stations and routinely calibrating them. The CalME software requires detailed truck traffic information, but the requirements are less demanding than those of the MEPDG. CalME needs two types of truck traffic information: traffic volume and axle load spectra. Traffic volume includes three variables: number of axles per truck, number of axles per year per design lane, and growth rate. Four axle groups are considered: steering, single, tandem, and tridem. The hourly load spectra of each axle group are needed for the entire year. However, because most projects will still not have a WIM station within them, a set of typical axle load spectrums have been established (Lu 2008).

A procedure was developed and has been implemented in CalME to estimate truck traffic inputs for CalME and MEPDG (adapted by Caltrans for joint plain concrete pavement design) for highways where site-specific traffic data are unavailable or incomplete. Based on cluster analysis of axle load spectra, the WIM sites were divided into eight groups, and default truck traffic inputs were developed for each group. A decision tree was developed to decide which group a highway section will fall into. The inputs for the decision tree are geographic locations (county, route, post-miles), and traffic volume and composition that are obtainable from the Caltrans annual report of Average Annual Daily Truck Traffic (AADTT).

For each axle spectra group CalME provides the default traffic inputs including the number of axles per truck and the hourly load spectra (from analysis of hourly WIM data across the state) of steering, single, tandem, and tridem axles. The default traffic inputs for each group, along with the traffic inputs for each WIM site, are stored in a Microsoft Access database, from which the needed information are retrieved by the CalME software. The designer inputs the expected number of trucks in the first year. All of the default data can be edited by the user, if warranted. Figure 1 shows plots of all WIM spectra in three main groups for tandem axles, as an example. Group 2 was divided into two (2a and 2b) groups in the final database; examples for all axle types are in (Lu 2008).

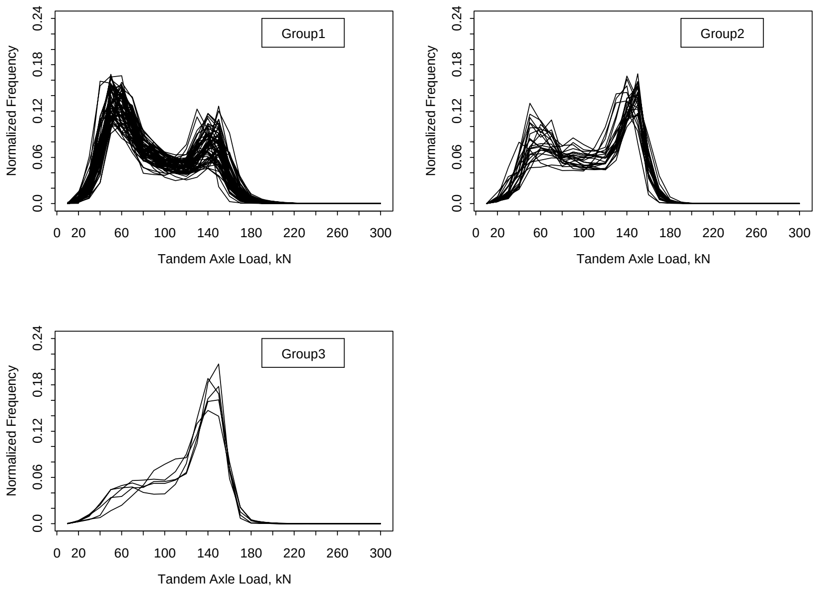

Figure 1: Tandem axle load spectra in each group.

2.2 Climate Characterization

Pavement temperatures are affected by air temperatures as well as precipitation, wind speed, and solar radiation. The response of a pavement system is highly influenced by the temperature of the surface layers and moisture content of the unbound soils. Annual, seasonal, and daily variations in temperature and precipitation have large influences on pavement service life. CalME currently calculates pavement temperatures and considers their effect on asphalt stiffness. The original assumption in the set up of *CalME* was that unbound materials should have sinusoidal type functions for stiffness to simulate seasonal variability, since there are distinct dry and wet seasons and freeze-thaw is not an issue in most of the state. It has been found through field deflection testing that “typical” seasonal variability associated with drainage conditions, cut and fill, perched water tables at higher elevations, and agricultural and landscape irrigation does not exist along many routes. Calibration of variation of subgrade and unbound layer stiffnesses is therefore left for the designer to input, and the default is “no variation”.

CalME currently operates using a database of pavement temperatures calculated using the stand-alone Enhanced Integrated Climate Model (EICM) version 3 (Larson et al, 2003). A 30 GB database was originally created using six cities with first-level weather data, each representing a climate region, using weather data obtained from the National Climatic Database Center CD-ROMS (1994) and the California Department of Water Resources (2003). The weather data includes 30 years (1961-1990) of daily maximum and minimum temperatures, daily average percent sunshine, daily average rainfall, daily average wind speed for the representative cities in each region. The database has recently been increased to consider three additional mountain climate regions in the state, now totaling nine, which is aligned with the Caltrans PG asphalt grade specification.

The EICM program was used to evaluate 28 different flexible pavements and 4 different composite pavements with combinations of layer thicknesses covering the expected range in the state for each climate region over a 30-year period (1961–1990). Temperature and moisture changes in the rigid pavement under the asphalt in the composite pavements are not currently included in the reflection cracking model in CalME.

CalMe is currently set up to access pavement surface temperature data from a 100 MB database that only contains the surface temperatures from the original 30 GB database and computes the temperatures below the surface using a fast one-dimensional finite element method routine. This process uses an internal database of thermal diffusivity constants for each material, where diffusivity is a function of the heat capacity and the thermal conductivity. This algorithm can run 30 years of full-depth pavement temperatures in less than 0.1 seconds. To check the method, comparisons were made with at-depth EICM results and the results were found acceptable. In contrast, the MEPDG runs EICM internally each time an analysis is performed, which makes the run times long enough that Monte Carlo simulation is essentially impractical.

If a deterministic analysis is being performed (no Monte Carlo), CalME only uses the data from each hour of the first day of each month through the 30 years of data, which misses a significant amount of actual variability because only one day is analyzed.

Analyses were performed to evaluate the year-to-year variability of temperature and rainfall data and the effects on pavement temperatures (Ongel et al, 2004). It was found that the distribution of temperature data was reasonably stable, except for the number of extreme temperature days. It was also found that annual rainfall is extremely variable in California from year to year. Based on the rainfall variability it was decided to use the full 30 years data for analyses. For analysis periods longer than 30 years, the 30 year data is repeated. Albedo of a given pavement surface, or its solar reflectivity was also considered. The solar absorptivity value changes according to pavement type and pavement age. It was assumed to be 0.90 or 0.95 for new flexible pavements and for old flexible pavements 0.80 based on measurements by Pomerantz et al (2000). The effect of solar absorptivity values was significant at higher temperatures, increasing pavement surface temperatures by approximately 5ºC for the range of albedos considered on the hottest days, and therefore increased the risk of rutting. Solar absorptivity values have no effect on surface temperatures at colder temperatures.

2.3 Damage and Performance Models

CalME currently, or by July 2010, will include stiffness models, damage and rutting models, and the transfer functions from damage to distress shown in Table 1. All damage and rutting models are incremental-recursive, meaning that the properties of the materials are updated after loading in each time period for each axle load spectrum group and temperature combination. The process of developing and calibrating these models using HVS and test track data is described in Ullidtz et al, 2010 and other papers and articles.

Table 1: Damage or rutting models and transfer functions for all materials.

Material	Damage or Rutting Model	Transfer Function

Hot Mix Asphalt (various mixes), Rubberized Hot Mix Asphalt mixes, Polymer modified mixes	Bottom-up fatigue for all layers, bottom-up load related reflection cracking fatigue on cracked HMA and PCC, rutting for all layers within 100 mm of surface	Fatigue damage to surface cracking
Cement treated materials	Bottom-up fatigue, crushing	
Unbound granular materials	Rutting for each layer	
Full-depth recycling as pulverization, foamed asphalt/cement bound	Fatigue, rutting	
Subgrade	Rutting	
Hot-in-place recycling, cold-in-place recycling	Rutting, fatigue	

2.4 Materials and Layer Thickness Characterization

A general description of materials characterization for CalME is described in another paper at this conference. For rehabilitation projects, CalME is designed to work with the companion layer stiffness back-calculation called CalBack. The guideline for FWD testing is that deflections should be repeated at a portion of the deflection locations at two times of the day, to provide two points for characterization of the HMA master stiffness curve.

CalME imports means and standard deviations of layer stiffnesses from CalBack. The designer uses either measured means and standard deviations of layer thicknesses from cores or ground penetrating radar (GPR), or can use typical values included in the program database. In addition, the program can consider variability of the shift factor (A) for each damage function. The standard deviations are needed for running Monte Carlo simulation. An example of the variability inputs for layer thickness, layer stiffness, values of parameter A for permanent deformation (PdA), fatigue damage (FtA) and crushing damage (CrA) is shown in Figure 2.

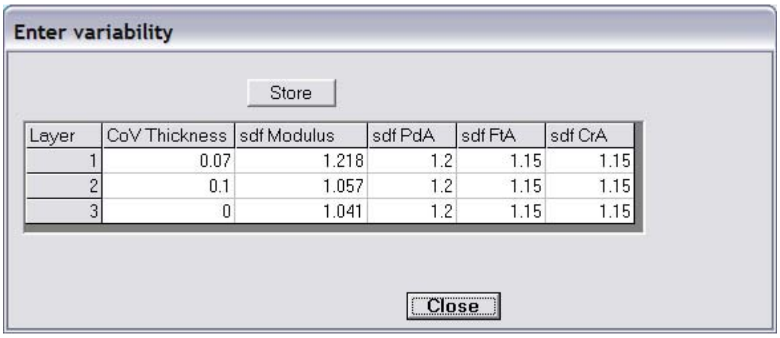

Figure 1: example of variability inputs for Monte Carlo simulation.

Layer thickness is assumed to have a normal distribution while all other variables shown in Figure 2 are assumed to follow a log normal distribution, used in part to avoid values less than zero and matching distributions typical in the state. Even though crushing model parameters are shown to have variability, they are not active unless the crushing model is used.Caltrans is currently in the middle of a contract to collect GPR data for every lane-km in the state network. The data will be analyzed to produce pavement structural cross-sections for a large portion of the network at intervals of either every 10 m (more important routes) or every 100 m (less important routes). It is anticipated that the lanes that are not analyzed as part of that project will be analyzed later when project-level analysis for rehabilitation or pavement preservation is performed. GPR data produces a continuous trace of reflections from the pavement, which can be analyzed for discrete points, or where possible or necessary, continuously, which will provide detailed thickness information for effective back-calculation of stiffnesses.

2.5 Consideration of Variability and Reliability

Deterministic analyses can be performed using CalME. CalME uses Monte Carlo simulation to simulate variability for probabilistic analysis based on variability of key pavement properties such as stiffness, thickness, etc. In contrast, the reliability calculation in the MEPDG is essentially an analysis of the calibration error of the method. The Monte Carlo simulation in CalME is for “within section” variability, as opposed to “between section” variability. It is recommended that sensitivity analysis be used to consider the effects of different materials supplied to the project by the low bidder in the Design-Bid-Build (DBB) project delivery method generally used by Caltrans. Variability as reflected in Figure 2 is for a given set of materials supplied to the project. CalME randomly varies stiffness and thickness using Monte Carlo simulation, knowing that the effects of variability in stiffness and thickness will be transformed into variations in damage, and then from damage into performance by the respective functions. This will provide an indication of the variability of the design based on the two primary factors that can be controlled by the designer and constructer.

Permanent deformation and damage are predicted for a single point and the variations of these values are considered to be within section variations, section distributions of the variables shown in Figure 2. For rutting, Monte Carlo simulation produces the mean and standard deviation of rut depth. At a future point in development of CalME, and if sufficient data is available, the variance of the rut depths and the auto-correlation function for the rut depths will be used to develop simulate International Roughness Index on the simulated longitudinal profile.

The crack propagation is defined in terms of time to some threshold extent of cracking in terms of crack length per surface area of the wheelpath in sub-sections within the project. The number of sub-sections is defined by the number of simulations included in the Monte Carlo simulation. For example, as shown in Figure 3, ten simulations have been run, and the years to different percentages of the wheelpaths being cracked is defined by the time to reach 1 m/m^2 of cracking in each of ten sub-sections of the project.

With regard to temperature variability, CalME randomly selects the initial year within the available database to produce a data set for a given simulation. For example, for the first simulation the initial year of climate data may be 1988, and for a five year analysis period climate data will be taken in sequence starting in that year, and proceeding through 1989, 1990, 1960 and 1961. Within each month of each year, CalME randomly selects the day used to characterize the hourly pavement temperatures for the month (default analysis increment is one month, although this can be changed by the designer). CalME calculates pavement response to load and environment and the resultant damage recursively, meaning that the damage calculated in previous time periods influences the pavement response in the current time period. The order in which temperatures occur therefore influences the outcome of the simulation.

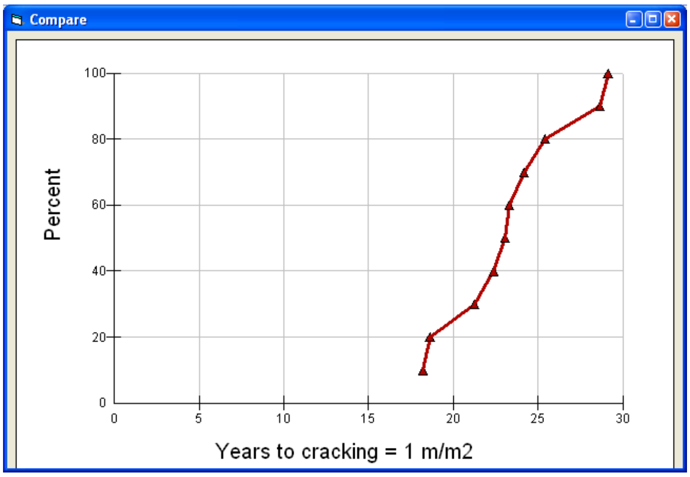

Figure 3. Percent of wheelpath cracked as defined by time to threshold cracking in each sub-section of project.

Traffic estimation is part of the planning process, not pavement design. The pavement is designed to withstand the design number of traffic repetitions, whether those occur in the expected time or not. Long-term plans for maintenance and rehabilitation can be adjusted in the PMS if traffic projections begin to deviate from the design traffic. Inclusion of the variance of traffic estimation would result in unnecessarily conservative designs.

Traffic is a stochastic process. However, it cannot be assumed that traffic will occur as predicted by previously observed distributions of repetitions, axles, speeds, etc. Some of these can be predicted fairly well over shorter periods, such as axle load spectrum, provided there is no abrupt change in the system such as a change in the axle load limits. It will depend on growth trends in the economy, local development patterns, connection of routes and development of local road networks, etc. For this reason sensitivity analysis is recommended for considering traffic, not random variation. Traffic scenarios recommended to be checked in the design process:

- Best Estimate: the best estimate for axle load spectrum and future repetitions.
- Low Estimate: based on projections, this may come from different curve types fit to the historical traffic growth data, or a variance in traffic growth between estimated and actual traffic growth from historical data.
- High Estimate: estimated in same manner as Low Estimate.

The key question from the sensitivity analysis is whether the LCCA result changes significantly when the traffic estimate changes from Best Estimate to Low or High. Eventually, the within-section analyses should include the dynamic interaction of longitudinal profile from rut depth variation and the vehicle.

In summary, the recommended practice for determining reliability of a pavement design for a given project is:

1. Run the CalME simulations using the within-project variabilities, expected traffic and random sampling of the initial year of climate data when evaluating sensitivity of a design for construction variability. This will provide the designer with a value for expected variation and reliability due to construction and climate combined.
2. If warranted by the expense of the project, repeat the simulations using the high and low traffic estimates. Decision: if the network is of sufficient importance,

consider making a policy decision to use the results from the high traffic estimate.

2.6 Consideration of Pavement Preservation

CalME simulates pavement preservation as part of the pavement damage simulation, following maintenance and rehabilitation strategies (M&R) designated by the designer or included in the decision tree from the PMS. CalME simulates M&R activities automatically based on triggering criteria predefined for each strategy and simulates pavement performance accordingly. M&R activities can be triggered by either distresses such as rutting and cracking, or age of the wearing course. All of the predefined CalME M&R strategies are listed in the “M and R strategy” combo box in the incremental-recursive design window. These strategies are grouped into three philosophies: rehabilitation only (R); rehabilitation followed by preservation, preservation, rehabilitation (PPR), and perpetual pavement preservation (PPP) in which there is only preservation and no additional rehabilitation after initial rehabilitation. Currently CalME has more than forty built-in M&R strategies depending on the philosophy adopted and surface materials used. In addition designers can define their own site specific strategy. Figure 4 shows a simulation with four pavement preservation treatments triggered or scheduled in the 50 year analysis period.

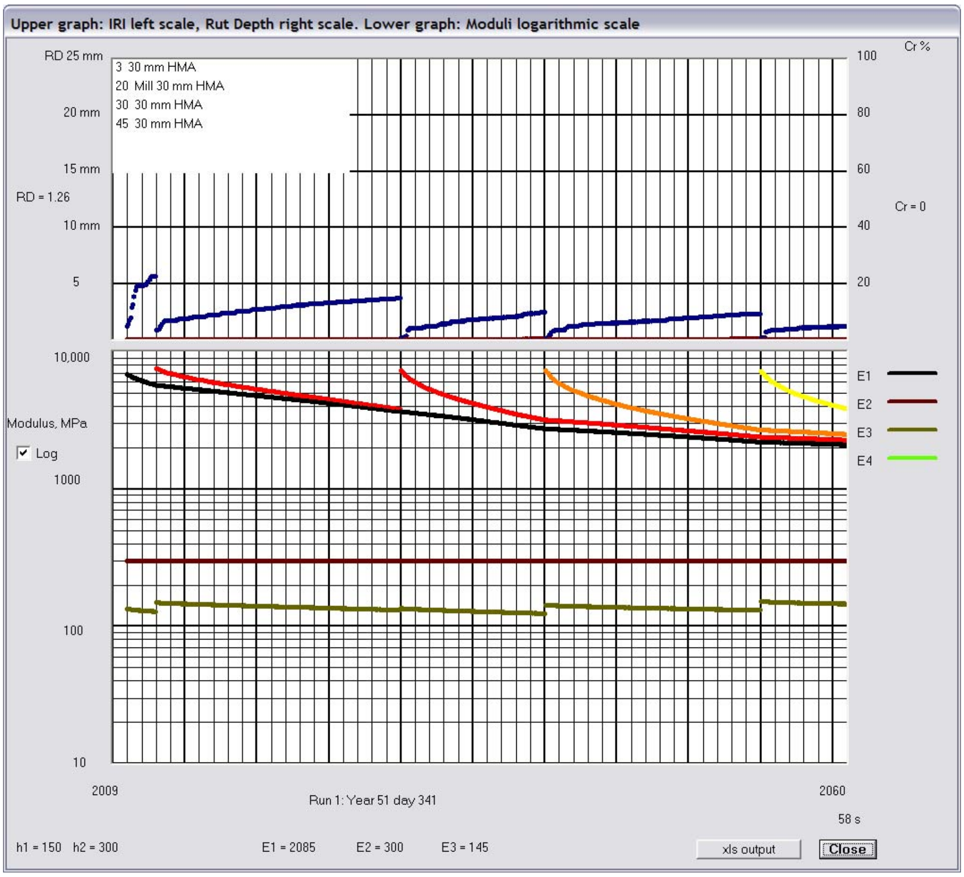

Figure 4. CalME simulation following a PPP strategy using 30-mm HMA. The maintenance activities are listed at the top left corner of the window. The first overlay occurred at year 3 and was triggered by 7-mm of total rut, the second overlay was triggered by age of the wearing course (17 years), the third, fourth and fifth overlays

were triggered by cracking in the wearing course.

2.7 Integration with PMS

The primary integration points between CalME and the new Caltrans PMS are:

- Distress definitions are compatible between CalME and the new pavement condition survey guide
- CalME M&R simulations will follow the decision tree in the new PMS
- It is planned that CalME will be used to produce the first estimate of pavement performance for after M&R activities by running CalME with as-built properties and variabilities. This initial performance estimate will then be updated by annual condition survey data.

3 SUMMARY

This paper has summarized the approaches for climate, traffic and materials characterization in the new asphalt pavement design and analysis program CalME. Also presented were the approaches for considering variability and pavement preservation, and plans for integration of ME design with the new Caltrans PMS. The differences between CalME and the flexible design approach in MEPDG were highlighted.

REFERENCES

Larson, G. and B. Dempsey. 2003. EICM Software. Enhanced Integrated Climatic Model Version 3.0 (EICM). Urbana, Illinois: University of Illinois

Lu, Q. 2008. Estimation of Truck Traffic Inputs Based on Weigh-In-Motion Data in California. Draft Technical Memo: UCPRC-TM-2008-xx (not yet published), University of California Pavement Research Center, Davis and Berkeley, CA.

NCHRP, 2004 Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. National Cooperative Highway Research Program, Report 1-37A.

National Climate Data Center (NCDC) Summary of the Day West 1 1994 CD-ROM. Boulder, Colorado: EarthInfo Inc.

Ongel, A., Harvey, J.T. 2004. Analysis of 30 Years of Pavement Temperatures using the Enhanced Integrated Climate Model (EICM). UCPRC-RR-2004/05, University of California Pavement Research Center, Davis and Berkeley, CA.

California Department of Water Resources, http://cdec.water.ca.gov, July 2003

Pomerantz, M., B. Pon. 2000. The Effects of Pavements' Temperatures on Air Temperatures in Large Cities, Berkeley, California.

Ullidtz, P., Harvey, J., Basheer, I., Wu, R., Lea, J. D. 2010. Process of Developing a Mechanistic Empirical Asphalt Pavement Design System for California. Submitted to the ISAP Conference, Nagoya, Japan.