PAVEMENT TECHNOLOGY UPDATE

TECHNOLOGY TRANSFER PROGRAM MAY 2011, VOL. 3, NO. 1

California's Transition to Mechanistic-Empirical Pavement Design

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Introduction

Mechanistic-Empirical (ME) pavement design is a new process used to analyze and design pavements. This method combines mechanistic models, which calculate the primary response of a pavement in terms of stresses, strains, and displacement, and empirical models, which then relate the calculated response to pavement performance.

The University of California Pavement Research Center (UCPRC) is assisting the California Department of Transportation (Caltrans) with transition to the ME pavement design approach. The goal is to transition to an ME design and analysis system with software, databases, guidelines, and test methods that will result in pavements with more cost-effective life-cycles.

This article provides an overview of the new design methods that use the ME approach and the process for transitioning to them in California.

Use of the ME pavement design process can improve efficiency of pavement design and analysis so as to reduce life-cycle costs and limit traffic delays on California's freeway network.

SOURCE: BILL FARNBACH, CALIFORNIA DEPARTMENT OF TRANSPORTATION

This Technology Transfer Program publication is funded by the Division of Research and Innovation at the California Department of Transportation. Content is provided by the University of California Pavement Research Center.

The University of California Pavement Research Center

Using innovative research and sound engineering principles to improve pavement structures, materials, and technologies.

The University of California Pavement Research Center (UCPRC) conducts research on pavements of all types, including concrete and asphalt. It has operated facilities at UC Berkeley since 1948 and at UC Davis since 2002, and also conducts research on California highways. Primary funding for the UCPRC is provided by Caltrans. Most of the UCPRC's work is done through the Partnered Pavement Research Center contract, whose mission is to apply innovative research and sound engineering principles to improve pavement structures, materials, and technologies through partnership between academia, Caltrans, and industry.

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Background

OVERVIEW OF MECHANISTIC ANALYSIS

Mechanistic analysis uses solid mechanics to model the reactions of pavement in terms of stresses, strains and deformations to traffic loads, temperature, and water content changes. The damage is then calculated in terms of distresses like cracking, rutting, and faulting that occur as a result of the modeled reactions.

A purely mechanistic analysis model would include a laboratory test to characterize a material and a computer analysis using mechanistic-based models to predict the development of distresses in the pavement. However, it would be difficult to design purely mechanistic analysis models for pavement design and analysis because pavement materials are among the most complex and non-homogenous materials used for engineered structures. Pavements are made with soil and crushed stone taken from natural deposits. Manufactured materials such as cement or asphalt are subject to variability in the manufacturing process and the source of the natural materials. These materials are highly non-linear, non-homogeneous, non-isotropic, and inelastic in their behavior, making engineering mechanics calculations and modeling difficult.

OVERVIEW OF EMPIRICAL ANALYSIS

In empirical analysis, the relationships between design and construction variables and resulting performance are determined primarily by constructing pavements or test sections, monitoring them to failure, and then using statistical regression theory to develop equations predicting performance. This method is currently in use in California for flexible pavement design. The benefit of this method is the reliability of observing real pavement performance, such as the development of cracking, rutting or faulting.

However, using a purely empirical approach introduces many limitations:

- Since it is a trial-and-error approach, many bad pavements have to be built to define what works and what doesn't.
- It takes many years–sometimes decades–of monitoring pavement before failure occurs. This results in an extremely slow pace of innovation or requires use of accelerated pavement testing (APT).
- Complex variables are extremely simplified.
- The trial-and-error process and the time needed for execution make it costly to update empirical design systems and difficult to predict the changes that might occur in performance when new materials, layer configurations, traffic loading, or construction specifications and practices are to be used.

CURRENT NEEDS AND CHALLENGES

Pavement engineers and managers today are facing tremendous pressure for rapid innovation, including:

- Reducing the cost of paving projects
- Improving the environmental sustainability of pavements
- Focusing on maintenance and rehabilitation as opposed to building new pavements
- Handling larger volumes of mixed traffic and new types of tires and axles
- Using new materials and new kinds of recycled materials
- Accommodating changes in historically-used materials
- Evaluating new construction specifications

Clearly, a process of innovation that takes many years to produce answers is not viable. The ME design approach was developed to address these concerns.

Research and History

Universities and material suppliers developed many ME design methods from the 1970s to the 1990s. In the United States, some state departments of transportation (DOTs) developed and implemented ME design methods, often working with research universities in their states. Some, such as California, continued to use and develop empirical methods. Most state DOTs used a "national" empirical method developed for and supported by the American Association of State Highway and Transportation Officials (AASHTO) in the 1960s and updated periodically. The latest version is the 1993 AASHTO Pavement Design Guide and its associated software, which many states currently use.

DEVELOPMENT OF THE MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE (MEPDG)

In the late 1990s, it was clear to most state DOTs that empirical approaches could not address the growing list of unmet needs for innovation. As a result, a project was sponsored through the National Cooperative Highway Research Program (NCHRP) to produce new ME methods for flexible and rigid pavement design and analysis for AASHTO. The result of these efforts is the AASHTO MEPDG, which is depicted in Figure 1. This program was first released in 2008 as a development product and is currently being recoded and documented for release as an AASHTO commercial product later in 2011.

The UCPRC has worked extensively for Caltrans with the MEPDG since its development. This work includes evaluation of the asphalt and concrete damage models and intensive work with the concrete pavement models and software including sensitivity analysis, and validation and calibration using Caltrans pavement performance data.

FIGURE 1
The AASHTO Mechanistic-Empirical Design Guide (MEPDG)

During the development of the MEPDG, researchers identified limitations of the guide's models for flexible pavements. As a result, UCPRC recommended use of the MEPDG for concrete surfaced pavements only. With funding from Caltrans, UCPRC produced, calibrated and implemented an alternative set of design and analysis models for asphalt surfaced pavements. The resulting program is called CalME.

DEVELOPMENT OF CALME

CalME (Figure 2) is a software program that is used to analyze and design the performance of flexible pavements. Unlike the method used in MEPDG for flexible pavements, CalME uses an "incremental-recursive" (I-R) approach that models the entire damage process, not just the initial condition after construction and the final failure condition. This has allowed use of the extensive Caltrans/UCPRC database of Heavy Vehicle Simulator (HVS) data and instrumented test track data for calibration of response and damage models from the first load through the end of the project, with many data points in between.

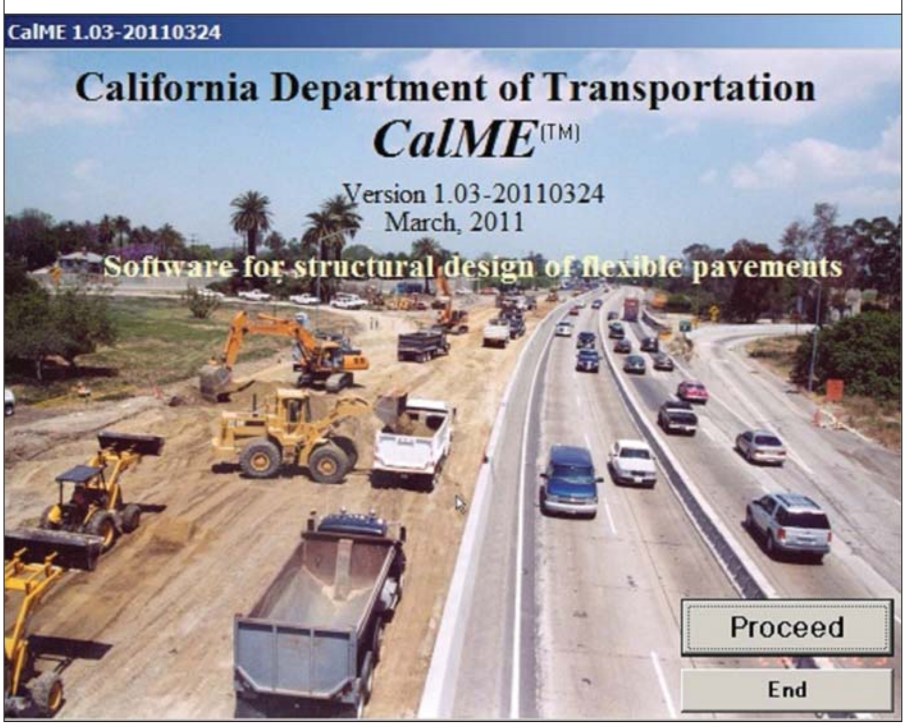
In contrast, to analyze flexible pavements, the MEPDG and many other ME methods use a basic form of Miner's law (hypothesis of linear accumulation of damage), which takes the initial undamaged pavement stress, strain, and deformation responses to temperature and load and assumes the entire damage process to the end failure state.

The I-R approach permits designers to calibrate damaged models with deflection and other response data collected from tracking the damage and aging processes on test tracks and field sections. Provided that measurements are regularly taken after construction, this data may even include damage that cannot yet be seen on the pavement surface.

Finally, in contrast to the MEPDG—which is primarily focused on new pavement design—CalME is designed to maximize utility for the majority of the asphalt pavement work for which Caltrans, local government, and consultant engineers will use it by focusing on:

- Rehabilitation, pavement preservation and reconstruction
- New materials and in-place recycling
- Construction quality
- Integration with improved pavement management systems (PMS), such as the new system Caltrans is currently developing, which will begin to come into use over the next two years.

FIGURE 2 **The University of California Pavement Research Center's CalME**



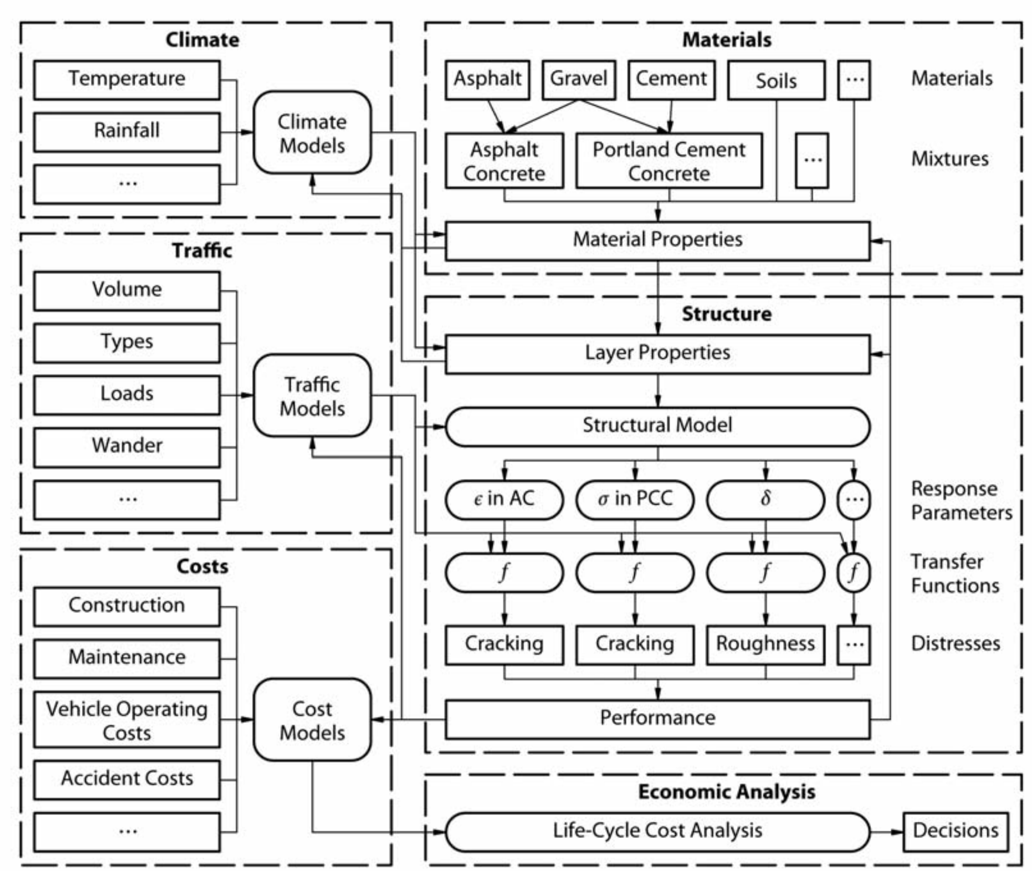
Features of ME Design and Analysis

PRIMARY INPUTS

The general processes for conducting ME design and analysis are the same for pavements with concrete or asphalt surfaces. A flow chart of a general ME design is shown in Figure 3.

Before performing an ME design analysis, the designer must determine the inputs for traffic, climate, layer thicknesses, material stiffnesses, and damage models. Once the input data are ready, the designer analyzes the performance of a number of alternative designs with different structures (layer types and thicknesses). These analyses are essentially simulations of the pavement damage and distress development process under traffic and climate loading. The designer then evaluates the results of these

FIGURE 3 General process of an ME design



SOURCE: JEREMY LEA, UNIVERSITY OF CALIFORNIA, DAVIS

simulations to determine which designs meet performance requirements. Subsequently, the designer recommends one of those candidate designs using life-cycle cost analysis (LCCA) and other selection criteria.

A brief discussion of each of the major inputs required by the ME analysis process follows.

TRAFFIC CHARACTERIZATION FOR CALME AND MEPDG

For truck traffic inputs, CalME and MEPDG use two types of truck traffic information: traffic volume and axle load spectra. To collect data, Caltrans has made a major investment in establishing more than 110 permanent weigh-in-motion (WIM) stations and routinely calibrating them. Traffic volume inputs include three variables: number of axles per truck, number of axles per year per design lane, and traffic growth rate.

To simplify calculations, empirical design methods convert all truck axle loads into approximately equivalent passes of a standard 18-kip axle load in a method known as Equivalent Standard Axle Load (ESAL). In the axle load spectrum approach, the responses of different loads on four types of axles (steering, single, tandem, and tridem) are calculated separately. The damage caused by each load, on each axle type, and under each climate condition during the year is simulated through the life of the pavement.

However, because many project areas do not have a WIM station on-site, a set of typical axle load spectrums have been established by the UCPRC for all routes on the California state network. The procedure for estimating truck traffic inputs for highways where site-specific traffic data are unavailable or incomplete is based on cluster analysis utilizing available axle load spectra. In this method, the WIM sites are divided into eight groups, and default truck traffic inputs were developed for each group. A decision tree based on the developed grouping has been embedded in the CalME software to decide into which group a highway section will fall. The inputs for the decision tree are geographic location (district, county, route number, beginning post-mile), traffic volume, and the truck type (long-haul versus short-haul) using the route segment.

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 designer is required to only input the number of trucks expected in the first year. The user can then adjust the default data, if warranted.

Axle load spectrum inputs formatted for the MEPDG software will use the same decision trees developed for CalME and will be produced by the new Caltrans PMS.

CLIMATE CHARACTERIZATION FOR CALME AND MEPDG

Concrete and asphalt pavement performance are strongly affected by the complex interactions of traffic loading with pavement temperature and water content. Air temperature, precipitation, wind speed, and solar radiation affect pavement surface temperature. The response of a pavement system is highly influenced by the temperature of the surface layer and moisture content of the unbound soil. Annual, seasonal, and daily variations in temperature and precipitation affect the strength of each layer and influence pavement service life.

Both CalME and MEPDG use the Enhanced Integrated Climate Model (EICM), which calculates pavement temperature profiles within each pavement layer based on hourly climate data such as air temperature, wind speed, rainfall, solar radiation, latitude, and pavement properties such as surface reflectivity (albedo), heat capacity, and thermal conductivity. The EICM code is built into the MEPDG software, while CalME performs calculations using a database of previously-run EICM values, which makes the calculations more than 1,000 times faster. MEPDG uses an internal database of climate information.

Differences in temperature between the top and bottom of jointed plain concrete pavements (JPCP) cause concrete slabs to change shape. When concrete is heated, it expands. When it cools, it contracts. The amount of contraction or expansion per degree of temperature change is called the Coefficient of Thermal Expansion (CTE). The top of a concrete slab will be cooler than the bottom during the night, which causes contraction of the top relative to the bottom. The corners of the slab can lift off the base a few millimeters. The weight of the cantilevered slab corners will pull them back toward the base. When combined with traffic loads, the result is high tensile stresses on the top of the slab that lead to fatigue cracking.

A similar phenomenon occurs during the day, when the top of the concrete is hotter than the bottom, causing high tensile stresses at the bottom of the slab. Accurate prediction of pavement temperature differences between the top and bottom of the slab and consideration of the CTE are important for designing JPCP to resist cracking.

For asphalt materials, CalME calculates pavement temperatures and considers their effect on asphalt stiffness. Asphalt stiffness can change by more than one order of magnitude between the coldest winter night and the hottest summer afternoon (10 to 20 times softer). CalME uses a database of pavement temperatures previously calculated using the stand-alone EICM version 3. The weather data includes 30 years (1961-1990) of daily maximum and minimum temperature, daily average percent sunshine, daily average rainfall, and daily average wind speed for representative cities in six climate regions. The database was recently increased to consider three additional mountain climate regions in the state, now totaling nine, which is aligned with Caltrans Performance Graded (PG) asphalt grade specifications.

The EICM program was used to evaluate 28 different flexible pavements and four different composite pavements with combinations of layer thicknesses covering the expected range in the state for each climate region. Temperature and moisture changes in the rigid pavement under the asphalt in composite pavements are not yet included in the reflection cracking model (cracks in the underlying concrete moving up through an asphalt overlay) in CalME.

Using the database of pavement temperatures referenced above, CalME computes 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.

Researchers performed analyses to evaluate how the year-to-year variability of temperature and rainfall data affect pavement temperatures. 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, researchers decided the full 30 years of data should be included in CalME analyses. For analysis periods longer than 30 years, the 30-year data is repeated.

Albedo (or reflectivity coefficient) of a given pavement surface was also considered. The solar reflectivity value changes according to pavement type and pavement age. It was assumed to be 0.10 or 0.05 for new flexible pavements, and 0.20 for old flexible pavements based on measurements performed at the Lawrence Berkeley National Laboratory. The effect of solar absorptivity values was significant at higher temperatures, increasing pavement surface temperatures by approximately 5°C (9°F) for the range of albedos considered on the hottest days, and therefore increasing the risk of rutting for asphalt layers. Solar reflectivity values were found to have no effect on surface temperatures at colder temperatures during the winter.

Also important for flexible pavements are changes in the stiffness of the aggregate base and subbase layers and the subgrade that might be caused by moisture changes. The original assumption in the set up of CalME was that these 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. However, field deflection testing found that "typical" seasonal variability does not exist along many routes because of drainage conditions, cut and fill sections, perched water tables at elevations above the road, and agricultural and landscape irrigation which often makes pavements wetter in the summer than the winter. Calibration of variation of subgrade and unbound layer stiffnesses is therefore left for the designer to input, and the default is "no variation."

MATERIALS CHARACTERIZATION FOR CALME

The materials data input for CalME for asphalt surfaced pavements has been set up with the constraints of the Design-Bid-Build (DBB) or "low-bid" project delivery approach in mind, and can also be used for Design-Build (DB) projects.

A "standard materials" database based on UCPRC laboratory and field testing was built and includes at least one example of each type of material that a designer working on a Caltrans project should be able to consider. Each material includes coefficients for a standard equation for stiffness, with different equations for asphalt and unbound materials, and coefficients for performance equations for damage (fatigue for asphalt, crushing and fatigue for cemented layers) and permanent deformation (asphalt and unbound layers), so that no new testing is needed when a standard material is selected.

The performance equations have a standard format, with different variables including critical stresses, strains and/or stiffness/temperature, and coefficients for each material. The coefficients for each equation

TABLE 1 Test methods and inputs to models for use in CalME

Material Type	Stiffness Equation	Damage Performance Equation	Rutting Performance Equation	Shift Factor
In-place uncracked asphalt materials	Backcalculation for project	Test field beams using AASHTO T321 or use standard material	Test using AASHTO T320 or use standard material	Standard shift factor
In-place stabilized and granular materials	Backcalculation for project	Use standard material	Use standard material	Standard shift factor
Standard and new* asphalt materials	Flexural frequency sweep AASHTO T 321	Flexural fatigue AASHTO T321	RSST-CH AASHTO T320	Test tracks and field sections
Standard and new unbound granular materials	Backcalculation of field and test sections or RLT		RLT, HVS, test tracks and field sections or use standard material	HVS, test tracks and field sections
Standard and new in-place recycled materials	Backcalculation of field and test sections or RLT		RLT, HVS, test tracks and field sections or use standard material	Field sections
Standard cemented materials	Backcalculation of field and test sections	Fatigue and Crushing: HVS and field sections		Field sections
Subgrades (based on USCS)	Backcalculation of field and test sections		HVS, test track, field sections	HVS, test track, field sections

Notes: RSST-CH = repeated simple shear test at constant height; RLT = repeated load triaxial test, HVS=Heavy Vehicle Simulator, USCS=Unified Soil Classification System.
* Perform laboratory and APT testing to calibrate new materials coefficients and shift factors.

have been determined by laboratory and/or field testing for the standard materials in the CalME database.

Table 1 provides a list of the various test methods and inputs for the models used in CalME. Alternatively, for designing rigid pavements, the materials data input for MEPDG design is much simpler than for the larger variety of asphalt surfaced pavements. A key consideration for rigid pavement designs will be estimation of the expected CTE, stiffness of the new concrete, and the amount of bonding between the base and the concrete slabs.

As part of California's transition to ME design, data on binder and aggregate combinations available within a region for flexible pavement design and CTE and stiffness for all possible concrete options will be added to the initial standard materials. The stiffness database for all pavement layers will include additional backcalculation of Falling Weight Deflectometer (FWD) data from each project. The standard materials performance equation database will include laboratory testing of new materials from larger projects, where the cost of testing likely materials is justified. AASHTO T-320 and T-321 have been used to characterize asphalt materials in the standard database. The Caltrans state transportation laboratory in Sacramento and several consultants in nearby states are equipped to perform these tests, although some additional capability would need to be developed in the state.

CALME DAMAGE AND PERFORMANCE MODELS FOR ASPHALT SURFACED PAVEMENTS

CalME calculates distresses that affect each layer within the pavement in terms of layer properties and traffic loading. The distresses calculated in CalME are shown in Table 2. For rehabilitation projects, CalME is designed to work with CalBack, a companion layer backcalculation program that calculates the stiffnesses of materials in existing pavements using nondestructive FWD data for rehabilitation and reconstruction projects.

All damage and rutting models use the I-R approach. CalME has a prototype model for simulating smoothness through a pavement's life, but it has not yet been calibrated.

The development and calibration of CalME relied heavily on the two HVSs owned by Caltrans (Figure 4). The results from more than 35 test sections were used for verification of the mechanistic primary response models (stresses, strains, and deflections) and for the calibration of the empirical performance (damage) models. The HVS tests provided intensively instrumented results under controlled temperatures and loading on full-scale pavements, but have the limitation of only simulating slow traffic.

TABLE 2 Distress models for all materials used in CalME

Material Type	Distress Models Used in CalME
Hot Mix Asphalt (HMA) - 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 Portland Cement Concrete (PCC), rutting for all layers within 100 mm of surface
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

FIGURE 4 Heavy Vehicle Simulator (HVS)

SOURCE: UNIVERSITY OF CALIFORNIA PAVEMENT RESEARCH CENTER

TABLE 3 Distress models for JPCP and CRCP in MEPDG

Distress	Damage Model	Transfer Function
Transverse cracking (JPCP)	Bottom-up and top-down fatigue damage considering traffic loads, load position on slab and temperature/shrinkage gradient in slab	Fatigue damage percent slabs cracked
Faulting (JPCP)	Transverse joint faulting contribution based on difference in deflection across joint	Fault height
Smoothness (JPCP)	International Roughness Index (IRI) as a function of initial IRI and distress (cracking, spalling, and faulting) development	Estimated IRI
Punch-outs (CRCP)	Accumulated fatigue damage due to top-down stresses developing due to slab bending in the transverse direction	Total number of medium and high severity punch-outs per mile
Smoothness (CRCP)	IRI as a function of initial IRI and number of medium and high severity punch-outs	Estimated IRI

The California HVS tests were complemented by track tests with high-speed traffic, at facilities including WesTrack (Federal Highway Administration, near Carson City, Nevada), NCAT (National Center for Asphalt Technology, Auburn, Alabama), CEDEX (Centro de Estudios y Experimentación de Obras Públicas, near Madrid, Spain) and MnRoad (Minnesota DOT, near Minneapolis), with additional HVS testing by the Swedish National Road and Transport Research Institute.

MEPDG DAMAGE AND PERFORMANCE MODELS FOR JPCP AND CONTINUOUSLY REINFORCED CONCRETE PAVEMENT (CRCP)

The distress models for JPCP in MEPDG are shown in Table 3. The MEPDG version released for evaluation in 2005 has a model for simulating pavement smoothness throughout the pavement life-cycle that was nationally calibrated primarily using FHWA Long-Term Pavement Performance (LTPP) data, with very few sections from California. Soon after the release of MEPDG, Caltrans asked the UCPRC to calibrate the design models using field data from California sections. To calibrate the models, 52 rigid and 43 crack, seat, and overlay sections—covering the state's major climate regions—were sampled and all the inputs needed to run MEPDG were collected. A pavement condition survey was conducted at the time of field sampling and data was also mined from the Caltrans Pavement Condition Survey (PCS) database.

Simulations of the calibration sections showed that reasonable results could be obtained from the transverse cracking model provided that a consistent method was used to develop inputs used for stiffness and bonding between the slabs and base layer. Recommendations were made to Caltrans regarding the best stiffness and bonding assumptions to use. Data from historic Caltrans faulting studies were used for faulting model validation. These data showed that the faulting model predictions are reasonable and that modifying the model parameters is not required.

One of the UCPRC study's limitations is that the calibration dataset does not include pavement structures with design features such as tied concrete shoulders, widened truck lanes, and doweled transverse joints. Also, sections that had a granular base were limited in number.

In spite of the limitations, the study provided an understanding of the model predictions for California conditions and helped in identifying key variables that affect the performance of the JPCP.

SIMULATION OF PAVEMENT PRESERVATION TREATMENTS IN CALME

The CalME program includes a feature that simulates pavement preservation treatments following maintenance and rehabilitation (M&R) strategies designated by the designer or included in the decision tree from the PMS. CalME simulates M&R treatments triggered by criteria predefined by the designer for each strategy and simulates pavement performance accordingly. M&R treatments can be triggered by either distresses such as rutting and cracking, or age of the wearing course.

CalME M&R strategies are grouped into three philosophies: rehabilitation only (R); rehabilitation followed by two preservation treatments, then rehabilitation (PPR), and perpetual pavement preservation (PPP), in which there is only preservation and no additional rehabilitation after initial rehabilitation.

Currently, CalME includes more than forty built-in M&R treatments. In addition, designers can define their own site-specific strategy. Figure 5 shows a CalME simulation with four pavement preservation treatments triggered or scheduled in the 50-year analysis period.

CONSIDERATION OF RELIABILITY

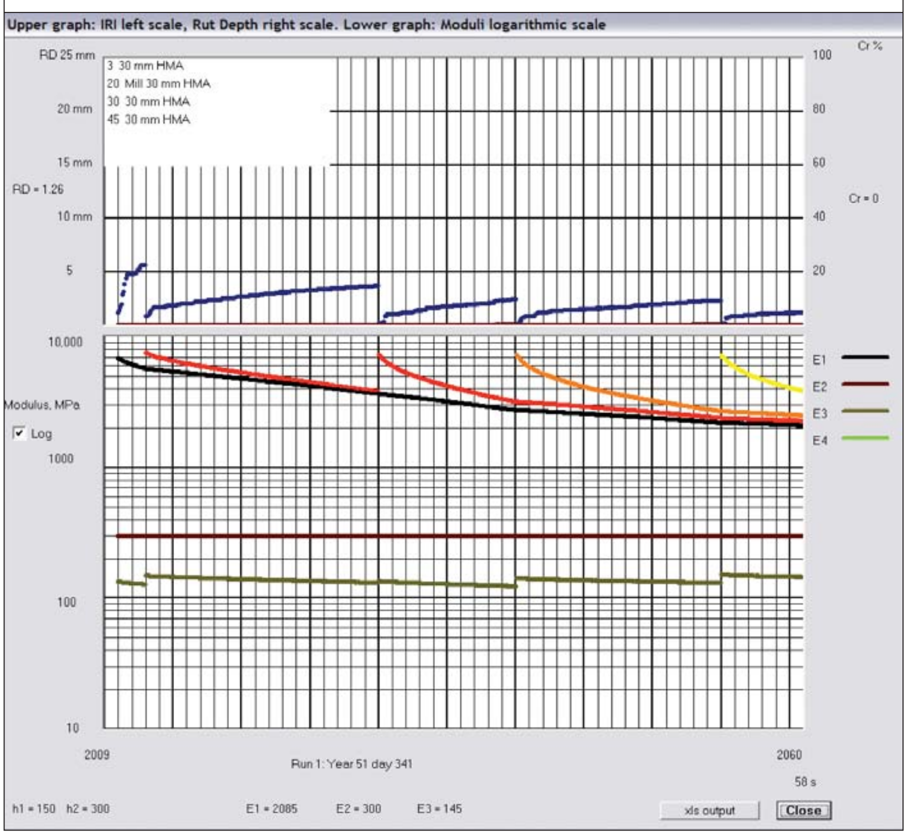
"Reliability" refers to the likelihood of a new pavement treatment reaching a critical distress level at a given age considering the variation in materials, construction, climate, and/or traffic. Consideration of pavement reliability is an essential element of modern ME design methods.

CalME and MEPDG can perform deterministic analyses. Deterministic analyses do not consider variability in materials, construction, climate or traffic, and are useful for initial calculations because only one value is used for each variable. While results are less reliable, using the model this way is faster for initial calculations and can be used to reduce the number of design options to a few best options for more detailed analysis.

CalME also performs probabilistic analyses, using Monte Carlo simulation, a process in which the performance simulation is run many times, each time randomly sampling values for key input variables such as stiffness and thickness. At this time, the MEPDG cannot perform Monte Carlo simulation because of excessive runtimes. In the interim, the reliability calculation in the MEPDG is based on an analysis of the calibration error of the method.

The Monte Carlo simulation in CalME is for "within-section" variability for materials and construction supplied by a single contractor and his/her materials suppliers on a single project, as opposed to "between-section" variability, which would consider the differences in materials and construction between different contractors and suppliers on different projects. Sensitivity analysis should be conducted to consider the effects of different materials supplied to a project by the low bidder in the DBB project delivery method generally used by Caltrans. The effects of variability in stiffness and thickness are transformed into variations in damage, and then from damage into performance by the respective ME functions. This provides an indication of the variability of the design based on the two primary factors that can be controlled by the designer and construction contractor.

FIGURE 5
A CalME simulation with four pavement preservation treatments triggered or scheduled



With regard to temperature variability, CalME randomly selects the initial year within the available database to produce a dataset for a given simulation then proceeds in chronological order. Within each month of each year, CalME randomly selects the day used to characterize the hourly pavement temperatures for the month (the default analysis increment is one month, although this can be changed by the designer). CalME calculates pavement response to load and environment and the resulting damage recursively, meaning that the damage calculated in previous time periods influences the pavement response in a current time period. The order in which temperatures occur can therefore influence the outcome of the simulation.

To consider traffic, sensitivity analysis is recommended, instead of random variation. Traffic estimation is part of the planning process, not pavement design, and pavement is designed to withstand the design number of traffic repetitions, whether those occur in the expected time, sooner, or later. Inclusion of the variance of traffic estimation would result in unnecessarily conservative designs. However, it cannot be assumed that traffic will occur as predicted by previously observed distributions of repetitions, axles, or speeds. Some of these—such as axle load spectrum—can be predicted fairly well over shorter periods, provided there is no abrupt change, such as a change in axle load limits. It will depend on factors such as growth trends in the economy, local development patterns, connection of routes, and development of local road networks.

Transition to Use of ME Design in California

CALTRANS' PAVEMENT NETWORK

Caltrans owns and operates a network of approximately 24,000 centerline kilometers (14,880 miles) and 80,000 lane-kilometers (49,600 miles). Approximately one-third of the network is concrete pavement, which is mostly on urban high-volume freeways. The asphalt-surfaced pavements include composite (asphalt on concrete), semi-rigid (asphalt on cemented soil), full-depth (asphalt on native soil) and conventional (asphalt on aggregate base) flexible pavement structures. Most of the freeway (multi-lane dual carriageway high-traffic volume) routes in the state were built between 1955 and 1975 with 20-year design lives, and many have had several rehabilitation and/or maintenance interventions since original construction. Approximately 90 percent of the asphalt pavement design work is rehabilitation and preservation; the remaining work mostly consists of lane additions or shoulder widening on existing routes.

Since 1970, California's population has nearly doubled to 37 million, while the network has grown at a far slower rate. In this period, the estimated annual vehicle miles traveled (VMT) has quadrupled to nearly 400 billion. Much of the reconstruction, rehabilitation and preservation work is done at night or with extended closures with 24-hour operations due to extremely heavy traffic volumes and resulting economic loss due to delays. At the same time, design lives are being increased, wherever possible, to minimize both life-cycle cost and future traffic delay.

One of the goals of ME design implementation is to help meet the competing requirements of reduced construction time, which is primarily dependent on total pavement cross-section thickness (thicker takes longer), and longer life (thicker lasts longer), through use of innovative construction, materials, and structures that cannot be considered using the current empirical methods.

The 20-year design lane traffic levels range between approximately 500,000 ESALs (Traffic Index of 8) on rural mountain highways and 140,000,000 ESALs (Traffic Index of 16) on main freeways connecting the state's seaports to the rest of the U.S. There are nine climate regions for pavement design in California, including mild coastal regions, hot deserts, rain forests, mountains and cold plateaus.

EMPIRICAL ANALYSIS IN CALIFORNIA AND ITS LIMITATIONS

For years, Caltrans used the R-value empirical design method originally developed by Francis Hveem and last calibrated in the 1960s to design new and reconstructed asphalt pavements. From the 1970s on, Caltrans used a deflection-reduction method for design of asphalt overlays. An empirical design catalog of cross-sections and layer thicknesses, periodically updated, was used for rigid pavements from the 1970s until the 2000s.

The transition from these empirical design methods to ME-based methods will involve replacement of the empirical R-value and deflection reduction methods with CalME. Because the ME method utilizes material stiffness (also referred to as modulus) rather than R-value or gravel factors used by older methods, Caltrans developed and uses the CalBack program for back-calculation of stiffness from deflections non-destructively measured using a FWD on the existing road surface.

The transition will also require replacement of the empirical rigid pavement design method with ME design using the MEPDG to analyze faulting and transverse cracking. The Caltrans-developed RadiCal will also be used to assess the risk of longitudinal and corner cracking not considered by the MEPDG.

There are many issues of importance to Caltrans and local governments that empirical methods cannot adequately consider. These include:

- Performance prediction
- Integration with PMS
- Pavement preservation
- Longer design lives for new pavements
- New materials, including rubberized, polymer-modified and warm-mix asphalts, PG graded asphalts, and the range of asphalt, concrete and granular materials produced from different aggregate sources and manufacturers in the state
- Reflection cracking in asphalt pavements
- Dowels in concrete pavements
- Different joint spacing, tied concrete shoulders, and widened truck lanes in concrete pavements
- Recycled materials, including in-place and plant-recycled asphalt, concrete, and granular materials
- Construction compaction and mix design, and the ability of engineers to specify different properties of materials using only compaction and mix design
- Existing pavement structures
- CRCP as an alternative to JPCP
- Climate regions and the ranges of temperature and rainfall present across the state
- Increased tire inflation pressures and axle loads
- Traffic speeds, such as differences between city streets, intersections, and highways
- Construction-related variability in layer thicknesses, stiffnesses and materials production
- Extreme levels of truck traffic repetitions on major freight corridors

STEPS TOWARD USE OF ME METHODS IN CALIFORNIA

Realizing the ability of ME methods to address pavement and design needs better than current empirical design methods, in 2005 Caltrans approved *Adoption of Mechanistic-Empirical (ME) Pavement Design Method*, an issue memorandum that calls for ME pavement design methodology to replace existing empirical methods. The issue memorandum led to local calibration and adoption of the MEPDG for JPCP design and support for completion, calibration and implementation of CalME to address the issues described above and to integrate with the improved Caltrans PMS currently being implemented.

Caltrans and the UCPRC used the initially released version of the MEPDG and the results of the California calibration studies completed in 2007 to produce a design catalog for JPCP, which is included in the current Caltrans Highway Design Manual. The design catalog will be revised, if necessary, once the 2011 AASHTO version of the MEPDG has been evaluated, and as new performance data becomes available from the Caltrans PMS. The new design catalog is expected to produce much better results than previous empirical versions. However, by its nature, a design catalog can only consider a limited number of variables.

LESSONS LEARNED

Several high-profile California projects have used ME design and analysis in the past 10 years, including long-life rehabilitation of the I-710 freeway in Long Beach using asphalt, and long-life rehabilitation of the I-15 freeway near Devore using concrete. It has also been used on some lower-volume state highways to consider alternatives—such as full-depth reclamation—that are not included in the current empirical design methods.

ME design and analysis tools can also be used to better quantify changes in performance estimates for inputs to life-cycle cost analysis for assessment of policy questions, such as establishment of construction quality levels, determination of permitted levels of recycled asphalt pavement usage in different asphalt layers, and calculation of construction quality pay factors. Furthermore, ME methods can be effective tools in the forensic investigation of premature pavement failures.

Some lessons learned from previous implementation of new pavement technologies include:

- There must be a good implementation plan, with continued support from upper management that includes workload relief to allow workers to learn the new method and tests.
- Momentum must be kept up to overcome technical and institutional obstacles.
- The mandate to use ME design where policy indicates that it is cost-effective must be enforced as the tools are made available and the training completed.
- There should be ongoing support to users through a User's Group. This would provide a forum to identify problems and propose solutions, standardize best practices, provide peer review, and as a means for including Caltrans consultants.
- There should be ongoing feedback from the PMS to verify and update the method, something that has not been done for many empirical and ME methods around the world after implementation.
- Testing methods must fit within workload constraints or additional resources must be justified to operate ME.
- Testing procedures and equipment must be robust and simple enough to function, and must have clear purpose in the method and workarounds must be provided wherever possible. For example, many states in the US established triaxial testing capabilities for soil stiffness testing for use with the 1983 AASHTO method, most of which disappeared within a few years because of the difficulty of performing the test, and the difficulty of relating one soil test at a given compaction level and water content to the variability present in a project on the ground. New testing equipment and laboratory technicians must undergo periodic certification to ensure quality test results.
- Any inconsistent performance or failure must be thoroughly investigated to identify the true cause of the problem. If this is not done, the new technology (in this instance the use of ME design) will be "blamed" for the problem, leading to reduced confidence in the method and a return to the use of empirical methods.

RECOMMENDATIONS FOR ADOPTING ME DESIGN METHODS IN CALIFORNIA

To successfully adopt ME methods in California, Caltrans and other agencies will need to address the issues identified and meet the following objectives:

- Identify and provide the resources necessary to use the ME methods
- Identify the most cost-effective use of ME designs and quantify cost savings
- Train and maintain a cadre of designer/analysts experienced in the use of the methods
- Train and cost-effectively maintain certified testing engineers, technicians and field and laboratory equipment to support the method
- Develop new Quality Control/Quality Assurance test methods and processes
- Calibrate and update the ME methods as innovations emerge using laboratory testing, modeling, and APT and PMS data
- Require work from consultants consistent with the practice of Caltrans engineers

There is a break point at which the potential life-cycle cost savings of use of an ME design method will not be sufficient to justify the increased costs of training, materials testing and characterization, and analysis time. Eventually, the costs of the ME technology will decrease as its use becomes more widespread and routine.

Now, researchers and practitioners must determine where it is appropriate to use ME design going forward. In California, initial implementation of CalME and MEPDG should be on projects where the current empirical methods are not appropriate, or where the cost of the project is sufficient to justify additional engineering costs. These include projects that have one or more of the following characteristics:

- Design lives are longer than can be considered in the current design method
- Truck traffic volumes are larger than those for which the current method was calibrated
- New materials, including various types of recycled material, that current methods cannot effectively consider
- New pavement structures, such as concrete pavement with different flexural strengths or CTE, hot mix asphalt long life pavements incorporating greater compaction or rich-bottom asphalt layers, stiffer binders and polymer-modified mixes

Next Steps

Caltrans is currently developing a plan for transitioning to ME design for selected projects based on the criteria discussed in this article. The plan will include use on additional pilot projects, establishment of required testing and analysis capabilities, training, and communication of the results of this transition. As part of the implementation efforts, flexible pavement rehabilitation projects on Interstate 5 near the northern California towns of Red Bluff and Weed have been identified as pilot projects for design with CalME.

The success of implementation largely depends on the ability of the new ME methods to address issues that the current methods cannot, produce more cost-effective designs, and facilitate innovation that leads to greater efficiency and better use of available financial and materials resources. Although models and databases are never perfect, a new method that is substantially better than the current method may best address the need for effective pavement design and analysis.

ITS Berkeley TECH TRANSFER

PAVEMENT TECHNOLOGY UPDATE
MAY 2011, VOL. 3, NO. 1

This publication was produced by the Technology Transfer Program at the UC Berkeley Institute of Transportation Studies, with funding from the Caltrans Division of Research and Innovation.

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