Transition to Mechanistic Empirical Pavement Design in California

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ABSTRACT

In 2005, the California Department of Transportation (Caltrans) approved an issue memorandum titled "Adoption of Mechanistic-Empirical (ME) Pavement Design Method", which calls for the adoption of ME pavement design methodology to replace the existing empirical design methods, which have been in place since the early 1960s. This paper presents a discussion of issues associated with the transition to use new ME methods in a large highway agency, based on Caltrans' experience to date. Major issues include identification of the target groups of designers and types of projects where full-scale complex ME models will be used, and those where simpler and faster tools based on ME and current empirical methods will be used. Practical considerations for implementation of ME include employee background, training, cost, equipment and staff work load requirements. Technical considerations include establishing and maintaining capabilities for new types of field and laboratory testing to provide ME inputs for both new design (less common) and rehabilitation (majority of work), and creation of databases for traffic and climate inputs. The development of guidelines for practicing engineers (agency staff and consultants) intended to lead to uniform use of ME design methods, with the intent to minimize variability of design due to widely varying assumptions, is also discussed. Finally, the paper discusses the planned interactions of ME design and the agency's pavement management system. The focus is on flexible design, although Caltrans is implementing ME for rigid and flexible pavements.

KEY WORDS: Mechanistic-empirical, rehabilitation, preservation, design.

1 INTRODUCTION

A number of highway agencies have transitioned from using empirical to mechanistic-empirical (ME) methods for pavement design over the past twenty years. This paper discusses this transition process being undertaken by the California Department of Transportation (Caltrans).

1.1 Background

Caltrans owns and operates a network of approximately 24,000 centerline kilometers and 80,000 lane-kilometers (Caltrans, 2008). Approximately one third of the network is concrete pavement, mostly on urban high-volume freeways. The asphalt surfaced pavements include composite, semi-rigid, full-depth and conventional 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 pavement preservation, with most of the remainder consisting of lane additions or shoulder widening on existing routes.

Since 1970, California's population has nearly doubled to 37 million while the network has increased 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 (55 hours up to one week) with 24-hour operations due to extremely heavy traffic volumes and resultant 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 implementation is to help meet the competing design requirements of reduced construction time, which is primarily dependent on total pavement cross-section thickness (Lee et al, 2009), and longer life, through use of innovative construction, materials and structures.

The 20 year design lane traffic levels range between approximately 500,000 (rural mountain highways) and 140,000,000 (main freeways connecting ports to the rest of the US) equivalent 80 kN single axles. There are nine climate regions for pavement design in California, including mild coastal regions, hot deserts, rain forest, mountains and cold plateaus.

California 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. The transition from these empirical design methods to the ME-based methods will require the following:

1. Replacing the empirical R-value and deflection reduction methods with an incremental-recursive ME method called *CalME* (Ullidtz et al, 2008) currently being developed for Caltrans. Because the ME method utilizes material modulus rather than R-value or gravel factors traditionally used by the current methods, Caltrans has developed a backcalculation program, *CalBack* (Lu et al. 2009), as a tool for in-situ material characterization using nondestructive FWD data for rehabilitation projects.
2. Replacing the empirical rigid pavement design method with ME design using the *MEPDG* (NCHRP, 2004), and *RadiCal* (Hiller et al, 2005).

The current design methods are extremely limited in their ability to consider 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; the use continuously reinforced concrete pavements as an alternative to jointed-plain concrete pavements, 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 ME pavement design methodology to replace existing empirical methods. The issue memorandum has lead to local calibration and adoption of the *MEPDG* for jointed-plain concrete pavement design and support for completion, calibration and implementation of *CalME* to address the issues described above, as well as integration with the improved Caltrans PMS currently being implemented.

Caltrans’ current practice of pavement design involves approximately 25 pavement engineers across 12 districts performing design and providing alternative pavement structures to project designers. These engineers are complemented by approximately 15 headquarters pavement engineers responsible for changes to the design method, policy and guidelines. Consultants are engaged to provide pavement evaluation and design recommendations in times of heavy work load, as well as for projects partially funded by local agencies that provide their own alternative designs and toll road concessions. Responsibility for maintaining locally funded projects and toll roads usually reverts to Caltrans after a number of years, and there is often a desire to reduce the pavement thickness and initial cost on the part of the sponsors. A variety of ME and other methods and assumptions are often used by consultants, which must be reviewed and approved by Caltrans pavement engineers.

Caltrans currently operates a fleet of four falling weight deflectometers (FWD), used primarily for the deflection reduction asphalt overlay method. ME requires a larger number of material parameters that cannot be evaluated with the existing test methods. In most instances, the districts do not have the required testing infrastructure and equipment in their laboratories. Current QC/QA methods may not be adequate for constructing pavements designed with the new ME methods, specifically with regard to assessing whether key design parameters such as layer thickness and stiffnesses have been achieved.

1.2 Goal and Objectives of Transition to ME

The goal of Caltrans transition to ME design is to be able to address the issues described above by completing 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 test methods as needed by the new design methods
- Calibrate and update the ME methods as innovations appear using laboratory testing, modeling, accelerated pavement testing (APT) and PMS data;
- Require work from consultants consistent with the practice of Caltrans engineers.

2 TRANSITION ISSUES

The following section presents some of the expected challenges and the authors’ opinions on how to deal with them.

2.1 State of Methods at Time of Implementation

The first issue associated with ME implementation is what state of calibration and refinement is necessary for the methods at the time of implementation. There are essentially two scenarios:

- The models are complete and have gone through an initial calibration and validation, the minimum set of materials data is in place, and traffic and climate databases have sufficient data to provide reasonable designs and analysis.
- The models have had a comprehensive set of calibrations and validations, and materials, climate and traffic databases are essentially complete for most applications.

In the former case, the models and databases will continue to be expanded and improved as the method is used. In the latter case, the method is essentially complete and will have less significant improvements as it is used.

The success of implementation largely depends on the perception by the future users and management of the gap between the capabilities of the new ME method and the current method being used. If there is clearly a strong need to fill a large gap, then the urgency to implement will help users and management persevere with the process of overcoming implementation difficulties, and implementation can begin at an earlier stage of development. Strong upper management support and understanding of the benefits of implementing provides an argument for implementation at an earlier stage of development. On the other hand, if there is a history of difficulty in implementing large changes in technology, and if there is a high aversion to accepting the risk of potential failure of new technologies, then the development should be carried further to reduce the risk of problems that may lead to a management decision to slow or stop implementation.

Risk aversion is usually extremely high at the practicing engineer and middle management levels as well, where problems may be attributed to the engineer and not the method, and where additional time given to advance up the learning curve with the method may not be sufficient. Strong upper management support, encouragement and protection will help isolate and overcome these difficulties. Strong cases must be made to upper management to create that support, which will evaporate if there are several projects in succession with problems. A high level of technical support must be included in the plan for the early projects, as well as a strong technology transfer approach through the initial projects and identification of how the new method will provide benefits, and clearly identify new costs.

ME methods generally increase the cost of engineering for pavement projects, which in many states in the US are very low relative to the total project cost, compared to other civil infrastructure. Those costs are also low relative to the difference that good design and project evaluation can make in life-cycle cost. An approach for measuring the reductions in life cycle cost from implementation of ME design will be needed in California to justify those additional costs when fiscal scarcity results in pressure to reduce project support costs.

Models and databases are never perfect, the question that has to be asked is: "*Is the new method substantially better (by whatever definition) than the current method?*" However, in light of the current situation in California, a fairly advanced state of calibration, validation and well-prepared implementation plans, guidelines etc are felt necessary before implementation.

2.2 Where Should the New ME Methods be Used?

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 or characterization, and analysis time. The break point will depend in part on the level of sophistication of the inputs including the extent of field testing, and the availability of simplified methods. However, regardless of the level of sophistication, there will be many cases for pavement preservation overlays and design of roadways where the additional cost will not be justified, although eventually the costs of the ME technology will decrease as its use becomes more widespread and routine. The issue is where to appropriately use ME.

To deal with this issue in California, initial implementation of *CalME* (for designing new and rehabilitation of existing flexible pavements) in California will need to be on projects where the current empirical methods are not appropriate, or where the cost of the project is sufficient to justify the additional engineering costs. These include projects that have one or more of the following characteristics:

- Design lives longer than the what the current methods were calibrated for,
- Truck traffic volumes larger than what the current methods were calibrated for,
- New materials, including various types of recycling (e.g. full-depth recycling as granular base, with cement, foamed asphalt/cement, or asphalt emulsion/cement; hot-in-place recycling, cold-in-place recycling; recycled concrete, etc), that the current methods cannot effectively consider,
- New pavement structures, such as (i) HMA long life pavements incorporating greater compaction, (ii) rich-bottom asphalt layers, stiffer binders and polymer-modified mixes, as was used on the I-710 freeway (Monismith et al, 2004), (iii) overlays of concrete pavement designed for reflection cracking, and (iv) pavements in extreme environments such as the hot desert where the current design methods do not accurately predict the severity of rutting in HMA.
- Unique loading situations, such as special permit loads.

ME design and analysis tools should also be used to better quantify changes in performance estimates for input to life-cycle cost analysis (LCCA) 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. It can also be used to investigate premature pavements failures.

2.3 Considerations for Design-Bid-Build Project Delivery

In a Design-Build (DB) project delivery environment, the designer knows the sources of new materials and can test for materials properties for input in the design/analysis method. Specific alternative materials can be considered to develop the lowest cost project meeting the design requirements. An issue in a Design-Bid-Build (DBB) environment, is that HMA and other engineered materials are usually specified in terms of the binder grade, aggregate gradation, and some basic mix design properties, but the stiffness, aging, fatigue, and rutting properties cannot be measured for use in the design because the sources of the material will be determined by the selection of the lowest bidder. For example, in California, it has been found that binders from two different sources, both meeting the same PG grade, can have extremely different aging properties (one exhibited twice as much increase in stiffness with aging compared to the other under similar conditions) and fatigue properties (one having nearly twice the fatigue resistance as the other under same conditions). In addition, the source of binders used at refineries in California change periodically depending on the profit margins for different products at the time, and designs may be performed several years in advance of procurement of the materials by the contractor.

To deal with this issue, three approaches can be used to deal with this source of variability in as-built properties versus properties assumed in design:

1. Use performance-related specifications tied to design assumptions for stiffness, aging, fatigue and rutting, or

2. Design for either “typical” or “the worst” materials properties that are likely to be delivered, or
3. Permit changes in the thickness design depending on the properties of the materials to be supplied once the low bidder has been selected.

On the LA-710 freeway rehabilitation project, performance-related specifications that require minimum stiffness, fatigue and rutting properties for each of the three asphalt concrete layers in very heavy duty asphalt pavements have been used on several projects along the same route. The important issue in this approach is designing for, and specifying properties that a number of bidders can supply, which is primarily dependent on their aggregate source and the amount of crushing it is subjected to if it is of alluvial origin. However, in many locations in the state, the chaotic geology results in a number of widely varying aggregate sources being available. It appears that the performance-related specifications need to be statistically based rather than “go/no-go” to account for the variability in performance-related testing.

In the second alternative, the design can be carried out using properties from the expected “worst” mix that might be included in a bid in the region that still meets the mix specifications. This would result in a number of designs performing better than the intended design reliability resulting in longer service life but higher initial cost. The life cycle cost implications would need to be analyzed to determine if this is better. Alternatively, a mix with “typical” properties, falling in the middle of the mixes that might be supplied to the project, can be used for design. The net effect on the reliability of the total set of projects would depend in part on the probability of different properties being supplied by the lowest bidders. If analysis indicates that a wide range of properties are being supplied, then “typical” properties can be used, if properties skew towards the “poor” end, then those properties should be used for design. In the latter case, identification of this issue by use of ME design will hopefully result in improvement of mix specifications where it is cost-effective. Following this approach, the standard materials library for *CalME* has been designed to include a factorial of mix properties measured during development of the method that includes five typical PG binder grades and two aggregate sources, one with properties near the “best” and the other near the “worst” for use in either of these scenarios, either designing for the poorer performing mix or selecting a design that falls within that of the two mixes.

The third approach of checking the design once the low bidder submits their mix and then adjusting the design thicknesses and/or construction compaction specifications if the design is deficient would require major changes in the legal framework for project delivery. This approach is a major step towards DB project delivery where the contractor bids a lump sum total for the project, instead of unit prices for each material. This is required because the quantities of materials would change and the lowest unit cost bid could result in a higher price than that of another bidder. However, a number of issues arise. For example, if the materials supplied result in a predicted life that is longer than the design life, engineers could either reduce the thickness of the pavement and pay the contractor less (i.e. a negative incentive), or retain the design and pay the contractor a portion of the expected life-cycle cost savings (i.e. a positive incentive) A strict set of testing and analysis guidelines for use of the method and a great deal of faith in the ME design predictions would be required for this approach to avoid inappropriate use. This is not likely to occur during the early years of implementation.

2.4 Climate, Traffic, Materials Data Testing and Access

Another issue is that the agency and consultants will need to establish and maintain capabilities for accessing design data and new types of field and laboratory testing to provide

ME inputs for design of both new lanes (less common) and rehabilitation and partial reconstruction of existing lanes (most of the anticipated work in California). The databases and testing methods must be established and maintained in order to minimize the time requirements for each design, and to obtain as much consistency as possible between designers, including agency and consultant engineers, by making data easily accessible and providing guidelines or software solutions for its use.

The ME methods (*CalME* and *MEPDG)* use 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 WIM database used by *CalME* and *MEPDG* can be updated every few years. Eventually, a web-based version of *CalME* is anticipated that will operate off of an independent axle load spectrum database maintained by the Caltrans traffic operations division. Since most projects will still not have a WIM station within them, a set of typical axle load spectrums have been established (Lu et al 2006) that are selected for a given project based on truck classification counts and a few other regional factors.

CalME was set up to access pavement surface temperature data from a database of Enhanced Integrated Climate Model runs (the stand-alone version of EICM) and compute the temperatures below the surface using a fast one-dimensional finite element method routine. The database includes thirty years of data for various types and thicknesses of asphalt pavement. This approach greatly reduces computation time compared to repeating the EICM calculation for each run of the program, and also permits periodic updating, such as recently when the number of climate regions in the database was increased from six to nine.

The materials data input for *CalME* has been set up with the constraints of the DBB project delivery approach, discussed above, in mind. This approach is applicable to the DB approach as well. A great deal of work has been spent setting up a “standard materials” database which is intended to include 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). The performance equations also all have a standard format, with different variables (critical stresses, strains and/or stiffness/temperature) and coefficients for each material.

The coefficients for each equation must be determined by laboratory and/or field testing for the standard materials. The shift factors and the transfer function from damage to surface cracking have been determined from a combination of accelerated pavement tests using the Caltrans Heavy Vehicle Simulator (HVS), test track date, and limited field test section data as noted in the following table.

Material Type	Stiffness Equation	Damage Performance Equation	Rutting Performance Equation	Shift Factor
In-place uncracked asphalt materials	Back-calculation 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	Back-calculation 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	RLT, back-calculation of field and test sections		RLT, HVS, test tracks and field sections	HVS, test tracks and field sections
Standard and new in-place recycled materials	RLT, back-calculation of field and test sections		RLT, HVS, test tracks and field sections	Field sections
Standard cemented materials	back-calculation of field and test sections	Fatigue and Crushing: HVS and field sections		Field sections
Subgrades (based on USCS)	back-calculation 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.				

The transition to ME is expected to include expansion of the initial standard materials database to include as many as possible binder and aggregate combinations available within a region. The stiffness database will expand with additional back-calculation of FWD data from each project. The standard materials performance equation database will expand with 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. Caltrans and several consultants in nearby states are equipped to perform these tests, although some additional capability would need to be developed in the state. The models in *CalME* for damage and permanent deformation can be recalibrated using coefficients from alternative tests, such as the RLT and uniaxial fatigue testing, or a device such as the Texas Reflection Cracking device, or other tests developed in the future, if warranted. The laboratory-to-field shift factors are expected to be improved with additional HVS testing, and data coming from the improved Caltrans PMS.

The *CalME* software uploads *CalBack* back-calculation files, and then calculates stiffnesses for the existing pavement layers for design and analysis, and quantifies the variability of the existing layer stiffnesses for a Monte Carlo simulation used in the reliability-based design. The plan is to rely on back-calculation to characterize in-place materials stiffness, with performance equation coefficients and shift factors from the database from HVS and test track calibrations, instead of laboratory testing. Caltrans is currently beginning a three year ground penetrating radar survey (GPR) inventory of the entire network to fill in major gaps in historical construction records. Inventory project funding is available for analysis of approximately 50 percent of the network at 100 m or shorter intervals. The remainder of the GPR files will be analyzed on a project by project basis. The GPR data, combined with the current level of coring and additional work for dynamic cone penetration and, where possible, test pits, will provide pavement layer type and thickness calibration data for analysis of the GPR data. This transition will require some additional resources for deflection testing and back-calculation, and analysis of raw GPR data where not previously analyzed, as well as better site investigations.

Overall, the plan is to build the kernel of a state standard materials database, with each region augmenting the database for materials that are locally available over time. The intent is to minimize the amount of performance-related laboratory testing necessary for a given project to only those projects using new types of materials and larger projects with long design lives where the time and cost of performance-related testing is warranted for alternative local materials that may be selected by low bid, and require it for those larger, costlier projects. Additional research funding will be needed periodically to revise calibrations of coefficients and shift factors using HVS testing, field test sections and PMS data, and to develop coefficients and factors for new types of material or major changes in the truck fleet.

3 DEVELOPMENT AND MAINTENANCE OF EXPERTISE

Caltrans and consultants will need to develop and maintain expertise in the use of the ME methods, and the associated field and laboratory testing. Caltrans needs to maintain core competency for oversight of consultants and to provide continuous improvement of the method and to establish and maintain guidelines and policies for use of ME design. It is anticipated that approximately 20 Caltrans engineers will use the method, with approximately five in headquarters establishing guidelines and policy and providing support, and 15 in the regions performing actual designs. There will need to be a well-planned training program and comprehensive training materials. All of these engineers have extensive experience with the current empirical design methods and extensive field experience and knowledge of materials. However, only a few have had any detailed training in ME design.

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

- There must be a good implementation plan, with continued support from upper management, including work load relief 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 needs to be ongoing support to users through a User's Group to identify problems, standardize best practice, and provide peer review, and a means for including Caltrans consultants needs to be developed;
- There needs to 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 once they have been implemented;
- Testing methods must fit within work-load 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 work-arounds must be provided wherever possible. Sophisticated performance-related testing cannot be expected to be performed on a routine basis. For example, many states in the US established triaxial testing capabilities for soils 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 soils 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 failures 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.

4 SUMMARY

The majority of issues associated with transition from an empirical design method to an ME design method have been identified, and the development of the *CalME* program for asphalt pavement design and analysis has attempted to address these issues in California. The plan for implementation of ME design and analysis considering major implementation issues was outlined in this paper.

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