MECHANISTIC-EMPERICAL PAVEMENT DESIGN: EVOLUTION AND FUTURE CHALLENGES

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ABSTRACT

Today's mechanistic-Empirical (M-E) pavement design involves comprehensive, computerized packages. However, this also brings with it major challenges of calibration and validation, determination of appropriate input values, resource needs for implementation and balancing complexity and comprehensiveness with understandability and practicality.

This paper starts with a brief summary of the evolution of M-E design, and lists a number of available, computerized analytical solutions. It then describes the basic inputs and outcomes that should be incorporated in a design procedure, as well as considerations in choosing an appropriate M-E procedure.

Two case examples of challenges in implementing an M-E procedure are presented. The first involves a simplified, equivalent two-layer elastic model where calibration consisted of two stages, the first based on an extensive data base of field performance, and the second based on an expert panel's design estimates in a matrix of factor combinations. The second example involves AASHTO's new Mechanistic-Empirical Pavement Design Guide (MEPDG) where the hierarchical levels of design inputs are first described, and a summary description of a recent sensitivity analysis of the input factors in the rutting and fatigue models is then provided.

Finally, the paper suggests some future challenges and opportunities could include comparative sensitivity or interactions of factors analysis for the MEPDG as well as documentation and dissemination of calibration and validation results. Additionally, there is the potential of moving to more fundamental analytical techniques, such as application of micromechanics.

INTRODUCTION

Pavement design was almost exclusively empirical or experience based until about the end of World War II (mid 1940's), at which time fundamental or theoretically based principles started to appear. In fact, the first International Conference on the Structural Design of Asphalt Pavements (Ann Arber, Michigan, 1962) could be considered as the starting point for applying these principles to pavement design (1). Over the next several decades, many advances toward what we now call mechanistic-empirical (M-E) pavement design methodology occurred in various countries around the world.

While this paper focuses on asphalt pavements, it should be noted that concrete pavement design has also benefited substantially from various fundamental or theoretically based developments. These go back to the 1920's and the Westergoard equations, as so well described in the classic textbook, "Principles of Pavement Design" by Yoder (2). Current developments are incorporated in the new ASSHTO Guide (see subsequent reference).

However, there is still widespread use of essentially empirical methods, ranging from "catalogues" of structural designs for various combinations of traffic loads and subgrade strength, to regression based design charts which incorporate such factors as material properties, temperature variations, equivalent single axle load (ESAL) applications, and bearing capacity. Complementing these structural designs is a large variety of performance prediction models ((eg., International Roughness Index, IRI, vs age), distress prediction models (eg., fatigue damage and rutting damage vs ESAL accumulation, plus thermal cracking vs age) and life cycle cost analyses (LCCA) methodology.

While the rationale for M-E based design is essentially having a sound basis of good science and engineering, as in many other areas of technology, empirical methods still hold an attraction mainly because of a long record of experience and familiarity with the procedures. Thus, M-E methods still have considerable scope for more widespread use and verification, and this represents a major challenge to pavement engineers.

Accordingly, the presentation herein is directed to the dimensions of this challenge and to some suggestions on achieving improvements in calibration and implementation. More specifically, the following are addressed:

- Evolution of mechanistic-empirical (M-E) pavement design methodology, including background, fundamentals of mechanistic analysis, developments in computer based packages, and basic inputs and outputs of a M-E design analysis.
- Choosing an appropriate (M-E?) design procedure
- Examples of widely known mechanistically based design procedures
- Range of challenges in actually implementing a M-E design procedure, with case examples involving a simplified system, OPAC 2000, and the new AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG).
- Future challenges and opportunities for advancing the state of technology and the state of practice.

EVOLUTION OF MECHANISTIC-EMPIRICAL PAVEMENT DESIGN

An excellent and comprehensive description of the evolution of M-E pavement design methodology for asphalt pavements has been in Ref (1). The following discussion makes extensive use of this reference.

Background

The fundamental basis for M-E pavement design could arguably go all the way back to Boussinesq elastic theory, but the more modern basis could well be attributed to Burmister’s solutions for two and three layer elastic systems responses to loads (3).

Major impetus to more fundamentally based pavement design was provided by the heavy aircraft load impacts on airfield pavement design in World War II. Pioneering work, for example, was carried out by Dr. Norman McLeod in Canada, based on ultimate strength theory for a plate load (4), by the U.S. Army Corps of Engineers using a modified CBR procedure and Boussinesq theory (5). As well, road tests in the 1950’s; eg., the WASHO Road Test in Idaho (6), and the AASHO Road Test in Illinois (7), were instrumental in advancing the state of pavement design technology. In Canada, a comprehensive nationwide study on pavement performance was carried out in the late 1950’s and early

1960's (8), which was also a valuable forerunner to the subsequent development of mechanistically based pavement design.

In fact, the Brampton Test Road (9,10) is one of the first explicit applications of elastic layer theory to pavement design in Canada. This project illustrated that calculated pavement response, particularly subgrade deflection, was strongly correlated to observed pavement performance. It also provided valuable information for later development of Ontario's simplified mechanistic- empirical pavement design method, "OPAC", as subsequently discussed.

The 1970's, 1980's, 1990's and now the 2000's with AASHTO's "MEPDG" saw a continuing evolution of M-E pavement design methods, as described in Ref (1) and summarized briefly in the following discussion. A noteworthy feature of this evolution is the expansion of capabilities and comprehensiveness, as well as the availability of vastly increased computer power. Nevertheless, the mechanistic part of all these methods remains the same, fundamentally- that is, the ability to calculate stresses, strains or displacements at various points in the pavement structure.

FUNDAMENTALS OF THE MECHANISTIC ANALYSIS PART OF M-E PAVEMENT DESIGN

It is useful to briefly review the fundamental outputs of mechanistic analysis, which can be based on linear elastic, non-linear elastic, viscoelastic, or plasticity theory. Usually, however, linear elastic is the theory of choice in practice, with some exceptions.

Essentially, the mechanistic part of M-E design is directed to calculating one or more responses in the pavement structure as a function of material properties, layer thicknesses and loading conditions. These response(s) must then be related to observed performance (e.g, smoothness deterioration, fatigue cracking progression, rutting progression). That is the empirical part of the M-E design.

Schematically, the possible responses which can be used in design are shown in Figure 1(a), while the pavement performance to which it needs to be related is shown in Figure 1(b). In fact, establishing these relationships, in view of a wide variety of materials, loads, and environment that exists in practice has been a real and continuing challenge to pavement engineers over many years.

Not all of the responses in Figure 1(a) are used in any given design method. Most often used are horizontal strain at the bottom of the asphalt layer and vertical strain or deflection at the surface of the sub grade. The various computer based analyses subsequently listed provide the capability to calculate these responses, provided the materials properties, loading conditions and layer thicknesses are available as inputs.

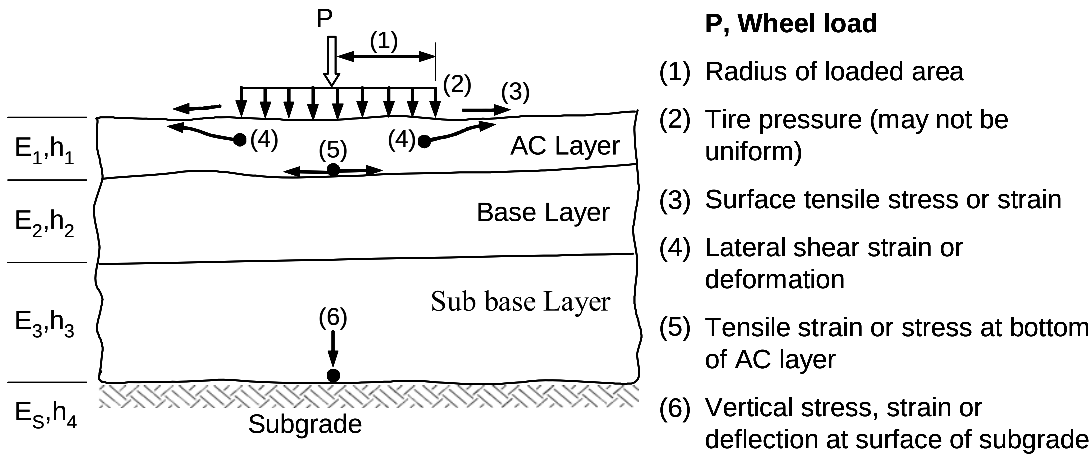

Figure 1a. Fundamental Pavement Responses as a Function of Load, Material Properties and Layer Thicknesses (Mechanistic part).

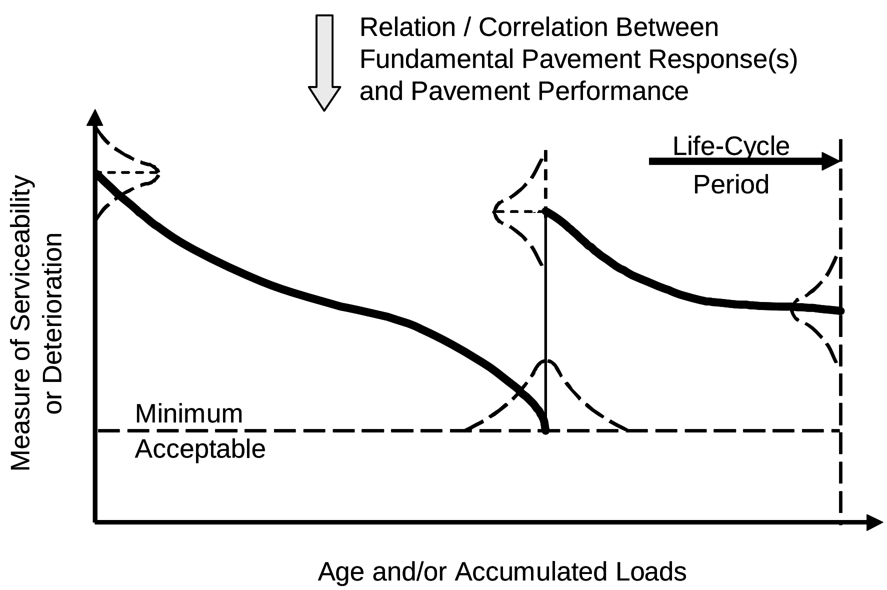

Figure 1b. Pavement Performance to Which Mechanistic Response(s) Must be Related / Correlated (Empirical Part)

2.3 COMPUTER BASED MECHANISTIC ANALYSIS PACKAGES

The availability of computer based packages for mechanistic analysis provided a powerful tool for pavement engineers. A summary listing of some of the more well known programs is shown in Table 1. Two of these programs, BISTRO and CHEV5L, were in fact used for the Brampton Test Road analysis in the early 1970's (10).

It can be seen that multi-layer elastic (MLE) is the most widely adopted theoretical basis. Because of the assumptions involved, including homogeneous isotopic and linear elastic material properties, no shear stresses at the surface and uniformly distributed load, "strictly speaking, elastic layer theory is not a good model of a pavement structure yet the basic conclusion is that elastic layer theory is a useful model for the analysis of pavements provided the input data is properly formatted and the output is properly interpreted" (11).

Finite element and viscoelastic layer theory have seen more limited use, possibly because of the difficulty in obtaining the required materials input and the complexity involved.

3. BASIC INPUTS AND OUTCOMES OF A M-E DESIGN ANALYSIS

Any pavement design procedure should incorporate a range of relevant factors or variables as inputs, and be able to predict outcomes in terms of serviceability- age history (e.g. International Roughness Index vs. age and/or accumulated traffic loads) as a minimum. In addition, it is desirable to have the capability of predicting the following measures of deterioration or damage, also as a function of age and/or accumulated traffic loads:

- Fatigue cracking
- Permanent deformation or rutting
- Thermally associated cracking

Figure 2 illustrates the range of factors and sub factors that might be considered as well as the interactions (dotted lines). Obviously it would be difficult, time consuming and literally impossible to obtain quantitative data on all these input factors for any given design situation. Thus, it is common in several design approaches to calculate fatigue cracking, rutting and thermal cracking as a design check, where the serviceability-age prediction is the main control.

Table 1 Summary of Some Computer-Based Analytical Solutions for Asphalt Concrete Pavements (Modified from Ref. 3)

Program and Ref.	Theoretical Basis	No. Layers (max)	No .of Loads (max)	Program Source	Remarks
CHEV5L Internal Rpt	MLE	5	1	Chevron Research	Can not calculate subgrade strain
BISAR[1] (De Jong et al 1973, Ref. 12)	MLE	5	10	Shell International	The program BISTRO was a forerunner of this program
ELSYM[2] (Ahlborn 1972, Ref. 13)	MLE	5	10	FHWA (UCB)	Widely used MLE analysis program
PDMAP (PSAD) (Finn et al 1977, Ref. 14)	MLE	5	2	NCHRP Project 1-10	Includes provisions for iteration to reflect non-linear response in untreated aggregate layers
JULEA[3]	MLE	5	4+	USACE WES	Used in Program LEDFAA
CIRCLY[4] (Wardle 1977, Ref. 15)	MLE	5+	100	MINCAD, Australia	Includes provisions for horizontal loads and frictionless as well as full-friction interfaces
VESYS (Kenis 1978, Ref. 16)	MLE or MLVE	5	2	FHWA	Can be operated using elastic or viscoelastic materials response
VEROAD (Nilsson et al 1996, Ref. 17)	MLVE	15 (resulting in half-space)		Delft Technical University	Viscoelastic response in shear; elastic response for volume change
ILLIPAVE (Thompson & Elliot 1988, Ref. 18)	FE		1	University of Illinois	
FENLAP (Brunton & d'Almeida 1992, Ref. 19)	FE		1	University of Nottingham	Specifically developed to accommodate non- linear resilient materials properties
SAPSI-M (Chatti and Yun, 1996), Ref. 20)	Layered, damped elastic medium	N layers resting on elastic half-space or rigid base	Multiple	Michigan State Univ./Univ. of California Berkeley	Complex response method of transient analysis-continuum solution in horizontal direction and finite element solution in vertical direction

MLE – multilayer elastic
MLVE – multilayer viscoelastic
FE – finite element

1. Current version is described in "Shell Pavement Design Manual" (Personal Computer Version SPDM-PC), by J.N. Preston 1996, Shell, Delft
2. ELSYM5 is available from McTRANS™ in Florida
3. JULEA is described in LEDFAA (Layered Elastic Design Federal Aviation Administration), User's Manual, FAA, Washington, D.C., 1995
4. CIRCLY4 is the current version, Wardle and Rodway, Proc., Transport 98, ARRB Transport Res., Victoria, Australia, 1998. Recently, Wardle, Rickards and Lancaster have adopted/modified CIRCLY4 in developing "HIPAVE" for the M-E design of heavy duty industrial pavements (sec ICAP10 Proc., Quebec, 2006)

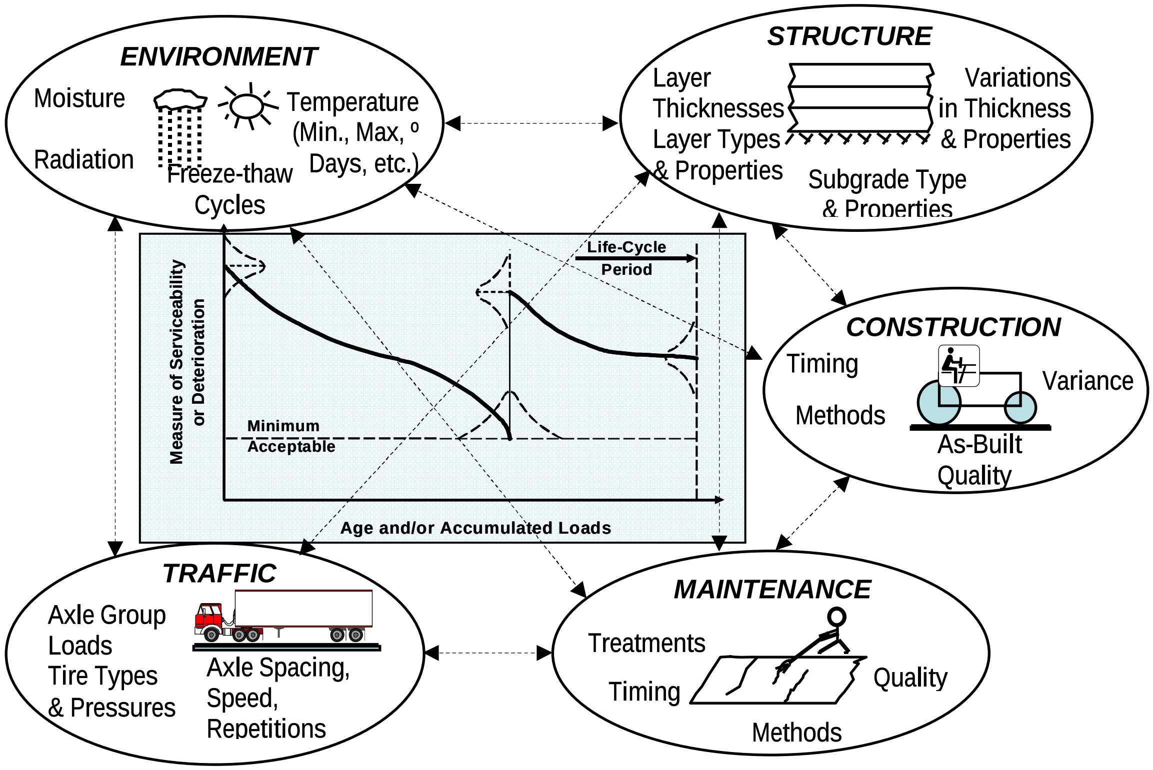

Figure 2 Input Factors and Interactions Relevant to a Design Performance Prediction

The mechanistic part of the analysis of course only calculates a primary response(s), such as stress, strain and deformation at critical points in the pavement structure. Thus, a complete design analysis must relate primary response(s) to performance (e.g. IRI vs. age)and accumulated deterioration. In turn, this means an M-E design analysis must be calibrated to observed or measured field performance and this represents a major challenge, as subsequently discussed.

While the foregoing applies in general, it does not indicate, which M-E approach or methodology is most applicable for a given agency. This is also a major challenge, as discussed in the following section.

CHOOSING AN APPROPRIATE M-E DESIGN PROCEDURE

The American Association of State Highway and Transportation officials (AASHTO) has invested considerable time and resources in producing a series of pavement design guides (e.g. the 1972 Interim Guide, then the 1986 and 1993 Guides, and currently the Mechanistic- Empirical Pavement Design Guide, MEPDG, which is the outcome of NCHRP Project 1-37a (21). While the MEDPG represents a massive effort, expenditures of many millions of dollars and currently a group of lead States for implementation, it should be noted that most States still use some version of the earlier Guides. As well, the various states comprising AASHTO are still to vote on the MEPDG, through a balloting procedure, likely to occur sometime in 2007.

In Canada, a Transportation Association of Canada (TAC) project on the MEPDG is underway, involving a university, provincial, private sector consortium (22, 23). The project is still in the early stages and full scale implementation by any one or group of Canadian agencies may still be several years away. It should be noted that the situation of pavement design in Canada is still quite varied between provinces and cities, as documented in Ref. (24).

Whether in Canada or any other country, the decision to choose a M-E design procedure, or to retain an existing procedure, involves a number of factors. Figure 3 summarizes the range of options and the factors that should be considered. These options, and the factors, in essence also represent a challenge.

Basically, the choices vary from retaining an existing procedure (empirical or M-E based) to updating an existing procedure to phasing into a new M-E procedure (either simplified or the new MEPDG). The new MEPDG is certainly the most comprehensive and incorporates flexibility (e.g. three levels of design), but the factors listed in Figure 3 should to be carefully considered before adapting any option.

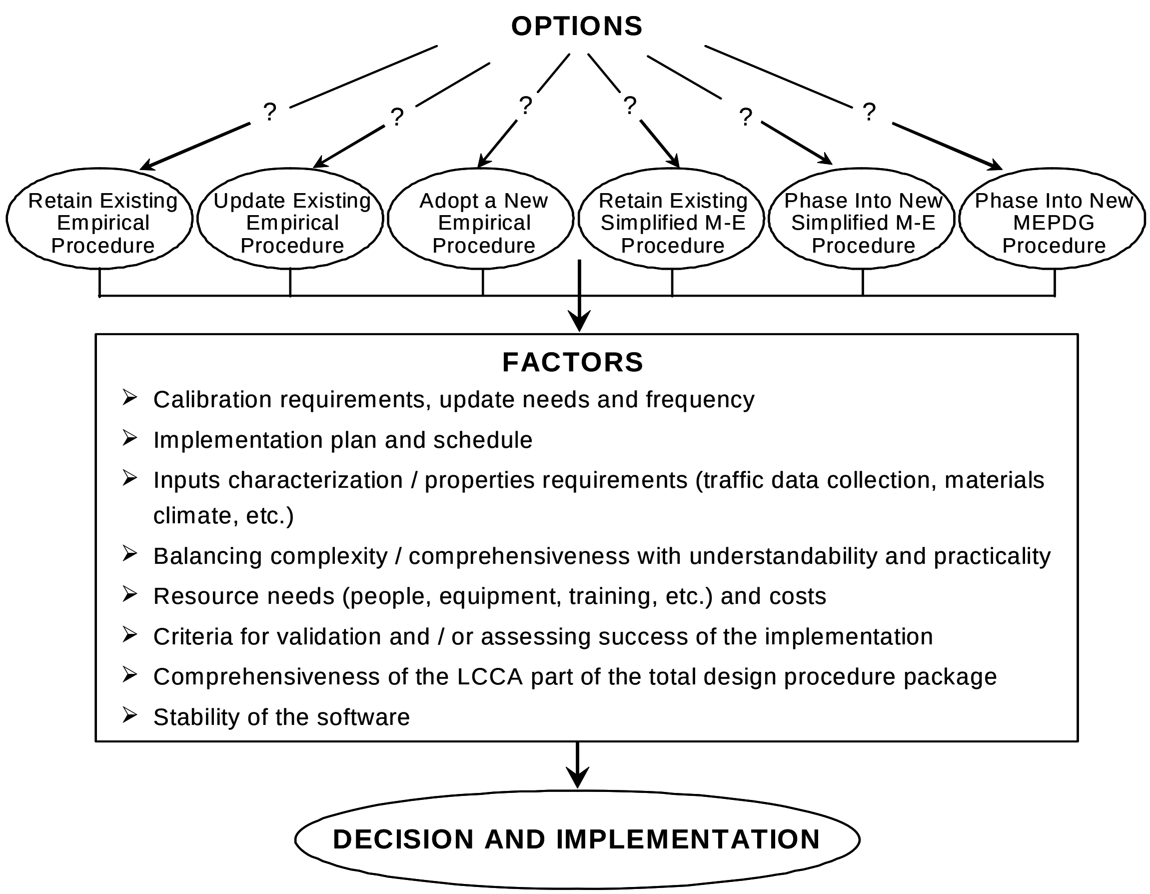

Figure 3. Basic Options and Factors in Choosing a (M-E ?) Pavement Design Procedure

EXAMPLES OF MECHANISTICALLY BASED PROCEDURES

An excellent summary listing of mechanistic-empirical design procedures is provided in Ref. (1). Table 2 provides the listing from Ref. (1), with the addition of OPAC 2000, a simplified mechanistic empirical design method developed for the Ministry of Transportation Ontario (25). This method contains some unique features related to one of the most critical challenges in M-E design, that of calibration, as subsequently discussed.

A multi-layer elastic solid seems to be the common pavement structure representation in Table 2, and the design procedures listed are by and large well established. They also have computer packages as part of the procedure, and have been calibrated to local or regional conditions by user agencies to varying degrees. Adoption of any particular approach by user agencies has taken the factors of Fig 3 into account in some way, albeit generally more implicitly than explicit. In essence, these agencies have addressed the challenge(s) involved.

It should be noted that there are many excellent contributions on M-E design in the 10th International Conference on Asphalt Pavement Proceedings in 2006 (26). About 10% directly address M-E design analysis, most but not all in the context of the MEPDG.

CHALLENGES IN IMPLEMENTING A M-E DESIGN PROCEDURE: CASE EXAMPLES

The M-E procedures listed in Table 2 could all form the basis for discussing the implementation challenges. Obviously any such meaningful discussion is beyond the scope of this presentation. Consequently two case examples have been selected: first, the simplified, two-layer equivalent structure in OPAC 2000, and second AASHTO's new Mechanistic Empirical Pavement Design Guide (MEPDG).

Reasons for the first choice include a somewhat unique, two-stage calibration to bring the package to full operational implementation, reasonable and practical inputs requirements and resources needs and a balance between complexity/comprehensiveness and understandability. As well, the OPAC 2000 procedure placed major emphasis on a comprehensive LCCA module.

Reasons for the second case example choice include the fact it is the newest, most comprehensive package in existence, it has generated extensive interest in the United States, Canada and other countries, and there are major challenges of calibration and implementation. Moreover, a decision to adopt the MEPDG by any user agency carries along with it a commitment to investing in the technology and resource requirements as well as acceptance of a timeline of perhaps several years before full implementation.

The OPAC 2000 Simplified M-E Based System

The original Ontario Pavement Analysis of Costs (OPAC) system was developed in the 1970's, drawing heavily from the AASHO Road test and Brampton Road Test findings. A more comprehensive, updated system was considered necessary by the early 1990's and accordingly a project involving the University of Waterloo, Ministry of Transportation Ontario and Stantec Consulting Ltd. was carried out to produce OPAC 2000(He, et al 1996)

OPAC 2000 Framework and Models

The following discussion focuses only on model calibration. In total, however, OPAC 2000 is a comprehensive design system, as described in Ref. (25).

The pavement performance prediction model is divided into two parts: traffic-associated and environment-associated as expressed by the following equation:

$$P = P_0 - P_T - P_E$$

where: P_0 is the initial pavement performance index (Riding Comfort Index, RCI, Pavement Condition Index, PCI or International Roughness Index, IRI) and P_T and P_E are the performance losses due to traffic and environment, respectively. At the time the model was developed, a roughness based pavement performance index RCI (Riding Comfort Index), on a scale of 0 to 10, was used. Currently, PCI, on a scale of 0 to 100 is used, where PCI ≈ 10% RCI. As well, a study by Hein (37) has shown that IRI is highly correlated with RCI, and can be estimated as IRI = 5.588 – 0.578 x RCI.

Table 2 Examples of Mechanistically Based Design Procedures (Modified from Ref. 1)

Organization	Pavement Representation	Distress Modes	Environment a)Effects	Pavement Materials	Design Format
Shell International Petroleum Co., Ltd., London, England (Claessen et al 1977, Ref. 27)	Multilayer elastic solid	• Fatigue in treated layers; • Rutting based on subgrade strain	Temperature	Asphalt concrete, untreated aggregate, cement stabilized aggregate	Design charts, computer program BISAR is used for analysis
National Cooperative Highway Research Program (NCHRP) Project 1-10B (Finn et al 1977, Ref. 14)	Multilayer elastic solid	Fatigue in treated layers, Rutting	Temperature	Asphalt concrete, asphalt stabilized bases, untreated aggregates	Design charts, computer program PDMAP
The Asphalt Institute (Shook et al 1982, Ref. 28)	Multilayer elastic solid	• Fatigue in asphalt treated layers • Rutting based on subgrade strain	Temperature, freezing and thawing	Asphalt concrete, asphalt emulsion, treated bases, untreated aggregate	Design charts: computer program DAMA

TABLE 2 Continued

Laboratoire Central des Ponts et Chaussées (LCPC 1997, Ref. 29)	Multilayer elastic solid	• Fatigue in treated layers, Rutting	Temperature	Asphalt concrete, asphalt-treated bases, cement stabilized aggregates, untreated aggregates	Catalogue of designs, computer program (ELIZE) for analysis
Centre de Recherches Routieres, Belgium (Verstraeten et al 1982, Ref. 30)	Multilayer elastic solid	• Fatigue in treated layers, Rutting	Temperature	Asphalt concrete, asphalt-stabilized bases, untreated aggregates	Design charts; computer program (MTC093)
National Institute for Transportation and Road Research, South Africa (Freeme et al 1982, Ref. 31)	Multilayer elastic solid	• Fatigue in treated layers; • Rutting based on subgrade strain and shear in granular layers	Temperature	Gap-graded asphalt mix, asphalt concrete, cement-stabilized aggregate, untreated aggregate	Catalogue of designs; computer programs
National Cooperative Highway Research Program (NCHRP) Project 1-26 (Thompson & Barenberg 1981, Ref. 32)	Finite element idealization, multilayer elastic solid	• Fatigue in treated layers • Rutting based on subgrade strain	Temperature	Asphalt concrete, untreated aggregates	ILLI-PAVE elastic layer programs (e.g., ELSYM)
Federal Highway Administration U.S. DOT, Washington, D.C. (Kenis et al 1982, Ref. 33)	Multilayer elastic or viscoelastic solid	• Fatigue in treated layers • Rutting, estimate at surface • Serviceability as measured by PSI)	Temperature	Asphalt concrete, cement stabilized aggregate, untreated aggregate, sulphur-treated materials	Computer program, VESYS
University of Nottingham, Great Britain (Brown et al 1982, Ref. 34)	Multilayer elastic solid	• Fatigue in treated layers; • Rutting based on subgrade strain	Temperature	Continuous or gap-graded asphalt mixes of known volumetrics on standard UK materials	Design charts; computer program (ANPAD)

TABLE 2 Continued

Austroads (Austroads 1992, Ref. 35)	Multilayer elastic solid	• Fatigue in treated layers; • Rutting based on subgrade strain	Temperature, moisture	Asphalt concrete, untreated aggregates, cement stabilized aggregates	Design charts, computer program (CIRCLY)
Ministry of Transportation Ontario (He et al 1996, Ref. 25)	Simplified two-layer elastic equivalent	• Progression of IRI as function of age and traffic	Climatic regions	Asphalt concrete, treated or untreated base and subbase layers	Computer Package (OPAC 2000)
National Cooperative Highway Research Program (NCHRP) Project 1-37A, Ref. 36	Multilayer elastic	• Fatigue in treated layers; • Rutting based on subgrade strain and asphalt concrete, time hardening • Low temperature cracking	Temperature, Moisture	Asphalt concrete, untreated aggregates, chemical stabilized materials	Computer program (JULEA)

The fact that traffic associated and environment associated loss are calculated separately, as components of total loss, is a unique feature of OPAC 2000. As well, the two-stage calibration is also a unique feature, as subsequently discussed.

The basic design factor is:

$$H_e = a_1h_1 + a_2h_2 + a_3h_3 + \ldots$$

where H_e (mm) is the equivalent granular thickness; h_1, h_2, h_3 are the actual thicknesses of the asphalt, base and subbase layers; a_1, a_2, a_3 are strength coefficients of the asphalt, base and subbase layer materials. They are also known as "granular base equivalency (GBE) factors".

This calculation of equivalent granular thickness allows the pavement to be transformed into a two layer equivalent structure, and thus the (Odemark) subgrade deflection, W_S can be calculated as:

$$W_s = 1000 \times \frac{P}{2M_sZ\sqrt{1+(\frac{a}{Z})^2}} \tag{3}$$

where

P	=	total load (i.e., 40 kN on a dual tire)
M_2	=	modulus of the equivalent granular base material (average 345 MPa)
M_s	=	modulus of the subgrade (MPa)

Z	=	$0.9H_e\sqrt[3]{\dfrac{M_2}{M_s}}$
a	=	radius of loaded area (i.e., approximately 163 mm for an equivalent circular imprint of a dual tire).

The calculation of the Riding Comfort Index loss due to traffic is as follows:

$$\Delta RCI_T = 2.4455\Psi + 8.805\Psi^3 \tag{4}$$

where

Ψ	=	$3.7239 \times 10^{-6} \times W_S^6 \times N$ (for W_S in mm)
N	=	number of (80 kN or 18 Kip) equivalent single axle load (ESAL) applications

The final equation for calculating the environment-associated performance loss in the OPAC model is given as:

$$\Delta RCI_E = P_o(1 - \frac{1}{1+\beta W_S})(1 - e^{\alpha Y}) \tag{5}$$

where

P_0	=	initial RCI
W_S	=	as previously defined.
Y	=	pavement age
	=	constants

Yearly performance index of a pavement is predicted by substituting P_T and P_E in Equation (1) with ΔRCI_T and ΔRCI_E from Equations (4) and (5), respectively.

OPAC 2000 First Stage Calibration

The flexible pavement design module in OPAC 2000 is used for carrying out new flexible pavement designs and the flexible pavement overlay designs. Both are based on the new, calibrated pavement performance prediction models as subsequently described.

Since the variation of regional conditions was considered to have greater impacts on the environmental part of the model (Equation 7) than on the traffic part (Equation 4), model calibration was therefore concentrated on the environmental part. It was based on long term performance data for 94 sections from all over the province. Cluster analysis was used to subdivide sections into smaller groups to reduce the overall prediction error of the performance model. In the final analysis, two climatic regions were considered sufficient and the calibration proceeded on that basis..

The model updating is in effect to calibrate coefficients β and α based on the observed PCI values for P and P_o. The performance loss due to traffic, P_T, is calculated using Equation (4) based on the collected traffic data. Applying the clustering result, the database was divided into two groups, Southern Ontario and Northern Ontario. Two sets of new coefficients were acquired, each for one group, as given in Table 3.

Table 3 Summary Results of Model Coefficients Calibration for OPAC 2000 (After Ref. (25)

Parameter	Southern Ontario	Northern Ontario
β	12.7211	10.5478
α	-0.0329	-0.0415
R^2	0.707	0.866
SSE*	2.966	0.383

* Sum of squared error.

OPAC 2000 Second Stage Calibration and Validation

The newly developed OPAC 2000 predictions showed lower design thicknesses than would be expected in some situations. Consequently, a second stage calibration and validation was carried out using an expert, experience based matrix. The procedure involved the development of a matrix of combinations of subgrade and traffic level conditions (38). Pavement designers from the various regions and head office were asked to fill in a matrix for five traffic levels based on Equivalent Single Axle Loads (ESALs) and three subgrade types. The matrix was constructed for both northern and southern Ontario. In short, for a given subgrade type and traffic loading the designers were asked to fill in a predicted or estimated granular base equivalency (H_e) and an expected service life. Table 4 shows the results of one of the combinations of traffic and subgrade type.

Table 4 Sample Experience Based Matrix Estimated for 50,000 – 200,000 ESAL/Year and Medium Subgrade (Second Stage Calibration)

Region	**ESAL/Year**	**Subgrade**	**H_e (mm)**	**Initial Service Life (Years)**
Eastern	50,000 – 200,000	Medium	530 – 710	12 – 14
Central			780 – 930	15 – 18
Southwestern			700 – 800	15 – 18
Northern			750 – 1100	15 – 18
Northwestern			530 – 730	15 - 18
Head Office*			700 – 800	15 – 18
Head Office**			800 – 1100	15 – 18

Notes * denotes Southern Ontario
** denotes Northern Ontario

The data from the experience based matrix was divided into southern and northern Ontario and a regression analysis was performed, as described in Ref. (36). In this analysis, if the H_e values were statistically the same as those predicted in the expert matrix, at the 90% level, the expert matrix was deemed to be validated. If not, recalibration of the parameters was carried out for those combinations where predicted and observed values differed.

AASHTO'S Mechanistic-Empirical Pavement Design Guide

The MEPDG is the result of an extensive project (originally termed the "AASHTO 2002 Guide") carried out under NCHRP Project 1-37A (36). As noted previously, it has generated widespread interest because of its comprehensiveness, the design philosophy incorporated and the potential benefits. However, it also brings with it major challenges in calibration, implementation, resource needs, and characterization of inputs.

It is not possible herein to adequately cover all the features of the MEPDG, but fortunately a Transportation Association of Canada project (22) has produced a summary of the key features, as well as some notes on implementation (23).

MEPDG Approach

The MEPDG builds on state-of-practice methodologies, provides versatility in terms of a wide range of design and material options for new and rehabilitated pavements, and it incorporates three hierarchical levels of design inputs.

The design process consists of three major stages. Stage 1 is directed to developing input values and evaluation, Stage 2 involves the structural analysis of trial designs, including performance modelling. In Stage 3, the evaluation of viable alternatives is carried out, including life cycle cost analysis, culminating in a final strategy or design selection. In essence, the design process incorporates a comprehensive range of factors, but there is a caution that the "MEPDG cannot include all of the site-specific conditions that occur. It is therefore necessary for the user to adapt local experience to use of the MEPDG (22).

Hierarchical Design Levels and Inputs

This feature of the Guide provides designers with the flexibility to range from a high level of inputs completeness and accuracy, such as for a high traffic volume expressway design, to a lower level of inputs involving approximations and estimates, such as for a secondary highway. More specifically, the three levels are:
Level 1 is directed to the highest accuracy and lowest uncertainty. It requires direct laboratory or field testing, such as dynamic modulus of the asphalt concrete, non-destructive deflection testing (eg., rehabilitation design for an existing pavement), and site-specific axle load spectra. Obviously, this requires more resources and time than for other levels, but should be warranted for high traffic volume facility design involving a threshold level of expenditure.

Level 2 would be consistent with much of the current practice where inputs are based on limited testing and/or the agency's data base and/or correlations with independent variables (eg., estimating dynamic modulus of the asphalt concrete from aggregate, binder and other mix properties).
Level 3 would be applicable to design situations where a higher level of risk can be accepted, and the inputs would be user-selected for typical local or regional values.

It should be noted that the computations and outputs are the same for all three levels; what varies is the accuracy and/or direct characterization of inputs. The likely scenario for most use in practice of the MEPDG will be Levels 2 and 3, although inputs can vary across levels. Characterization and calibration of input values, and the associated commitment of implementation resources, poses a substantive challenge. As well, establishing the sensitivity of these inputs to pavement performance is a major challenge, although some work in this regard has already occurred (see various conference proceedings, such as Ref. 21, Ref. 39 and 40, and the 1997 TRB conference proceedings).

Performance and Distress Modelling

Performance modelling is in terms of user related serviceability or smoothness, and in the MEPDG this is International Roughness Index, IRI, which varies with age. There is an as-built IRI, which then increases over time as a function of distress accumulation, maintenance and site conditions.

Distress modelling for rutting and fatigue is related to structural response (e.g., critical stresses, strains and displacements) due to traffic loads and environmental factors, which is then used in damage models. These models estimate rutting progression or accumulation, bottom up and top down fatigue cracking, and longitudinal fatigue cracking. A multi-layer elastic program JULEA (see the listing in Table 1) is used to calculate structural response.

The rutting model's sensitivity to various input parameters has been analyzed, for example for example by (39). They used 17 input variables and three climatic regions (representing Minneapolis for cold climate, Oklahoma City for intermediate and Phoenix for hot weather). Two traffic load approaches were used, a classical ESAL approach and a Level 1 load spectrum. The sensitivity runs used low, medium and high values for the inputs, and were generally based on varying one factor at a time while holding the others constant.

The paper contains numerous plots of these variations; however, several key observations can be made, as follows:

- The magnitude of rutting is highly sensitive to AC mix stiffness
- The greatest potential for rutting is for AC layers in the 3in to 5in (75mm to 125mm) range, and higher mean average annual air temperatures (MAAT) increase the potential for rutting quite substantially
- Subgrade modulus does not have a significant influence on AC layer rutting
- The use of actual traffic load spectra (eg. Level 1 input) results in substantially increased rut depth as compared to using the empirical ESAL approach

The results of the foregoing analysis in Ref. (39) provides valuable guidance to pavement design engineers in understanding and using the MEPDG. However, while varying one factor at a time represented a very large amount of work, interactions do occur (See Fig. 2) and this certainly needs to be examined in future work. For example, it is possible that the interaction between AC mix stiffness, MAAT and Level 1 load spectra could result in larger rut depth predictions than from the individual input factors. As well, the substantial variations noted even for individual factors suggest that considerable work to calibrate or adapt to specific regions or agencies is needed (a current NCHRP Project 1-40A is directed to guidelines for this purpose).

The authors of the rutting sensitivity analysis also evaluated the sensitivity of the fatigue cracking models in the MEPDG (40). In this case, they varied 12 input factors, and several key observations can be made:

- Alligator cracking can increase substantially with thin AC layers (in the 3in to 5 in range), but can be with reduced with lower stiffness AC (effect on rutting?)
- The potential for longitudinal (top down) cracking is substantially increased with thin, stiff AC layers and stiffer subgrades; lower stiffer subgrade support results in lower fatigue cracking
- Air void content of the AC mix is a critical factor in both alligator and longitudinal cracking
- The effect of Level 1 traffic input (load spectra) compared to ESAL input does not have much effect on fatigue cracking; however, for higher traffic volumes, the increase in longitudinal cracking by using load spectra can be several orders of magnitude greater than for using ESAL's.

Again, the results of this analysis can provide valuable guidance to pavement engineers. But clearly there are some major challenges in calibration; for example the effect of using load spectra vs ESAL's. As well, there may well be significant interactions (eg., AC layer thickness vs subgrade stiffness vs AC layer thickness vs load applications) which should be evaluated in any future work.

MEPDG Implementation Challenges

The following are based on Ref. (23) and on previous discussion in this paper:

- Participation and "buy-in" from agency staff (administrators, regional offices, designers, materials people, etc.)
- An effective implementation plan, including:
    - Responsibilities, timelines
    - Resource allocation (people, lab and field equipment, computers and software, training, etc.) and cost estimates/budgets
    - Calibration tasks/activities and schedule
- Development of implementation criteria
    - Objectively based performance indicators
    - Oversight or steering committee
    - Audit process
    - Update and/or improvement needs assessment
- Actual calibration and validation of the models, including:
    - Adjustment/calibration factors for the IRI and distress models (rutting, fatigue cracking, thermal cracking)
    - Library of materials and subgrade properties for local/regional areas and conditions
    - Development of guidelines for calibration and validation
    - Collection of traffic data (eg., axle load spectra, lane distributions, volume variations, tire pressures)
    - Collection/establishment of climate and moisture data for the "Enhanced Integrated Climate Model"

It has been suggested that following the U.S. States balloting on the (2007), and in turn then releasing it as a provisional guide, the time required for implementation, at least in

Canada, will be 3 to 4 years (23). The degree to which the foregoing challenges are met will impact on this timeline.

FUTURE CHALLENGES AND OPPORTUNITIES

Future challenges will undoubtedly include many of those facing M-E design today. Certainly the opportunities will include those of advancing pavement design to a new level which is based on the best science and engineering available; in essence, longer lasting, more cost-effective designs at a high level of reliability.

This of course comes with additional challenges, and some of these are:

- Establishing the comparative sensitivity and interactions of factors in the MEPDG. This will enable more efficient calibration efforts, but because of the comprehensiveness and complexity of the MEPDG, it is in turn a complex task. One possibility is the use of a randomized latin hypercube approach where the factor values are allowed to vary randomly, within limits, and repeated runs of the model(s) can enable identification of the most sensitive factors. This method was used quite effectively in a sensitivity analysis of the World Bank's HDM model (41)
- Documentation and dissemination of calibration and validation results by lead states groups, and other users; eg., lessons learned, and pitfalls
- Realizing the potential of more fundamental analytical techniques in design, such as the application of micromechanics to establishing materials properties and response to loads, temperatures, etc.
- Expanding the flexibility of current M-E procedures to go beyond changes of materials properties with time to incorporate such effects as "self healing" structures (eg., based on nanotechnology and micro electrical mechanical sensors, MEMS) and new construction and maintenance processes
- Moving toward simplification, not of the M-E methods themselves but in terms of catalogues of representative designs against which to check designs coming directly from M-E analysis
- Avoiding the tendency to use M-E design packages, particularly the MEPDG, as a "black box" through guidelines for checks on reasonableness of the results

CONCLUSIONS

Mechanistic-empirical design methods provide the opportunity to put pavement design on a more sound basis of science and engineering than methods which are purely empirical or experience based. The new AASHTO Mechanistic Empirical Pavement Design Guide (MEPDG) represents a particularly strong and comprehensive opportunity in this regard.

However, the MEPDG, as with other M-E methods, comes with major challenges. These include calibration and validation requirements, implementation guidelines, commitment of resources, equipment, training, input data requirements and balancing complexity/comprehensiveness with understandability and practicality.

Future challenges and opportunities will undoubtedly include many of those existing today but also include better establishment and understanding of the sensitivity of various factors and their interactions, good documentation and dissemination of calibration and validation results, realizing the potential of more fundamental analytical techniques such as the application of micromechanics to materials properties and responses, and avoiding the tendency to use M-E design packages as "black boxes" through guidelines for checking the reasonableness of results.

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