The 2002 Mechanistic-Empirical Design Procedure for Flexible Pavements: How to Implement it in Italy

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Synopsis

A new Mechanistic-Empirical Pavement Design Guide (MEPDG), also known as the 2002 Design Guide, has been recently proposed in the United States. The development of such a procedure was conducted by the National Cooperative Highway Research Program (NCHRP) under sponsorship by the AASHTO. The Design Guide represents a challenging innovation in the way pavement design is performed: design inputs include traffic (full load spectra for single, tandem, tridem, and quad axles), material and subgrade characterization, climatic factors, performance criteria and many others. One of the most interesting aspects of the design procedure is its hierarchical approach, i.e. the consideration of different levels of inputs. Level 1 requires the engineer to obtain the most accurate design inputs (e.g., direct testing of the materials, on-site WIM, etc.). Level 2 requires testing, but the use of correlations is allowed (for example, subgrade modulus estimated through correlation with another test), and Level 3 generally uses estimated values. Thus, Level 1 has the least possible error associated with inputs, Level 2 uses regional defaults or correlations, and Level 3 is based on the default values. A trial structure is then analyzed for adequacy through the prediction of key distresses and smoothness (as a measure of ride quality): if the design does not meet desired performance criteria, the structure must be revised and the evaluation process repeated.

Although evaluation of this procedure is still underway, many State transportation agencies have already begun adaptation and local calibration of this procedure. This paper addresses the key aspects of the design procedure for flexible pavements and the way it can be transferred to Italy.

To implement this procedure for Italian conditions, various issues should be addressed. This includes material evaluation, availability of traffic and climatic data, contracting methods and need of new specifications. In Italy, where pavement design is mostly based on the use of a Catalog, the implementation of the 2002 AASHTO Design Guide or any mechanistic-based design procedure will require a lot of effort, but it will provide a powerful tool accounting for changes in traffic, materials, construction, design concept, climate and so on.

INTRODUCTION

Deteriorating infrastructure, constant increase in traffic volume and introduction of new materials present a constant challenge to the pavement engineering community. Traditional empirical design procedures cannot be easily adapted to these changes. This is why during the last few decades Italy has been paying an increased attention to developing more analytical design methods for pavement systems.

The only official (but not mandatory) Italian pavement design method is the Catalog developed in 1993 (CNR, 1994). This catalog provides a series of typical pavement design solution for a standard mix of traffic. A Mechanistic-Empirical design would provide a more versatile and robust approach to pavement design than empirical procedures or catalog-based ones, in terms of accommodation of new load configurations and new materials.

The development and the implementation of a brand new mechanistic-based design procedure will be a challenge for the Italian community of civil engineers and will require substantial time and resources. This task might be somewhat simplified if instead of new development, the recently developed Mechanistic-Empirical Pavement Design Guide (MEPDG), also known as the 2002 Design Guide, is adopted for Italian conditions.

This paper is focused on the MEPDG procedure for new flexible pavement design in order to evaluate specific needs of Italy in areas of design, material evaluation, training of staff, contracting methods and preparation of new specification. A brief description the 2002 Design Guide for flexible pavement is given, then the current Italian design policy is presented briefly along with the above mentioned needs for implementing a M-E design method. Implementation issues and recommendations will be discussed, followed by conclusions.

BACKGROUND

Starting in 1996, the AASHTO Joint Task Force on Pavements (JTFP) sponsored the development of a mechanistic-empirical design guide for new and rehabilitated pavements. National Cooperative Highway research Program (NCHRP) Project 1-37 A, the largest project in the over 40-year history of the program (NCHRP, 2004a), was recently concluded with the release of the Mechanistic-Empirical Pavement Design Guide (MEPDG).

The current 1993 AASHTO Guide for Design of Pavement Structures (AASHTO, 1993) is based on empirical equations derived from the AASHO Road Test. That test was conducted between 1958 and 1960, with limited structural sections at one location (Ottawa, Illinois) and with modest traffic levels compared with those of the present day. As such, designs accomplished with the 1993 AASHTO Guide are projected far beyond the interference space of the original data. The goal of the JTFP was to conduct a specific research program to develop a pavement design guide based on mechanistic empirical principles with numerical models calibrated with pavement-performance data from the LTPP (Long Term Pavement Performance) sections.

The MEPDG uses mechanistic-empirical numerical models to analyze input data for traffic, climate, materials and proposed structure and to estimate damage accumulation over service life. It is applicable for designs of new and rehabilitated flexible, rigid and semi-rigid pavements. The concept of pavement performance accounts for functional performance, structural performance and safety. The Guide is primarily concerned with functional and structural performance. Performance predictions are made in terms of pavement distresses and ride quality. Prediction of the following distresses is included in the MEPDG:

- Flexible pavements:
    - Rutting (El-Basyouny *et al*. 2005a, El-Basyouny *et al*. 2005b)
    - Bottom-up AC fatigue cracking (Witczak and Mirza 2000, El-Basyouny and Witczak 2005a, Basyouny and Witczak 2005b, Basyouny and Witczak 2005c)
    - Top-dowm AC fatigue cracking (Witczak and Mirza 2000, El-Basyouny and Witczak 2005a, El-Basyouny and Witczak 2005d)
    - Thermal cracking (Roque *et al*. 1995)
- Jointed concrete pavement
    - Joint faulting (Darter *et al*. 2001, Khazanovich *et al*. 2004)
    - Transverse cracking (Darter *et al*. 2001)
- Continuoulsly reinforced rigid pavements
    - Punchouts (Selesneva *et al.* 2004)

For all pavement types, mechanistic-empirical distress predictions are empirically correlated to the International Roughness Index (IRI). The IRI is employed as a functional criterion in the design process.

The MEPDG provides significant potential benefits over the 1993 AASHTO Guide in achieving cost-effective pavement designs and rehabilitation strategies. Its user-oriented computational software implements an integrated analysis approach for predicting pavement condition over time. These predictions account for the interaction of traffic, climate, and pavement structure. The MEPDG has the capability of changing and adapting to new developments in pavement design by relying on mechanics of materials. For example, M-E design can accurately examine the effect of new load configurations on a particular pavement. Empirical design, on the contrary, is limited to the observations on which the procedure was based (e.g. equivalent single axle load). Additionally, since the process is compartmentalized, new advances in pavement design may be incorporated without altering the overall procedure.

Though M-E design is conceptually straightforward, the development and implementation of such a procedure poses many challenges (Birgisson *et al.* 2000, Smiley, 1998; Timm *et al.* 2000a and 2000b). Specifically, the problem of material characterization, load configuration, pavement life equations, accumulating damage and seasonal variations should be taken into account.

CURRENT ITALIAN DESIGN PROCEDURE

Several analytical approaches are currently in use in Italy for pavement design, each of them chosen by practitioners for their own applications. The Italian Catalog for road pavements is the only official document, even though it is not legally binding.

The Italian Pavement Design Catalog for flexible, plain rigid, reinforced rigid, and composite pavements was developed in 1993 (CNR, 1994). It provides a series of standard pavement structures for 8 different types of road, in which the Italian road network is subdivided for Catalog purposes: rural highways, urban highways, high volume primary and secondary rural roads, low volume primary and secondary rural roads, ordinary secondary rural roads, tourist secondary rural roads, urban connection roads, urban access roads and reserved lanes. The Catalog was developed using both an analytical approach and an empirical one (AASHTO, 1986). The analytical method uses a linear multi-layer elastic model to calculate the horizontal tensile strain at the bottom of the bituminous layers and the vertical compressive stress at the top of the subgrade, as induced by each of the 16 standard reference vehicles that compose each of the 8 different traffic spectra. These stresses and strains are then used to predict the cumulative fatigue damage and the cumulating of permanent deformation in the asphalt layers, so that fatigue cracking and rutting are the main distress mechanisms addressed by the Italian design method (due to Mediterranean climate that allows to neglect thermal cracking).

With the empirical method, design solutions are provided for a standard mix of traffic, converting the commercial traffic flow into a number of Equivalent Standard Axle Loads (ESALs) by the use of conversion factors obtained from the AASHO Road Tests (AASHTO, 1972) that were derived for one single deterioration mode, i.e. loss of serviceability. However, it is acknowledged that the destructive effect of an axle load depends on the deterioration mode that is being analyzed, the construction of the pavement and the actual condition of the pavement itself.

All the calculations for the Catalog for flexible pavement solutions were carried out with reference to hypothetical average conditions:

- climate: only one average climatic condition chosen in the central Italy, considered as representative of the whole national territory, neglecting, therefore, the effect of different hydrologic conditions and climatic variation on the pavement structure’s performance;
- traffic: assumed corresponding to each different road type, but not estimated with reference to the actual function that the road will have to perform within the road network.

Furthermore, the Catalog considers only a limited range of materials, having average performances:

- for the bituminous materials, only dense mixtures (with continuous gradation), whose performance are characterized only via traditional Marshall stability;
- for subgrade, only three types, each one characterized by a constant resilient modulus set equal to 30, 90 and 150 MPa, respectively.

It can be noticed, therefore, that the Catalog is not very flexible in terms of structural solution provided: it doesn’t allow to consider structural solution that optimize, under the economic point of view, the use of locally available natural resources or to use different materials than those considered, and to take into account specific construction needs (structural effectiveness being equal, the Catalog prefers to make use of bituminous mixtures rather than unbound materials).

WHY ITALY SHOULD ADOPT A MECHANISTIC BASED DESIGN PROCESS

Many millions of Euros are spent each year in Italy on road construction and maintenance and there is a continuing requirement for more efficient methods of pavement design which generate solutions that are less disruptive to the environment and the road users, as well as being more economic and of higher quality than those in present use. What is more, Italy has a quite well developed road network and, in future, maintenance and rehabilitation of the existing network will be major issues for the Italian Road Authorities. On the other hand, part of this network itself is somewhat obsolete and the major need for dealing with it will be to upgrade or even to expand it: in this case the policy is more likely to be directed towards the design of new roads.

So far, the Italian pavement design method has not addressed a comprehensive design process. Thus, the twofold above mentioned requirements accentuate the need for an enhanced pavement design method for both new and rehabilitation projects, which would be beneficial for improving pavement technology, as well.

The ways in which the various input parameters can affect the pavement performance bring to light the complex nature of pavement design: there are several cyclical effects and systematic changes that occur during the service life of the pavement. Materials properties can change for different reasons and some of the causes are acting in the opposite sense, which makes the prediction of pavement life very difficult.

The situation is extremely complex and there is also strong interdependence between all layers of the road structure. A design model that does not recognize this interdependence and the changing properties of the layers with time, traffic loading and climate is unlikely to be successful. In order to be able to deal with this complexity, an incremental procedure should be used to predict pavement deterioration. Due to this approach, changes in the pavement structure and in material properties that occur during the life of the pavement can be taken into account. The chosen design should consist of a modular framework so that the method itself could be updated as new deterioration mechanisms are included and as improved deterioration models are developed.

A mechanistic-empirical design method matches up quite well with all the above mentioned characteristics. Moving from a catalog-based to a mechanistic-based design method will benefit many groups of users. First of all, it will be beneficial for Road Policy Makers, since a better pavement design brings the assurance that the available money is spent in an optimal way, based on the understanding of the links between the level of road investment and the subsequent consequences. Also, it will be beneficial for Road Administration Engineers, since they will be able to straightforwardly compare different pavement types or materials and to assess the technical merits of alternative bids. In fact, the MEPDG will allow pavement designers to make better-informed decisions and take cost-effective advantage of new materials and features. Finally, it will be beneficial to road users and environment, too. Road users will benefit from improved pavement conditions during the whole service life of the road. In fact, a more appropriate pavement design through better input values for materials behavior and traffic will result in decreased repair needs, along with decreased traffic interruption and lower risk of accidents. The benefit for the environment, lastly, will be mainly concerning better use of existing natural resources and, marginally, reduction of fuel consumption and, thus, reduction of emission as a consequence of the reduced traffic congestion due to road work.

M-E AASHTO GUIDE FOR FLEXIBLE PAVEMENTS

Overview of flexible pavement design process

The overall design process for asphalt pavements is illustrated in figure 1. The Guide uses the term “asphalt pavement” in order to refer to any new, reconstructed or rehabilitated pavement that has an asphalt surface layer. The main steps in the design process include the following:

1. Assemble a trial design for specific site conditions and available materials—define traffic loads, climate, pavement type and design and construction features (even the pavement construction month and year, and the traffic opening month and year).
2. Establish criteria for acceptable pavement performance at the desired level of reliability at the end of the design period (i.e., acceptable levels of rutting, fatigue cracking, thermal cracking, and ride quality).
3. Process input to obtain monthly values of traffic inputs and seasonal variations of material and climatic inputs needed in the design evaluations for the entire design period.

4. Compute structural responses (stresses and strains) using multilayer elastic theory or finite element based pavement response models for each axle type and load and for each damage-calculation increment throughout the design period.
5. Calculate accumulated distress and/or damage at the end of each analysis period for the entire design period.
6. Predict key distresses at the end of each analysis period throughout the design life using the calibrated mechanistic-empirical performance models provided in the Guide.
7. Predict smoothness (IRI) as a function of initial IRI, distresses that accumulate over time, and site factors at the end of each analysis increment.
8. Evaluate the expected performance of the trial design checking if the distress and smoothness predictions meet selected criteria at the desired level of reliability.
9. If the trial design does not meet the performance criteria, modify the design and repeat the steps 3 through 8 above until the design does meet the criteria.

The designs that satisfy performance criteria are considered feasible from a structural and functional viewpoint and can be further considered for other evaluations, such as life cycle cost analysis and/or their specific constructability issues.

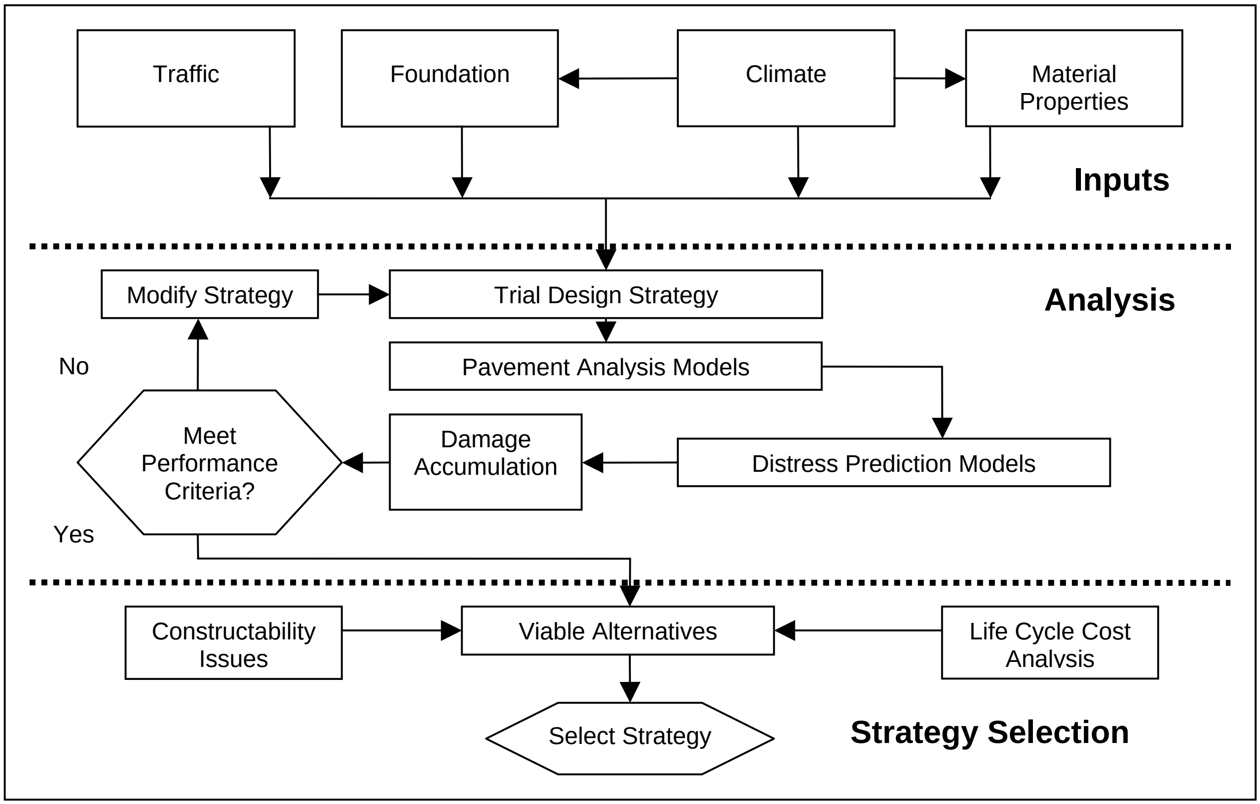


Figure 1. Overall design process for flexible pavements (NCHRP 2004c)

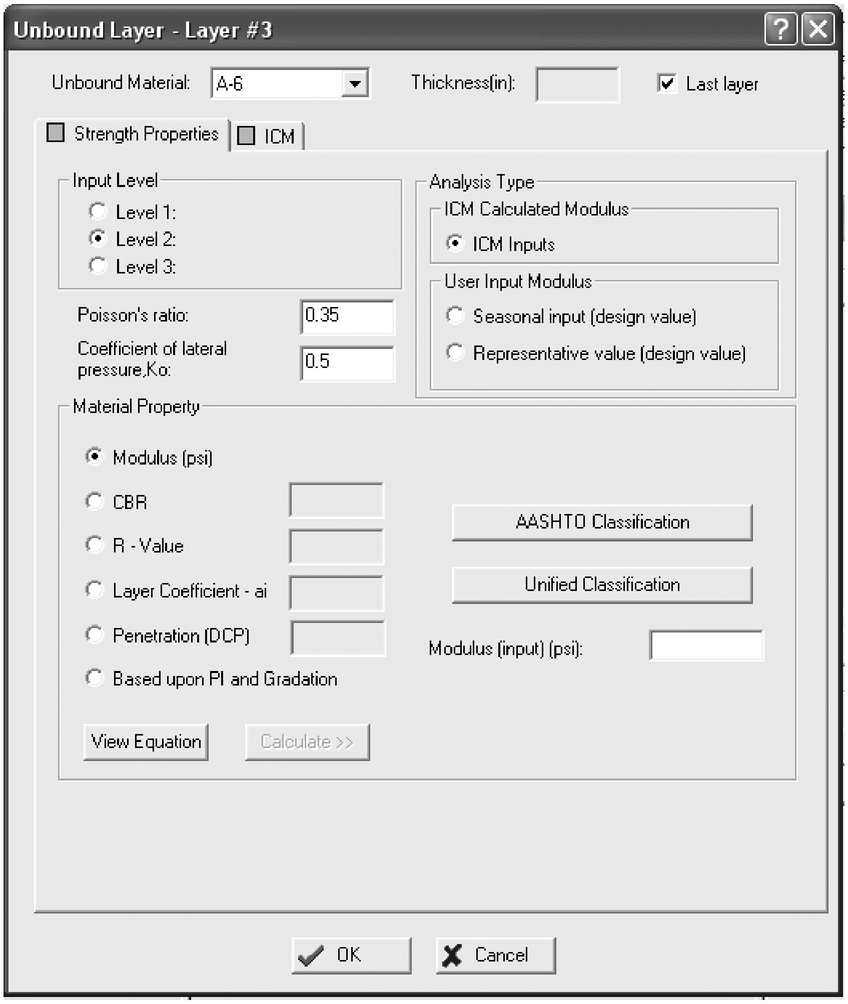
Design Inputs

Inputs for flexible pavement design include traffic (full load spectra for single, tandem, tridem, and quad axles), material and subgrade characterization, climatic factors, performance criteria, and others (NCHRP, 2004b). One of the most interesting aspects of the design procedure is its hierarchical approach, i.e. the consideration of different levels of inputs:

- Level 1 requires the engineer to obtain the most accurate design inputs. Level 1 data include material properties obtained through direct laboratory testing of the materials, measured traffic volumes and weights (such as on-site WIM data), FWD testing, etc..
- Level 2 requires testing, but use of correlations is allowed. For example, subgrade modulus can be estimated through empirical correlation with other tests, such as California Bearing Ratio (CBR) test,

Dynamic Cone Penetrometer (DCP) test, etc. **Figure 2** shows a screen shot of the Level 2 input of the MEPDG software.

- Level 3 inputs consist of estimated or default values.



Unbound Layer - Layer #3

Unbound Material: A-6

Thickness(in):

☑ Last layer

Strength Properties | ICM

Input Level
- ○ Level 1:
- ● Level 2:
- ○ Level 3:

Poisson's ratio: 0.35

Coefficient of lateral pressure,Ko: 0.5

Analysis Type

ICM Calculated Modulus
- ● ICM Inputs

User Input Modulus
- ○ Seasonal input (design value)
- ○ Representative value (design value)

Material Property
- ● Modulus (psi)
- ○ CBR
- ○ R - Value
- ○ Layer Coefficient - ai
- ○ Penetration (DCP)
- ○ Based upon PI and Gradation

AASHTO Classification

Unified Classification

Modulus (input) (psi):

View Equation | Calculate >>

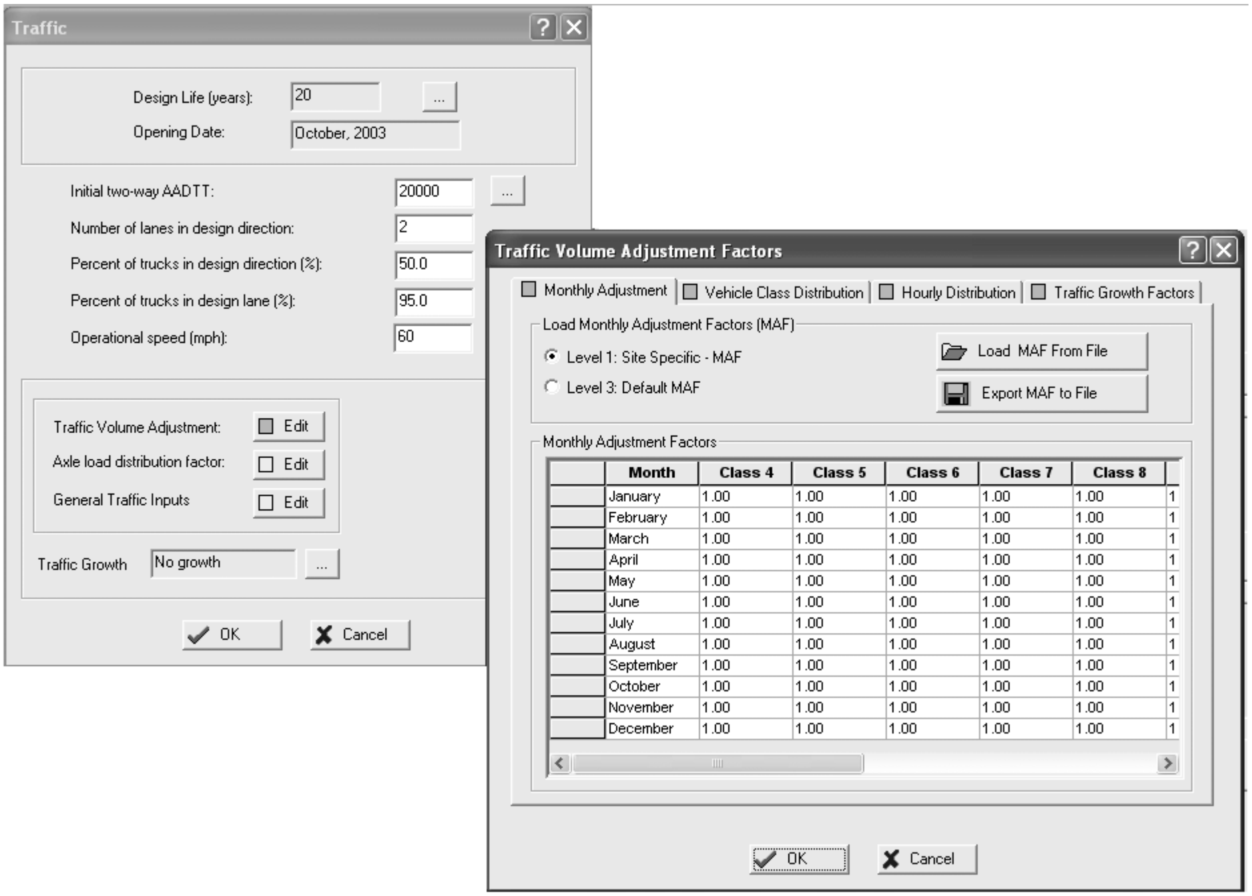
OK | Cancel

Figure 2. A screenshot of Level 2 subgrade modulus input of the MEPDG software

Required analysis inputs are summarized in **Table 1**, while **Figure 3** gives an example of traffic input.

Table 1. Summary of design factors and required inputs (NCHRP 2004b)

DESIGN FACTORS	INPUTS
TRAFFIC	• Base year traffic volume • Operational speed • Traffic directional and lane distribution factors • Vehicle class distribution • Axle load distribution factors • Axle and wheel configurations • Tire characteristics and inflation pressure • Lateral distribution factor • Traffic growth factors
CLIMATE	For computational purposes, hourly values of actual weather station data are needed over a minimum of 24 months: • Air temperature • Precipitation • Wind speed • Percentage sunshine • Relative humidity Seasonal or constant water table depth at the project site is also required
PAVEMENT STRUCTURE	Layer geometry and properties, drainage and surface characteristics



Traffic

Design Life (years): 20
Opening Date: October, 2003
Initial two-way AADTT: 20000
Number of lanes in design direction: 2
Percent of trucks in design direction (%): 50.0
Percent of trucks in design lane (%): 95.0
Operational speed (mph): 60
Traffic Volume Adjustment: ☐ Edit
Axle load distribution factor: ☐ Edit
General Traffic Inputs ☐ Edit
Traffic Growth: No growth

Traffic Volume Adjustment Factors

Load Monthly Adjustment Factors (MAF)
● Level 1: Site Specific - MAF
○ Level 3: Default MAF

Monthly Adjustment Factors

	Month	Class 4	Class 5	Class 6	Class 7	Class 8	
	January	1.00	1.00	1.00	1.00	1.00	1
	February	1.00	1.00	1.00	1.00	1.00	1
	March	1.00	1.00	1.00	1.00	1.00	1
	April	1.00	1.00	1.00	1.00	1.00	1
	May	1.00	1.00	1.00	1.00	1.00	1
	June	1.00	1.00	1.00	1.00	1.00	1
	July	1.00	1.00	1.00	1.00	1.00	1
	August	1.00	1.00	1.00	1.00	1.00	1
	September	1.00	1.00	1.00	1.00	1.00	1
	October	1.00	1.00	1.00	1.00	1.00	1
	November	1.00	1.00	1.00	1.00	1.00	1
	December	1.00	1.00	1.00	1.00	1.00	1

Figure 3. Screenshots of the traffic inputs of the MEPDG software.

Hence, Level 1 has the least error associated with inputs and Level 2 more and Level 3 the most. The input level chosen for a specific parameter, however, may have a significant effect on project design, costs and reliability.

Implementation of the M-E design guide with Level 1 inputs for all input parameters should not create any significant difficulties, but it would be impractical. To make Level 2 and Level 3 inputs applicable for the Italian conditions, the following activities should be conducted:

- Correlation between AC mix design, AC binder properties, and AC complex modulus for typical AC mixes should be developed.
- Correlations between penetration of a dynamic cone penetrometer (DCP), California Bearing Ratio (CBR), or gradation for typical Italian soils and subgrade and resilient moduli should be developed.
- Typical traffic distributions during a year should be obtained.
- Typical axle distributions for vehicle types, etc, should be evaluated.

Although these activities are quite straightforward, they are time-consuming and require significant resources.

PAVEMENT RESPONSE MODELING AND INCREMENTAL DAMAGE ACCUMULATION

Mechanistic-empirical design procedures require calculation of the critical structural responses (stresses, strains, or displacements) within the pavement layers induced by traffic and/or environmental loading. These responses are used to predict damage in the pavement system which is later related to the pavement distresses (cracking or rutting). The MEPDG uses two models to calculate critical responses for asphalt pavements:

- A Multi-layered elastic theory (MLET) program JULEA (Uzan, 1989)
- A non-linear axis-symmetric finite element program DSC-2D (Desai, 2000).

The finite element program requires the user to provide stress-strain relationships for the unbound layers (granular bases and subgrade). These relationships should be obtained from the laboratory resilient moduli tests. Therefore, the stress-dependent finite element model should be used only with Level 1 inputs. It is anticipated that for a routine analysis the MLET program will be used. This program is much more computationally efficient and requires only assignment of resilient moduli for unbound pavement layers.

The structure response model of the pavement system during the service life due to traffic loads and environment is determined using a pavement response model (NCHRP, 2000c). Inputs to the flexible pavement response are:

- Thicknesses of the pavement layers
- Material properties (moduli of elasticity and Poisson’s ratio) adjusted for age and seasonal variation
- Traffic loading (weight, wheel spacing, and axle spacing)

Since the properties of the individual pavement layers may substantially vary throughout the depth due to variation of temperature (for AC layers) or moisture (for unbound layers), the layers may be subdivided into the sublayers. This subdivision is performed by the MEPDG software transparent for the user. The adjustment of the sublayer properties is performed based on the results of the climatic analysis performed by the Enhanced Integrated Climatic Model (EICM) incorporated into the MEPDG software.

A variety of loading conditions does not permit assignment of the most critical location for which the pavement responses should be predicted. The MEPDG specifies several locations for which the responses should be computed. These responses are later used for damage computation and the point with the highest damage from all loads is later used for prediction of pavement distresses (cracking in AC layer, rutting in AC and unbound layers). Naturally, even for the AC layer, each type of distress (bottom-up cracking, top-down cracking, and rutting) will correspond to different critical point.

One of the main distinguished features of the MEPDG compare to other M-E design procedures is that MEPDG employs the incremental damage approach. This permits accounting for changing of many pavement design parameters (climatic conditions, traffic loading, material properties, etc.) over the pavement design life. For design of flexible pavements, the shortest increment is two weeks and the longest is one month.

KEY MECHANISTIC BASED DISTRESS MODELS

Four types of flexible pavement distresses are considered, using calibrated mechanistic-empirical performance models: rutting, bottom-up cracking, top-down cracking, and thermal cracking (NCHRP, 2004c).

Permanent Deformation

The MEPDG estimates the permanent deformations within all rut susceptible layers (asphalt bound and unbound layers) over the pavement design life. Using the incremental damage, the permanent deformations of each sublayer of the pavement structure is determined for each time increment. The overall permanent deformation is the sum of the deformations calculated for each individual layer, as given by the following Equation 1:

$$PD = \sum_{i=1}^{nsublayers} \varepsilon_p^i \cdot h^i \qquad \text{Eq. 1}$$

where:

PD = Permanent deformation;
nsublayers = number of sublayers;
ε^i_p = Plastic strain in sublayer i;
h^i = thickness of sublayer i.

The process is repeated for each load level, load lateral position (to account for traffic wander), and subincrement of the analysis period. Permanent deformation in asphalt mixtures is based upon laboratory repeated load permanent deformation tests, according to Equation 2:

$$\frac{\varepsilon_p}{\varepsilon_r} = \beta_{r1} \cdot k_1 10^{-3.4488} T^{\beta_{r2}\cdot *(-1.5606)} N^{\beta_{r3}*0.479244} \qquad \text{Eq. 2}$$

where:

ε_p = plastic strain cumulated at N load repetitions
ε_r = resilient strain of the asphalt material,
N = number of load repetitions
T = temperature
K_1 = function of total asphalt layer thickness and depth to computational point to correct for the confining pressure at different depths
β_{ri} = field calibration factors (equal to 1 if the US natinal calibration model is used)

The following model for prediction of permanent deformations in unbound layers was adopted:

$$\delta_a(N) = \beta_f \beta \left(\frac{\varepsilon_0}{\varepsilon_r}\right) e^{-\left(\frac{\rho}{N}\right)^{\beta}} \varepsilon_V h \qquad \text{Eq. 3}$$

where:

δ_a = permanent deformation for the sublayer
N = number of load repetitions
ε_0, β and ρ = material properties
ε_r = resilient strain imposed in laboratory test to obtain the above material properties
ε_V = vertical resilient strain as obtained from the primary creep model
β_f = field calibration factor (equal to 1 if the US natinal calibration model is used).

The MEPDG rutting model permits the user to evaluate the effect of many pavement parameters and site conditions on rutting of Ac pavements: pavement layer thickness, AS mix design, changes in asphalt modulus and hardening of the asphalt binder, monthly variations in surface and pavement temperature, moisture variations in subgrade and unbound layers, loading frequency (traffic speed), load configuration and lateral traffic wander. The model was calibrated using pavement performance data from 88 sections evaluated under the Long Term Pavement Performance (LTPP) program. The calibration ensured reasonable rutting prediction for a wide range of US climatic conditions, materials and design practices. However, the Guide recommends local calibration for individual States or regions. The MEPDG software allows the user to modify the field calibration factors β_{r1}, β_{r2}, β_{r2}, and β_f, will ensure that predictions are optimized for the local conditions. Therefore, local calibration is required to make the model applicable for the Italian conditions.

Fatigue cracking

Accumulation of micro damage after each axle pass on a bituminous pavements leads to progressive loss of stiffness and, eventually, to fatigue cracking. Repeated loads initiate cracks at critical locations in the pavement structure, i.e. the locations where the excessive tensile stresses or strains occur. The continuous action of traffic causes these cracks to propagate through the entire bound layer.

The cracks in the asphalt layer may initiate at the bottom of the layer and propagate to the top surface of the layer, or may initiate at the top surface of the asphalt layer and propagate downward. The MEPDG predicts both types of crack propagation. To account for contribution of the individual axle load applications, Miner's law is used, so that the total damage can be computed as follows:

$$D = \sum_{i=1}^{T} \frac{n_i}{N_i} \qquad \text{Eq. 4}$$

where:

D = total damage;
T = total number of period;
n_i = actual traffic for period *I;*
N_i = traffic allowed under conditions prevailing in *i;* predicted based on the Asphalt Institute model that can be expressed as:

$$N_f = \beta_{f1} \cdot k_1 \cdot C \cdot \left(\frac{1}{\varepsilon_t}\right)^{\beta_{f2}\cdot k_2} \left(\frac{1}{E}\right)^{\beta_{f3} k_3} \qquad \text{Eq. 5}$$

$$C = 10^M$$

$$M = 4.84 \cdot \left(\frac{V_a}{V_b + V_a} - 0.69\right)$$

where:

N_f = number of repetitions to fatigue cracking
ε_f = tensile strain at the critical location
E = stiffness of the material
k_i = non linear regression coefficients from laboratory tests
β_i = calibration parameters
C = laboratory to field adjustment factor
V_b = effective binder content (%)
V_a = air voids (%)

In this model, the parameter $\beta_{f1} = k'_1$ provides a correction for different asphalt layer thickness effects:

A For the bottom-up cracking

$$\beta_{f1} = k_1' = \left(0.000398 + \frac{0.003602}{1 + e^{(11.02 - 3.49 \cdot h_{AC}}}\right)^{-1} \qquad \text{Eq. 6}$$

B For the top-down cracking

$$\beta_{f1} = k_1' = \left(0.0001 + \frac{29.8442}{1 + e^{(30.544 - 5.7357 \cdot h_{AC}}}\right)^{-1} \qquad \text{Eq. 7}$$

where:

h_{AC} = total thickness of the asphalt layers

Based on the previous fatigue damage calculation, final transfer functions are used to calculate fatigue cracking. The fatigue cracking models were calibrated using data from 82 LTPP sections. Like the rutting model, the fatigue model was determined to account for the most significant factors that affect the amount of fatigue cracking within the asphalt layers of the pavement structure during the pavement service life.

Thermal cracking

The MEPDG also recognizes that in severe winter conditions thermal stresses can induce spontaneous surface cracking in the AC layer. The thermal cracking model implemented is an enhanced version of the one developed under the SHRP A-005 research contract. Prediction of the expected amount of transverse cracking in the pavement system is made according to:

$$C_f = \beta_1 \cdot N \cdot \left(\frac{\log C / h_{AC}}{\sigma} \right) \qquad \text{Eq. 8}$$

where:

C_f = amount of thermal cracking
β_1 = regression coefficient determined via field calibration
σ = standard deviation of the log of the depth of cracks in the pavement
C = crack depth
h_{AC} = thickness of asphalt layer.

The stage of stable crack growth is described by Paris's law:

$$\Delta C = A \cdot \Delta K^{n} \qquad \text{Eq. 9}$$

where:

K = stress intensity factor
A, n = fracture parameters of the asphalt mixture.

For appropriate thermal cracking prediction, time increments are automatically set in the Guide equal to one month, in order to be able to account for effect of seasonal variations of temperature and resulting variations of creep compliance and tensile strength of the asphalt mixture.

Smoothness (IRI) prediction

The IRI over the design period depends upon the initial as-constructed profile of the pavement from which the initial IRI is computed, the following development of distresses such as rutting, rut depth variance and fatigue cracking. A model was developed for flexible pavement that relates the IRI at any time to the initial as-constructed IRI and to the occurrence of the previously described distresses. The model also accounts for other distresses such as potholes or longitudinal cracking via directly introducing the potential of occurrence of such distresses while modeling smoothness. In addition, site and climatic calibration factors are considered. IRI is estimated for each time increment throughout the design period. The functional IRI model for flexible pavement is given as follows:

$$S(t) = S_0 + a_1 D(t)_1 + a_2 D(t)_2 + \ldots\ldots\ldots\ldots + a_n D(t)_n \qquad \text{Eq. 10}$$

where

$S(t)$ = pavement smoothness over time (IRI, m/km)
S_0 = initial smoothness (IRI, m/km)
a_i, b_j = regression constants
$D(t)_i$ = function of the i_{th} distress at a given time t

IMPLEMENTATION ISSUES AND RECOMMENDATIONS

The MEPDG presents a tremendous opportunity for improvement of the pavement design practices in Italy. It will provide a powerful tool able to take into account changes in traffic, materials, construction, design concept, climate and so on. However, the implementation of this Guide is not a trivial task. Any possible plan for implementation will face three challenging and interactive major issues:

- local calibration and adaptation,
- education and training, and
- acceptance by the Road Authorities.

As it was stated above, local calibration and adaptation of the performance prediction models are required to optimize the design process for Italian conditions. To conduct local calibration and adaptation, substantial volume of information should be acquired. As a minimum, the following data should be collected:

- comprehensive climatic data
- subgrade properties
- typical traffic patterns (axle configurations, axle load distributions, seasonal variations in traffic, etc.)
- properties of typical AC mixes and other constructed pavement layers
- inventory data
- pavement performance data

For each input level, a procedure or standard for obtaining each input value should be adopted. Italian construction practices, operation capabilities, and quality control are different from the US ones. Therefore, before accepting any of the default values suggested by the MEPDG for US materials, it should be determined if it is appropriate for Italian materials as well. This will require acquiring of the testing equipment and conduction of series of tests for typical Italian construction materials. If the MEPDG default values turn out not to be appropriate, they should be modified appropriately. The MEPDG software provides sufficient flexibility to modify the defaults.

After the required data are collected, the performance prediction models should be re-calibrated. The current performance models were calibrated using the LTPP database data for typical US pavement sections. Without re-calibration, these models cannot be used for prediction of pavement distresses for Italian conditions with sufficient degree of confidence. This means that in order to be able to adapt the distress models to Italian conditions, it would be necessary to fit their calibration constants on field data similar to those of the LTPP program so that the new calibration curves can generally represent expected performance of flexible pavements in Italy.

Unlike the design catalogue, which has only a limited number of input parameters and offers the designer very few options to choose from, the MEPDG requires an iterative hands-on approach by the designer. The designer must make an informed selection of a trial design and then analyze the design in detail to determine if it meets the established performance criteria. Therefore, education and training of the potential users are required to make sure that they are familiar with the principles of the mechanistic-empirical design, able to properly assign required inputs, and understand relationships between the design inputs and predicted performance. To achieve these objectives, on-site training and periodic seminars reaching the pavement engineering practitioners should be available.

Finally, the procedure should be accepted by the Italian Road Authorities (at national, regional and municipal level) as an official design procedure for all major pavement projects. This will ensure the highest impact of the procedure and will provide substantial benefit for the public by optimizing pavement design and, consequently, public investment in the infrastructure.

CONCLUSIONS

During the last few decades Italy has been paying an increased attention to developing more analytical design methods for pavement systems. However, presently, the only official pavement design method in Italy is the Catalog developed in 1993. This catalogue provides a series of typical pavement design solution for a standard mix of traffic. Though based on analytical models, all the calculations for the Catalog for flexible pavement solutions are carried out with reference to hypothetical average conditions (especially the climatic and the traffic-related ones), considering only a limited range of materials and possible pavement structures.

The ever growing requirements for optimising the use of locally available natural resources, as well as specific construction needs, make it necessary to have at one’s disposal a more flexible design tool than the Catalog-based ones, such as, for example, a mechanistic design procedure, with incremental approach to the design life of the pavement (as far as damage accumulation is concerned).

Specific advantages of M-E design over traditional procedures are:
- consideration of changing load types;
- better utilization and characterization of available materials;
- the existing pavement layer properties to be better defined;
- accommodation of environmental and aging effect of materials;
- the role of construction to be better defined;

- improved performance predictions;
- material properties to be related to actual pavement performance.

Various issues have to be taken into account when moving to a mechanistic-empirical design approach, such as those regarding the acquisition of comprehensive and accurate information and calibration/validation of the predictive models to Italian conditions.

The 2002 AASHTO Design Guide described in this paper does exemplify very well the needed integrated analysis approach that is necessary for achieving all the above mentioned advantages in pavement design.

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