Mechanistic-empirical pavement design guide: features and distinctive elements

Mechanistic-empirical pavement design guide: características y elementos distintivos

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Abstract

This paper is aimed at describing the most distinctive features of the pavement design method known as Mechanistic-Empirical Pavement Design Guide and to compare it with other renowned methodologies, while emphasizing its advantages and disadvantages. The MEPDG can accurately predict damage evolution, thus helping to choose the most appropriate design for new pavements or to schedule the conservation of the already existing ones. After analyzing different pavement design and management methods, the MEPDG stands out as the most comprehensive one as it takes into account and properly combines the greatest number of factors that affect the pavement. Therefore, some countries outside the USA have already imported and calibrated this method, what, at the same time, allows the scientific community to carry out comparative studies and improve its small deficiencies.

Keywords: Pavement, design, management, incremental damage, optimization

Resumen

El objetivo de este artículo es describir los rasgos más característicos del método de diseño de firmes conocido como Mechanistic-Empirical Pavement Design Guide, así como compararlo con otras metodologías de renombre, destacando sus ventajas y desventajas. El MEPDG puede predecir con precisión la evolución de los deterioros, ayudando por tanto a elegir el diseño más adecuado para el caso de firmes de nueva construcción, o a programar la conservación de los ya existentes. Tras analizar diferentes métodos de diseño y gestión de firmes, el MEPDG destaca como el más completo al ser el que tiene en cuenta un mayor número de factores que afectan al firme. Por ello algunos países fuera de EEUU ya han importado y calibrado este método, lo que al mismo tiempo permite a la comunidad científica llevar a cabo estudios comparativos y mejorar sus pequeñas deficiencias.

Palabras Claves: Pavimentos, diseño, administración, daño incremental, optimización.

Introduction.

Pavement design constitutes one of the essential aspects of any road, not only because it is directly related to its functionality and users' safety, but also because of its cost-related implications. The existence of new materials and production methods, as well as the new requirements that current traffic imposes, make necessary the development of innovative methods for the design of road pavement structural sections or for the management of the already constructed ones. Most of the methods used to date only take into account a small part of the parameters that affect pavement throughout its useful life. Thus, certain designs are therefore accepted without considering other possibilities that could provide a more desirable response to external loads and better recoup the allocated investment. The innovative and comprehensive design method known as Mechanistic-Empirical Pavement Design Guide (MEPDG) has been developed in the United States to change this trend. It also allows the user to predict the evolution of existing pavements, what helps to propose actions to extend their useful life and to avoid failures otherwise unexpected. This paper discusses the advantages of this method, studies its most distinctive features and analyzes its differences with respect to other methodologies of pavement design or management, especially comprehensive in the case of the HDM-IV, and mainly focusing on the case of flexible pavements. It also highlights those aspects in which the MEPDG could be further improved.

Background.

Until the mid-20th century, American engineers designed pavements simply on the basis of their experience. This procedure started in 1950, when the American Association of State Highway Officials (AASHO) deliberately carried out various tests on a track in Ottawa, Illinois. By using regression models, they developed empirical equations based on the results, which were compiled in the AASHTO Guide for the Design of Pavement Structures in 1993 (AASHTO, 1993). As time passed, it was noticed that this purely empirical design system could not handle new traffics (about 30 times higher), new materials or boundary conditions of other regions. The lack of accuracy in the designs led to the expenditure of more than $20 billion per year to improve the national pavement network (Ali, 2005).In addition to this method and other merely empirical procedures, diverse analytical design methods have been developed since 1940. The pavement is modeled as a multilayer structure whose layers show a certain behavior (linear–elastic, plastic, linear or nonlinear-viscoelastic, etc.) assigned in accordance with their nature. These methods predict the response of each layer depending on traffic loads and some factors related to climate. They first calculate the stresses, strains and displacements to which pavement will be subjected. Then, by means of the numerical resolution of a series of equations based on the multilayer theory (Burmister, 1945), they determine the number of applications of the pattern load that the structure can bear until failure. Commercial programs such as Alize, Kenlayer, Chevron, Elsym, Bisar, etc. are based on these models. Among analytical or rational methods there are some which use finite elements and others which utilize finite differences, such as Axidin, Abaqus, Cesar, Michpave, Nottingham, etc.

The problem is that the expected results derived from the individual application of empirical or analytical methods do not always agree with those obtained in the field. That is the reason why the MEPDG was developed between 1996 and 2004 (with its subsequent revisions) in the frame of the American National Cooperative Highway Research Program (NCHRP Project 1-37A). It includes a guide to carry out the design and the mechanistic–empirical analysis, the software (DARWinME) with its corresponding manual and additional documentation

about materials, climatic models, etc. The MEPDG is already in use outside the borders of the USA, mainly in Canada and South American countries.

Method distinctive features.

The singular characteristics of the aforementioned method are briefly exposed in the following sections. Figure 1 summarizes its scope.

Figure 1. Scope of the MEPDG (Source: own elaboration).
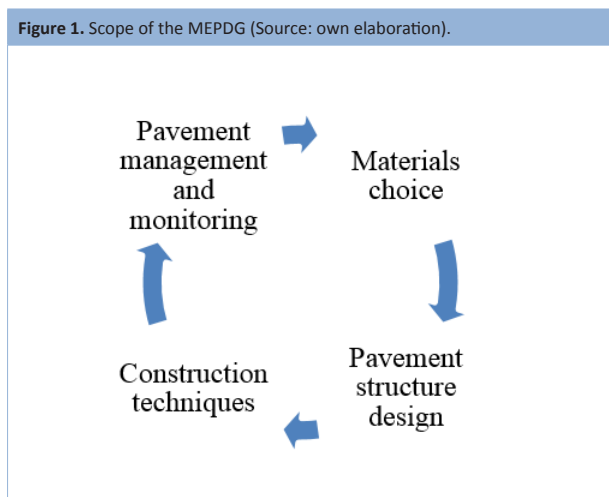
Input and output data.

The great variety of input data accepted by the program shows the accuracy that it is possible to achieve, providing that these inputs have been correctly and expressly obtained. No other method processes such an amount of data simultaneously (Momin, 2011). The main inputs for flexible pavements are the following. a) Related to traffic: *annual volumes:* two-way annual average daily truck traffic volume, number of vehicles in the same direction, % of trucks in the design direction, % of trucks in the design lane, operational speed, design speed (if operational speed is not available). *adjustment factors:* monthly adjustment factor, vehicle class, hourly distribution of trucks, traffic growth. *loads / axle:* single, tandem, tridem, quadruple. *general data:* mean wheel location, truck wander, design lane width, number of axles per truck, axle configuration, tire pressure, wheel spacing, axle spacing, average axle width. b) Related to climate: temperatures, wind speed, cloudiness, precipitation, relative humidity. c) Related to materials: *unbound layers and subgrade materials:* classification, volumetric properties, seasonally adjusted resilient modulus, coefficient of lateral pressure, plasticity index, gradation, dry density, unit weight, Poisson's ratio, optimum moisture content, Atterberg limits, soil water characteristic curve. *bedrock:* classification, elastic modulus. *bituminous mixture:* dynamic modulus (depending on temperature and load frequency), creep compliance, indirect tensile strength, volumetric properties, reference temperature, complete cha- racterization of binder, unit weight, Poisson's ratio, thermal conductivity, heat capacity, surface shortwave absorptivity.

Besides, a huge amount of output values are also provided (Table 1). Instead of the thickness of the layers (provided through the structural number in the former AASHTO), the MEDPG supplies damage predictions. They are obtained by calculating the stresses and the incremental strains throughout the useful life of the pavement and transforming them into modes of failure by means of transfer mathematical-empi-

rical functions. The values provided must be compared with those considered as thresholds (Table 1) in order to accept or refuse the initial design. The IRI (International Roughness Index) is considered a key element with regard to functionality and safety (Li et al., 2011; Baus et al., 2010).Other analytical or finite elements programs also provide information about the expected damage, but only on the basis of merely theoretical information and, therefore, with less accuracy.

Table 1. Main outputs of the MEPDG for flexible pavements and threshold recommended values (Source: own elaboration).

BEHAVIOR CRITERIA	ROAD TYPES	USA UNITS	VALUE	SI UNITS	VALUE
Alligator cracking	Interstate	% of lane area	10	% of lane area	10
	Primary		20		20
	Secondary		35		35
Permanent deformation	Interstate	inches (in)	0.40	cm	1.02
	Primary		0.50		1.27
	With s< 45 mph (72.5 Km/h)		0.65		1.65
Longitudinal cracking	Interstate	feet/mile (ft/mile)	500	m/Km	94.70
	Primary		700		132.58
	Secondary		700		132.58
Transverse cracking	Interstate	feet/mile (ft/mile)	500	m/Km	94.70
	Primary		700		132.58
	Secondary		700		132.58
IRI	Interstate	inches/mile (in/mile)	160	m/Km	2.53
	Primary		200		3.16
	Secondary		200		3.16

Accuracy levels of the analysis.

The MEPDG allows the user to work with three different levels of accuracy depending on the road requirements, the economic capacity and, even, the deadline of the design. In practice, the choice of one or another level necessarily involves calculating a higher or a smaller number of inputs. That is the reason why the accuracy of the predictions will be different in spite of the fact that the response models are identical at all levels (AASHTO, 2008):

Level 1: the most precise and, therefore, the most reliable. It is used in the case of heavily trafficked highways or for the analysis of areas with high level of distresses or serious safety problems. It approximately requires 100 inputs. Data of materials is obtained from tests; traffic data from gauging stations and "weigh in motion" (WIM) systems (specialized sensors); climate inputs from meteorological stations, etc.

Level 2: intermediate level of accuracy. The most commonly used for ordinary design. It uses data from official agencies, empirical correlations or estimates to determine the required inputs. For example, traffic inputs are estimated based on official data and the dynamic modulus based on results of tests performed to binder and aggregates or on other mechanical properties of the mix.

Level 3: the least precise. It is used for the design of roads with low traffic or to analyze roads in which safety is not compromised. Data is selected among existing default values at a national or regional level. Thus, mixes are characterized with the general physical properties they are supposed to have with regard to their type and binder. The expected traffic loads on a road with the same category are also considered in this case.

Load spectra of traffic input.

The load spectra is introduced into the program by creating a series of spreadsheets, in which the different types of vehicles (according to the official classification of the Federal Highway Administration and without taking into account two-wheel drives, private cars or vans) are placed in rows for each month of the year. Axle types are indicated in the columns. Thus, the cells contain the percentage of axles of each category for each group of vehicles and month. Several computer programs (e.g. Trafload, PrepMe, etc.) have been designed to receive the information and convert it into the format the MEPDG needs. The number of applications of each type of axle and its corresponding load increase are used to calculate the pavement response and to predict damages and failures. Data such as wheel spacing, tire type, pressure, etc. is also included. Another key factor related to traffic is the variation in its distribution per lane, which is supposed to show a normal probability. Vehicle speed is also very important, since it directly affects the response of layers with viscoelastic materials.

Dynamic modulus master curves of asphalt mixtures

The MEPDG allows the user to work with the dynamic modulus IE*I master curves of bituminous mixes in order to take into account the influence of both the load frequency and the temperature of the response of the pavement. The DARwinME uses master curves in the permanent deformation and fatigue cracking prediction models. At present, the software is able to build these curves itself from information introduced by the user. The designer must perform the necessary tests to calculate the value of the IE*I at up to 8 temperatures and 6 different load frequencies (5x4 values are usually enough). The software is also capable of estimating the curves from inputs of materials (aggregates gradation, bitumen grade and volumetric properties of the mixture). This last option should only be chosen as a last resort, since it negatively affects accuracy.

Climate

Climate changes have a great influence in the behavior of pavements. They significantly affect the properties of their materials and, therefore, their strength, durability and ability to bear loads. The MEPDG includes the EICM (Enhanced Integrated Climatic Model), which simulates the changes in the behavior and characteristics of the pavement and its underlying materials due to climatic variations (Zapata et al., 2008). Its 3 differentiated modules are (Ali, 2005):

The CMS (Climatic Material Structural Model) is an advanced finite differences program that calculates the temperature and moisture profiles of the pavement, as well as the strength properties of its materials. The FHTS (Frost Heave and Thaw Settlement Model) uses the results of the CMS to evaluate the considerable effect of freeze-thaw cycles (Lytton et al., 2012). The ID (Infiltration and Drainage model) analyzes, based on the assumption that pavement foundations are permeable, water infiltration through hollows or cracks and its related consequences. The user must specify the project location and choose a climate file among those stored in the EICM's database (elaborated from data of 800 meteorological stations around the USA) or interpolate them to create a specific virtual meteorological station. Since the MEPDG predicts the long-term behavior of pavements, it is advisable to randomly verify some of the results obtained by these models by using any other climate forecasting method (Johanneck, 2011).

LTPP Database

The Long Term Pavement Performance Database (LTPP, Figure 2.) constitutes one of the most important strengths of this method. It is the best data source of the field behavior of practically all the existing types of pavements under different load conditions, with different subgrades and foundations and in very diverse climatic zones. It has been created from general pavement studies (GPS), but also from specific pavement studies (SPS), expressly built to obtain some kind of information. Their combination allows the user to rely on data of more than 2,500 test sections, which are periodically updated and revised (Momin, 2011). Despite the power of this database, the accuracy of the results depends on the possibility of obtaining precise additional information of the construction area.

Figure 2. Screen shot from the LTTP Website (Source: FHWA)

Pavement structural models

The MEPDG incorporates two models for the calculation of stresses and strains in the bituminous layers, the base, the subbase and the top of the subgrade of flexible pavements. The elastic-linear multilayer Jacob Uzan Layered Elastic Analysis (JULEA) model assumes that each layer is homogeneous, has a finite thickness (except the subgrade) and is isotropic. It also supposes that there is total adherence among the layers, but that there is not any shear force on the surface. For its part, the two-dimensional finite elements Disturbed State Concept (DSC2D) model, only available at the first level of accuracy, takes into account the nonlinear behavior of unbound materials.

Distress models.

As mentioned, the critical values of stresses and strains obtained by the structural response models are turned into predictions of incremental damage by means of transfer functions included in the software. These models are calibrated by using information from existing pavements (LTPP or regional data) in the case of new construction roads or from already constructed roads in the case of conservation or rehabilitation activities. The MEPDG is the first design procedure with the ability to predict the accumulated damage in monthly periods (even fortnightly, although it is less usual) throughout the whole design period of the pavement. Therefore, the representative modules of bituminous mixtures in each monthly period are used and the progressive aging of materials is taken into account at the moment of predicting the evolution of an existing pavement (Li et. at., 2011). The four models for the case of flexible pavements are summarized below.

Rutting

The MEPDG predicts the permanent deformation of each layer as a function of time and traffic, but also bearing in mind other factors such as temperature and moisture. The structural model calculates vertical deformation at any depth assuming elastic properties for the material (εr). From that point on, it predicts plastic deformation with the empirical Equation 1 explained below:

$$\Delta p = \varepsilon_p h = \beta_{1r} k_z \varepsilon_r 10^{k_1 r} n^{k_2 r \beta_{2r}} T^{k_3 r \beta_{3r}} \qquad (1)$$

Where:

Δp: Deformation in the layer (in)

ε_p: Accumulated permanent vertical deformation in the layer (in.)

ε_r: Resilient or elastic strain calculated by the JULEA at the middle-depth of each layer (in. / in.)

h: Layer thickness (in.)

n: Number of axle load repetitions

It evaluates the rutting of each layer and, also, of the complete pavement structure taking into account the resilient modulus of the granular or stabilized layers.

Fatigue cracking

Repeated traffic loads cause shear and tensile stresses in the pavement. The MEPDG uses the following Equation 2 as a starting point to calculate cracks.
After calculating Nf, damage is estimated by using the Miner's law. Then, two empirical transfer functions are applied to convert mechanical damage into distresses (top-down and bottom-up cracking).

$$N_f = 0.00342 k_{f1} C k'_1 \beta_{f1} \left(\frac{1}{\varepsilon_t}\right)^{k_{f2}\beta_{f2}} \left(\frac{1}{E^*}\right)^{k_{f3}\beta_{f3}} \qquad (2)$$

Where:

N_f: number of repetitions up to fatigue cracking
ε_t: tensile strain at critical location (in./in)
E^*: stiffness of the material (psi. - 1psi=6.9 KPa)
$k_{f1,f2,f3}$: adjustment factors obtained after calibration with LTPP global data
$\beta_{f1,f2,f3}$: adjustment factors obtained after calibration with local data from LTPP or from other sources
k'_1: thickness adjustment according to load and cracking type
C: adjustment laboratory-field factor , which depends on the volumetric characteristics of the mix

Thermal transverse cracking

Thermal cracking is caused by the fragility the pavement acquires due to the decrease of temperature or to thermal fatigue. These cracks start on the surface of the structure and spread down to the lowest layer through the different thermal cycles following the Paris' law.
Before its use, the MEPDG predicts the expected amount of transverse cracking by relating the crack depth to its frequency by means of Equation 3.
The indirect tensile characterization of the mixture (AASHTO T322) is necessary to measure its creep compliance and its strength.

$$C_f = \beta_{t1} N(z) \frac{1}{\sigma} log\left(\frac{C_d}{h_{ac}}\right) \qquad (3)$$

Where:

C_f: observed amount of thermal cracking (ft/mile)

β_{t1}: regression coefficient determined through global field calibration from LTPP data

σ: standard deviation of the log of the depth of cracks (normal distribution) in the pavement (in)

$N(z)$: standard normal distribution evaluated at the particular position z.

C_d: crack depth (in)

h_{ac}: thickness of the pavement layers (in)

Roughness

Roughness is the parameter that best defines the quality of the rolling of a pavement, since a road with irregularities on its surface may lead to vibrations in vehicles and, therefore, to inconveniences and dangers to users. The MEPDG adopts the IRI as a measure of this irregularity. Its initial value introduced in the program changes throughout the design period according to the loads borne by the pavement, the local conditions and possible maintenance activities. Other types of damage such as potholes, longitudinal cracks, etc., may also be taken into account.

The MEPDG predicts the IRI's evolution depending on its initial value (usually from 50 to 100 inches per mile -0.79 m/Km- for new construction roads), on fatigue and transverse cracking, and on local factors (calculated according to the age of the pavement, the climatic information and the plasticity index of the area), as Equation 4 indicates. There are three models to calculate its evolution in accordance with the nature of the base and subbase courses.

$$IRI = IRI_0 + 0.0150 SF + 0.4000 FC_{total} + 0.0080 TC + 40.0 TC \qquad (4)$$

Where:

IRI_0 : immediate initial IRI after construction, or default value if they are not constructed yet

SF: local factor

FC_{total} : percentage of the total lane area subjected to fatigue cracking (considering alligator, longitudinal and reflection cracking in the wheel path). All loads related to longitudinal cracks are multiplied by 1 foot (30.48 cm) to work on an area basis.

TC: lenght of transv. cracking, including reflection of transv. cracks in existing pavements (ft/mile)

RD: average ruth depth (in)

Reliability

The design of flexible pavements depends on many factors that provide great variability, such as traffic levels, the properties of materials, the quality of the construction or the accuracy of the models. In the context of the MEPDG, reliability is defined as the probability that the pavement structure behaves satisfactorily during its design period. A series of values for the possible types of damage are defined, and they must not be exceeded. The AASHTO recommends adopting those values included in Table 1.
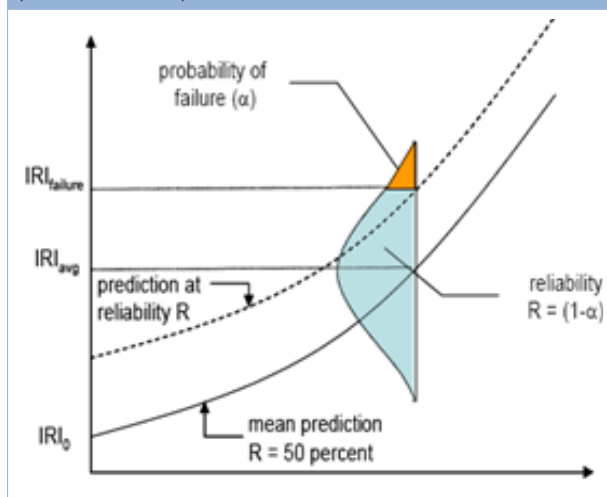
The necessary reliability level is established for each of the key deteriorations that pavement can suffer depending on the functional classification of the road, as well as on its rural or urban location. Supposing that the probability of each damage and of the evolution of the IRI follow a normal distribution (Figure 3, Li et al., 2011), their value for the wanted reliability level can be calculated with Equation 5 once its particular representative function (made on the basis of local calibration data) has been obtained. By default, the software provides, for each design proof, a prediction based on average or usual values for all inputs, which correspond to 50% of reliability. The designer usually demands a higher reliability level so that the pavement fulfills the expected requirements throughout its useful life (Timm et al., 2007).

$$DET_R = DET_M + DET_{STDC} \; x \; Z_R \qquad (5)$$

Where:

DET_R: amount of damage considering reliability R

DET_M: average value of damage for 50% of reliability, on the basis of average data

DET_{STDC}: standard deviation from the distribution function of the damage, calculated from local calibration

Z_R: standard normal deviation corresponding to reliability level R

Considerations about the method: Future challenges

In spite of the potential of the MEPDG, it is expected that later versions correct some of its deficiencies:The program does not consider bituminous mixes as viscoelastic materials, thus simplifying their behavior as linear elastic and preventing them from characterizing the time-frequency-temperature dependence of their response. Therefore, it leads to less precise predictions at high temperatures and low load frequencies.

The load spectra definition only allows them to be modeled as static. The contact area between the tire and the pavement is simplified to a circular one. Therefore, a uniformly distributed pressure is used in calculations, what would produce less damage than the actually existing one (Im et al., 2012). The

consideration of dynamic loads and 3D contacts would definitely add certainty to the results.

The different models allow the system to consider the existence or lack of adherence between layers, but not to quantify it. Neither the influence of tack nor the penetration prime coats are considered.The same mathematical model is used at all levels of accuracy to impose the desired reliability level, what does not actually make too much sense. This model is also the same for all the states, so the influence of factors such as their particular regulations, constructive technologies or quality control methods is not taken into account.

The EICM's temperature and moisture calculation models for the different pavement layers would also need further improvement. They require too many inputs that, in most cases, must be poorly estimated. In addition, parameters related to climate change should also be included.Most of the differences found between the damage predictions provided by this method and the field values are due to mistakes in the initial traffic inputs. The employment of WIM systems requires a previous check of the information. This examination is incorporated to the LTPP in 12 steps, but its sequence, established in 1990, should also be checked and calibrated (Li et at., 2011).

The local calibration of data is fundamental throughout the whole method (Delgadillo, 2011). This makes the import of the MEPDG into other countries quite difficult, since the use of some good and updated databases, which do not always exist, would also be needed.The software does not allow the inclusion of conservation plans, which influence the evolution of pavements and should be taken into account when making predictions.

It is necessary to study in depth how sensible the results provided by the MEPDG are in order to establish the degree of certainty of each input. This would allow the user, in case of experiencing difficulties to obtain data, to simply focus on the most influential ones. Generally speaking, the climatic data, load spectra, dynamic modulus, strength and creep compliance of the bituminous mixes, as well as the resilient modulus of the subgrade, are very influential parameters (Li et at., 2011). For example, outputs like the IRI are closely linked to traffic and permanent deformation strongly depends on the thickness of the layer and on heavy traffic volumes, whereas cracking is much more complex and depends on many more parameters (Bayomi et al., 2012). The NCHRP project 1-47 (TRB, 2011) has partially studied this aspect. However, an analysis using local pavement structures, materials, climate and traffic data would be also desirable.

Comparison of the MEPDG with other existing design methods.

According to the statements in sections 2 and 3, the MEPDG has unquestionable advantages over the traditional American method (AASHTO Guides from 1993) and its exclusively empirical nature. The MEPDG and its auxiliary elements (LTPP, EICM, etc.) were designed to correct its multiple deficiencies. With regard to the traditional analytical methods based on the multi-layer theory, one of their main handicaps is that they barely include calibration data to adapt mathematical models to a particular study, what adds certain degree of inaccuracy. Another disadvantage is that they do not have a climate database but they simply allow the user to establish seasonal values for a few inputs.

Some of them base the study of traffic on the idea of equivalent single axles loads (e.g.: Alize, Lady), whereas others which are more evolved allow the user to define these loads (e.g.: Kenlayer, Michpave). Most of them do not take into account the viscoelasticity of bituminous materials (e.g.: Bisar, Nottingham), although some of them already include this aspect (e.g.: Kenlayer, Veroad). However, the great majority is only able to estimate the useful life of a certain pavement instead of making incremental calculations of the deteriorations which fit the inputs according to their evolution throughout very short time periods, as it is the case of the MEPDG. None of them consider either the evolution of the IRI or the thermal cracking. They do not include several levels of analysis with different degrees of accuracy and it is not possible to set up particular reliability levels for the outputs. For their part, finite elements methods, as those of finite differences, improve the MEPDG in some aspects, but not the whole procedure.

A notable improvement is the fact that these methods take into account the viscoelastic behavior of bituminous materials and, therefore, the dependence of their response to temperature and load frequency. In addition, they model the pavement as a three-dimensional structure, what allows the program, for example, to take discontinuities into account. The footprint of the tires is also represented in 3D, thus considering the real distribution of pressures under them, which the MEPDG simplifies to uniform. However, these methods have considerable disadvantages. First of all, their use is usually very complex for designers who are not experts in programming.

Secondly, their outputs depend on the density of the mesh designed in the modeling. If it is slightly dense, the numerical solution usually turns out to be rather inaccurate, as it has been proven by field data. If it is very dense, it is possible to predict the space-temporary variation of stresses and strains, but the computational costs and the time needed for the calculations are excessive. A habitual procedure is to calculate the deteriorations caused by a certain number of load cycles and to extrapolate them to the total useful life of the pavement, thus definitely leading to a high degree of uncertainty (Im et al., 2012). In addition, these types of methods are not usually related to empirical calibration data or, if that is the case, they are linked to a lesser extent than with the MEPDG. Besides, they do not take into account the steady variation in the properties of the materials caused by climate effects or because of accumulated damage or, at the most, they do it every long periods of time.

Finally, it is necessary to emphasize that most of the models of finite elements only take into account the energy dissipation due to the viscoelastic nature of bituminous mixes, i.e., they consider some deteriorations as rutting or fatigue cracking, but not thermal cracking. None of them include roughness predictions. As the previous methods, they do not have different levels of accuracy to carry out the analysis and it is not possible to set up particular levels of reliability for the outputs. Other simpler design methods, such as catalogues of sections or nomograms, only work well if they are used in the same boundary conditions (loads, materials, etc.) as those in which they were created and do not allow the program to optimize the pavement structure because they cannot predict deteriorations.

The MEPDG is not the only mechanistic-empirical method that exists, but it is the most comprehensive. Other examples could be the HIPAVE, which has quite satisfactory results, although it was mainly thought to design industrial pavements (Pradena et al., 2009), or the CALME, developed in California by Caltrans and focused at its first stage on the prediction of permanent deformation. In this software, mechanistic-empirical modeling is based on a linear elastic multi-layer theory whose results are used in permanent deformation distress functions. An incremental analysis of damage is carried out and the results of each increment are used in the analysis of the next increment. Only in this particular sense it even improves the functioning of the MEPDG, as it is an incremental-recursive model (Ullidtz et al., 2010).

It must be highlighted that this paper is focused on the analysis of flexible pavements with bituminous mixes (hot, cold, warm or half-warm, either recycled or not), but the accuracy of the method in the study of unbounded, stabilized or concrete layers, etc., is undeniable, what represents another advantage with regard to the rest of methodologies. In addition, most of the previous methods are only suitable for the design of new pavements and not for predicting the evolution of those already constructed. Taking into account that the current context turns road conservation into one of the main activities of the construction industry, the choice of the MEPDG instead of other programs is widely defended. Table 2 contains in rough outlines a comparison among the aforementioned methods and the MEPDG.

Comparison of the MEPDG with pavement management methods. The particular case of the HDM-IV.

Pavement management software and the MEPDG are tools designed with very different aims, but it is not infrequent to use them in a complementary way for some studies. The HDM-IV (Highway Development and Management Model IV) has been chosen for the analysis because it is the most powerful and worldwide used program for pavement management and analysis of investments. It was designed by the Massachusetts Technological Institute (MIT) after a project undertaken by several American and English associations, on initiative of the World Bank. To sum up, it is possible to affirm that the main objective of the MEPDG is to predict the deteriorations of pavement (already constructed or not) throughout its useful life, whereas that of the HDM-IV is to make a life cycle analysis of different pavement (usually already constructed) maintenance alternatives. The HDM-IV can predict pavement damages, program advisable maintenance treatments, estimate the global costs allocated to the aforementioned pavement, choose the most suitable way of distributing the budget allocated to a project or to the whole net of roads, and another wide range of special uses (Núñez et al., 2005).

Its tools of economic analysis are powerful, but its main problem resides in its eminently empirical nature that requires a solid database, which is normally not available. Its efficiency is very dependent on the degree of accuracy with which numerous factors are known, such as the structural design of the roads, the nature and initial state of the materials, the constructive techniques, the traffic, the operating costs, the climate, the maintenance actions, etc. Therefore, in order to use this program successfully, its models must be calibrated with a great amount of local data (Li, 2004).

The analytical frame of the program is based on the concept of pavement life cycle analysis, which usually lasts between 15 and 40 years. This analysis includes four principal stages: road deterioration prediction, effects of maintenance or rehabilitation actions, consequences of the state of the road for its users (operating costs of vehicles, travel times, costs due to accidents, etc.) and environmental and socioeconomic effects. Therefore, it is in the first stage where it shows a clear link with the MEPDG.

Conclusions

The models that the HDM-IV uses to calculate the evolution of deteriorations combine theory-based mechanical models with the experimental ones developed from behaviors observed in empirical studies. The main inputs of the HDM-IV 's distresses prediction model for flexible pavements are followings. *Referencing:* road location. *Materials:* materials included in the pavement, pavement layers, initial general condition and damage initial level, age. *Structural capacity:* adjusted structural number (SNP). Based on the structural number of the former AASHTO design method, in which a structural coefficient is assigned to each layer. This coefficient represents the contribution of the layer to the behavior of the pavement. The SNP inserts an adjustment factor depending on the depth of the layer. *Construction quality:* relative compaction among the base course, the subbase and the subgrade, construction faults of the wearing course and effective binder content and rigidity of this layer, construction faults of the base course. *Completed actions:* conservation, rehabilitation. *Drainage:* drainage rehabilitation, initial condition. *Environmental conditions that prevail in the region:* temperature, precipitation, moisture. *Traffic:* traffic volumes, hourly distribution of traffic volume, composition, growth rate, axle load, equivalent single axle load, capacity, capacity-speed relationships.

Regarding the outputs, the main provided by the HDM-IV 's distresses prediction model for flexible pavements are the followings. *Structural cracking:* total % of the carriageway area. *Thermal cracking:* total % of the carriageway area. *Aggregate leakage:* because of stripping (from the base) or raveling (from the surface), total % of the carriageway area. *Potholes:* cavities on the road surface with an average diameter equal or bigger than 150 mm and at least 25 mm deep (it is calculated on the basis of the cracking and leakage results obtained), number of potholes within an area of 0.1 m2 /km. *Edges breaking:* on roads with a narrow carriageway (< 7.5 m), loss of materials in m2/km. *Rutting:* annual evolution, rut depth in mm. *Roughness:* annual evolution, IRI in m/km. *Macro and microtexture:* macrotexture (mm), microtexture (punctual and transversal friction coefficients).

It is noticed that most of the results that the HDM-IV provides initially agree with those that the MEPDG shows, although there are evident differences: a) The type of inputs needed by the HDM-IV is much simpler than those that the MEPDG demands. The main variables are: traffic, age of the pavement, climate and structural resistance (Pradera, 2008). b) These inputs usually come from very general databases and do not often agree with those who really exist in the area of analysis. The program does not have, as the MEPDG does, specific databases (LTPP, EICM). In any case, the best option always resides in obtaining empirical particular data for the calibration of the models. But even in this scenario, the HDM-IV is not oriented to the accomplishment of laboratory tests, but only to obtain field data. c) The HDM-IV relies on a modified structural number, which is not accurate enough to define the structural capacity of the pavement. d) Besides, the number of traffic inputs is lower and most of them still rely on the ESAL's concept (equivalent simple axle loads). d) The monitoring of the evolution of deteriorations is made on a year basis instead of monthly (or fortnightly). e) A deeper analysis of the HDM-IV goes beyond the purpose of this paper. The disadvantages that it could have in contrast to the MEPDG do not imply that it is not a good program. Simply, the designer must be aware of what he is looking for.

After the analysis of the different existing pavement design methods, it can be concluded that the mechanistic-empirical method called MEPDG is the most complete tool that exists at present in this regard. It allows the user not only to design new pavements, but also to schedule the maintenance of roads in service. It brings together well constructed mathematical models with a huge amount of empirical data that practically includes all the cases which a designer must face. It is able to predict the usual types of pavement damage throughout their useful life with a level of reliability chosen by the user. In addition, the calculation of these deteriorations is incrementally made on the basis of very discretized time periods. The update of inputs in each iteration leads to very precise results.

The MEPDG has already evolved from its first version up to now in order to improve some particular aspects in which other methods have overcome it. Some additional changes must still be made such as the consideration of the viscoelastic behavior of flexible layers or the exact footprints of tires. As it has been already pointed out, a lot of studies support the degree of certainty of its predictions.

Some pavement management programs are also able to predict the evolution of deteriorations, such as the HDM-IV. Nevertheless, this is not its ultimate purpose and, therefore, their results are often less precise than those of design programs and, particularly, than those provided by the MEPDG. It is advisable and quite frequent in the USA to use the MEPDG as a complementary tool to the aforementioned management systems in order to improve predictions and reach optimization.

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COMPARISON AMONG THE MEPDG AND OTHER METHODS			
COMPARED PARAMETER	AASHTO 1993	MEPDG	OTHER
SUPPORT			
Paper documentation	yes	yes	few
User friendly software	yes	yes	yes
Need of calculus power	none	low	finite elements methods: high. The other: low.
TYPE OF PAVEMENT AND TYPE OF ANALYSIS			
Design of all types of new-construction pavements	yes	yes	yes
Rehabilitation of all types of pavements	no	yes	few
DIFFERENT ACCURACY LEVELS DEP. ON INPUTS	no	yes	no (expressly).
TRAFFIC INPUTS			
Load spectra	no	yes	few
ESALs 18 Kip	yes	yes, although it is not usually used.	yes
Hourly, daily, monthly traffic distribution	no	yes	few
Traffic wander	no	yes	almost none
Traffic speed (load speed)	no	yes	yes
Analysis of damage caused by special vehicles	no	yes	almost none
CLIMATE			
Possibility of introducing any type of climate state	no	yes	no
Continuous adaptation of climate parameters during the analyzed period	no	yes	no. At the most seasonally, with preset data chosen by the user.
MODELS FOR THE ANALYSIS OF MATERIALS AND STRUCTURE			
Non-linear characterization of unbound layers	no	yes	few
Unbound materials resilient modulus adjusted for moisture variation during pavement life	no, only seasonally variations are considered.	yes	no
Binder complete characterization	no	yes	no
Short and long-term hardening consideration	no	yes	almost none. At the most for long periods, with preset data chosen by the user.
Consideration of the variation of the modulus of asphalt mixes at different temperatures and load frequencies	no	yes	not worked out by the model. At the most introduced by the user for long time periods.
Consideration of the viscoelastic behavior of asphalt mixes	no	not in structural models. Yes in transfer equations.	yes, for example finite elements methods or finite differences methods.
CALIBRATION OF STRUCTURAL MODELS			
Models nationally calibrated and validated	no; only data of the ASSHO Road Test.	yes	almost none
Time length of the performance data used in the calibration	2 years (serviceability index)	more than 14 years	much smaller than MEPDG
Time length of the traffic data used in the calibration	only 1.1 M ESALs	more than 27 years	much smaller than MEPDG
DISTRESSES PREDICTION			
Accumulated damage prediction nearly in a continuous way (monthly intervals)	no	yes	no. Accumulated damage in relatively long time periods
Permanent deformation of bound and unbound layers	no	yes	yes
Alligator and/or longitudinal fatigue cracking	no	yes	yes
Transverse cracking	no	yes	almost none
Roughness	no	yes	not in design methods. Only in pavement management programs.

Table 2. Comparison between the MEPDG and other pavement design methods. (Source: own elaboration).