Οδοστρωματα: Απο τον Εμπειρικο στο Θεωριτικο Τροπο Σχεδιασης

Pavements: From the Empirical to the Mechanistic Design Methods

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ΠΕΡΙΛΗΨΗ: Το παρόν άρθρο παρουσιάζει μια συνοπτική εισαγωγή της νέας μεθόδου σχεδίασης οδοστρωμάτων που αναπτύχθηκε στις Ηνωμένες Πολιτείες από τη μελέτη 1-37A της NCHRP. Ονομάζεται Μηχανιστικός – Εμπειρικός Τρόπος Σχεδίασης Οδοστρωμάτων (M-E PDG) και δημοσιεύθηκε το 2004. Η μέθοδος αυτή χρησιμοποιεί είτε την ελαστική μέθοδο στρωσιγενούς εδάφους είτε τη μέθοδο πεπερασμένων στοιχείων για την ανάλυση των τάσεων σε ασφαλτικά οδοστρώματα ή οδοστρώματα από σκυρόδεμα τύπου Portland. Μετατρέπει τις τάσεις και παραμορφώσεις σε ζημιά και το άθροισμα των ζημιών ως υπερβολική ένταση στο οδόστρωμα (π.χ. ρωγμές). Η μέθοδος χρειάζεται λεπτομερή εισαγωγή δεδομένων σχετικά με τα υλικά του οδοστρώματος και τα φορτία κυκλοφορίας. Τα φορτία κυκλοφορίας, για παράδειγμα, εισάγονται με τη μορφή της κατανομής των φορτίων ανά άξονα οχήματος για όλη τη διάρκεια ζωής του οδοστρώματος. Τα στοιχεία αυτά συνθέτονται από δεδομένα αυτοματοποιημένων μηχανημάτων, τα οποία μετρούν, ζυγίζουν και ταξινομούν τα διάφορα οχήματα.

ABSTRACT: This paper provides a brief introduction of the new pavement design approach developed in the USA under NCHRP Study 1-37A. It is referred to as the Mechanistic-Empirical Pavement Design Guide (M-E PDG) released in 2004. This approach utilizes layer elastic/FEM stress analysis for asphalt/portland concrete pavements, respectively. It translates stress/strain into damage and accumulates the damage into pavement distresses (e.g., cracking). The approach requires detailed material and traffic input. Traffic data, for example, consist of load spectra for each axle configuration over the design life. It is typically synthesized from a variety of automated traffic load, classification and counting equipment.

1. INTRODUCTION

Pavement design has evolved considerably in the last decade. The traditional regression equations used to relate traffic in the form of 80 kN Equivalent Single Axle loads (ESALs) to changes in pavement serviceability (1) are finally being superseded by the mechanistic-empirical approach developed under NCHRP study 1-37A (2). The resulting Mechanistic-Empirical Pavement Design Guide (M-E PDG) was released in 2004. It provides a more fundamental approach for the analysis/design of both flexible and rigid pavement structures, as well as an excellent framework for research in the pavement engineering area. Due to its fundamental nature, it can be incorporated in the practice of geotechnical engineering (i.e., the majority of geotechnical consulting firms in the USA have pavement design expertise).

This new design approach is evolving in conjunction with developments in asphaltic material characterization methods developed under *Superpave* (3). *Superpave* was introduced in the early 1990s as an innovative approach for specifying asphalt binders. The technology developed allows the fundamental characterization of the visco-elastic properties of asphalt binders and asphalt concretes. Asphalt binders are characterized through their master curves (G* versus loading frequency at a reference temperature) fitted to Dynamic Shear Rheometer (DSR) measurements (AASHTO T315). The cold temperature resistance of binders is evaluated through flexural creep testing using a Bending Beam Rheometer (BBR) (AASHTO T313). Asphalt concretes are characterized through uniaxial sinusoidal and creep testing (AASHTO TP 62). This information allows estimating the dynamic modulus of asphalt concretes (E^*) at any temperature and loading frequency (i.e., vehicle speed).

This approach is in the process of being evaluated by AASHTO for adoption as a national design standard. American state highway agencies are currently implementing it. The objective of this paper is to provide a brief introduction to this new pavement design technology and perhaps motivate its adaption to the conditions encountered in Greece.

2. M-E PDG APPROACH

The M-E PDG involves computing the pavement structural responses to traffic loads (i.e., stresses/strains), translating them into damage, and accumulating the damage into distresses (e.g., cracking, rutting and so on), which reduce pavement performance over time. For this purpose, it requires disaggregate traffic input in the form of the number of axles by type and load level rather than ESALs. Furthermore, it considers the temporal variation in material properties, as well as the pavement damage (e.g., heave, cold temperature-induced transverse cracking and so on) caused by the environment itself.

3. TRAFFIC INPUT

The need for mechanistic analysis dictates the necessity of disaggregate traffic input. This is in the form of load spectra. They consist of the number of truck axles by axle configuration and load level at monthly intervals throughout the pavement life. They are synthesized as shown in Table 1. An additional breakdown of the traffic loads is made by specifying an average hourly distribution of traffic volumes. The resulting spectra input into the analysis are in the form of hourly counts of truck axles by configuration (i.e., single, tandem, triple and quad).

Πίνακας 1. Εισαγωγη δεδωμενων κυκλοφοριας
Table 1. Traffic Input to the M-E PDG

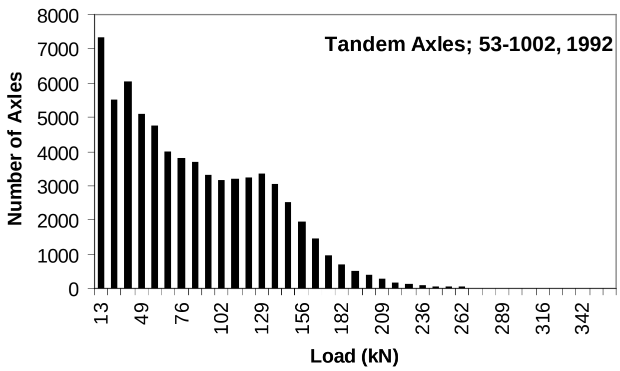
Main Data Element Input	Data Computed
Average annual daily trucks traffic (AADTT (1)	-
Distribution of trucks by class (i.e., FHWA classes 4-13) (1x10)	AADTT Number by class
Monthly adjustment factors (MAF) by truck class (12x10)	AADTT by class, by month
Number of axles by axle configuration, (single, tandem, triple, quad) by truck class (4x10)	Number of axles by axle configuration, by month
Load frequency (%) by axle configuration, by month, by truck class (4x12x10x41)	Number of axles by load range, by axle configuration, by month

This level of detail in traffic data can be obtained from weigh-in-motion (WIM) systems. In practice, this information is synthesized by a variety of site-specific, regional and national data from WIM as well as automated vehicle classifiers (AVC) and automatic traffic recorders (ATR). The combination of the information used defines the "level" in traffic input as described in Table 2. An example of a load spectrum for tandem axles is shown in Figure 1.

Πίνακας 2 Σύνθεση δεδομένων κυκλοφορίας

Table 2. Synthesizing Traffic Input

Data Element/Input Variables	Traffic Input Level			
	1	2	3	4
WIM Data – Site/Segment Specific	x			
WIM Data – Regional Representative Weight Data		x	x	
AVC Data – Site/Segment Specific	x	x		
AVC Data – Regional Represent. Truck Volume Data			x	
ATR– Site Specific			x	x



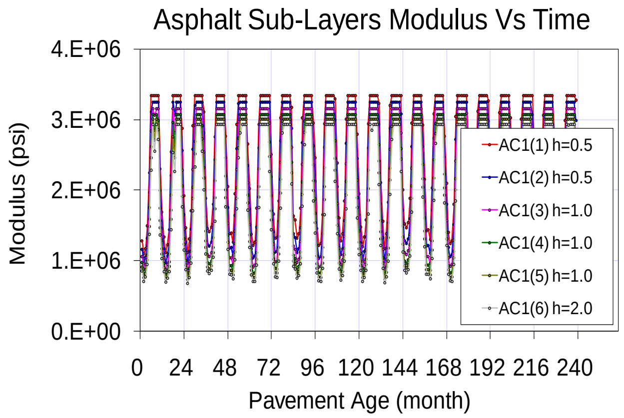
Σχήμα 1. Παραδειγμα κατανομης φορτιων
Figure 1. Example of a Load Spectrum

4. ENVIRONMENTAL EFFECTS

Pavement material properties and their response to traffic loads are affected by changes in moisture and temperature (e.g., the subgrade modulus is affected by moisture and the asphalt concrete modulus is affected by temperature). The M-E PDG estimates the temporal variations in moisture and temperature through the Enhanced Integrated

Climatic Model (EICM) (4), which has been incorporated into the M-E PDG software. This model provides estimates of the temporal changes in the distribution of moisture and temperature in the pavement layers. The input to this model includes the ambient air temperature, the latitude (i.e., it is used to define the amount of solar radiation and hence estimate pavement surface temperature) and the amount of precipitation at a design location. The input necessary for this is drawn from 20 years of historic environmental data collected at over 800 weather stations across the USA. A particular pavement design site is associated with a weather station via its coordinates (i.e., latitude and longitude). A state-by-state weather database can be downloaded from the Web, along with the M-E PDG software (5).

Air temperature and solar radiation data are used to estimate the distribution of temperature with depth on an hourly basis. This is done by solving the one-dimensional heat diffusion equation using numerical techniques (i.e., finite difference). The distribution of moisture with depth is similarly estimated from the amount of precipitation infiltrating through the pavement surface. This data is used to predict the distribution of layer mechanical properties with depth (e.g., Figure 2 shows the variation in asphalt concrete dynamic modulus *E** as a function of depth into the pavement layer and time, over a 20 year analysis period).



Σχήμα 2. Παράδειγμα της εποχιακής μεταβολής στο δυναμικό μέτρο ελαστικότητας (*E**) του ασφαλτικού σκυροδέματος
Figure 2. Example of temporal variation in the dynamic modulus (*E**) of asphalt concrete

Clearly incorporating the EICM model into the M-E PDG design methodology allows a detailed analysis of the site-specific environmental effects at a particular pavement design site.

5. FLEXIBLE PAVEMENT ANALYSIS

The analysis of flexible pavements consists of computing critical stresses/strains using layer elastic theory (6) for each axle configuration and load level. The modulus of the asphalt concrete can be estimated from either its volumetric and binder grade properties of from its master curve (i.e., *E** versus loading frequency at various temperatures), given the temperature and the vehicle speed. Base layer properties are estimated from moisture content predictions. The temporal variations in temperature and moisture are estimated by the EICM described earlier.

The computed response parameters are used as input to the damage functions described next for calculating the following pavement distresses:

- Asphalt concrete fatigue cracking (bottom-up and top-down).
- Rutting in the asphalt concrete granular layers (base and subgrade).
- Transverse cracking due to low temperature.
- Roughness.

5.1 Fatigue Cracking

Fatigue damage is accumulated for estimating bottom-up alligator cracking and top-down longitudinal cracking. The expression used for computing the number of repetitions to failure N_f for bottom-up and top-down cracking is a variation of the expression proposed by Finn et al. (7) and adopted by the AI mechanistic design approach:

$$N_f = 0.00432\, k_1{}'\, C \left(\frac{1}{\varepsilon_t}\right)^{3.9492} \left(\frac{1}{E}\right)^{1.281} \qquad (1)$$

where,
ε_t = tensile strain in the asphalt concrete layer,
E = layer stiffness (lbs/in^2) and,
C = calibration constant and,
$k_1{}'$ = a function of the thickness of the asphalt concrete layer h_{ac}.

The fatigue damage *FD* (percent) is accumulated separately for bottom-up and top-down cracking according to Miner's hypothesis expressed as:

$$FD = \sum \frac{n_{i,j,k,l,m}}{N_{i,j,k,l,m}} 100 \qquad (2)$$

where,
$n_{i,j,k,...}$ = applied number of load applications at condition *i, j, k, l, m, n,*
$N_{i,j,k,...}$ = number of axle load applications to cracking failure under conditions *i, j, k, l, m,* where,
i = month, which accounts for monthly changes in the moduli of base and subgrade due to moisture variations and asphalt concrete due to temperature variations,
j = time of the day, which accounts for hourly changes in the modulus of the asphalt concrete,
k = axle type, (i.e., single, tandem, triple and quad),
l = load level for each axle type,
m = traffic path, assuming a normally distributed lateral wheel wander.

5.2 Rutting

The plastic deformation *PD* is computed by dividing each layer into a number of sub-layers, computing the plastic strain in each sub-layer and adding the resulting plastic deformations through:

$$PD = \sum_{i=1}^{n} \varepsilon_p^i \, h^i \qquad (3)$$

where, ε_p^i is the plastic strain in sub-layer *i*, h^i is the thickness of sub-layer *i* and *n* is the number of sub-layers distinguished. As described next, the plastic strain ε_p in each pavement layer is computed from the corresponding elastic (or resilient) vertical strain ε_v using linear elastic analysis.

For the asphalt concrete layer, the plastic strain ε_p is computed as a function of the vertical elastic (resilient) strain ε_v obtained from elastic layered analysis using:

$$\frac{\varepsilon_p}{\varepsilon_v} = k_1 10^{-3.4488} \, T^{1.5606} N^{0.479244} \qquad (4)$$

where,
T is the asphalt concrete layer temperature (ºF), *N* is the cumulative number of loading cycles experienced and k_1 is a calibration factor accounting for the increased level of confinement with depth.

For unbound granular layers, the plastic strain ε_p is estimated using a model developed by Tseng and Lytton (8). It relates ε_p to the vertical elastic (resilient) strain ε_v calculated from layered elastic analysis using:

$$\frac{\varepsilon_p}{\varepsilon_v} = \beta_G \left(\frac{\varepsilon_0}{\varepsilon_r}\right) e^{-\left(\frac{\rho}{N}\right)^{\beta}} \qquad (5)$$

where, *β*, *ρ* and ε_0 are material properties obtained from laboratory testing involving repetitive loading at resilient strain level ε_r and *N* is the number of load cycles. The calibration constant β_G has the value of 1.673 for base layers and 1.35 for subgrades.

5.3 Cold-Temperature Cracking

Cold temperature cracking is estimated from the creep compliance of the asphalt concrete layer. This is obtained from creep testing (AASHTO TP 62).

5.5 Roughness

Roughens is perhaps the distress most difficult to predict mechanistically since it depends on a variety of factors, some of which contribute to distress. As a result it is estimated as a function of the pavement distresses computed, as well a variety of other factors, such as the activity of the subgrade (fraction of its gradation finer than 75 μm), possibility of frost (number of degree-days below freezing) and so on. Needless to say, the predictive ability of the roughness model is the weakest of all other damage models.

6. RIGID PAVEMENT ANALYSIS

The rigid pavement approach in the M-E PDG involves stress analysis through a three-dimensional finite element model (9). Two rigid pavement configurations are considered, namely jointed concrete pavements (JCP) and continuously reinforced concrete pavements (CRCP). Environmental and traffic associated stresses are computed at hourly intervals. For the latter, an artificial neural network algorithm is used to compute the location of the axles on the slab that result in the maximum stresses. Environmental stresses are computed in response to the moisture and temperature changes estimated from EICM, described earlier. Shrinkage in response to moisture changes is treated as equivalent temperature changes.

The following distresses are considered:

- Fatigue transverse cracking, both bottom-up and top-down, for JCP only,
- Joint faulting for JCP only,
- Punchouts for CRCP only and,
- Roughness for both JCP and CRCP.

6.1 Fatigue Cracking

Fatigue damage is accumulated using Miners hypothesis:

$$FD_{p,q} = \sum \frac{n_{i,j,k,l,m,n}}{N_{i,j,k,l,m,n}} \quad (6)$$

$FD_{p,q}$ = total fatigue damage for bottom-up or top-down cracking, accumulated according to Miner's hypothesis,
$n_{i,j,k,...}$ = applied number of load applications at condition $i, j, k, l, m, n,$
$N_{i,j,k,...}$ = number of load applications to failure, (i.e., 50% slab cracking) under conditions $i, j, k, l, m, n,$ (i.e., age, month, axle type, laod level, temperature difference top-bottom and traffic path, resp.). The number of load applications to failure, (i.e., 50% of the slabs cracked), $N_{i,j,k,l,m,n}$, under conditions i, j, k, l, m, n is given by:

$$\log\left(N_{i,j,k,l,m,n}\right) = 2.0\left(\frac{MR_i}{\sigma_{i,j,k,l,m,n}}\right)^{1.22} + 0.4371 \quad (7)$$

where, MR_i = modulus of rupture of Portland concrete (ASTM C 78) at age i and $\sigma_{i, j, k,, l, m, n}$ = critical stresses under load conditions $i, j, k, l, m, n,$ resp. The top-down and bottom-up fatigue damage is translated into percent fatigue cracking, CRK_p, CRK_q, resp., using:

$$CRK_{p,q} = \frac{1}{1 + FD_{p,q}^{-1.68}} \quad (8)$$

6.2 Joint Faulting

Faulting in JCPs is computed using an incremental approach, whereby the faulting increments by month i, $\Delta Fault_i$, are summed to compute the total faulting after m months, $Fault_m$:

$$Fault_m = \sum_{i=1}^{m} \Delta Fault_i \quad (9)$$

For each month, the faulting increment, $\Delta Fault_i$, is assumed proportional to the energy dissipated in deforming the slab support, expressed as:

$$\Delta Fault_i = C_{34}\left(FAULTMAX_{i-1} - Fault_{i-1}\right)^2 DE_i \quad (10)$$

where, $Fault_{i-1}$ is the accumulated mean faulting up to the previous month i-1, $FAULTMAX_{i-1}$ is the maximum mean faulting for the previous month, i-1, and DE_i is the differential energy of subgrade deformation.

Assuming a liquid foundation, allows computing the energy input into the subgrade as the product of the modulus of the subgrade reaction k multiplied by the square of the deflection differences:

$$DE = \frac{1}{2} k \left(w_l^{\,2} - w_{ul}^{\,2}\right) \quad (11)$$

where, w_l and w_{ul} are the surface vertical deflections at the loaded and unloaded edges of the joint. These deflections are associated with the load transfer efficiency of a joint, as derived from aggregate interlock, the contribution of the base support and the dowels, if present. These energy computations are repeated at monthly intervals and the accumulated damage is computed using Equation 8.

6.3 Punchouts

Punchouts in CRCP are the result of the formation of longitudinal top-down fatigue cracks spanning two adjacent transverse cracks. Computations are based on average crack spacing and crack opening. The latter relates to the load transfer between adjacent slabs.

6.4 Roughness

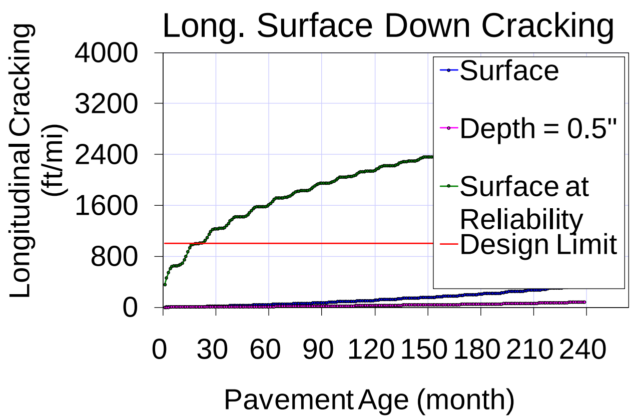
As for flexible pavements, roughness for rigid pavements is based on the distresses computed using an empirical expression.

7. EXAMPLE REUSLTS

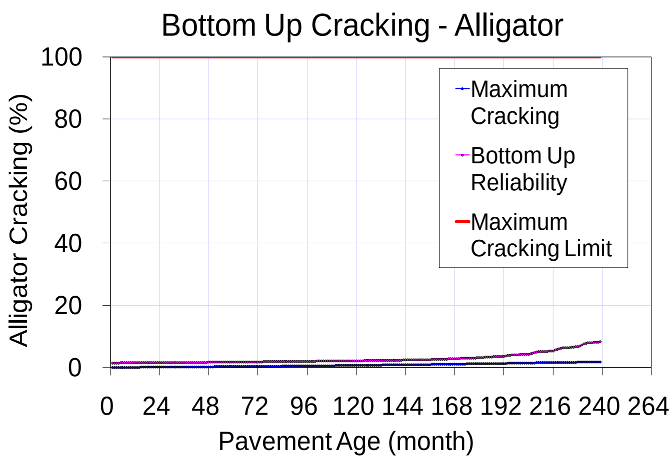
Examples of the output of the ME PDG are given next in the form of performance graphs, i.e., predictions of the progression of damage for each distress analyzed as a function of time. The following examples are from the 20-year-long analysis of a new flexible pavement. Figure 3 shows the average accumulation in wheel path top-down cracking (feet/mile) at the surface and at a depth of ½ inch (12.5 mm). In addition, it shows the 95th percentile top-down cracking and the specified design limit of 100 ft/mile (189 m/km).

Figures 4, 5 and 6 show similar graphs generated by the M-E PDG software, namely bottom-up alligator cracking (% of the wheel path area affected), rutting (depth of plastic deformation in the wheel paths in inches) and roughens (IRI inches/mile).

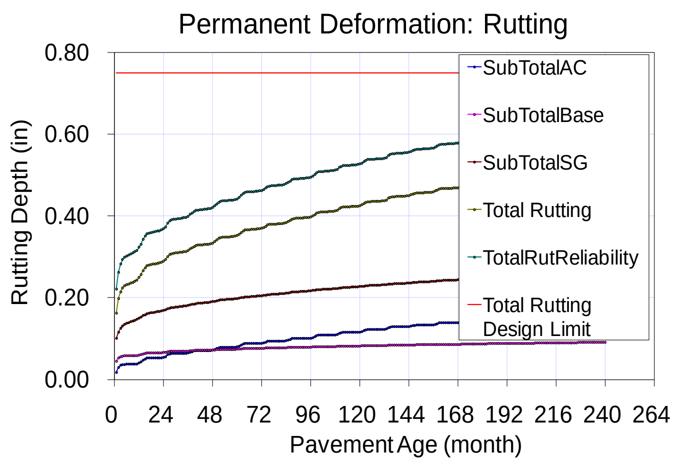
Note that design involves a number of trials whereby, layer properties and thicknesses are changed and the analysis is repeated until the desired pavement life is reached. The particular iteration shown here suggests that at 95% reliability, this pavement would not pass the top-down cracking test (Figure 3). Another analysis trial needs to be repeated with either a thicker or stronger asphalt concrete surface layer.



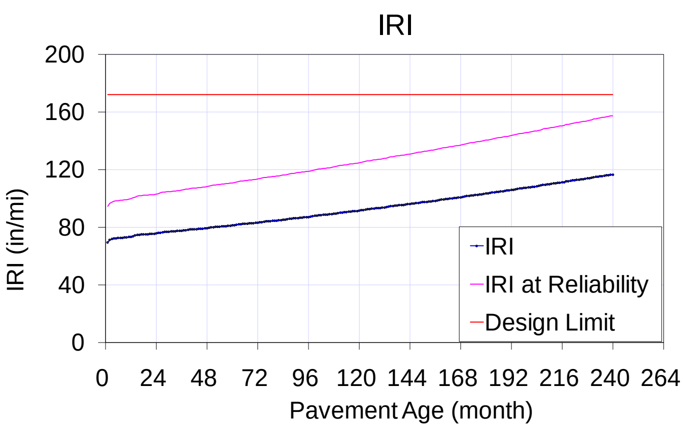
Σχήμα 3. Παράδειγμα αποτελεσμάτων: Ρωγμές από κάτω προς τα πάνω
Figure 3. Example output: Top-down cracking



Σχήμα 4. Παράδειγμα αποτελεσμάτων: Ρωγμές από πάνω προς τα κάτω
Figure 4. Example output: Bottom-up cracking



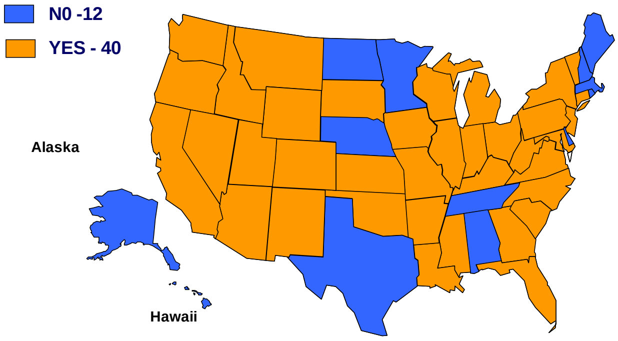
Σχήμα 5. Παραδειγμα αποτελεσματων: Πλαστικη παραμορφωση
Figure 5. Example output: Rutting



Σχήμα 6. Παραδειγμα αποτελεσματων: Ομαλοτητα (IRI)
Figure 6. Example output: Roughness (IRI)

8. IMPLEMENTATION

Since the release of the M-E PDG, the majority of State highway agencies have been in the process of implementing it (Figure 7). Their efforts have been mainly in traffic data collection, material characterization and calibration of the analysis results.



Σχήμα 7. Σχεδια για την χρησιμοποιηση του M-E PDG
Figure 7. M-E PDG implementation plans

Traffic data collection has been perhaps the most serious challenge, since never before traffic data has to be collected at such level of detail. Depending on the traffic input level (Table 2), the necessary traffic data (Table 1) is synthesized from site specific, regional and national data (e.g., site specific traffic counts, regional classification and national WIM). Needless to say, the more site-specific data is available and the longer its coverage, the higher is the accuracy of the pavement design (10). State highway agencies are currently developing software that will allow direct reading of the output of WIM and AVC equipment and produce input to the M-E PDG.

Another task necessary for meaningful implementation of the M-E PDG is the advanced material characterization required for some of the pavement layers. The biggest departure from conventional material testing procedures has been the area of asphalt binder and asphalt concrete characterization introduced by *Superpave*. As an example, the elastic modulus of the asphalt concrete layer has been replaced with its dynamic modulus (E*). The master curve of the dynamic modulus and the phase angle, obtained through sinusoidal uniaxial testing, allows computing the elastic modulus of the asphalt concrete at any temperature and lading frequency (i.e., vehicle speed). Testing to obtain these properties requires a substantial commitment on the part of State highway departments. Regardless, most of them are in the process of creating property “libraries” of their most commonly used pavement materials.

Calibration of the M-E PDG is taking place by comparing the performance predicted by the M-E PDG to that observed in the field. Most states use their own pavement management databases for this purpose. However, some rely on national pavement performance data such as:

- the Long Term Pavement Performance database (11),
- the MnRoad test flexible and rigid database (12) and,
- the WesTrack flexible pavement database (13)

More details on the new M-E PDG can be found in Ref. 2. Additional training resources can be found in the textbook *Pavement Design and Materials* recently published by Wiley and Sons (14).

9. REFERENCES

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