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Evelopment of a Practical Mechanistic-Empirical design Procedure for Flexible Pavements

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Abstract

Design methods for new flexible pavements and overlays are in the transition from empirical to mechanistic approach, and many state highway agencies trend to move toward the adoption and use of mechanistic-empirical (M-E) design in new constructions and rehabilitations of flexible pavements. Hence, the Michigan Department of Transportation (MDOT) decided to develop a M-E flexible pavement design procedure, in which major pavement distresses such as fatigue cracking and rutting are employed as indicators of the serviceability of a flexible pavement. The main concept of the developed design procedure is that a designed pavement that is supposed to carry a certain number of traffic must satisfy designated thresholds of rut depths and fatigue lives during a service period. For the M-E design procedure, transfer functions were developed to predict rut-depths and fatigue lives. These functions related the pavement responses to pavement performance. For validation, three current new flexible pavement design cases were obtained from the MDOT. In these cases, asphalt concrete (AC) layer thicknesses determined by the suggested M-E procedure compare favorably with those determined by the current MDOT design practice that is based on AASHTO design guide. This finding implies that the suggested Michigan M-E flexible pavement design procedure can provide a good opportunity to improve the current design practice.

Keywords: *M-E pavement design, flexible pavement, distress model, rutting, fatigue cracking*

요 지

현재 도로 설계는 기존의 경험적인 설계법에서 역학적인 설계법으로 바뀌고 있는 추세이다. 이러한 전환기에서 세계 많은 도로국들은 역학적-경험적인 도로 설계법을 개발하고 있고 혹은 이미 채택하여 적용하고 있다. 이에 실제 미국 미시간 도로국에서 나온 자료를 바탕으로 역학적-경험적 설계법을 개발 하였다. 이 역학적-경험적 설계법의 연결 함수 (transfer function)로 사용될 소성 변형 예측 모델과 피로 균열 예측 모델도 함께 개발 되었다. 여기서는 이 설계법을 개발하는데 사용된 자료와 예측 모델, 설계 알고리듬등이 소개 된다. 이 설계법의 검증을 위해 기존의 경험적 설계법에한 설계와 새로 제시된 설계법에 의한 설계가 비교된다. 새로 설계된 설계법은 설계자 혹은 사용자가 도로 파손의 기준을 정량적으로 정함으로서 좀더 구체적으로 설계를 할 수가 있다.

핵심용어 : M-E설계법, 연성포장, 파손예측모델, 소성변형, 피로균열

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Introduction

Today, design methods for flexible pavements and overlays can be divided into two groups, empirical and mechanistic-empirical methods. The main design considerations in both groups are to limit the compressive strains induced at the top of the subgrade/asphalt concrete (AC) layer to control permanent deformation and to limit the tensile strain induced at the bottom of the AC layer to minimize fatigue cracking. Empirical procedures are relatively easy to use. However, their application is limited since they are mainly derived from experience, lack of theoretical background, and are often custom designed. Mechanistic-empirical design methods are supported by theory, but are unable to model the interaction of all factors (e.g., environmental drainage) that cause pavement distress.

Most of the designs in the United States, currently, are based on empirical methods (AASHTO Guide 1993). In recent years, most state highway agencies (SHA's) recognized the need to change their empirical flexible pavement design practices to mechanistic based approaches. In the period of transition from empirical to mechanistic methods, mechanistic-empirical (M-E) design procedures have been developed by some SHA's, for instances, Illinois, Kentucky, and Washington in the U.S. and highway agencies in countries such as South Africa and France (IDOT 1995, Southgate and Deen 1987, Pierce et al. 1993, Theyse at al. 1999, Corte and Goux 1999). The Michigan Department of Transportation (MDOT) also recognized the need to change pavement design practice from a purely empirical method to a mechanistic-based method, and has directed effort at the development of M-E flexible pavement design procedures, the outcome of which is described hereafter.

Development of Distress Prediction Models

The major components of the M-E design are the determination of critical stress, strain, and/or deflection in the pavement by mechanistic analysis using the available structural models or computer codes such as MICH-PAVE, ILLI-PAVE, CHEVRON, ELSYM5, BISAR, WESLEA and prediction of resulting damages by empirical failure criteria such as rutting, fatigue cracking, roughness. Distress models, so-called transfer functions, relate the pavement responses determined from mechanistic analyses to pavement performance as measured by the type and severity of distress.

Two types of load related distresses (rutting and fatigue distress cracking) were considered in the study for the thickness design of the AC layer in a new pavement, or the overlay thickness design of an existing pavement. Rut is defined as the accumulation of permanent deformation in the wheel path. Fatigue cracks are load-induced longitudinal cracks in the wheel path. Both types of distresses are affected by traffic volume and load, material properties, construction quality, layer thickness, and the environment. Hence, any methodologies solely based on empirical or mechanistic approaches without considering all the factors will fail to model the pavement behavior effectively.

Data Collection and Analysis

In order to develop distress prediction models, thirty-nine test sections were selected in Michigan. The locations of these sites are presented in Figure 1. For each selected pavement section, the distress data (rut-depth and fatigue cracking), cross-sectional properties, traffic, and deflection data were collected and stored. Measuring the rut-depth, a six-foot long straightedge leveling rod with an accuracy of 0.05inch (1.27mm) was used. The rut-depth was measured at an interval of 40ft (12.2m) for both inner and outer wheel paths and recorded in inches. Length of fatigue cracks in the traffic direction in both inner and outer wheel paths was measured and the percentage of the total length of both inner and outer wheel paths that exhibits fatigue cracks were used for the fatigue model development (Figure 2). Rut-depths of 930 locations and fatigue cracking were measured on 36 in-service Michigan pavement sections from 1991 to 1998. For further validation of the rut prediction model, twenty-four General Pavement Study (GPS) sections were selected from the LTPP database using DATAPAVE.

The deflections measured by KUAB were normalized to a 9000 lb (40kN) load level and then backcalculated on an individual drop basis, while that of LTPP-GPS database were backclaculated on an individual drop basis without the normalization. The backcalculation program MICHBACK was used to backcalculate pavement layer elastic moduli (Harichandran, 1994).

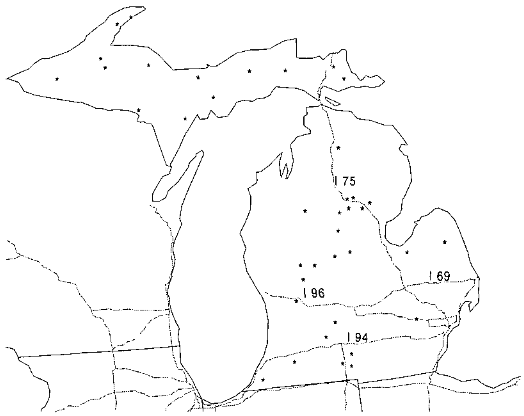
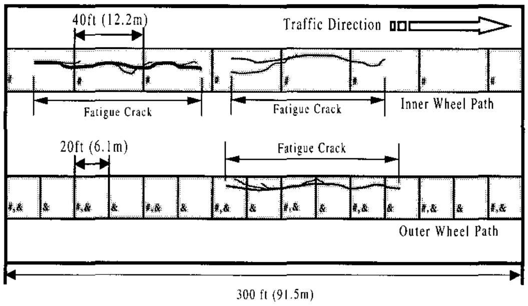


Figure 1. Distribution of Test Sites across the State of Michigan



: measurement of rut-depth
& : measurement of deflection using FWD
Note : Fatigue crack length in the traffic direction in both inner and outer wheel paths was measured for fatigue crack measurement.

Figure 2. Description of Typical Test Site

For the overlay design, it is necessary to characterize in situ structural properties of the existing pavement, and the use of falling weight deflectometer (FWD) data has become one of the primary means. Backcalculated modulus of the AC layer, however, is strongly influenced by ambient and pavement temperatures. In order to accurately determine the AC modulus, a two-step correction procedure needs to be applied. Typically the first step consists of predicting the effective temperature of the AC layer, and the second step consists of adjusting the computed AC modulus to a standard reference temperature. For development of a pavement temperature prediction model and correction factor, four in-service flexible pavement sites were selected.

Table 1 shows the summary of statistics of the variables that were analyzed. These variables were incorporated in the development of rutting and fatigue prediction models. Detailed data collection and analysis for development of distress models and temperature correction of backcalculated AC moduli are found in the published papers (Buch et al., 1999, Kim et al. 2000, Park et al. 2001).

Adjustment of Backcalculated AC Modulus for Temperature Influence

Table 1. Summary of Statistics of Analyzed Variables

(a) Data from '91 and 97' Field Observation in Michigan

	AC Thickness (in)	Base Thickness (in)	Subbase Thickness (in)	AC Modulus (psi)	Base Modulus (psi)	Subbase Modulus (psi)	Subgrade Modulus (psi)	Annual Ambient Temperature (F)	Average Rut-Depth (in)	*Fatigue Crack (%)	Traffic (ESAL)
Mean	6.34	11.04	21.64	823,442	57,070	37,858	11,605	43.90	0.203	46.39	660,510
Stdev	2.44	4.71	6.69	466,998	36,992	24,533	4,792	2.53	0.098	29.63	586,431
Max	14.50	27.00	32.00	2,699,344	173,118	86,289	30,933	49.40	0.538	99.17	2,753,922
Min	2.70	5.50	10.00	301,277	7,687	5,435	4,488	40.00	0.045	1.33	55,427

*Fatigue crack is data from 1997, and 1998.

(b) Data from '98 Field Observation in Michigan

	AC Thickness (in)	Base Thickness (in)	Subbase Thickness (in)	AC Modulus (psi)	Base Modulus (psi)	Subbase Modulus (psi)	Subgrade Modulus (psi)	Annual Ambient Temperature (F)	Average Rut-Depth (in)	Traffic (ESAL)
Mean	5.81	12.17	22.17	847,056	69,995	38,851	11,120	42.69	0.215	883,900
Stdev	1.54	5.96	4.67	558,773	35,849	13,922	6,723	2.58	0.135	675,780
Max	8.20	22.00	28.00	2,069,484	160,818	55,602	31,273	46.90	0.507	2,144,690
Min	3.50	5.50	18.00	277,594	26,878	21,145	4,537	39.99	0.071	69,807

Structural capacity (deflection and modulus) of the asphalt concrete (AC) layer is strongly influenced by ambient and pavement temperatures. In order to accurately determine or backcalculate the AC modulus, a two-step correction procedure needs to be applied. Typically the first step consists of predicting the effective temperature of the AC layer, and the second step consists of adjusting the FWD deflection or the computed modulus to a reference temperature using a correction factor. For the AC modulus adjustment to a reference temperature, it was suggested that selected input variables should be (a) easily obtained in the field during FWD testing and from the DOT inventory database and (b) enough to predict the subsurface temperature, Tz. Existing effective pavement temperature prediction models and methods were first reviewed in this study. However, few models that satisfy the above conditions were found. Recognizing the urgent need to develop a more accurate and practical temperature-modulus correction procedure for pavement designs, pavement depth, time of FWD testing, and pavement surface temperature were selected as input variables for the new model, and a temperature prediction model was developed using 197 data points from the three sites. Based on the process of numerical optimization using Quasi-Newton Method, SYSTAT (Leland 1992), a statistical computer program, converged on the solution, and the following model was developed:

$$T_z = T_{surf} + (-0.3451z - 0.0432z^2 + 0.00196z^3)\sin(-6.3252t+5.0967) \qquad (1)$$

where:

T_z = Temperature at mid-depth of the AC layer z, °C

T_{surf} = Temperature at the surface of the AC layer, °C

z = Mid-depth at which temperature is to be determined, cm. (1cm = 0.3937 in)

sin = Sine function, radians

t = Time when the AC surface temperature was measured, (days: $0 < t < 1$)

(e.g., 1:30 p.m. = 13.5/24 = 0.5625 days)

The developed temperature prediction model is simpler than many existing ones but predict field measurements accurately. The developed temperature prediction model has a R^2 greater than 0.9. Figure 3 compares the measured temperature to the predicted temperature for test sites. Results from the model overlap the 1:1 or 45° line indicating a very good fit. The temperature prediction model was further validated using data from seven Seasonal Monitoring Program (SMP) sites in DATAPAVE 2.0 (Park 2000, Park et al. 2001).

The AC modulus at the standard reference temperature is obtained from the backcalculated AC modulus by

$$E_{Tr} = E_T \times CF \qquad (2)$$

$$CF = 10^{a(Tr-T)} \qquad (3)$$

where

E_{Tr} = Corrected AC modulus to the standard reference temperature T_r, such as 20 °C

E_T = Backcalculated AC modulus at measured middepth temperature T

CF = Correction factor

a = Constant (0.022)

T = Middepth temperature

Further detailed temperature correction procedures are found in published sources (Park 2000, Park et al. 2001).

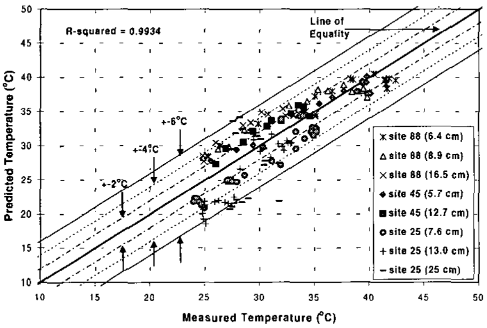


Figure 3. Measured vs. Predicted Temperature for AC Temperature Prediction Model

Rut Prediction Model

A nonlinear regression analysis for the rut prediction model was conducted with data collected from 39 test sections in 1991 and 1997. More than 760 data points from the 39 test sections were analyzed and were then grouped into 51 statistical samples representing every test site. Based on the process of numerical optimization using SYSTAT (Leland 1992), a statistical computer program, the following model was developed:

$$RD = (-0.061H_{AC} + 0.033\,\mathrm{In}\,(SD) + 0.011\,T_{annual} - 0.01\,\mathrm{In}\,(KV)) \cdot$$

$$\left(-2.703 + 0.657(\varepsilon_{v,\,base})^{0.097} + 0.271(\varepsilon_{v,\,SG})^{0.883} + 0.258\,\mathrm{In}\,(ESAL_R) - 0.034\,\mathrm{In}\left(\frac{E_{AC}}{E_{SG}}\right)\right) \tag{4}$$

where

RD = Average rut depth along a specified wheel path segment (inch)

H_{AC} = Thickness of the asphalt concrete (in.)

SD = Pavement surface deflection from the structural analysis (in.)

T_{annual} = Annual ambient temperature (°F)

KV = Kinematic viscosity at 275 °F (centistroke)

$\varepsilon_{v,base}$ = Vertical compressive strain at the top of base layer (10^{-3})

$\varepsilon_{v,SG}$ = Vertical compressive strain at the top of subgrade (10^{-3})

$ESAL_R$ = Cumulative traffic volume (number of equivalent single axle loads (ESALs))

E_{AC} = Resilient modulus of the asphalt concrete (psi)

E_{SG} = Resilient modulus of the subgrade (psi)

The R^2 of 0.9 indicates that the rut prediction of this nonlinear regression equation can be considered relatively useful. The comparison between measured versus predicted rut-depth is shown in Figure 4. There is a certain amount of bias associated with the measurement of rutting, estimation of traffic and determination of material and cross-sectional properties. Hence, rut-depth prediction should include a confidence interval. For the purpose of this study, a tolerance level of ±0.25mm (±0.1inch) was set up. If the difference between the observed and predicted rut-depth is within this tolerance level, it can be considered that the rutting prediction by the model is accurate. 43 of 51 sample groups are within this tolerance level indicating that a reasonable fit between the model and the data exists (Figure 4).

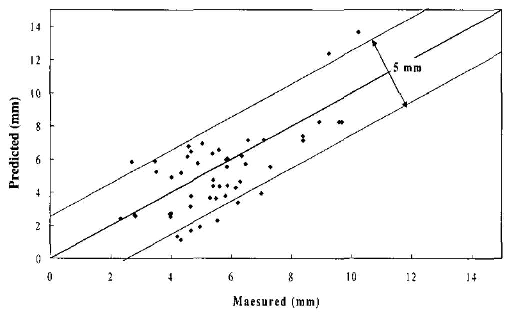


Figure 4. Measured versus predicted rut depths

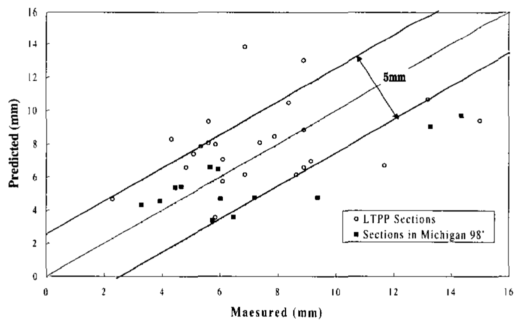


Figure 5. Measured versus predicted rut depth for LTPP sections.

The data collected from test sites in Michigan in 1998 and data from twenty-four LTPP-GPS sections were used to evaluate the accuracy of new rut prediction model and confirm the model's validity. Figure 5 is a graphical presentation of this evaluation. The difference between observed and predicted rut-depth for most of data points (70% of data from Michigan 1998 and 79% of selected LTPP data) employed are less than 0.25cm implying that a new rutting prediction model developed in this study has potential for nation-wide application. Figure 6 presents the relationship between traffic and rut-depth development based on observed data from the sections of AASHO Road Test and a prediction made by the developed model. In the figure, the rate of pavement rutting development increases rapidly at the beginning of pavement performance and then stabilizes as the pavement age increases. This trend of pavement rutting behavior corresponds well with the results from field investigations regarding rutting development of in-service pavement (Lister 1985). Detailed rut prediction model is found in the published source (Kim et al., 2000).

Fatigue Distress Prediction Model

The developed model uses the proportion of length on both inner and outer wheel paths that display fatigue cracks. Most observed cracks from test sites were at low, medium, or medium high severity levels. A nonlinear regression analysis was also conducted for the development of the fatigue distress model. 19 data points were collected from 14 test sites in 1997 and 1998. The extent of fatigue cracks along inner and outer wheel paths at each test site was measured and the percent of the total wheel path length exhibiting fatigue cracks, FT, was calculated. The number of EASLs needed to

$$\mathrm{In}\,(ESAL_F) = -3.454\,\mathrm{In}\,(SD) + 0.018FT - 0.223\,\mathrm{In}\,(\varepsilon_1) + 3.477\,\mathrm{In}\,(H_{AC}) - 3.521\,\mathrm{In}\,(KV) + 0.053\,\mathrm{In}\,(E_{AC}) - 1.027\,\mathrm{In}\,(E_{BS}) - 1.515\,\mathrm{In}\,(E_{SG}) + 32.156 \quad (5)$$

generate fatigue cracks over FT is predicted by

where

$ESAL_F$ = Cumulative traffic volume (number of equivalent single axle loads (ESALs))

FT = Percentage of the total length of both inner and outer wheel paths displaying fatigue cracks

ϵ_t = Tensile strain at the bottom of the AC layer

H_{AC} = Thickness of the asphalt concrete (in.)

SD = Pavement surface deflection from the structural analysis (in.)

KV = Kinematic viscosity at 275 °F (centistroke)

E_{BS} = Modulus of the base layer (psi)

E_{SG} = Resilient modulus of the subgrade (psi)

E_{AC} = Resilient modulus of the asphalt concrete (psi)

The R^2 of this nonlinear regression equation is 0.99, which represents how well the fatigue crack is explained by the regression. Figure 7 shows the comparison between the logarithm of the measured and predicted ESALs. Detailed fatigue distress prediction model is found in the published source (Buch et al. 1999)

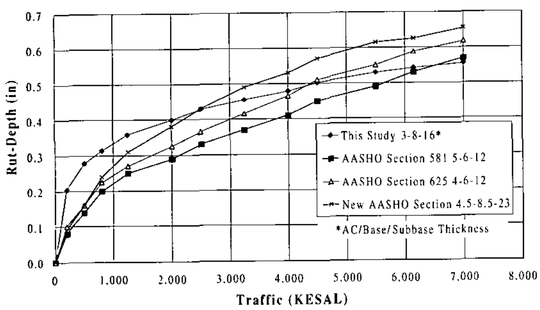


Figure 6. Rut-Depth Development with Increase of Traffic

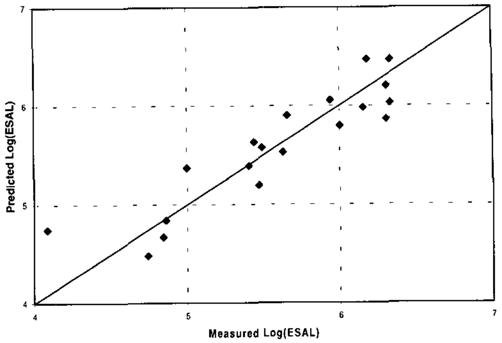


Figure 7. Measured vs. predicted Log(EASL) for fatigue model

Mechanistic-Empirical Design Procedure

The developed design procedures focus on the selection of the AC thickness for new pavement designs because the thickness of base and subbase layers is usually determined based on frost protection considerations. This procedure can be applied to the overlay thickness design. Permanent deformation (rutting) and fatigue cracking are major distresses that lead to a reduction in the serviceability of AC pavements. The main concept of the developed design procedure is to ensure that predicted rut depth and fatigue lives are within design thresholds. An optimal/design AC thickness can be computed by an iterative process, which produces an allowable traffic volume meeting the design life (design traffic volume). First, based on inventory and material data the initial AC thickness is selected. The next step is to evaluate the thickness for structural adequacy and compute quantities of responses in rut and fatigue models. Then, allowable ESALs of the new or overlay pavement are computed using rut and fatigue models (Equations 6 and 5, respectively). The allowable ESALs required to limit rutting and/or fatigue are then compared with the design ESAL.

Rut prediction model:

$$\ln(ESAL_R) = (1/0.258)\{\{RD/[-0.016*ThT_{AC}+0.033*\ln(SD)+0.011*T_a-0.01*\ln(KV)]\} - \{-2.703+0.657*(\varepsilon_b)^{0.097}+0.271*(\varepsilon_r)^{0.883} - 0.034*\ln(EE_{AC}/E_R)\} \quad (6)$$

If the difference between the allowable and design ESALs does not converge to zero, this procedure is repeated with a different AC thickness, and iterated until an adequate thickness is obtained that satisfies the following equation.

$$ESAL_{Des} - \min(ESAL_R, ESAL_F) \approx 0 \quad (7)$$

where:

$ESAL_{Des}$ = Design ESAL

$ESAL_R$ = Computed allowable ESAL based on the design threshold of rut depth,

$ESAL_F$ = Computed allowable ESAL based on the design threshold of fatigue life,

For example, if $ESAL_{Des}$ - min ($ESAL_R$, $ESAL_F$) is greater than zero, the AC thickness is increased until satisfying Equation 7. On the other hand, if $ESAL_{Des}$ - min ($ESAL_R$, $ESAL_F$) is less than zero, then the AC thickness is decreased until satisfying the equation. For the overlay design, the overlay and existing AC layer are combined into a single layer having a effective modulus and thickness given by (Figure 8)

$$EE_{AC} = [(EAC)^{1/3}\, Th_{AC} + (E_{OL})^{1/3}\, ThOL]^3 / [Th_{AC}+Th_{OL}] \quad (8)$$

$$ThT_{AC} = Th_{AC}+Th_{OL} \quad (9)$$

where

EE_{AC} = Effective AC modulus of the overlayed AC layer

E_{AC} = Resilient modulus of the existing AC layer

Th_{AC} = Thickness of the existing AC layer

E_{OL} = Overlay AC Modulus: new AC only

Th_{OL} = Initial AC overlay thickness

Th_B = Thickness of Base

Th_{Sb} = Thickness of Subbase

ThT_{AC} = Total Thickness of the existing AC and overlay AC

Illustrative Examples of Design Procedures

The proposed design procedure can be applied to both a new and an overlay pavement design. Comparisons of the existing new pavement design in Michigan and the proposed design are summarized in Table 2. The design thickness from the MDOT was compared with the design thickness based on the proposed procedure (Table 2 (b)). The AC design thickness resulting from the current MDOT method based on the AASHTO design guide and that from the developed M-E procedure are favorably close enough to instill confidence in the developed M-E design procedure. In addition, major pavement distresses (rutting and fatigue cracking) were employed as indicators of the serviceability of a flexible pavement in the proposed design.

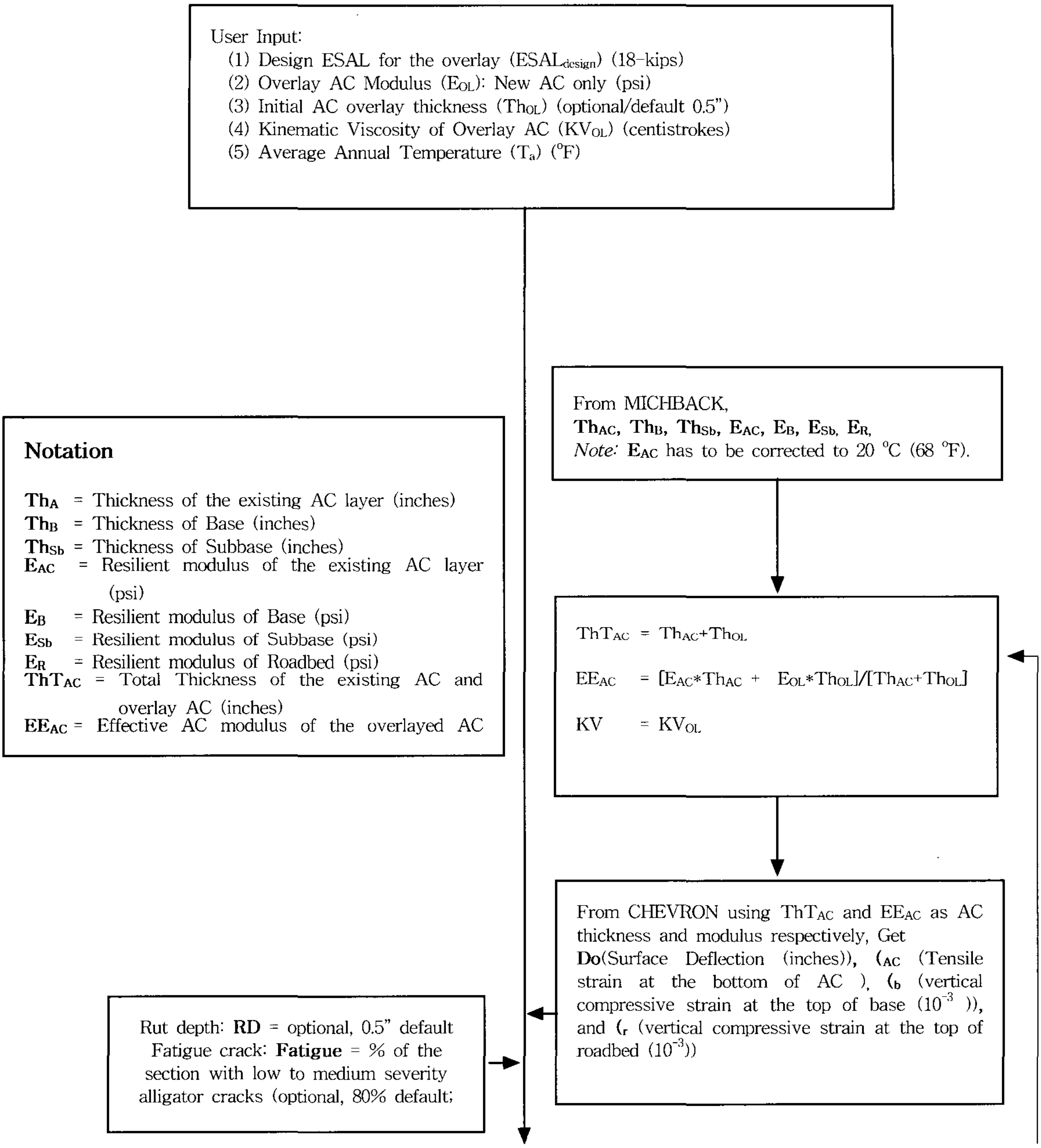


Figure 8. Flowchart for the Case of Overlay Design (Continued)

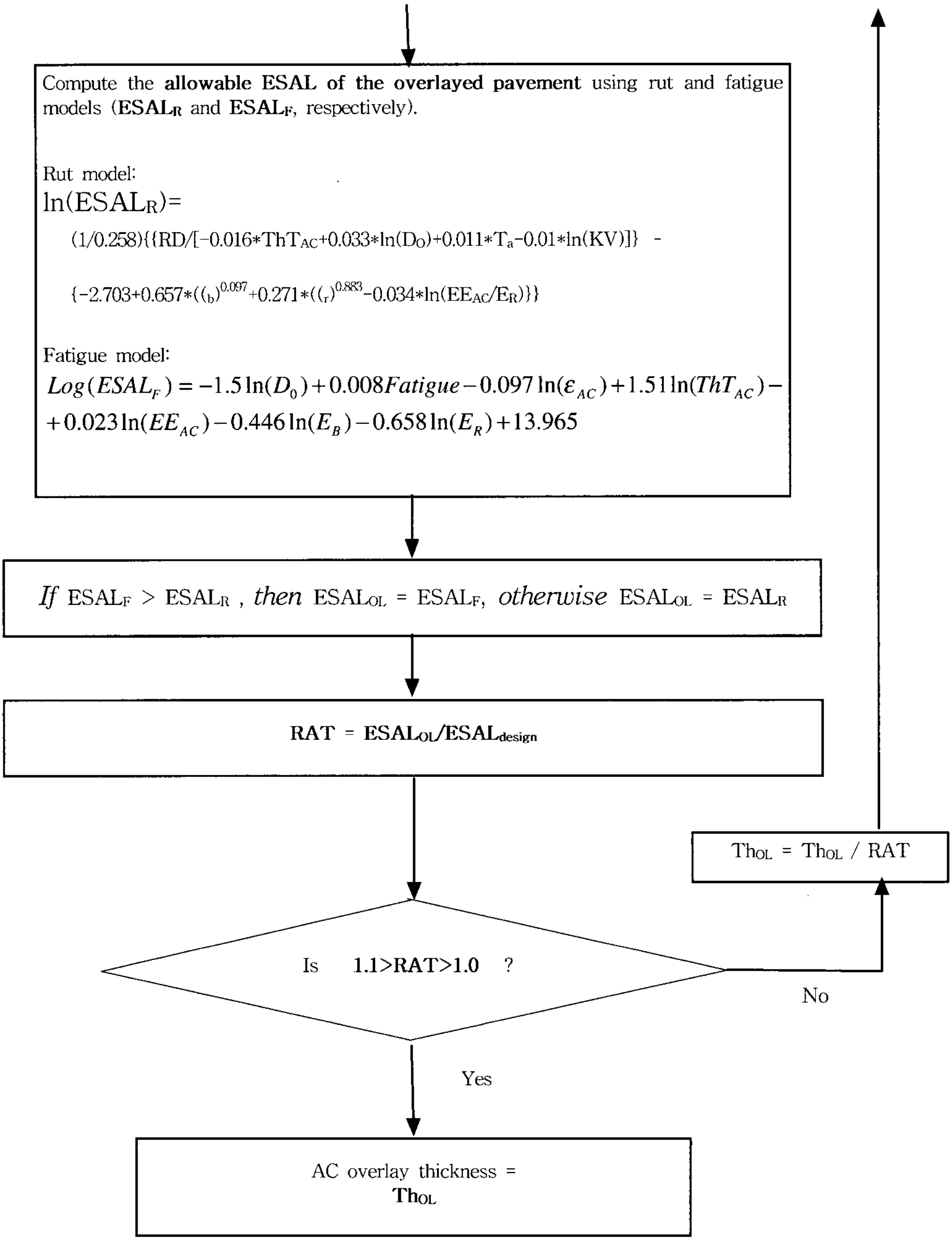


Figure 8. Flowchart for the Case of Overlay Design

Table 2. Illustrative Examples of New Pavement Design.

(a) Pavement Location

	Control Section	Route	Design Traffic Volume (million ESAL)	Location
Case 1	82194-82195	I-75	37.1	NYC Railroad to Gratiot Ave.
Case 2	12033	I-69	14.2	State Line to Lake Warren Road
Case 3	41133/59012	U.S 131	8.4	From M-46 (west segment) north to Cannonsville Road

(b) Inputs and Results for the new Pavement design

	Input									Design Result	
	Threshold		Cross-section(in)		Modulus(psi)				Annual Temperature (°F)	AC Thickness(in)	
	RD (in)	Fatique (%)	Base	Sibbase	AC	Base	Sub-base	Road-bed		ADOT	M-E
	0.3	50									12
Case 1	0.4	70	6	18	390000	30000	14000	3200		13.5	10.5
	0.5	80									10
	0.3	50									10.5
Case 2	0.4	70	13.8	9.8	400000	30000	15000	7000	45	7.9	8.5
	0.5	80									8
	0.3	50									9.5
Case 3	0.4	70	13	10	400000	44000	14000	6000		6	8
	0.5	80									7.5

Conclusions

A M-E pavement design procedure has been developed using the rut and fatigue life prediction models. For the development of M-E design procedure, the structural models (rutting and fatigue cracking models) were used as transfer functions. These functions related the pavement responses to pavement performance.

In this method, the design thickness is chosen so that user-specified thresholds on rut depth and fatigue life are met. For validation, three current new flexible pavement design cases were obtained from MDOT and compared with theproposed M-E design. AC layer thicknesses obtained using this method compare favorably with AC thicknesses selected by current MDOT design practice. This instills confidence in the developed M-E method.

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