# SENSITIVITY ANALYSIS TO DETERMINE THE RELATIVE INFLUENCE OF MATERIALS CHARACTERIZATION ON A FATIGUE-DAMAGE MODEL

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The concept of and a procedure for conducting a deterministic sensitivity analysis to establish the relative influence of materials characterization on the prediction of the fatigue performance of asphalt concrete pavements are presented. The effects of isotropic linear-elastic materials characterization on fatigue performance prediction are compared with the effects associated with construction, environment, and fatigue criteria variability. The results of the study have permitted an evaluation of the adequacy of an isotropic linear-elastic characterization of the three most common types of materials used in flexible pavement construction (asphalt concrete, untreated granular base course, and subgrade) for three typical structural sections and for a range of temperatures. For several specific structural sections and environments, it was found that improved material characterization beyond isotropic linear elasticity could significantly reduce the uncertainty (variation) of fatigue life prediction. However, both the construction control of air voids in the asphalt concrete and the inherent variability in the experimental definition of the fatigue criteria themselves always contributed more uncertainty to the prediction of fatigue performance than the uncertainty contribution associated with linear isotropic materials characterization.

•IT is generally accepted that the level of characterization of pavement materials has reached a degree of sophistication such that further refinements would require considerable investments in time and money. Before making such commitments, it is pertinent to ask whether, in the present context of the state of development of pavement design and performance prediction models, further refinements are necessary.

The adequacy of a characterization can be measured by the degree to which deviations from the idealized material behavior influence the objective of predicting pavement performance and must be measured relative to the influence on performance of variations in other inputs. In order to do this, a sensitivity analysis was conducted under contract with FHWA. Implicit in the sensitivity results is that the pavement design method used is based on a layered system representation that directly accounts for the influence of individual layer properties and temperature on pavement performance.

## GENERAL CONCEPT AND PROCEDURE FOR CONDUCTING SENSITIVITY ANALYSIS

Let us consider a system with the following three essential components: inputs, a law of transformation, and outputs. Outputs are generally considered in the context of the performance of the system being modeled. The basic concept in a sensitivity analysis is to relate variations in input to variations in the output. In general, a reduction in the uncertainty (variation) of the inputs will result in a reduced variation in the outputs. However, because the effect on the output of each input is not the same, it is not necessarily logical that each input be defined to the same degree of accuracy (level of

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uncertainty). For example, a variation of 50 percent in one input may have the same effect on the output as a 1 percent variation in some other input.

A rigorous treatment of the uncertainties would require that the problem be considered in probabilistic terms. A closed-form probabilistic pavement performance prediction model is currently being evaluated by FHWA. However, it was not available at the time this study was initiated. Hence, the sensitivity analysis was conducted deterministically by considering ranges of variation from average values of the inputs. These variations in the inputs will be referred to as input uncertainties for the sake of brevity in the remainder of the paper.

It should be recognized that all system models represent idealizations of a real physical system, and, therefore, the system model within whose framework the sensitivity analysis is conducted is, in itself, an approximation. The accuracy of the overall model, in terms of the factors that are included or omitted, has a bearing on the desired accuracy of the various components of the model. This line of reasoning leads to the conclusion that it is necessary to develop a complete system model prior to conducting any sensitivity analysis. However, because a complete model of a pavement system was not available at the time this study was conducted, it was necessary to consider the specific subsystems that were available. Because materials characterization is primarily an input to the structural subsystem, it is within the context of the structural subsystem that a sensitivity analysis with respect to materials characterization was conducted.

The procedure utilized for conducting the sensitivity analysis is shown in Figure 1. It should be recognized that the entire sensitivity analysis is conducted within the context of the performance (failure) prediction model that has been selected. The subsequent sections discuss the sensitivity analysis in accordance with the steps shown in Figure 1.

## SELECTION OF PERFORMANCE (FAILURE) PREDICTION MODEL

The failure mode considered in this study was fatigue due to repeated application of vehicle loads. This model can be defined by describing the inputs considered, the failure model, and the structural analysis model.

### Inputs to the Sensitivity Analysis

The following inputs were considered in the sensitivity analysis: traffic, material constitutive equations, material failure characteristics, environment, structural section, and construction effects.

In this sensitivity study, only initial design was considered; hence, maintenance effects were not included in the subsystem. Traffic volume was not directly considered, and the performance of the pavement system was measured in terms of the number of repetitions needed to cause failure. The life or performance of the pavement, in terms of time, is dependent on the volume of traffic. No particular volume of traffic was assumed in the analysis.

### Failure Model

Although local conditions may cause variations in pavement behavior, it is generally agreed that cracking due to the repeated action of traffic (fatigue) is a major contributor to pavement distress (1). Because fatigue cracking is of major significance in the failure of pavement systems, it is logical that this initial sensitivity analysis of materials characterization be conducted utilizing the fatigue components of the structural subsystem.

The fatigue criteria developed at the University of California at Berkeley by Monismith and his associates were utilized to predict the initiation of cracks in the pavement. These criteria are well documented in the literature (2, 3, 4, 5).

### Structural Analysis Model

The structural analysis of the pavement system was performed using a layered, isotropic, linear-elastic boundary value representation of the pavement system. Although

other boundary value representations that are possibly more representative of a pavement system are available (e.g., non-linear-elastic layered system, and linear-viscoelastic layered systems), the linear-elastic representation was selected because it could adequately reflect the fatigue behavior of a pavement system if proper consideration was given to the effect of temperature, load duration, and stress levels on the material properties. In addition, information concerning material properties and failure characteristics is most commonly analyzed and reported assuming linear-elastic behavior. Furthermore, this representation is the most commonly used and widely understood.

For the purpose of determining the controlling strain value used for fatigue life prediction, both isotropic linear viscoelasticity and isotropic linear elasticity can be considered equivalent if proper consideration is given in the latter characterization to temperature and load duration effects. Viscoelastic theory provides for the dependence of the material properties on temperature and load duration directly in the theory. If elastic theory is used, the material properties must be selected based on the temperature and load duration of interest.

## TYPICAL STRUCTURAL SECTIONS

Three pavement section geometries representative of possible design alternatives for a major highway were considered. The pavement sections range from full-depth asphalt concrete to a thin-surfaced layer of asphalt concrete over an untreated base course material. These sections are representative of a highway built on a relatively weak subgrade (CBR $\cong$ 3, E $\cong$ 5,000 psi, and R $\cong$ 15) with a relatively high traffic volume (DTN $\cong$ 550 and TI $\cong$ 10.5). The geometry of the actual sections analyzed is shown in Figure 2.

## MATERIAL TYPES AND AVERAGE PROPERTIES

The three types of materials that are most prevalent in the asphalt pavement section (asphalt concrete surfacing, untreated granular base course, and subgrade) were investigated in the sensitivity analysis.

### Asphalt Concrete

The average asphalt concrete properties used (6, 7) are shown in Figure 3. The asphalt concrete specimens were subjected to a range of simultaneously cycled axial and radial stress varying from 70-psi compression to 70-psi tension for axial stress and 0- to 70-psi compression for radial stresses. The average elastic modulus of the asphalt concrete was taken from the dotted line shown in Figure 3 for each temperature analyzed. An average value of Poisson's ratio of 0.4 was assumed for all temperatures analyzed.

### Untreated Base Course

It was recognized that the modulus and Poisson's ratio of untreated base course material are strongly affected by stress level (6, 8). However, the material was taken to be linearly elastic in accordance with the structural analysis model selected. The results of this sensitivity analysis will yield the effect of assuming a constant linear-elastic modulus and a constant average Poisson's ratio. The average values of modulus and Poisson's ratio selected were based on experimental results and preliminary structural analysis of the pavement section geometries using a layered "ad hoc" non-linear-elastic boundary value representation. These results indicated that a realistic average modulus value was 10,000 psi, and the average Poisson's ratio was selected as 0.3.

### Subgrade

The selection of average properties for the subgrade material was restricted by the geometry of the structural sections and traffic volume chosen for the sensitivity analy-

**Figure 1. Procedure for conduct of sensitivity analysis.**

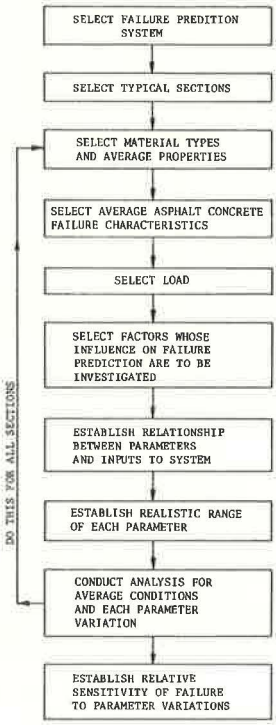



**Figure 2. Geometries of structural sections.**

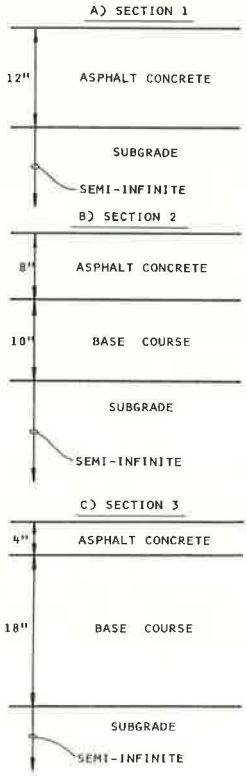
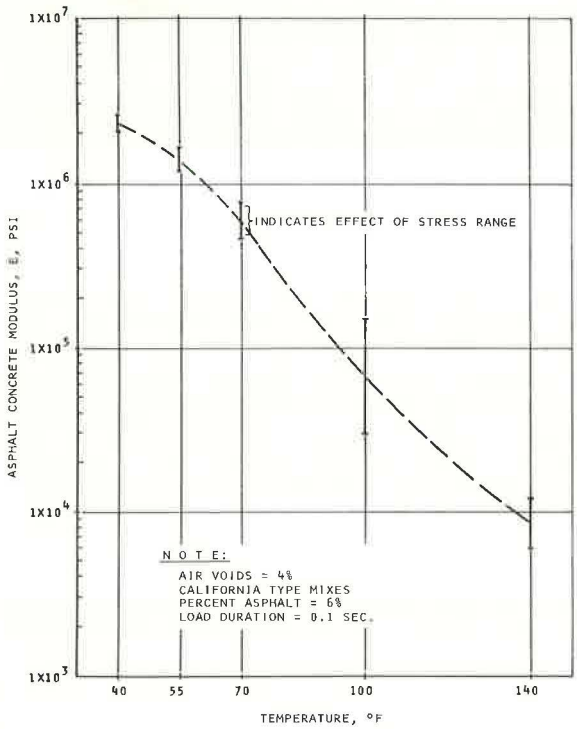



**Figure 3. Temperature dependence of asphalt concrete modulus (6, 7).**



sis. These structural sections are representative of a pavement constructed on a subgrade with an average modulus of 5,000 psi. An average value for Poisson's ratio of 0.4 was selected as representative of most subgrades.

## ASPHALT CONCRETE FAILURE CHARACTERISTICS

The fatigue failure characteristics of the asphalt concrete used in this analysis were those developed by Monismith et al. (5). These failure criteria were determined from laboratory repeated flexure tests on asphalt concrete beams and a regression fit of the data. The results are presented in the form of maximum initial tensile bending strain compared with repetitions to failure as shown in Figure 4. The fatigue life (number of repetitions to failure) was determined from this figure for each particular strain and asphalt concrete stiffness (temperature). The general form of the fatigue criteria is $N_f = K_1 (1/\epsilon)^{K_2}$, where $N_f$ is the fatigue life, $K_1$ and $K_2$ are constants that depend on asphalt concrete modulus, and $\epsilon$ is the maximum tensile strain in the asphalt concrete.

## LOADING CONDITION

One loading condition was used for the entire sensitivity analysis. It was recognized that the load magnitudes applied to a pavement are distributed in some random fashion. Normally, the effect on fatigue life prediction of varying load magnitudes is considered through Miner's hypothesis of a linear summation of damage due to each load magnitude. For the purposes of this sensitivity analysis, it was sufficient to examine one typical loading condition.

The loading condition analyzed was a single 9,000-lb wheel load with a tire pressure of 70 psi. The load area was assumed to be circular, which resulted in a load radius of 6.40 in.

## FACTORS INFLUENCING FAILURE PREDICTION

The following factors were considered significant in their influence on the prediction of fatigue failure in an asphalt concrete pavement: environment, construction effects, material characterization, and failure characteristics. It was necessary to translate the effects of these factors into actual inputs of the fatigue performance subsystem.

Variable inputs to the fatigue failure subsystem used for this sensitivity analysis were material properties and geometry. Therefore, within the context of the model, the influence of the preceding factors on the prediction of failure could only be analyzed through their effect on material properties and the structural section geometry inputs. These factors were subdivided into a number of specific parameters; e.g., environment was broken down into temperature and moisture. It was then necessary to establish the relations between material properties and the various parameters.

With these relations between material properties and parameters affecting fatigue performance, it was possible to examine the influence of variations in each parameter on the prediction of pavement failure. This information could then be used to examine the relative importance of the uncertainty (range of variation) associated with each parameter on the prediction of fatigue performance.

## RANGE OF PARAMETERS AND RELATION TO INPUTS

### Environment

The environment was assumed to affect only the material properties and not the geometry of the pavement material. The environment can be described by temperature and moisture parameters.

Temperature—Temperature was assumed to affect only the asphalt concrete properties. Temperature exerts a major influence on both the asphalt concrete modulus and fatigue characteristics. Therefore, two levels of the temperature parameter were considered in the analysis, a macrolevel and a microlevel.

Four macrolevels were considered: 40, 60, 80, and 100 F, which were representative of climates ranging from cold to hot. Within each macrotemperature level,

microtemperature variations of ±1, ±3, and ±6 F were considered. The microlevels represent the uncertainty in the predicted temperature environment used for design and the actual temperature environment experienced by the pavement within each type of climate. The microtemperature uncertainties selected were small variations because most recently developed rational pavement design procedures consider the temperature environment in sufficient detail that the actual temperature environment will be well represented.

The temperature uncertainty was related to the modulus using Figure 3. Its effects on both the strain value predicted from the structural analysis model and the fatigue characteristics were considered.

Moisture—The moisture environment of a pavement system can vary throughout the year and was assumed to affect only the modulus of the untreated base course and subgrade. Relations between modulus and moisture content vary with the specific materials. Therefore, it was decided that selection of a representative effect would be more appropriate. A range of modulus variation of ±25 percent from the average value was selected as representative of seasonal moisture variation effects for the base course and the subgrade.

### Construction

Construction effects were selected to be representative of the differences that can be expected between design values and the actual as-built values because of the limits of construction control. Construction was considered to affect both the geometry of the pavement system and the material properties.

Thickness of Asphalt Concrete—The construction effect on geometry was considered only for the thickness of the asphalt concrete. Although it was recognized that the thicknesses of other layers will also be affected, these effects on the performance of the pavement are small in comparison. Thickness variations of ±¼ in. and ±½ in. from the average design values for the asphalt concrete were considered in the analysis. Construction effects on material properties were considered through variations expected for air void content of the asphalt concrete, placement water content, and density of the base course and subgrade.

Air Voids—Variations in air void content affect both the modulus and the fatigue characteristics (at a given modulus and strain level) of asphalt concrete. The effect of air void variations on modulus has been established (5, 9). It has been shown that, at a given temperature, the logarithm of modulus decreases linearly with increase in air voids. The effect of air void content on the fatigue life at a given modulus and strain level has been established (5): A linear decrease in the logarithm of fatigue life occurs with increase in air voids. The slopes of these relations were used to consider the effects of air void variations of ±1, ±2, and ±3 from the average (design) value.

Water Content and Density—The limits of construction control also induce variation from the design value of the water content and density of the base course and subgrade at the time of placement. The effect of water content and density variation on the moduli values is dependent on the specific materials used. Therefore, a representative range of variation of ±25 percent from the average value for both the base course and the subgrade modulus was selected.

## MATERIAL CHARACTERIZATION

All materials considered in this analysis were characterized by linear-isotropic elasticity. The two constitutive constants utilized were modulus and Poisson's ratio. Uncertainty in these material "constants" arises because of deviations from ideal behavior and possible experimental errors.

### Asphalt Concrete

The range of moduli values indicated by the vertical bars shown in Figure 3 at each temperature tested indicates the magnitude of uncertainty associated with a range of stress states representative of those expected for in-service conditions. Moduli varia-

tions of ±10, ±20, and ±40 percent from the average value at each temperature were considered. A ±0.1 variation in Poisson's ratio was analyzed.

Untreated Base Course

The preliminary layered non-linear-elastic analysis used to establish an average linear-elastic modulus for the base course was also used to select a representative range of variation of modulus. These results indicated that variations of -20, -40, -60, +25, +50, and +100 percent from the average modulus were representative of possible uncertainties associated with an average linear-elastic base course modulus. A variation of ±0.1 from the average Poisson's ratio was also considered.

Subgrade

The modulus of a particular subgrade varies with stress state and number of load repetitions. Subgrade modulus variations of -20, -40, -60, +25, +50, and +100 percent from the average value were considered. A ±0.1 variation of Poisson's ratio was also considered.

Asphalt Concrete Failure Characteristics

The fatigue failure characteristics for each asphalt concrete stiffness shown in Figure 4 are best-fit regression lines. The scatter of experimental results about each regression line can be measured by the standard error of estimate. Uncertainty in the fatigue criteria themselves was considered using a representative standard error magnitude of 0.2 (5) and ±1 and ±2 standard errors from the average regression fits.

The parameters considered in the sensitivity analysis, range of variations about their average value, and system inputs affected are given in Table 1. Temperature and air voids were not direct system inputs but were related to the system inputs utilizing previously mentioned relations. The range of uncertainty of each parameter given in Table 1 was investigated for each of the three structural sections and four macrotemperature levels.

## PROCEDURE FOR CONDUCT OF ANALYSIS

The procedure for conducting the analysis was to first predict the fatigue life for each structural section and macrotemperature level using the average values for all system inputs. These fatigue lives are considered to be the average fatigue life for each condition. Once the average fatigue life values had been established, the influence of variations (uncertainty) in the system inputs caused by variations in the parameters given in Table 1 was considered. Each level of uncertainty in each parameter was considered independently. Therefore, each fatigue life was determined by changing one parameter from its average value while holding all others at their average value. This defined a new fatigue life prediction caused by a change in each parameter. The change in fatigue life from the average value could then be expressed as a percentage of the average fatigue life. These percentage changes were utilized to evaluate the sensitivity of fatigue life to uncertainty levels in each parameter.

Figure 5 shows the percentage of decrease in fatigue life from the average fatigue life as a function of the range of variation of each parameter for section 2 at 60 F. Only parameter variations causing decreases in fatigue life are presented here because prevention of premature failures is normally the objective of a pavement design or construction specification. Similar plots were made for each structural section and macrotemperature level.

## RELATIVE SENSITIVITY OF FAILURE TO PARAMETER VARIATIONS

The relative sensitivity of fatigue life prediction to parameter variations is obtained by selecting and comparing the effect of compatible uncertainty (variation) levels of each parameter. The technique used to establish compatible uncertainty levels for each parameter was to select each parameter variation such that each had approximately the same likelihood of occurring.

**Figure 4. Fatigue failure criteria (5).**

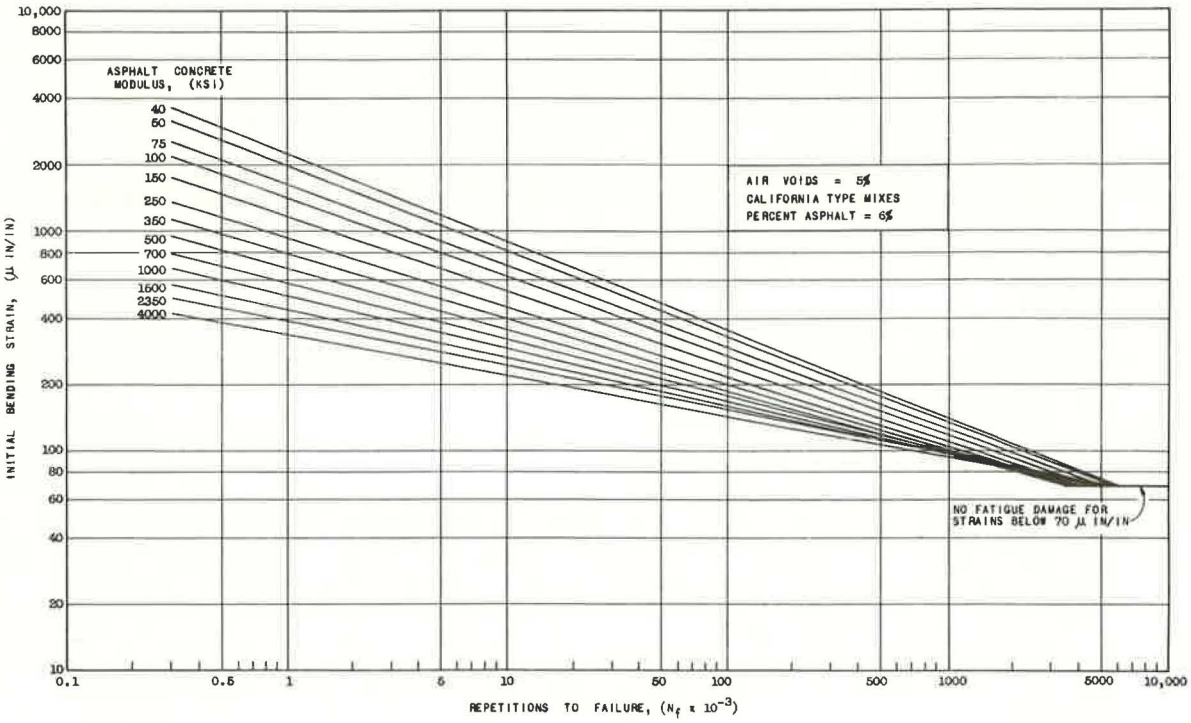



**Table 1. Study parameters.**

| Parameter | Range of Variation About Average Value | System Input Affected |
|---|---|---|
| Temperature (T) | ±1, ±3, ±6 F | Modulus of asphalt concrete and fatigue criteria |
| Air voids (AV) | ±1, ±2, ±3 percent | Modulus of asphalt concrete and fatigue criteria |
| Thickness of asphalt concrete[a] ($t_{AC}$) | ±¼, ±½ in. | Thickness of asphalt concrete |
| Fatigue criteria[a] ($N_f$) | ±0.2, ±0.4 (standard error) | Fatigue criteria |
| Modulus[a] | | |
| Asphalt concrete ($E_{AC}$) | ±10, ±20, ±40 percent | Modulus of asphalt concrete and fatigue criteria |
| Base course ($E_{BC}$) | -20, -40, -60, +25, +50, +100 percent | Modulus of base course |
| Subgrade ($E_{SG}$) | -20, -40, -60, +25, +50, +100 percent | Modulus of subgrade |
| Poisson's ratio[a] | | |
| Asphalt concrete ($\nu_{AC}$) | ±0.1 | Poisson's ratio of asphalt concrete |
| Base course ($\nu_{BC}$) | ±0.1 | Poisson's ratio of base course |
| Subgrade ($\nu_{SC}$) | ±0.1 | Poisson's ratio of subgrade |

[a]These represent system inputs.

The level of each compatible parameter variation was selected such that the probability that variations would be less than the selected level or of opposite sign was 0.7 to 0.8. This selection was based on experimental results and published statistical properties of each parameter when possible (6, 10, 11, 12).

Table 2 gives relative sensitivity results for section 2 at each macrotemperature level. The compatible (equal likelihood) uncertainty levels selected for each parameter are indicated in parentheses. Similar tables for sections 1 and 3 using the same compatible uncertainty levels were used to construct plots of the relative sensitivity results shown in Figures 6, 7, and 8.

Relative sensitivity results for section 1 at 40 and 60 F and section 2 at 40 F were not meaningful because the fatigue criteria utilized predict no fatigue damage for strains below 70 μin./in. Results for section 3 at 80 F and 100 F were not possible because the tensile strains exceed the defined range of the fatigue criteria.

Relative sensitivity results for both -25 and -50 percent variations, in untreated base course and subgrade moduli, are shown for each section because little information was available to separate the influence of deviations from ideal material behavior and variation of in-place properties (i.e., water content and density). The -25 percent results are thought to be representative of the influence of modulus uncertainty due to either cause, and the -50 percent results are representative of the combined influence of modulus uncertainty due to both in-place field variations and nonideal material behavior.

## INTERPRETATION OF RESULTS

The relative sensitivity results were derived for constitutive material characterization errors representative of those utilizing isotropic linear-elastic theory. However, the temperature dependence of asphalt concrete modulus was recognized and considered. Therefore, the uncertainties induced in fatigue life because of variations in the elastic parameters considered here reflect characterization uncertainties caused by anisotropy or nonlinearities and experimental error or both rather than the differences in viscoelastic or "pseudo" elastic characterizations.

The relative sensitivity analysis was conducted for several macrotemperature levels for each structural section and represents climates ranging from cold to hot. The variation of temperature about some average value influences the interpretation of the relative sensitivity results because a Miner's hypothesis for cumulative fatigue damage is normally used when more than one temperature level is considered.

The fatigue life at a particular strain level increases with temperature increase. However, because the asphalt concrete modulus decreases with increase in temperature, the maximum tensile strain in the asphalt concrete increases. The net result of a temperature increase for the pavement sections analyzed is that the effect of the higher strain level dominates and results in a smaller fatigue life. This is according to the criteria developed by Monismith and his associates. It is recognized that there are other fatigue criteria that would not give this result. Because the volume of traffic is normally considered uniformly distributed throughout the year and Miner's cumulative damage hypothesis is used, the majority of the fatigue damage occurs during the warmer months of the year. Therefore, the relative sensitivity of fatigue life to variable uncertainty at the higher macrotemperature levels is more significant than at lower macrotemperature levels for mixed temperature environments.

Note that uncertainty in fatigue life induced by uncertainty of in situ air voids, asphalt concrete thickness, and fatigue criteria definition can be considered independent of the constitutive parameter uncertainties because of the manner in which each was considered. The uncertainty induced by these three parameters would exist even if each material were perfectly characterized by linear-isotropic elasticity. Therefore, the combined uncertainty due to these three parameters can be used as a measure of the relative significance of constitutive parameter uncertainty.

The relative sensitivity results shown in Figures 6, 7, and 8 provide a quantitative measure of the relative importance of uncertainty induced by nonideal behavior and experimental errors in materials characterization on fatigue life prediction. Further-

**Figure 5. Sensitivity of fatigue life to parameter variations for section 2.**

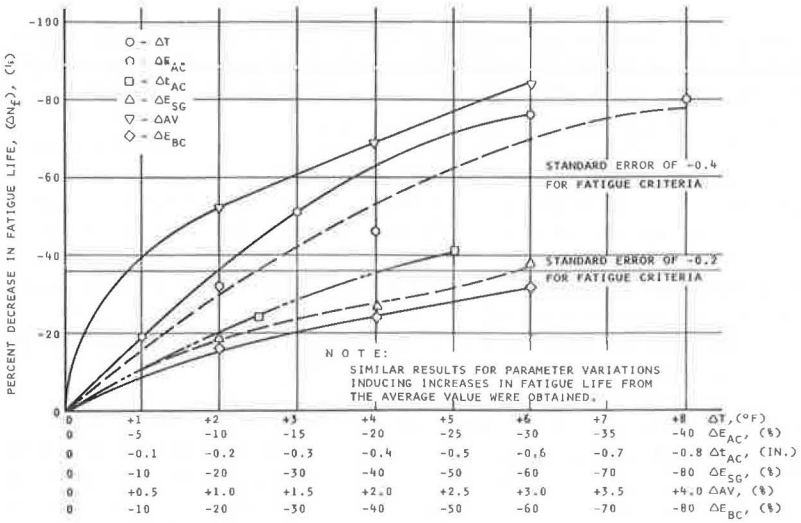



**Table 2. Relative sensitivity analysis of section 2.**

| Parameter | T = 40 F[a] ($\bar{\epsilon}$ = 50 μin./in., $\bar{N}_f$ = >5 × $10^6$) | | T = 60 F ($\bar{\epsilon}$ = 105 μin./in., $\bar{N}_f$ = 740 × $10^3$) | | T = 80 F ($\bar{\epsilon}$ = 300 μin./in., $\bar{N}_f$ = 36 × $10^3$) | | T = 100 F ($\bar{\epsilon}$ = 635 μin./in., $\bar{N}_f$ = 14 × $10^3$) | |
|---|---|---|---|---|---|---|---|---|
| | $\frac{\Delta N_f}{\bar{N}_f}$ (percent) | Percentage of Total | $\frac{\Delta N_f}{\bar{N}_f}$ (percent) | Percentage of Total | $\frac{\Delta N_f}{\bar{N}_f}$ (percent) | Percentage of Total | $\frac{\Delta N_f}{\bar{N}_f}$ (percent) | Percentage of Total |
| $\Delta E_{AC}$[b] (varies) | 0 | 0 | 30 | 12 | 22 | 13 | 7 | 4 |
| $\Delta T$ (+1 F) | 0 | 0 | 19 | 8 | 8 | 4 | 14 | 8 |
| $\Delta t_{AC}$ (-0.25 in.) | 0 | 0 | 24 | 10 | 11 | 6 | 14 | 8 |
| $\Delta N_f$ (-1 standard error) | 0 | 0 | 36 | 14 | 36 | 21 | 36 | 21 |
| $\Delta E_{SG}$ (-25 percent) | 0 | 0 | 21 | 8 | 10 | 6 | 9 | 5 |
| $\Delta E_{BC}$ (-25 percent) | 0 | 0 | 18 | 7 | 17 | 10 | 27 | 16 |
| $\Delta AV$ (+2 percent) | 0 | 0 | 69 | 27 | 47 | 27 | 43 | 25 |
| $\Delta \nu_{AC}$ (-0.1) | 0 | 0 | 16 | 6 | 14 | 8 | 4 | 2 |
| $\Delta \nu_{BC}$ (+0.1) | 0 | 0 | 11 | 4 | 6 | 3 | 11 | 7 |
| $\Delta \nu_{SG}$ (+0.1) | 0 | 0 | 11 | 4 | 4 | 2 | 4 | 2 |
| Total | 0 | 0 | 255 | 100 | 175 | 100 | 169 | 100 |

Note: $\Delta E_{BC} = \Delta E_{SG}$ = -25 percent.

[a]No fatigue damage for strains below 70 μin./in.

[b]$\Delta E_{AC}$ = -2 percent at T = 40 F, $\Delta E_{AC}$ = -10 percent at 60 F, $\Delta E_{AC}$ = -20 percent at 80 F, $\Delta E_{AC}$ = -35 percent at T = 100 F.

**Figure 6. Relative sensitivity of fatigue life to parameter variations for section 1.**

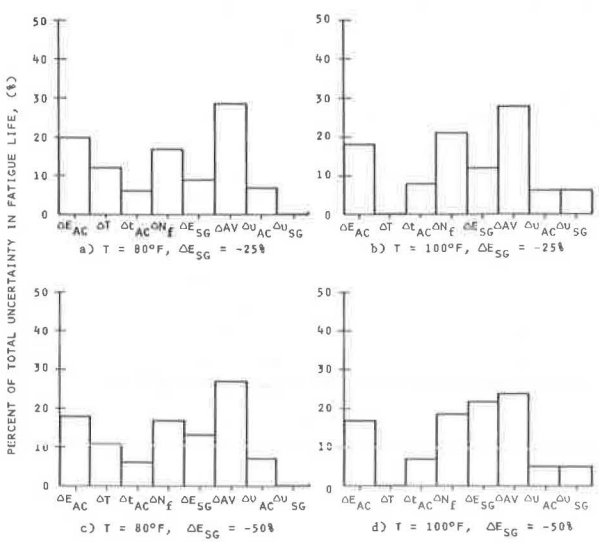


**Figure 7. Relative sensitivity of fatigue life to parameter variations for section 2.**

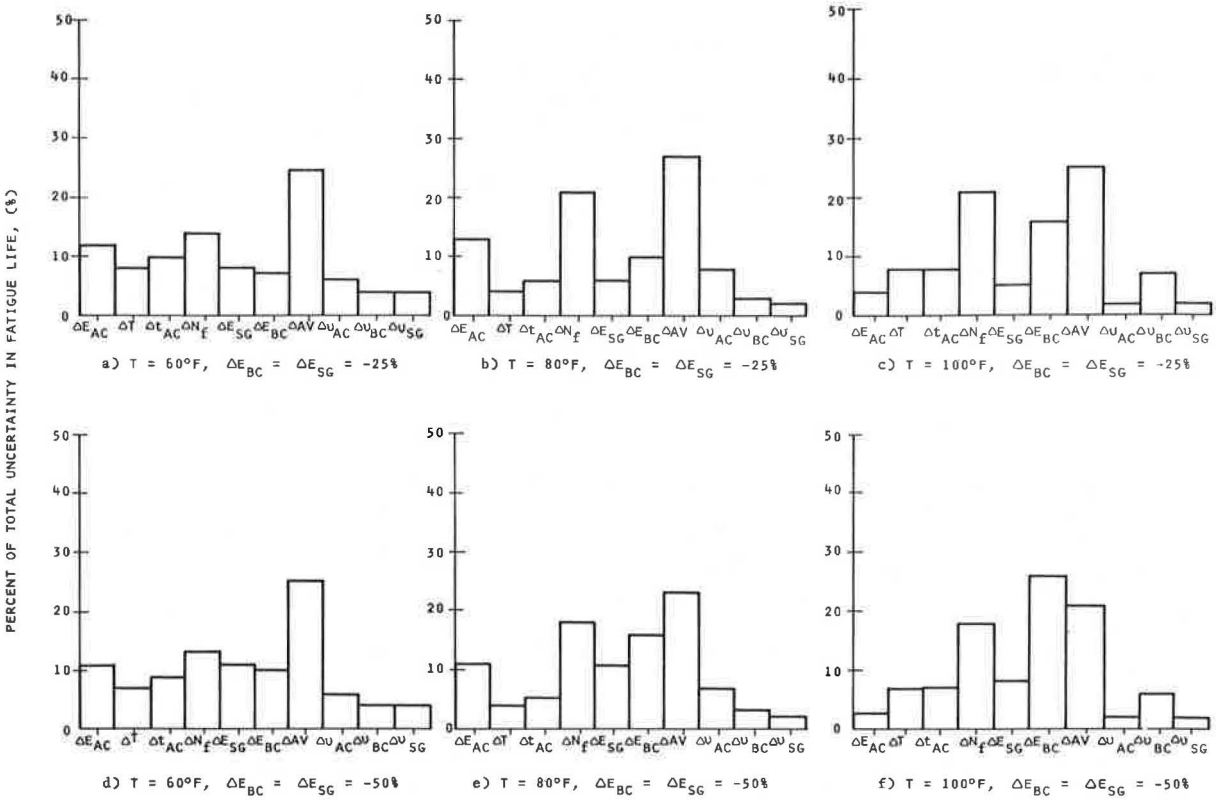
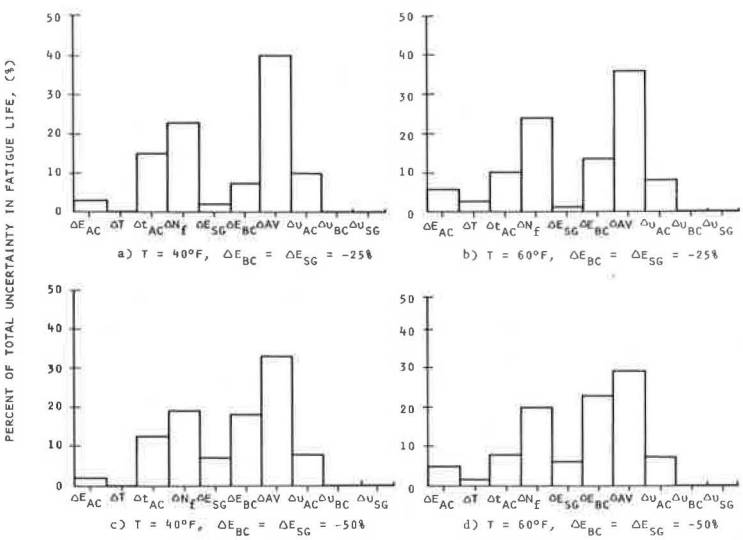



**Figure 8. Relative sensitivity of fatigue life to parameter variations for section 3.**



more, the relative sensitivity results can be utilized to select the areas of pavement research that could prove most beneficial in improving our ability to reduce fatigue failure of pavements. Better control or definition of parameters that induce large uncertainties in fatigue life would result in substantial reductions in highway maintenance costs.

With one exception, variation in the air void content of the asphalt concrete was the single most important parameter inducing uncertainty in the fatigue life of a pavement. It should be recognized that influence of air voids was examined through its effect on both the modulus and fatigue characteristics of the asphalt concrete. This dual influence emphasizes the need for better construction control techniques of asphalt concrete air void content.

The results also indicate that, generally, the second most important parameter variation inducing uncertainty in the fatigue life is that associated with the definition of the fatigue criteria themselves. Although much effort has been spent in developing the currently available fatigue criteria, it appears further work could greatly improve the ability to predict and, therefore, control the fatigue failure of flexible pavements.

The variability in the thickness of asphalt concrete surfacing due to construction practices has a relatively minor influence on the total uncertainty of fatigue life for pavement sections similar to sections 1 and 2. However, for pavements with thin asphalt concrete surfaces (section 3) the control of thickness is more critical.

The temperature parameter variation utilized for the relative sensitivity analysis was selected, based on accurate consideration of the temperature environment currently used in the more recently developed pavement design and analysis methods. Therefore, the variation more closely represents the uncertainty in predicting the average daily temperature rather than the uncertainty in predicting average yearly temperature. The effect of temperature variation was relatively minor for all cases. Methods that consider the temperature regime by an average yearly temperature would induce a much larger uncertainty in fatigue life because of the temperature parameter variation. Overall, the temperature regime itself has more influence on the fatigue life than any parameter considered in this analysis. This fact is not directly evident from the relative sensitivity analysis because the influence of the temperature regime was considered using several macrotemperature levels. In fact, the two levels (micro and macro) of the temperature parameter utilized in this analysis were motivated by this very fact.

The influence of water content and density variations in the base course and subgrade is revealed by comparison of the upper and lower (-25 percent and -50 percent) modular variation relative sensitivity results shown in Figures 6, 7, and 8. Examination of these results reveals that the importance of water content and density variations increases as temperature increases for each structural section. This occurs because the base course and subgrade contribute more to the total strength of the structural section as the temperature increases and the asphalt concrete contribution decreases. Thus, induced base course and subgrade modular variations at higher temperatures become more significant. It appears that measurable improvements in fatigue life could be gained from control and consideration of water content and density variations in the base course and subgrade for pavements in hot climates.

The effect of variations in the asphalt concrete modulus parameter induced by deviations from ideal isotropic linear-elastic behavior and experimental errors is more important for full-depth sections (section 1) than for thin-surfaced sections (section 3). (The uncertainty induced in fatigue life is of major significance for section 1, but of almost no significance for section 3. The effect on fatigue life for section 2 is intermediate, except at 100 F where it is of no practical significance.) Generally, the effect of asphalt concrete modular variations decreases with increase in temperature even though the percentage of variation in modulus used for the relative sensitivity analysis (characterization variations) increased with temperature (Table 2).

The influence of variation of the base course modulus parameter induced by isotropic linear-elastic characterization errors (-25 percent variation) was of similar magnitude to that associated with asphalt concrete modulus for the lower temperatures for section 2 and of greater significance at both temperatures for section 3.

The effect of variation in the subgrade modulus parameter induced by isotropic linear-elastic characterization errors (-25 percent variation) was generally of minor significance. The effect was of most importance for the full-depth section (section 1) and was of practically no significance for section 3.

The influence of variations in the Poisson's ratio parameter for each material was only of minor significance for all structural sections. In some cases, Poisson's ratio variations showed no measurable effect on fatigue life uncertainty.

It should be recognized that all the sensitivity results were based on only the fatigue mode of pavement distress. Although this is a logical initial step for determining the relative significance of adequate constitutive characterizations for each material type, the sensitivity results may be quite different for other modes of pavement distress. A pavement must be designed for all modes of pavement distress to ensure that it provides adequate performance. For example, this sensitivity analysis has shown that the single most important parameter uncertainty contributing to the total uncertainty in fatigue life was control of air voids in the field. The air void content uncertainty above a specified level can be reduced by increasing the asphalt content of the mix or by increasing the density. However, this may result in instability of the mix, unacceptable plastic deformations, and hazardous skid resistance conditions due to flushing of the asphalt. Therefore, all modes of pavement distress need to be considered for a complete definition of an adequate characterization of each material.

## CONCLUSIONS

The results of the relative sensitivity analysis indicate the following conclusions concerning the improvement of prediction and control of flexible pavement fatigue life:

1. The predominant parameter variation causing uncertainty in fatigue life is that associated with construction control of air voids in the asphalt concrete.
2. A more accurate definition of the fatigue failure criteria for asphalt concrete would be more beneficial than improvement of the constitutive material characterization beyond isotropic linear elasticity.
3. The uncertainty associated with characterization of pavement materials by isotropic linear elasticity can contribute significant uncertainty to the prediction of fatigue life. However, this induced uncertainty in fatigue life is of less significance than that induced by field control of air voids or fatigue criteria definition. Improved characterization of asphalt concrete would be most beneficial for full-depth and thick asphalt concrete surface pavements. More accurate characterization of untreated granular base course material would also be advantageous, especially for pavements located in hot climates. An isotropic linear-elastic characterization of subgrades is adequate if the characterization is performed under stress levels representative of in-service subgrades.
4. Consideration of variations in water content and densities of in situ base course and subgrade materials would be beneficial for pavements located in hot climates.
5. Within the existing techniques for considering temperature in the analysis, the ability to predict the temperature is sufficiently accurate.
6. Thickness control of the asphalt concrete layer during construction is currently sufficiently accurate.

It should be recognized that the adequacy of a material characterization is a dynamic phenomenon. As our ability to describe and control the effects of other parameters influencing the fatigue life of flexible pavements improves, currently adequate characterizations may become inadequate.

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