This paper summarizes the development of a workable design approach to analyze fatigue distress of full-depth asphalt airfield pavements. The design method uses multilayered elastic theory coupled with a limiting (critical) strain criterion developed from analysis of field results from the AASHO Road Test. The solution methodology requires that 2 specific functions be evaluated for design: the allowable traffic value function and the predicted traffic value function. The allowable traffic value represents the number of equivalent strain repetitions of a standard aircraft that a given thickness of full-depth pavement can withstand for a particular temperature and subgrade modulus combination. The predicted traffic value represents the number of equivalent aircraft strain repetitions estimated to occur during the selected design period for a given full-depth thickness. The thickness solution is obtained by the simultaneous graphical solution of both traffic value functions. Thickness design curves and aircraft equivalency diagrams are provided from which both traffic value functions are easily obtained. Design input variables needed for the thickness solution are the design subgrade modulus, mean annual air temperature, design period, and aircraft traffic forecast.

# Fatigue Subsystem Solution for Asphalt Concrete Airfield Pavements

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The Asphalt Institute has recently published a revised edition of its manual, Full-Depth Asphalt Pavements for Air Carrier Airports (11). A new thickness design procedure based on multilayered elastic concepts is introduced in the manual as a workable approach to the design of full-depth asphalt airfield pavements (an asphalt pavement in which asphalt mixtures are used for all courses above the subgrade or improved subgrade). The design procedure follows the general concepts of a systems-oriented solution to the overall pavement management process in that 2 unique pavement distress modes are recognized and considered independently in the thickness solution: fatigue of the asphalt concrete layer and permanent deformation within the subgrade layer.

The detailed documentation and analysis leading to the development of the overall design method used in Manual MS-11 can be found in other reports (17, 18). The purpose of this paper is to demonstrate the applicability of the fatigue subsystem distress mode, considered in the manual, as a workable design approach. Although the paper is confined to airfield pavement design technology, the concepts presented are generally applicable as a design approach to highway pavements.

## GENERAL SOLUTION

Figure 1 shows the thickness design procedure; a separate design is required for each of the 2 distress mechanisms previously described. Within each distress mode, 2 separate analyses must be accomplished. The first is termed the "allowable traffic value analysis." The solution yields the allowable number of strain repetitions of a standard aircraft (DC-8-63F) that a given thickness of full-depth pavement can sustain for a given distress type and a particular set of subgrade and environmental conditions. The second is termed the "predicted traffic analysis." The solution yields the predicted number of equivalent strain repetitions of the standard aircraft (DC-8-63F) due to the anticipated aircraft traffic mixture forecast for the service life of the airfield pavement.

The input necessary for the solution of the allowable traffic value analysis is the design subgrade modulus $E_s$ and the mean annual air temperature t for the design location. Mean air temperature data for most design locations are readily available through various weather bureau summaries and do not present any great problem in obtaining that design factor. The design subgrade modulus of elasticity $E_s$ is determined by 1 of 3 methods: direct measurement as described in the manual, an approximate relation to CBR, or an approximate relation to plate-bearing values.

The direct determination is made by a repeated load triaxial compression test detailed in the manual. The commonly used method of determining subgrade strength for airport pavements, the California bearing ratio (CBR), makes use of the relation $E_s$ = 1,500 CBR. AASHO Test Method T 193 or ASTM Test Method D 1883 is used for the CBR test. Samples are compacted according to method B or D of ASTM Test Method D 1557 (AASHO Test Method T 180).

The requirements for the plate-bearing test are detailed in Manual MS-10. The relation to $E_s$ is given in the design manual. The test is performed on compacted subgrade in trial sections prepared exactly as it will be done for the finished pavement.

Knowledge of those 2 variables allows one to select the appropriate design chart in Manual MS-11 for the distress mode considered. A schematic illustration of a typical allowable traffic curve is shown in Figure 2a for the fatigue mode of distress for a particular $E_s$ and t. The curve represents the allowable number of strain repetitions $N_a$ of the standard aircraft that a given full-depth pavement thickness can sustain in fatigue.

For the predicted traffic analysis, the requisites for solution are a prediction of the specific aircraft types and associated traffic levels of each aircraft within the design period evaluated. From that information, the predicted traffic curve can be developed from aircraft equivalency diagrams found in Manual MS-11. That curve is shown in Figure 2b and represents, at a given asphalt concrete thickness $T_A$, the number of equivalent strain repetitions of the standard aircraft caused by the anticipated aircraft mixture within the design life considered. The thickness solution for the fatigue subsystem is determined by the intersection of the 2 curves shown in Figure 2c. That is, at the design $T_A$ value, the predicted number of equivalent strain repetitions due to the mix is equal to the allowable number of fatigue strain repetitions of the standard aircraft that the pavement thickness can sustain for the given subgrade and environmental conditions.

## SUMMARY OF FACTORS CONSIDERED

The mechanics of the general solution provided in Manual MS-11 for either distress mode are quite straightforward. Required input variables are confined to those normally needed for most pavement design problems. Hence, the basic approach to the fatigue solution presented provides a workable system that can be used with identical input parameters required for most empirical design approaches.

Factors considered in the allowable traffic analysis, which has inputs of $E_s$ and t, are as follows:

- $E_n$, $\nu_n$, and $h_n$ = stress and strain states evaluated through multilayered theory and used to determine critical horizontal tensile strain values at the bottom of asphalt-bound layer;
- $N_f$-$\epsilon$ = failure criterion developed from actual pavement performance studies;
- $\sum(n_i/N_f)$ = 1, Miner's hypothesis, used as cumulative fatigue damage model;
- $E_1$-t-f = asphalt concrete characterization, average dynamic modulus-temperature-frequency response of dense-graded asphalt concrete mixtures obtained from laboratory tests;

$f$ = design frequency or rate of loading ($f$ = 2 cps) selected as representative loading rate of dual tandem standard aircraft gear at taxiway speed of 10 to 20 mph;
$m_q$ = monthly modulus distribution, which accounts for the predicted monthly distribution of asphalt concrete modulus for design environmental conditions (prediction based on field pavement temperature studies); and
$E_s$ = subgrade modulus, which accounts for variation in subgrade support due to effects of anticipated freeze-thaw conditions of subgrade.

Factors considered in the predicted traffic analysis, which has inputs of $j$, $p_j$, and $L_d$, are as follows:

$j$ = aircraft type, which accounts for specific aircraft types in the anticipated aircraft mix;
$p_j$ = number of passes, which considers predicted traffic volume levels for each aircraft type in the mix;
$L_d$ = design life, which allows for design solution to be determined for any desired service life;
$S$, $P$, and $p_t$ = aircraft characteristics, which includes the unique load distributing characteristics of each aircraft type in the mix, e.g., gear type, tire spacings, load per tire, and tire pressure;
$X_j$ = point of load application, which accounts for differences between aircraft types in the lateral distance between aircraft and main gear centerline; and
$\sigma_w$ = lateral wander effect of channelized taxiway traffic conditions.

The remaining sections of this paper discuss how those fundamental characteristics have been incorporated into the solution of the fatigue subsystem for full-depth airfield pavements.

## ALLOWABLE TRAFFIC ANALYSIS

### Allowable Traffic (Fatigue) Expression

The development of the design fatigue equation (allowable traffic equation) was accomplished through a series of multiple regression equations.

1. The monthly pavement temperature frequency distribution equation characterizes the mean and standard deviation of monthly pavement temperature distribution from mean monthly air temperature data. The equation is based on correlation studies from field tests in Arizona, Maryland, and New York and is valid only for thick (>10.0 in.) asphalt concrete layers.

$$\overline{t_{p_m}} = B_0 \left(\overline{t_{a_m}}\right) + B_1$$

$$\sigma = B_2 \tag{1}$$

where

$\overline{t_{p_m}}$ = mean monthly pavement temperature;
$\overline{t_{a_m}}$ = mean monthly air temperature;
$\sigma$ = standard deviation of pavement temperature; and
$B_0$, $B_1$, and $B_2$ = constants with values 1.05, 5, and 5 respectively.

2. The asphalt concrete modulus-temperature relation equation predicts the dynamic modulus of a dense-graded asphalt concrete mix for a given temperature. The rate of loading applicable for the equation is $f$ = 2 cps and is based on regression analysis of laboratory dynamic modulus test results.

$$E_1 = \frac{K_0}{K_1^{q^{d_1}}} \tag{2}$$

where

$q$ = pavement temperature; and
$K_0$, $K_1$, and $d_1$ = constants with values $3.8 \times 10^5$, 1.0046, and 1.45 respectively.

3. The multilayered principal asphalt concrete tensile strain for standard aircraft equation predicts the maximum principal tensile strain at the bottom of the full-depth pavement due to the standard aircraft (DC-8-63F) at the conditions of $h_1$, $E_1$, and $E_2$. Poisson's ratio values used to develop the equation are 0.40 and 0.45 for asphalt concrete layer and subgrade soil respectively.

$$\epsilon = \frac{M_0}{h_1^{A_1} E_1^{A_2} E_2^{A_3}} \tag{3}$$

where

$\epsilon$ = maximum principal tensile strain at bottom of asphalt concrete layer due to DC-8-63F aircraft;
$h_1$ = thickness of full-depth pavement;
$E_1$ = modulus of asphalt concrete layer;
$E_2$ = subgrade modulus of elasticity; and
$M_0$, $A_1$, $A_2$, and $A_3$ = constants with values $1.086 \times 10^3$, 1.19967, 0.66866, and 0.320867 respectively.

4. The fatigue criteria equation predicts the relation between the allowable number of tensile strain repetitions to failure and the associated tensile value for a given pavement temperature. Criteria were developed from analysis of AASHO Road Test data for thick asphalt concrete layers.

$$N_{f_q} = ab^{q^{d_1}} \left(\frac{1}{\epsilon}\right)^c \tag{4}$$

where

$N_{f_q}$ = number of allowable tensile strain repetitions at pavement temperature q;
$\epsilon$ = as defined in Eq. 3; and
a, b, c, and $d_1$ = constants with values $1.86351 \times 10^{-17}$, 1.01996, 4.995, and 1.45 respectively.

The major relation is that noted by Eq. 4, which expresses the fatigue criterion for a typical asphalt concrete mixture. Figure 3 shows that criterion in terms of mix temperature defined in accordance with Eq. 2. The equations given above coupled with Miner's hypothesis for cumulative damage on a monthly basis allowed the development of the following basic fatigue equation:

$$h_1 = T_A = \left[ \frac{N_f M_0^c}{12aK_0^{A_2c}} \sum_{i=1}^{12} \sum_{j}^{J} \left( \frac{m_{q_{ij}} K_1^{A_2 c q_j^{d_1}}}{b^{q_j^{d_0}} E_2 i^{A_3 c}} \right) \right]^{\frac{1}{A_1 c}} \tag{5}$$

Equation 5 yields the required thickness of full-depth asphalt concrete $T_A$ for the fatigue distress mode for a given allowable number of strain repetitions $N_f$, subgrade modulus for the i th month $E_2 i$, and monthly temperature data. $m_{q_{ij}}$ represents the monthly frequency of the i th month that the pavement temperature q will be within a certain temperature interval, $q_{ij} \pm \alpha$. The subscript j denotes the j th pavement temperature interval, 10 F. Therefore, even though mean air temperatures are used as input for any given month, the solution is based on a predicted normal distribution (frequency) of pavement temperatures for that month. A more thorough development and explanation of the equation is given in an earlier report (17).

Figure 1. Airport pavement thickness design procedure.

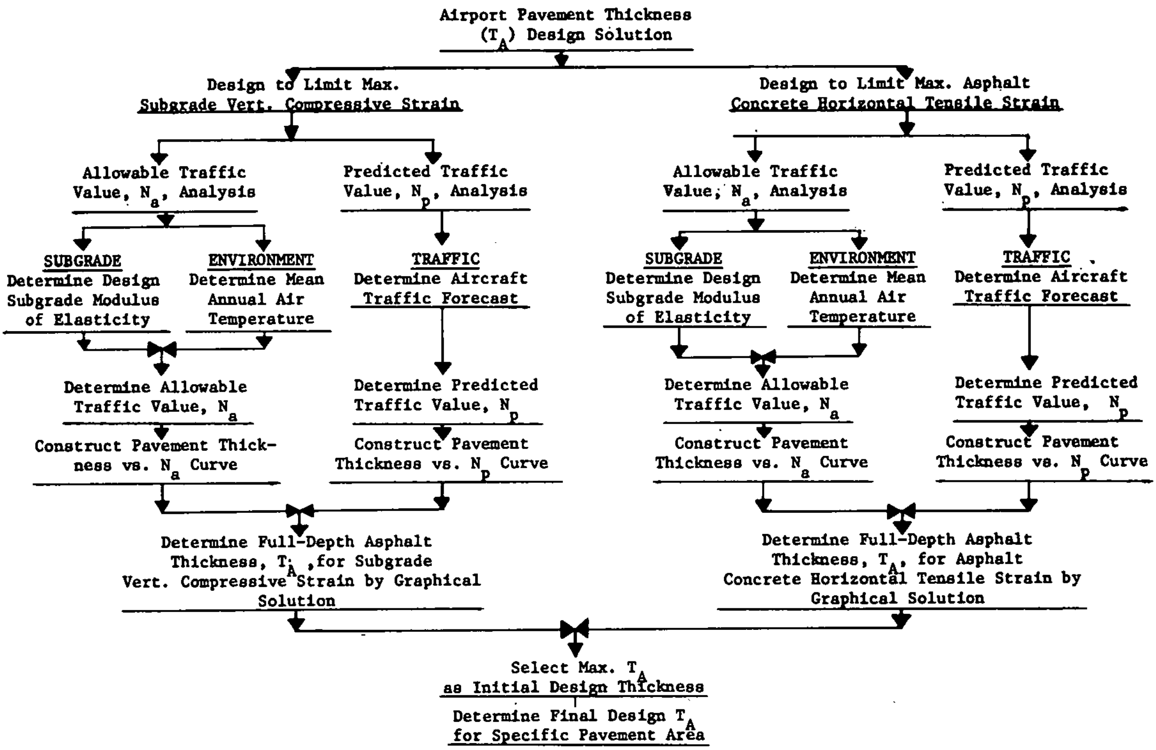



Figure 2. Schematic solution for $T_A$ design.

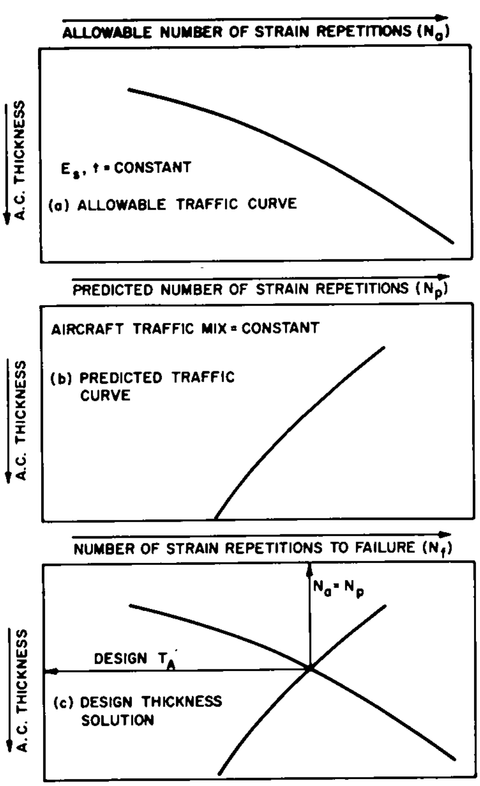
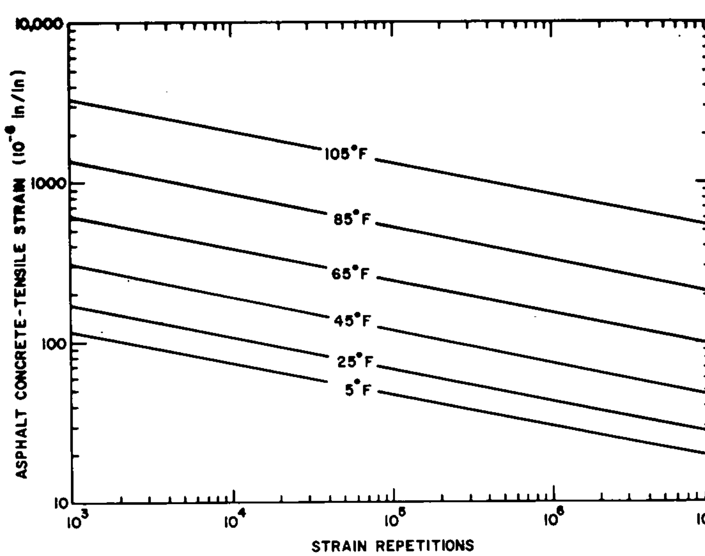



Figure 3. Allowable asphalt concrete tensile strain criteria.



## Environmental Effects

The major significance of the model developed is that it allows the effects of monthly variations of both predicted temperature distribution and subgrade support values to be investigated. Hence, through use of this expression, a comprehensive study was conducted to ascertain certain environmental effects on design thickness requirements for full-depth pavements.

A full-depth asphalt pavement possesses load-distributing characteristics similar to classical flexible and rigid pavement systems. The behavior is primarily influenced by the modulus of the asphalt layer, which in turn is significantly dependent on the pavement temperature. The extreme dependency of the elastic layered response (stress and strain) to the modulus logically implies that identical full-depth pavements should perform differently in differing environmental situations.

As an example of this aspect, Figure 4 shows a comparison of predicted yearly frequency distribution of moduli for thick asphalt concrete pavements placed in Brownsville, Texas, and in Winnipeg, Canada. The difference in the predicted distributions is apparent. For example, the mean moduli values are about 250,000 psi for Brownsville and 1,100,000 psi for Winnipeg. The percentage of the year the moduli will be above 500,000 psi is about 5 percent in the warm Texas climate and about 75 percent in Canada. In concept, if placed in the colder climate, the full-depth asphalt concrete modulus will approach values quite typical of that of a rigid pavement condition during a larger relative proportion of the year. Conversely, the yearly percentage when the asphalt concrete modulus will be in a more flexible state if placed in the Texas location should also be readily observable. It is subsequently felt that, for thick asphalt concrete pavements, the effect of environment on structural design considerations is as important a design variable as subgrade support and traffic.

## Predicted Monthly Damage Percentage

The design equation developed for the fatigue subsystem allowed the determination of the predicted monthly damage distribution for any environmental input; monthly temperature and subgrade modulus values are used in the predictions. Figure 5 shows the predicted fatigue in Swea City, Iowa. Monthly air temperature values for the site were translated into monthly pavement temperature frequencies from Eq. 1. Monthly subgrade modulus values were selected based on the anticipated duration of freezing and thawing developed from a freezing index analysis of the site. For this case, a normal modulus $E_{2_n}$ of 6,000 psi was selected with a minimum modulus of 0.4 $E_{2_n}$ during the thaw period and a maximum subgrade modulus of 4.0 $E_{2_n}$ during the freeze. Monthly moduli for the other months were selected by assuming that a linear relation existed between the normal, frozen, and thawed states.

Also shown in Figure 5 is the distribution of actual pavement failures (main factorial study) observed by month at the AASHO Road Test. The temperature and subgrade modulus distribution for the predicted damage location, although not identical, is quite similar to that found at Ottawa, Illinois, the site of the AASHO Road Test. Even though the actual distribution of pavement failures is for flexible (granular base) pavements and the predicted values are based upon full-depth concepts, the general agreement in magnitude and trends is felt to be quite encouraging and supports the basic model used in the analysis.

## Effect on Full-Depth Thickness

The effect of both variable monthly pavement temperature and subgrade values on full-depth thickness was determined by an analysis of more than 130 locations in North America through a computerized solution of the fatigue equation developed. Figure 6 shows the results of that study. Data are plotted by the mean annual air temperature of each site investigated against a thickness adjustment factor $T_F$. That factor is the ratio of the thickness obtained by a monthly cumulative damage model for the variable monthly conditions to the thickness obtained at a constant subgrade modulus and an arbitrarily selected constant pavement temperature of 40 F.

Figure 4. Yearly frequency distributions of asphalt concrete moduli for 2 locations.

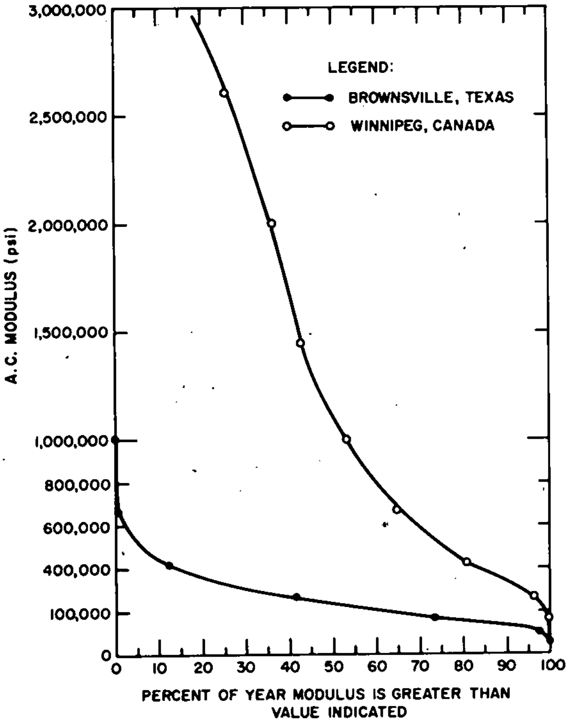



Figure 5. Predicted monthly fatigue damage to actual monthly failure distribution of main experiment.

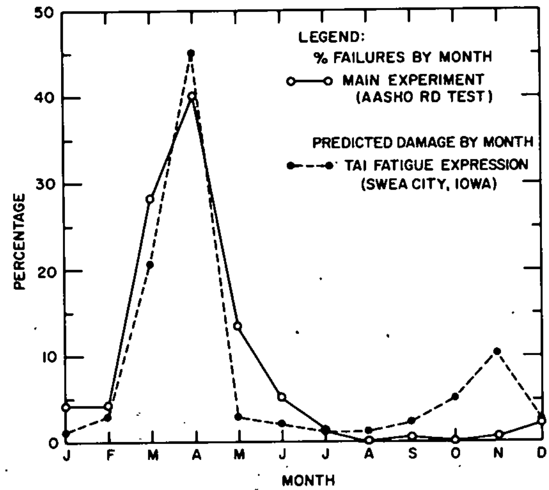
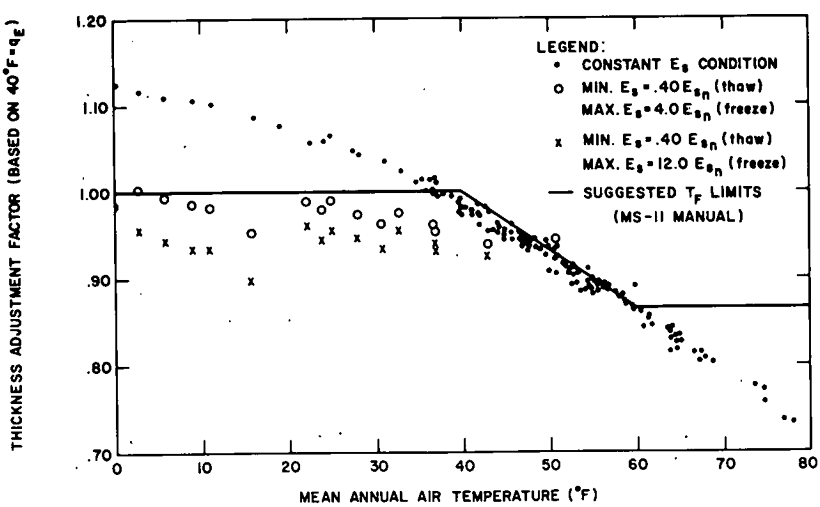



Figure 6. Suggested thickness adjustment factors for asphalt concrete tensile strain analysis.



Analyses were based on the assumption that the subgrade modulus would be constant throughout the year and would also vary because of freeze-thaw conditions in accordance with the procedure previously described. The results of that study show that, for the constant yearly subgrade modulus condition, greater full-depth thicknesses are required for colder conditions because of fatigue cracking within the asphalt-bound layer. However, when variable subgrade conditions are introduced to take into account monthly variations in modulus due to anticipated freeze-thaw states, thickness requirements generally occur below that shown for a constant subgrade condition corresponding to a mean annual air temperature of approximately 40 F.

The explanation for that occurrence is that during cooler periods, although tensile strains are more critical, the probability of a very stiff subgrade due to frozen conditions may be large. Therefore, the large frozen subgrade modulus results in extremely smaller tensile strains than would be obtained at the normal or constant subgrade modulus. Dempsey and Marek also found that to be conceptually true in their theoretical study of the bidaily radial stress and strain predictions of several test sections of the AASHO Road Test (10). Based on a combined heat-transfer model for evaluating the temperature regime and frost-line position in the pavement system and an elastic layer model for stress and strain determination, they found that during most of the frozen subgrade period the horizontal state of stress and strain existing at the asphalt concrete base interface was either close to zero or actually transferred into a compression phase.

Based on that analysis, the $T_F$ limits selected for use in Manual MS-11 are also shown in Figure 6. The lower limit of the adjustment factor used ($T_F = 0.866$) corresponds to a mean annual air temperature of approximately 60 F. That arbitrary limit was selected primarily on the basis of a conservative safety factor.

## Effective Temperature Concept

One of the important features of the developmental work leading to the fatigue subsystem design in Manual MS-11, and one with extreme practical applications, is that of the effective temperature concept (17). An effective pavement design temperature $q_e$ is defined as the unique pavement temperature at which the allowable number of strain repetitions to failure, obtained by using the variable monthly design equation, is equal to the failure repetitions obtained from Eq. 4 at $q = q_e$; the tensile strain value for the design load is calculated from multilayered theory at an asphalt concrete modulus corresponding to a temperature of $q_e$.

Figure 7 shows the relation between the mean annual air temperature for the design location and the effective pavement temperature to be used for the fatigue criterion. Figure 8 shows the relation between the mean annual air temperature and the effective asphalt concrete modulus to be used in the multilayered analysis of the tensile strain.

## Example Problem

The significance of using the thickness adjustment factor $T_F$ and the effective temperature $q_e$ methods to obtain an identical solution to the fatigue problem is demonstrated in the following example.

A full-depth pavement is to be analyzed for fatigue of the asphalt pavement layer. The subgrade modulus is 7,500 psi. The design aircraft is a DC-8-63F (358,000-lb max gross weight). Poisson's ratios of the asphalt and subgrade layers are 0.40 and 0.45 respectively. The mean annual air temperature at the design location is 60 F.

In the thickness adjustment factor analysis method, the basic fatigue criterion is always defined as q = 40 F by fatigue Eq. 4. Likewise, the asphalt concrete modulus used to evaluate the tensile strain is always 1,450,000 psi. A multilayered analysis using the Shell BISTRO computer solution for the design aircraft and $h_1 = 20$ in., $E_1 = 1{,}450{,}000$ psi, $\nu_1 = 0.40$, $E_2 = 7{,}500$ psi, and $\nu_2 = 0.45$ resulted in a maximum principal tensile strain of 137 $\mu$in./in. Based on q = 40 F and $\epsilon = 137 \times 10^{-6}$ in./in. from Eq. 4, the number of strain repetitions to failure for the fatigue distress mode is approximately 20,000. The design mean annual air temperature is 60 F, and the $T_F$ value for that location is $T_F = 0.866$. Therefore, the acutal full-depth thickness that would sustain 20,000 repetitions to failure would be $h_a = h_1(T_F) = 20(0.866) = 17.32$ in. In summary, a full-depth pavement 17.32 in. thick placed in a design locale having a mean annual air temperature of 60 F would be able to withstand approximately 20,000 strain repetitions of a DC-8-63F aircraft.

In the effective temperature concept analysis procedure, data shown in Figures 7 and 8 are used to determine the effective pavement temperature for use in the fatigue equation and the effective asphalt concrete modulus to be used in the multilayered analysis of the tensile strain. For a design air temperature of 60 F, $q_e$ = 62 F (Fig. 7). The effective asphalt concrete modulus $E_e$ is approximately 600,000 psi. For comparable conditions of the problem solved by the $T_F$ method, the multilayered input used is $h_1$ = 17.32 in., $E_1$ = 600,000 psi, $v_1$ = 0.40, $E_2$ = 7,500 psi, and $\nu_2$ = 0.45. The multilayered analysis of the DC-8-63F aircraft with the Shell BISTRO computer solution results in a tensile strain value of 280 $\mu$in./in. Therefore, the allowable number of strain repetitions to failure by fatigue Eq. 4 with $q_e$ = 62 F and $\epsilon = 280 \times 10^{-6}$ in./in. is 19,513.5 or 19,500. That value compares quite well with the 20,000 strain repetitions predicted by the $T_F$ method.

## Typical Fatigue Curves

Based on the concepts presented, full-depth design curves for the fatigue distress mode developed by the $T_F$ analysis are presented in Manual MS-11. A typical set of those curves is shown in Figure 9. The curves already incorporate the required thickness adjustment factor. The number of strain repetitions refers to the standard aircraft.

As noted previously, the only input needed for the solution of the allowable traffic curve is the mean annual air temperature and design subgrade modulus. A typical allowable traffic curve (fatigue mode only) is shown in Figure 10 for $E_s$ = 15,000 and t = 50 F. The $T_A$ values were obtained for the various strain repetition curves at an $E_s$ = 15,000 psi from the 50 F design curve shown in Figure 9.

# PREDICTED TRAFFIC ANALYSIS

## Predicted Traffic (Fatigue) Expression

The allowable traffic curves previously presented express the thickness of full-depth pavement necessary to prevent the fatigue mode of distress for any desired number of strain repetitions of a standard aircraft. The aircraft selected as the standard for use in Manual MS-11 is the DC-8-63F (358-kip maximum gross weight). The DC-8-63F, therefore, is the airfield design counterpart of the familiar 18-kip axle load used as the standard design vehicle in many highway pavement design methods. Because a standard aircraft is used, the effects of differing aircraft types on the cumulative fatigue damage are incorporated into the fatigue subsystem through the use of aircraft equivalency factors, which indicate the relative damage caused by any particular aircraft to that caused by the standard aircraft.

Unlike most highway considerations, the analysis of mixed airfield traffic possesses 3 important characteristics that distinguish it from the typical equivalency analysis commonly used in highway applications.

1. Each aircraft type has its own unique load-transmitting system; that is, the family of aircraft main gears comprises differing tire spacings, gear types, locations, gear loads, and tire pressures. That contrasts with the typical grouping of most highway vehicles in that the primary variable is a rather restricted range of axle loads, while tire pressures, spacings, and gear types vary over a relatively small range and may, for the most part, be considered as constants among vehicular types.
2. In highway pavements, the lateral wander effect of moving vehicles is extremely small and can be effectively assumed to be nonexistent. This implies that one pass, or movement, of a highway vehicle will cause one strain (stress or damage) repetition at the critical design location. However, airfield design studies have indicated that lateral distribution of aircraft should be considered for a more accurate estimate of the traffic analysis (4, 13, 14). Even for channelized taxiway conditions, N passes of an aircraft may not yield N strain repetitions at the maximum damage location but rather some defined percentage of that value.

Figure 7. Mean annual air temperature and effective pavement design temperature for establishing fatigue criterion.

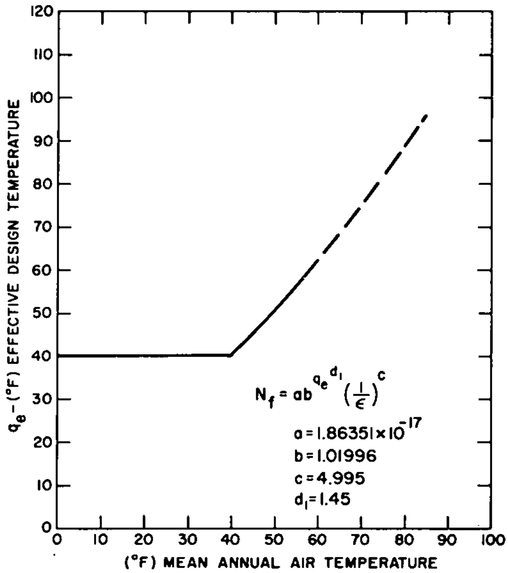



Figure 8. Mean annual air temperature and effective asphalt concrete modulus to be used in multilayer analysis for evaluating critical tensile strain.

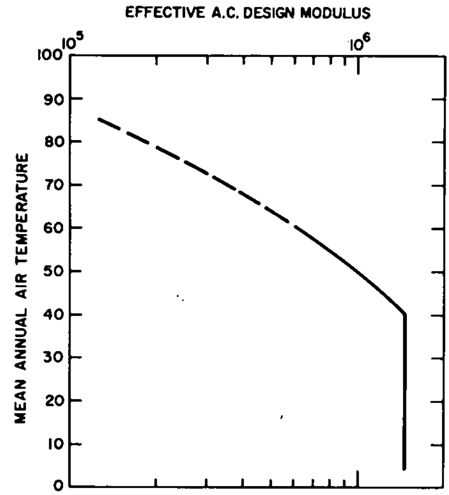
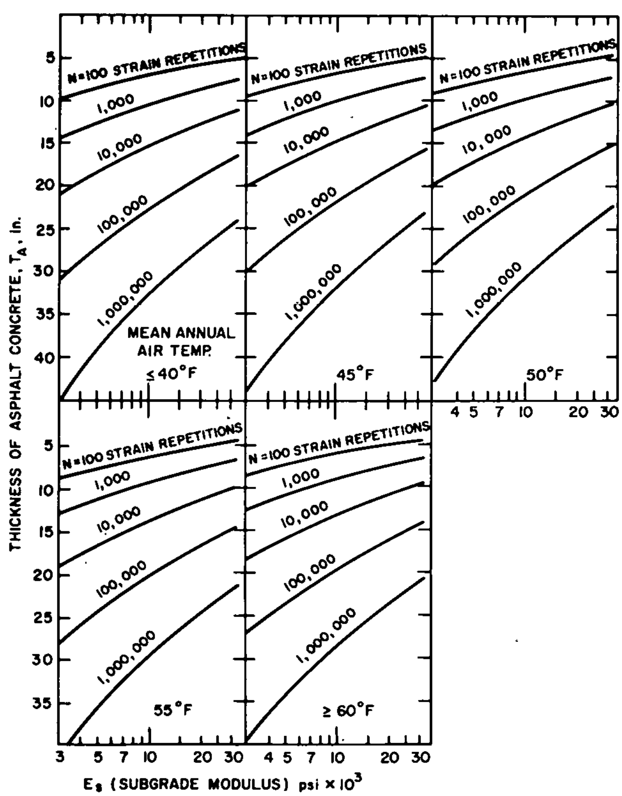



Figure 9. Design curves for asphalt concrete fatigue distress.



3. The final difference between the 2 types of analysis is the mean lateral location of the point of load application. In highways, the mean location is slightly more than 2 ft from the pavement edge and is assumed to be equal for all vehicular types. In airfield analysis, the distribution of aircraft is centered about the pavement centerline (taxiway or runway). For that situation, it is obvious that the point of maximum damage due to the main gear loads will differ significantly among the aircraft types because of inherent differences (6 to 19 ft) in the transverse spacings between aircraft and main gear centerlines. Consequently, 2 aircraft having those pronounced differences in gear locations and moving directly along the taxiway centerline would not cause strain or damage repetitions at the same location.

The aircraft traffic mixture analysis used in Manual MS-11 incorporates each of the characteristics. That results in a method that allows the determination of both the maximum anticipated number of equivalent DC-8-63F strain repetitions and the transverse taxiway location where that maximum damage will occur.

The design expression developed to account for the predicted mixture of aircraft traffic in the fatigue design of the critical taxiway is

$$n_e = \max \sum_{j=1}^{J} p_j f_{jx} F_{jh} \qquad (6)$$

where

- $n_e$ = the maximum (design) equivalent DC-8-63F strain repetitions predicted across (transverse) the taxiway;
- $p_j$ = number of taxiway passes of the j th aircraft;
- $f_{jx}$ = transverse distribution factor that relates the frequency percentage of tensile strain repetitions at the x th lateral taxiway interval (1 ft wide) due to the j th aircraft;
- $F_{jh}$ = equivalent aircraft damage factor of the j th aircraft on a full-depth pavement h thick (in this paper, the factor relates the equivalent damage only due to the fatigue mode of distress); and
- h = constant.

A detailed development of Eq. 6 can be found in another report (18).

Figure 11 shows, in schematic form, the basic concepts behind the equivalent damage equation: the frequency of strain repetitions along the taxiway for the 2 aircraft and the number of strain repetitions occurring along the taxiway due to p passes of each aircraft type. The product of the strain repetitions at a given interval with the equivalent damage factor yields the number of equivalent repetitions of the standard aircraft along the taxiway for each aircraft. Summing the equivalent repetitions, at a given interval for both aircraft, gives the cumulative distribution of equivalent repetitions across the taxiway. That is shown by the diagram at the bottom of the figure. The maximum value and its corresponding location yield the desired $n_e$ value of the design equation.

In the design expression, the aircraft passes are data input determined from an analysis of the anticipated aircraft traffic for the airfield in question. The solution, therefore, depends on the establishment of the transverse distribution factor $f_{jx}$ and the equivalent aircraft damage factor $F_{jh}$ for the specific aircraft in the mix.

## Characteristics of Design Expression

### Transverse Distribution Factor $f_{jx}$

The $f_{jx}$ factor represents the frequency of strain repetitions at the taxiway interval; x = (a - b) for the specific aircraft in question. That factor accounts for the lateral wander distribution $\sigma_w$ of channelized taxiway traffic and the lateral distance between aircraft and main gear centerlines $X_j$ for each specific aircraft type. The fundamental concept behind the $f_{jx}$ factor is that the lateral distribution of the maximum principal tensile strain is normally distributed and can be characterized by $u = \pm X_j$, $\sigma_w$ for all aircraft.

Studies have shown that, for channelized taxiway traffic, $\sigma_w$ is approximately 40 in. or about 3.5 ft. Because $X_j$ is unique for each aircraft type, the continuous normal distribution defined by those parameters can be translated into discrete frequency values f′, taken at 1-ft-wide taxiway intervals by the probability equation

$$f'_{(a-b)} = P_r\ (a < x < b) = P_r\ (x > a) - P_r\ (x > b) \tag{7}$$

Those discrete frequency values would be equivalent to the $f_{jx}$ value provided the width of the distressed region (strain width) is exactly 1 ft. That, however, is not the case for almost all aircraft. As a simplifying assumption, the effective width of the principal horizontal tensile strain at the bottom of the asphalt layer was selected to be equal to 2S (where S is the center-to-center spacing between outermost tires, in transverse direction, of the aircraft main gear). That assumption gives very excellent agreement with a more detailed study conducted by Deacon (4) using the actual variable transverse strain distribution for multiwheel aircraft. A further discussion of that comparison is given in another report (18).

Use of the foregoing assumption, coupled with the normal distribution characterization parameters previously defined, allowed the determination of $f_{jx}$ factors for 22 selected jet aircraft. Table 1 gives those values at selected taxiway intervals for the aircraft noted. The practical interpretation of the table is that, if 100 passes of a DC-9-41 aircraft occurred on a taxiway, 21 tensile strain repetitions (DC-9-41) would occur at a location ±12.5 ft from the taxiway centerline.

Equivalent Damage Factor $F_{jh}$

The $F_{jh}$ value indicates the unit damage caused by the j th aircraft relative to the unit damage caused by the standard s aircraft. For the fatigue distress mode, the $F_{jh}$ factor is $R^c$, where $R = (\epsilon_{tj}/\epsilon_{ts})$, the ratio of the maximum principal tensile strain of the j th aircraft relative to the maximum principal tensile strain of the standard aircraft evaluated under identical multilayered pavement conditions, and c represents the slope of the allowable fatigue criterion noted in Eq. 4.

The maximum principal tensile strain in the asphalt-bound layer in a full-depth pavement is a function of

$$\epsilon_t = f(j,\ h_1,\ E_1,\ E_2,\ v_1,\ v_2) \tag{8}$$

For a given aircraft type and constant Poisson's ratio values of 0.40 and 0.45 for the asphalt and subgrade layer respectively, the tensile strain and, hence, R value are analytically functions of the thickness $h_1$ and layered moduli values $E_1$ and $E_2$.

A multilayered study was undertaken to ascertain to what degree, if any, those variables influenced the $R_j$ value. Figure 12 shows a partial summary of the $R_j$ results developed. The major conclusion that can be drawn from that study is that, for all practical purposes, the $F_j$ factor is a function only of the asphalt concrete pavement thickness $h_1$. Because the particular set of moduli values used for both layers appears to be insignificant, the $F_{jh}$ values for fatigue distress are also applicable for layered systems comprising more than 2 layers. Similar conclusions have also been independently obtained by Deacon (4).

$F_{jh}$ values for the fatigue mode of distress for the 22 aircraft previously given in Table 1 were computed from multilayered theory by the use of the Shell BISTRO computer program. Individual aircraft gear characteristics were used for each layered input solution to determine the maximum principal tensile strain value. Constant layer moduli of $E_1$ = 500,000 psi and $E_2$ = 7,500 psi were selected for all problems analyzed. However, to take into account the effect of varying stress pulses (load frequency) on $E_1$ at a constant temperature, triple tandem aircraft gears were analyzed at an $E_1$ = 420,000 psi (approximately 1 cps), and dual tire aircraft gears were analyzed at an effective $E_1$ = 600,000 psi (approximately 4 cps). The standard aircraft has a dual tandem gear configuration corresponding to a frequency of about 2 cps for the design taxiway velocity chosen. Table 2 gives the $F_{jh}$ values for the selected aircraft. The

Figure 10. Allowable traffic value curve for asphalt concrete horizontal tensile strain.

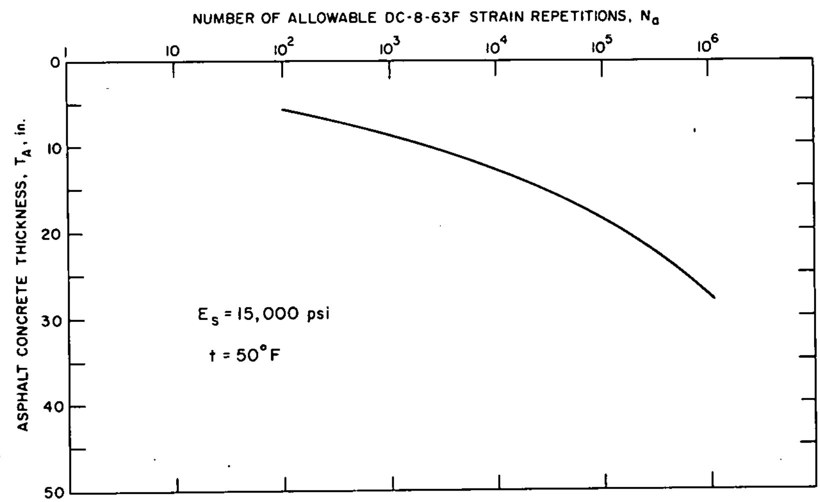
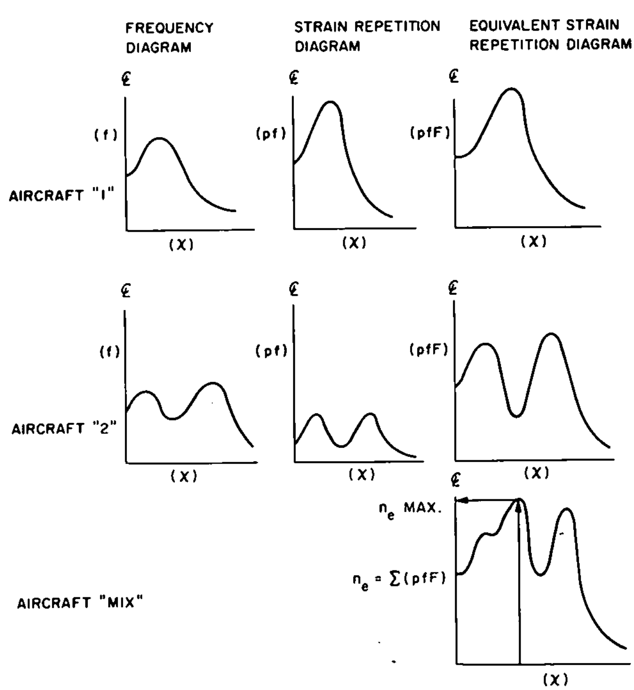



Table 1. $f_{jx}$ values for various intervals from taxiway centerline.

| Aircraft | 0-1 Ft | 4-5 Ft | 8-9 Ft | 12-13 Ft | 16-17 Ft | 20-21 Ft | 24-25 Ft | Max |
|---|---|---|---|---|---|---|---|---|
| B-747 | 0.45 | 0.68 | 0.62 | 0.45 | 0.68 | 0.59 | 0.18 | 0.71 |
| B-747F | 0.45 | 0.68 | 0.62 | 0.45 | 0.68 | 0.59 | 0.18 | 0.71 |
| B-707-320C | – | 0.15 | 0.52 | 0.60 | 0.23 | 0.02 | – | 0.64 |
| B-707-120B | – | 0.15 | 0.52 | 0.60 | 0.23 | 0.02 | – | 0.64 |
| B-720 | – | 0.11 | 0.44 | 0.51 | 0.18 | 0.01 | – | 0.54 |
| B-727-200 | 0.05 | 0.28 | 0.62 | 0.47 | 0.12 | – | – | 0.66 |
| B-737-200C | 0.05 | 0.30 | 0.56 | 0.30 | 0.04 | – | – | 0.56 |
| CV-990 | – | 0.14 | 0.42 | 0.36 | 0.09 | – | – | 0.46 |
| CV-880M | 0.01 | 0.17 | 0.44 | 0.32 | 0.06 | – | – | 0.46 |
| L-500 | 0.01 | 0.22 | 1.00 | 1.66 | 1.24 | 0.36 | 0.02 | 1.66 |
| L-1011-8 | – | – | 0.06 | 0.38 | 0.71 | 0.49 | 0.11 | 0.71 |
| L-1011-1 | – | – | 0.06 | 0.38 | 0.79 | 0.72 | 0.27 | 0.83 |
| DC-10-30CF | – | – | 0.09 | 0.44 | 0.81 | 0.67 | 0.23 | 0.84 |
| DC-10-10 | – | – | 0.09 | 0.44 | 0.81 | 0.67 | 0.23 | 0.84 |
| DC-8-63F | – | 0.15 | 0.48 | 0.48 | 0.15 | – | – | 0.56 |
| DC-8-61 | – | 0.15 | 0.48 | 0.48 | 0.15 | – | – | 0.56 |
| DC-9-41 | 0.07 | 0.29 | 0.46 | 0.21 | 0.02 | – | – | 0.46 |
| DC-9-15 | 0.07 | 0.29 | 0.46 | 0.21 | 0.02 | – | – | 0.46 |
| Concorde | – | 0.03 | 0.24 | 0.46 | 0.24 | 0.03 | – | 0.46 |
| BAC-1-11-500 | 0.14 | 0.36 | 0.42 | 0.14 | – | – | – | 0.46 |
| VIS-810 | – | 0.03 | 0.21 | 0.33 | 0.15 | 0.01 | – | 0.33 |
| SE-210-6R | 0.03 | 0.19 | 0.36 | 0.19 | 0.02 | – | – | 0.36 |

Figure 11. Schematic solution of basic equivalent damage equation.



interpretation of the data given in Table 2 is that an L-1011-8 aircraft is about 4 times (3.843) as damaging in the fatigue mode of distress as the DC-8-63F on a 20-in. full-depth pavement.

## Methods of Solution

### Manual Version

For a given aircraft type, the predicted traffic equation is

$$n_{e_x} = p_j f_{jx} F_{jh} \tag{9}$$

That equation, in logarithmic form, is linear with a slope of 1, and the intercept is defined by a unique combination of j, h, and x.

$$\log n_{e_x} = \log p_j + \log C \tag{10}$$

where $C = f_{jx} F_{jh}$.

The form of Eq. 10, which is valid for all aircraft, enables aircraft equivalency diagrams to be developed that relate the number of equivalent DC-8-63F tensile strain repetitions to the number of taxiway passes of the aircraft in question. Each relation defined is for a unique interval x and asphalt concrete thickness $h_1$.

That is the method presented in Manual MS-11 for the solution of the predicted traffic equation. A typical fatigue equivalency diagram from the manual is shown in Figure 13 for the L-1011-8 aircraft. Similar diagrams for all 22 aircraft given in Table 1 are presented for asphalt concrete thicknesses of 10, 30, and 50 in. A simple solution to determining the predicted traffic values is given in Manual MS-11; work sheets are included for use in a step-by-step solution.

### Computerized Version

Although the equivalency diagrams previously discussed can be used for any anticipated aircraft mixture, their use becomes quite laborious when many different aircraft types, traffic volumes, and design periods are evaluated. To alleviate that situation, a computer program was developed for the solution of any aircraft mixture forecast within the service life of the full-depth pavement. That program, itself, forms one of the subroutines of The Asphalt Institute's full-depth airfield design computer program.

The only input required by the design engineer is a traffic forecast of the aircraft types and estimated number of taxiway passes of each aircraft anticipated during given time intervals (5-year period) up to the service life. The program computes the distribution of the standard aircraft strain repetitions along specified taxiway intervals for asphalt concrete thicknesses of 10, 20, 30, and 40 in. for both modes of distress and determines the maximum design strain repetition value and transverse location of that maximum damage for the input data. An example illustrates the use, results, and interpretations of the program.

Table 3 gives a typical format entry of the input data. The numbers represent the anticipated number of taxiway passes within a 5-year period for each aircraft. The designer has complete flexibility to incorporate anticipated increases or decreases in traffic volume by aircraft type or take into account future aircraft types within the total forecast.

Figure 14 shows a plot of the typical output for the given aircraft mixture. The results shown are only for $h_1$ = 10 in., 20-year service life, and asphalt concrete tensile strain (fatigue) mode of distress. For those conditions, the maximum number of DC-8-63F strain repetitions due to the mix is approximately 130,000, and the maximum damage location occurs at about ±9.5 ft from the taxiway centerline.

Table 4 gives the summary version of the program output data. That portion summarizes the maximum strain repetitions and location of maximum damage, 4 levels of asphalt concrete thickness, and a 20-year service life. Similar results are also

Figure 12. Effect of various design parameters on ratio of principal tensile strains.

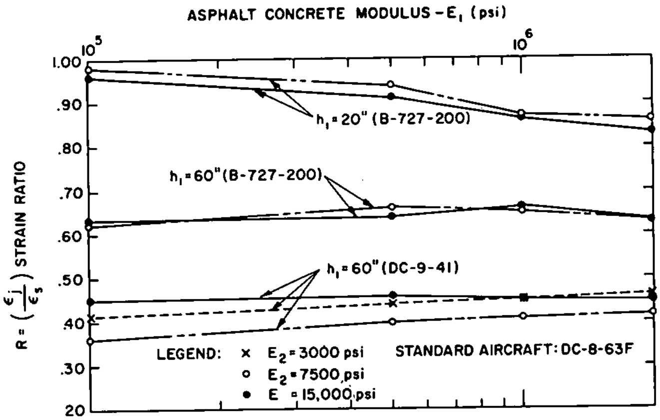



Table 2. $F_{jh}$ values for various asphalt concrete pavement thicknesses.

| Aircraft | 10 In. | 20 In. | 30 In. | 40 In. | 50 In. |
|---|---|---|---|---|---|
| L-500 | 0.368 | 0.721 | 1.098 | 1.49 | 1.832 |
| B-747-F | 0.594 | 1.383 | 2.197 | 3.045 | 3.742 |
| B-747 | 0.392 | 0.876 | 1.970 | 2.158 | 2.393 |
| L-1011-8 | 1.692 | 3.843 | 6.234 | 8.542 | 10.863 |
| DC-10-30 | 0.594 | 0.843 | 1.000 | 1.096 | 1.229 |
| DC-10-10 | 0.700 | 0.736 | 0.824 | 0.752 | 0.796 |
| L-1011-1 | 0.619 | 0.707 | 0.938 | 0.716 | 0.698 |
| Concorde | 0.820 | 1.432 | 1.665 | 2.335 | 2.652 |
| DC-8-63F | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| B-707-320C | 0.480 | 0.639 | 0.772 | 1.000 | 0.994 |
| DC-8-61 | 0.635 | 0.626 | 0.652 | 0.638 | 0.602 |
| B-707-120B | 0.158 | 0.189 | 0.233 | 0.255 | 0.270 |
| CV-990 | 0.277 | 0.446 | 0.547 | 0.606 | 0.698 |
| B-720B | 0.113 | 0.149 | 0.180 | 0.198 | 0.211 |
| CV-880M | 0.134 | 0.166 | 0.188 | 0.195 | 0.220 |
| B-727-200 | 0.645 | 0.303 | 0.172 | 0.119 | 0.088 |
| DC-9-41 | 0.264 | 0.076 | 0.037 | 0.022 | 0.015 |
| B-737-200C | 0.126 | 0.047 | 0.024 | 0.015 | 0.013 |
| SE-210-6R | 0.013 | 0.012 | 0.013 | 0.011 | 0.013 |
| BAC-1-11-5 | 0.291 | 0.063 | 0.026 | 0.014 | 0.009 |
| DC-9-15 | 0.084 | 0.026 | 0.011 | 0.007 | 0.005 |
| VIS-810 | 0.069 | 0.015 | 0.006 | 0.003 | 0.002 |

Table 3. Taxiway passes for various service-life intervals.

| Aircraft | 0-5 Years | 5-10 Years | 10-15 Years | 15-20 Years |
|---|---|---|---|---|
| DC-8-63F | 2,000 | 3,000 | 5,000 | 8,000 |
| DC-8-61 | 10,000 | 10,000 | 8,000 | 8,000 |
| DC-9-41 | 9,500 | 12,000 | 13,500 | 16,000 |
| DC-9-15 | 6,500 | 7,000 | 7,500 | 8,000 |
| B-707-120B | 7,500 | 6,000 | 5,000 | 4,000 |
| B-720 | 2,000 | 2,000 | 2,000 | 2,000 |
| B-727-200 | 40,000 | 50,000 | 65,000 | 80,000 |
| B-737-200C | 8,000 | 10,000 | 12,000 | 15,000 |
| CV-880M | 8,000 | 7,000 | 6,000 | 5,000 |
| BAC-1-11 | 2,000 | 1,500 | 1,500 | 1,000 |

Figure 13. Typical aircraft fatigue equivalency diagram.

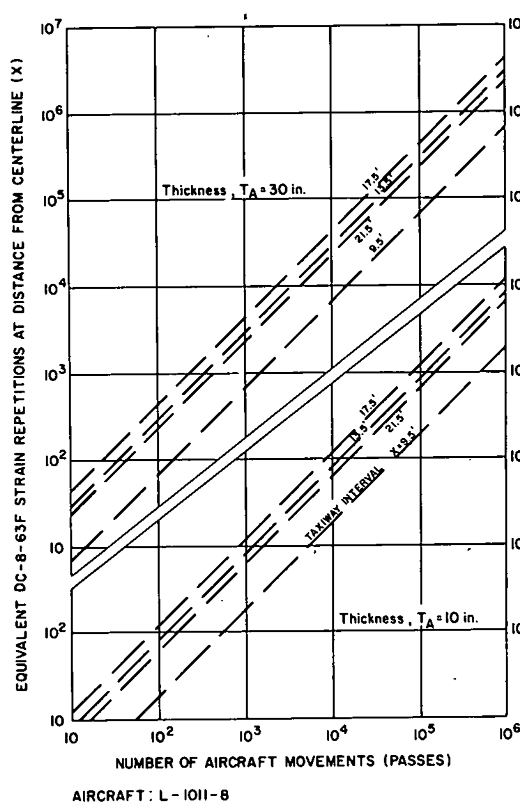


Figure 14. Computer program results of aircraft traffic mix analysis.

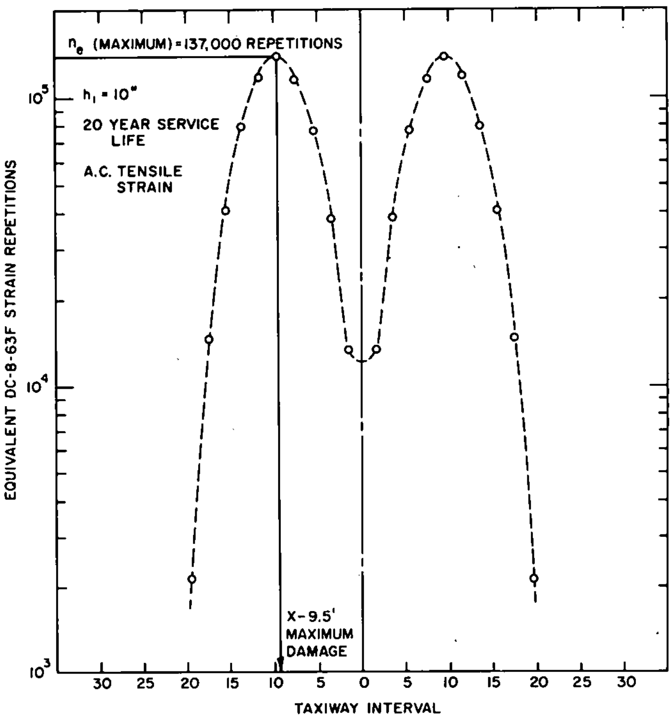



Table 4. Maximum equivalent DC-8-63F strain repetitions at various depths through year 20.

| Analysis | Asphalt Concrete Thickness (in.) | Taxiway Interval (ft) | Max |
|---|---|---|---|
| Asphalt concrete tensile strain | 10 | 9 to 10 | 137,103 |
| | 20 | 9 to 10 | 77,896 |
| | 30 | 9 to 10 | 57,101 |
| | 40 | 9 to 10 | 48,362 |
| Subgrade vertical strain | 10 | 9 to 10 | 134,099 |
| | 20 | 9 to 10 | 30,262 |
| | 30 | 9 to 10 | 20,162 |
| | 40 | 9 to 10 | 18,122 |

**Figure 15. Predicted traffic value curve.**

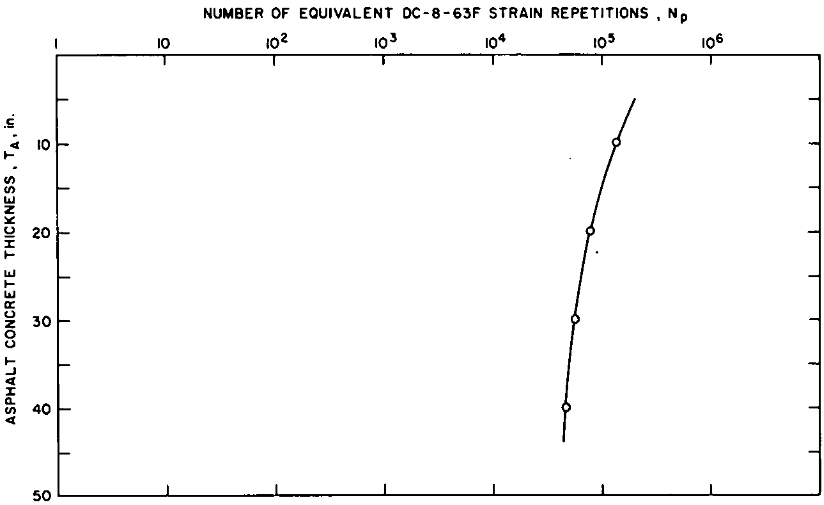
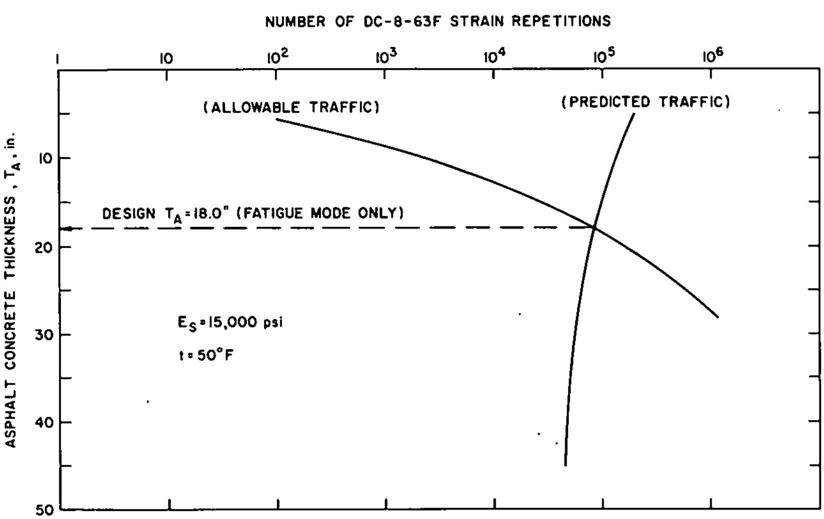



**Figure 16. Solutions of full-depth asphalt concrete thickness requirements to satisfy fatigue distress mode.**



generated for service lives of 5, 10, and 15 years for the mixture and allow the designer to use the traffic forecast for staged-construction purposes. The availability of the program allows a rapid method of analyzing even the most complex aircraft traffic mixtures. The final predicted traffic curve, for the fatigue mode of distress, for the data given in Table 6 is shown in Figure 15.

## SUMMARY

The solution of the predicted traffic value curve allows the final design thickness requirement for the fatigue distress mode to be determined from the allowable traffic value results. The solution is made by a simultaneous graphical solution of both traffic value curves. Figure 16 shows the solution for the subgrade modulus and temperature data shown in Figure 10 and the 20-year design analysis for the aircraft mix given in Table 3.

For that problem, the full-depth thickness requirement for the fatigue mode of failure is 18.0 in. That thickness requirement only satisfied the fatigue criterion, and another separate analysis has to be made to determine the thickness requirements to satisfy the permanent deformation (subgrade shear failure) mode of distress. The final design thickness requirement would be the larger of those 2 values.

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