Research Report
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A Computerized Analysis of Flexible Pavement Rutting Behavior (PAVRUT)

by

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INTRODUCTION

Flexible pavements are known to fail in several modes, one of which is rutting. In an effort to determine where in the pavement structure and to what extent rutting occurs and to determine the factors that control rutting, a comprehensive laboratory testing program was performed. Various traffic and environmental parameters were controlled in the study; and from the data, mathematical models that describe the rutting characteristics of an asphalt concrete, a dense-graded aggregate, and a subgrade soil were formulated. Details of the materials, equipment, and laboratory procedures were reported by Allen in a previous report (1). Also, the mathematical models were described in that report and are listed again in this report for convenience. A traffic and a temperature model were also formulated to provide necessary input into the rutting models. These are described in this report.

These models have been programmed and collected into a large computer program entitled PAVRUT. Using this program, an estimated rut depth can be calculated for any flexible pavement, assuming the volume and characteristics of the traffic stream are known.

CALCULATED RUT DEPTHS FROM PROGRAM

There are a number of figures included in Appendix A that show the relationship between the total rut depth of a pavement and thicknesses of asphaltic concrete and dense-graded aggregate. Curves were developed for four CBR values of the subgrade and four different values of equivalent 18-kip axleloads (EAL's). These curves can be used to estimate the amount of rutting expected for a particular structure after being subjected to some number of EAL's. To determine the estimated rut depth for some value of EAL or CBR not shown on the charts, linear interpolation may be used. This procedure is not entirely correct because the relationship between rut depth, CBR, and EAL is not linear. However, the error is small and is not significant for estimating purposes.

Because speed affects the length of time a tire print is on the pavement, which in turn affects the amount of rutting in the asphaltic concrete layers, an average vehicle speed of 50 miles per hour was assumed for the charts.

It should be noted that the charts in Appendix A apply only to new construction. If it is desired to estimate rutting for a new overlay on an old portland cement concrete pavement, Figure 1 must be used. In this type of problem, the program assumes that no rutting occurs in the concrete slab.

Charts in Appendix A can also be used to estimate rutting for a new asphaltic overlay on an old flexible pavement. As an example, a pavement with 6 inches (152 mm) of asphaltic concrete on 5 inches (127 mm) of dense-graded aggregate, and a subgrade CBR of 20 is to receive a 2-inch overlay. Also, assume the original structure has received one million EAL's. From the charts in Appendix A, the estimated rut depth for this condition would be 0.32 inches. After receiving the overlay, the new structure is to receive four million EAL's (this would make a total number of repetitions for the original portion of the structure equal to five million). Again, from the charts, five million repetitions for the original structure would yield a rut of 0.65

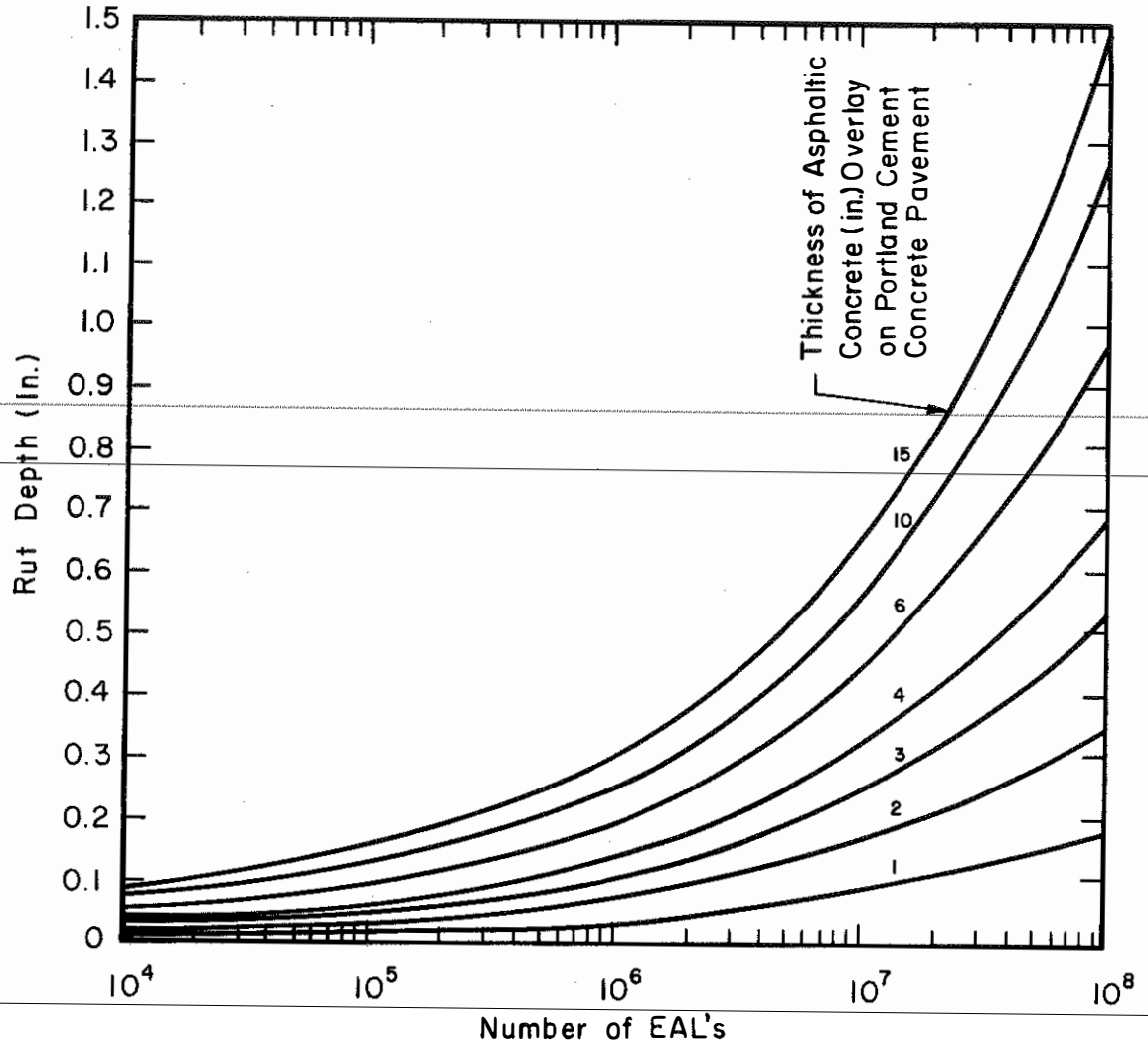


Figure 1. Estimated Rut Depths for Overlays on Portland Cement Concrete Slabs.

inches. However 0.32 inches occurred before the overlay. Therefore, 0.65 inches minus 0.32 inches equals 0.33 inches of additional rutting in the original portion of the structure after the overlay was placed. Although not entirely correct, Figure 1 can be used to estimate the rutting in the 2-inch overlay. From that figure, four million repetitions on the 2-inch overlay would result in 0.13 inches of rut. Therefore the total rut depth for the overlaid pavement after four million repetitions is equal to 0.33 inches plus 0.13 inches or 0.46 inches.

Care should be taken when running the program when the top layer is relatively thick. When reading in the depths at which the pavement stresses are calculated, the mid-point of the layer is always used. This technique assumes the distribution of stress from top to bottom is linear. This is not true, particularly for the layer immediately under the load (top layer). Consequently, if the upper layer is too thick, the stress for that layer will be underestimated. However, as depth in the pavement increases, this approximation becomes more accurate. Therefore, to avoid this problem, it is best to keep the top layer thickness less than 4 or 5 inches (102 or 127 mm).

In all charts in Appendix A, the total pavement structure was assumed to be 48 inches (1.2 m). Therefore, as the thickness of the asphaltic concrete and dense-graded aggregate layers increased, the thickness of the subgrade was reduced accordingly.

For values of EAL of 100,000 or less, for asphaltic concrete thickness of 2 inches (51 mm) and with no dense-graded aggregate, the calculated rut depth is sometimes less than that for the case with 5 inches (127 mm) of dense-graded aggregate. This is particularly true for higher values of subgrade CBR, because of the difference of response between the dense-graded aggregate model and the subgrade model. Dense-graded aggregate is more sensitive to rutting in the first few cycles than is the subgrade (the slope of the strain versus number-of-cycles curve for dense-graded aggregate is less than for subgrade materials). However, subgrade rutting quickly "catches up" with dense-graded aggregate rutting and becomes considerably more susceptible to rutting (dense-graded aggregate strain hardens more quickly).

COMPARISON OF CHARTS WITH FIELD MEASUREMENTS

Only one field site has been compared to the rutting charts. This site is at Station 141+50 on KY 627 in Clark County. The pavement structure is comprised of approximately 5/8 inch (16 mm) of asphalt surface, 5.5 inches (140 mm) of asphaltic concrete base, 9.5 (241 mm) inches of dense-graded aggregate and a limestone rock subgrade. A CBR value of approximately 50 was assumed for the subgrade. At the time the comparison was made, the pavement had been subjected to approximately 1.2 million EAL's. The measured rut depth was 0.30 inch (7.6 mm). Estimating and interpolating from the charts, the estimated value is 0.294 (7.5 mm). This is only two percent less than the actual value; this appears to be a good estimate.

DESCRIPTION AND OPERATIONS OF THE PROGRAM

MAIN PROGRAM

All input data is read into the MAIN PROGRAM. The following variables are input parameters:

TITLE - problem title or identification,
ANVOL - volume of vehicles,
SPEED - average speed of vehicles,
TRUCK - input as either 1.0 or 0.0, depending on whether trucks are to be treated separately from cars (it is 1.0 when trucks are separated),
IGIMIC - input as either 1 or 0 (1 if stresses are to be calculated at each new temperature and 0 if stresses are to be calculated at only one temperature),
ICON - input as either 1 or 0 (1 if the problem involves an overlay on a concrete slab),
NS - number of layers
PSIC - tire pressure for cars,
WGTC - wheel load for cars,
PSIT - tire pressure for trucks (if variable TRUCK is 0, this variable will be 0),
WGTT - wheel load for trucks (if variable TRUCK is 0, this variable will be 0),
LYN - layer number,
HH - layer thickness,
ANSDPT - depth at which rutting is calculated (from the surface),
MATYP - material type (1 = asphaltic concrete, 2 = dense-graded aggregate, 3 = subgrade),
W - moisture content (if this variable is not assigned a value, the program will assume one),
SIGMA3 - confining pressure for dense-graded aggregate and subgrade (if this variable is not assigned a value, the program will assume one),
CBR - California bearing ratio for subgrade (this variable is left blank when reading data for asphaltic concrete and dense-graded aggregate), and
V - Poisson's ratio for each layer.

Detailed instructions for input are given in Appendix B.

All output is printed from the MAIN PROGRAM. An example output is shown in Appendix B.

There are 8,760 hours in a 365-day year. To be entirely correct, it would be necessary to calculate stresses, temperatures, and traffic volumes for each hour of the year, and from those calculations, determine the amount of rutting in each layer for that particular hour, and finally, sum all rutting values for 8,760 hours to obtain the total rut accumulated in one year. However, this would consume an extremely large amount of computer time. Therefore, it was assumed that each month would have a "typical" day, so far as traffic and temperature are concerned. Subsequently, traffic and temperatures are determined for each hour of each "typical" day of the year. This means the program must cycle through each subroutine 288 times for each layer (12 "typical" days times 24 hours per day). In other words, to calculate rutting for one pavement, the program will cycle through most subroutines (except subroutine STRESS -- to be mentioned later) a total number of times equal to 288 multiplied by the number of layers.

The program will solve for rutting in any flexible pavement system having up to 15 layers. However, it should be noted the program

requires a large amount of computer time, and the amount of time required increases rapidly with each additional layer to be analyzed. Figure 2 shows the approximate amount of CPU time required as a function of number of layers (when IGIMIC is 0). An important word of caution should be given; variable IGIMIC should always, under normal runs, be 0. This is a CPU time-saving device. When IGIMIC is 1, stresses are calculated for each "typical" hour of the month. As mentioned earlier, this means the pavement stresses must be solved 24 times for each month or 288 times for a year for each layer. Each time the stresses are calculated, a matrix with dimensions of 396 by 15 must be solved, consumming a tremendous amount of time. Therefore, when the program is run with IGIMIC equal to 1, each run could cost several hundred dollars! Whereas, with IGIMIC equal to 0, a three-to-four layer problem can generally be run for less than 20 dollars. When IGIMIC is 0, pavement stresses are calculated only once for each month. Therefore, in a year, stresses are calculated only 12 times for each layer instead of 288 times. Obviously, this is a compromise on accuracy. Although the impact of this time-saving gimic has not been fully evaluated for all cases, it appears that on most problems this does not greatly affect the outcome.

A maximum of two classes of vehicles can be input per problem (such as automobiles and trucks) with a different wheel load and tire pressure for each vehicle class. However, if only one class of vehicle is used, the program assumes that 20 percent of the annual volume is truck traffic. Details on how annual volume is converted to actual wheel-passes per hour are described in the section entitled BLOCK DATA.

The following is a list of the major subroutines in the program:

1. ACRUT,
2. DGARUT,
3. SUBRUT,
4. POLYRT,
5. TEMP,
6. EMOD,
7. BLOCK DATA, and
8. STRESS.

Each subroutine will be discussed separately, and a source listing of PAVRUT is given in Appendix C.

SUBROUTINE ACRUT

This subroutine calculates the magnitude of expected rutting in the asphaltic concrete layers. The algorithm used was developed from experimental data obtained in the laboratory testing program. To predict the accumulation of rutting in the field, due to repeated service loads, it is necessary to determine the susceptibility of the asphaltic concrete mixture to deformation. To determine this susceptibility, twenty-seven unconfined repeated-load tests were performed on an asphaltic concrete base (asphalt cement grade was AC-20). The tests were run at three temperatures: 45 °F (7 °C), 77 °F (25 °C), and 100 °F (38 °C). Three vertical loads were used at each temperature: 80 psi (551 kPa), 50 psi (345 kPa), and 20 psi (138 kPa). A detailed discussion of methodology, equipment, and analyses for these tests is given in Reference 1.

Figure 3 is an example of the repeated-load data. A least-squares

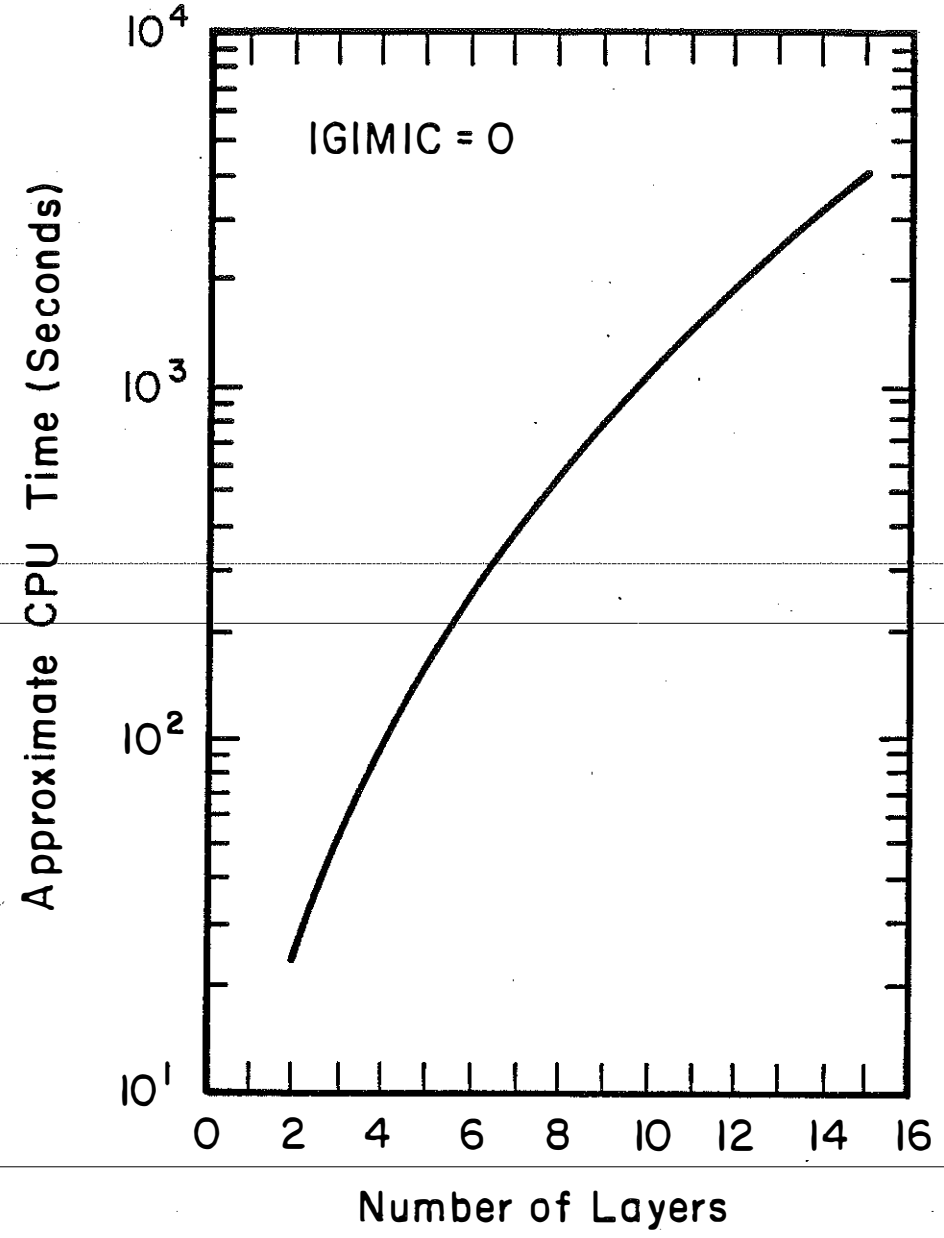


Figure 2. Number of Pavement Layers Versus CPU Time.

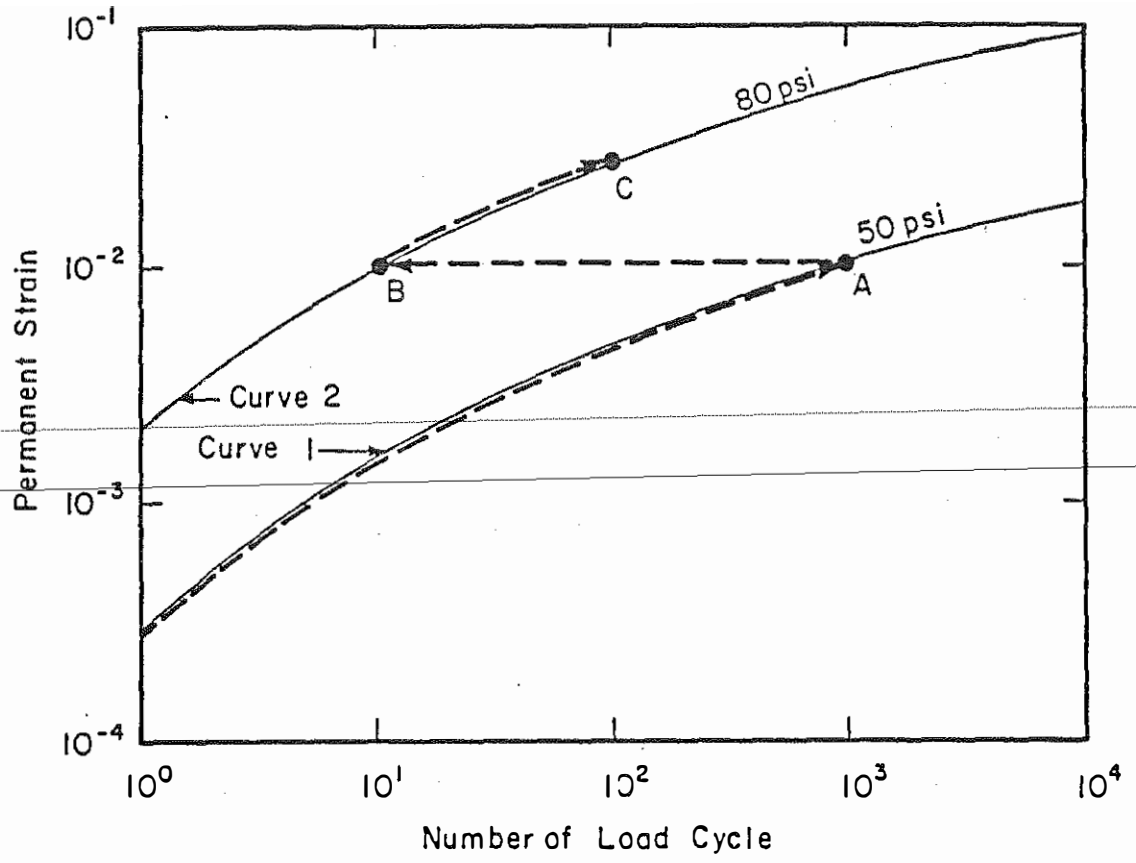


Figure 3. Illustration of How Permanent Strain is Accumulated for Two Different Loading Sequences.

regression analysis of all data resulted in an equation that described plastic deformation (rutting) as a function of temperature, stress, and load repetitions:

$$\log E_p = C_0 + C_1(\log N) - C_2(\log N)^2 + C_3(\log N)_3, \quad (1)$$

in which E_p = permanent strain,

N = number of stress repetitions,

$C_3 = 0.00938$,

$C_2 = 0.10392$,

$C_1 = 0.63974$,

$C_0 = [-0.000663\ T^2 + 0.1521\ T - 13.304] + [(1.46-0.00572\ T)\ (\log \sigma_1)]$,

T = temperature (°F), and

σ_1 = stress (psi).

The laboratory study indicated that samples at the same temperature and under the same stress will have the same amount of permanent deformation, assuming the total loading times are equivalent. For example, one sample might be subjected to 10 cycles of an 80-psi (551-kPa) stress where each cycle had a load duration of 1.0 second. This would give a total loading time of 10 seconds. A second sample might receive 20 cycles of the same stress for 0.5 second per cycle and also have a total loading time of 10 seconds. Therefore, their permanent deformations will be equal. Subroutine ACRUT uses this relationship to convert from a number of wheel passes per hour to total load time per hour. The average speed in miles per hour is converted to feet per second, and assuming a 1-foot tire print, this is converted to the amount of time each wheel contacts a particular point on the pavement. This is then multiplied by hourly volume to obtain total loading time for each hour.

Adding to the complexity of determining the permanent deformation of a particular sample or portion of flexible pavement is the fact that asphalt concrete is very sensitive to its previous temperature or stress history. For example, the permanent deformation produced by N_2 repetitions, of a stress of magnitude F_2 at a temperature of T_2 would vary greatly depending upon whether the sample had previously received N_1 repetitions of F_1 stress at temperature T_1. This is more clearly illustrated in Figure 3. In that figure, a hypothetical specimen has received 1,000 cycles of a 50 psi-stress, producing 0.01 strain (Point A, Curve 1). At the same time, the specimen has also been strained to an amount equivalent to 10 cycles of an 80-psi stress (Point B, Curve 2). If it were desired to add an additional 100 cycles of the 80-psi stress, the strain would progress along Curve 2 from Point B to Point C. Thus, this pattern of stress history would produce a total strain

of approximately 0.028.

To add the effects of different stress and temperature sequences, it becomes necessary to determine the abcissa value of some Point "B", as was done in the example in Figure 3. To accomplish this, the equation for curve 2 (see equation 1) must be set equal to the ordinate value of Point "B", and the roots of the third-degree polynomial are calculated, giving the abcissa value of Point "B". The roots of the polynomial are calculated in a subroutine entitled POLYRT (to be discussed later), and the values are transferred back to subroutine ACRUT and are used as the starting value of repetitions from which to begin the next sequence of loading.

Subroutine ACRUT continues, in the manner described above, to calculate the strain for each "typical" hour of the year and accumulates that strain with all the previously calculated hours until a full year is completed.

The above described rutting model does account for the decrease in void content under increasing repetitions of axleloads (See Reference 1).

SUBROUTINE DGARUT

Accumulated deformations in the dense-graded aggregate base are calculated by this subroutine. The algorithm in this subroutine was also developed from data obtained from a series of repeated-load tests on laboratory compacted specimens. The tests were performed at moisture contents of 1.7, 3.6, and 5.3 percent. Confining pressures of 5 psi (34 kPa), 10 psi (69kPa), and 15 psi (103 kPa) were used in the tests and, in addition deviator stresses of 10 psi (69 kPa), 20 psi (138 kPa), and 30 psi (207 kPa) were applied at each confining pressure. This was a total of 27 tests. Details of sample preparation, materials, and procedures have been reported by Allen (1).

As in the case for asphaltic concrete, analysis of the repeated-load test data (an example is shown in Figure 5) resulted in a third-degree polynomial describing the plastic deformation as a function of stress level, confining pressure, moisture content, and load repetitions:

$$\text{Log } E_p = C_0 + C_1(\log N) + C_2(\log N)^2 + C_3(\log N)^3 \qquad (2)$$

in which Ep = permanent strain,

N = number of repetitions,

$C_3 = 0.0066 - 0.004(\log W)$,

$C_2 = -0.142 + 0.092(\log W)$,

$C_1 = 0.72$,

$C_0 = [-4.41 + (0.173 + 0.003\ W)\ (\sigma_1)] - [(0.00075 + 0.0029\ W)\ (\sigma_3)]$,

W = moisture content (percent),

σ_1 = deviator stress (psi), and

σ_3 = confining pressure (psi).

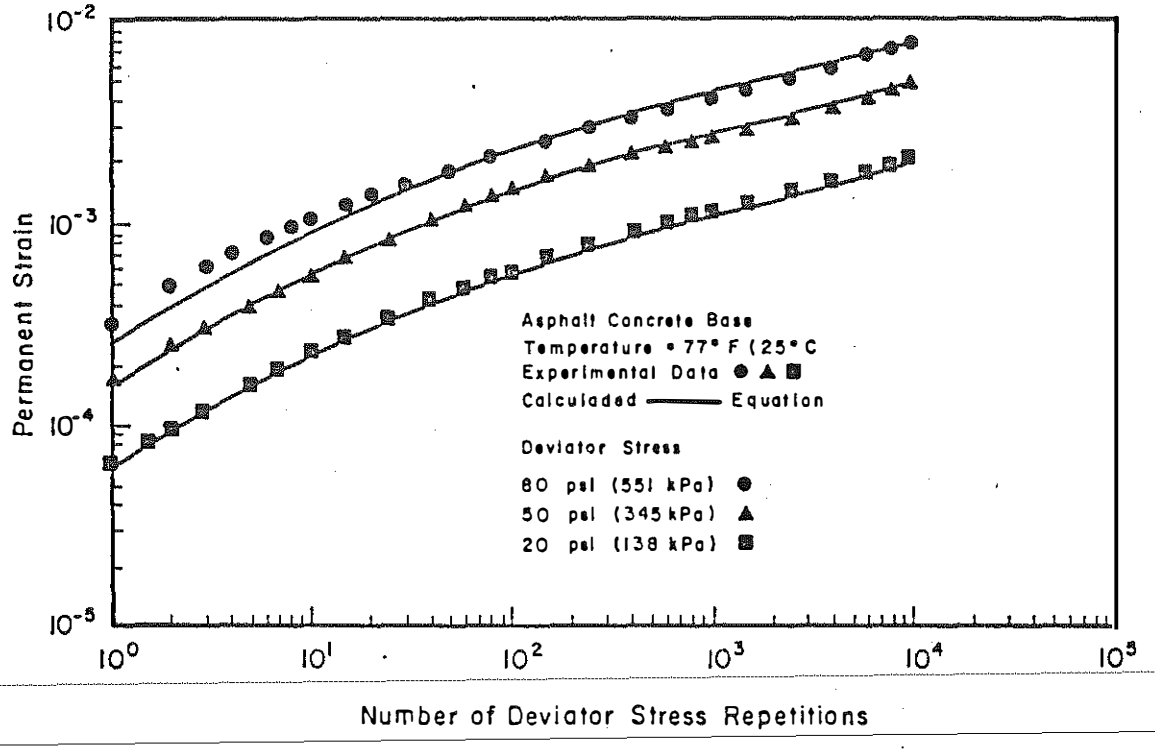


Figure 4. Permanent Strain as a Function of Number of Load Cycles (Asphaltic Concrete).

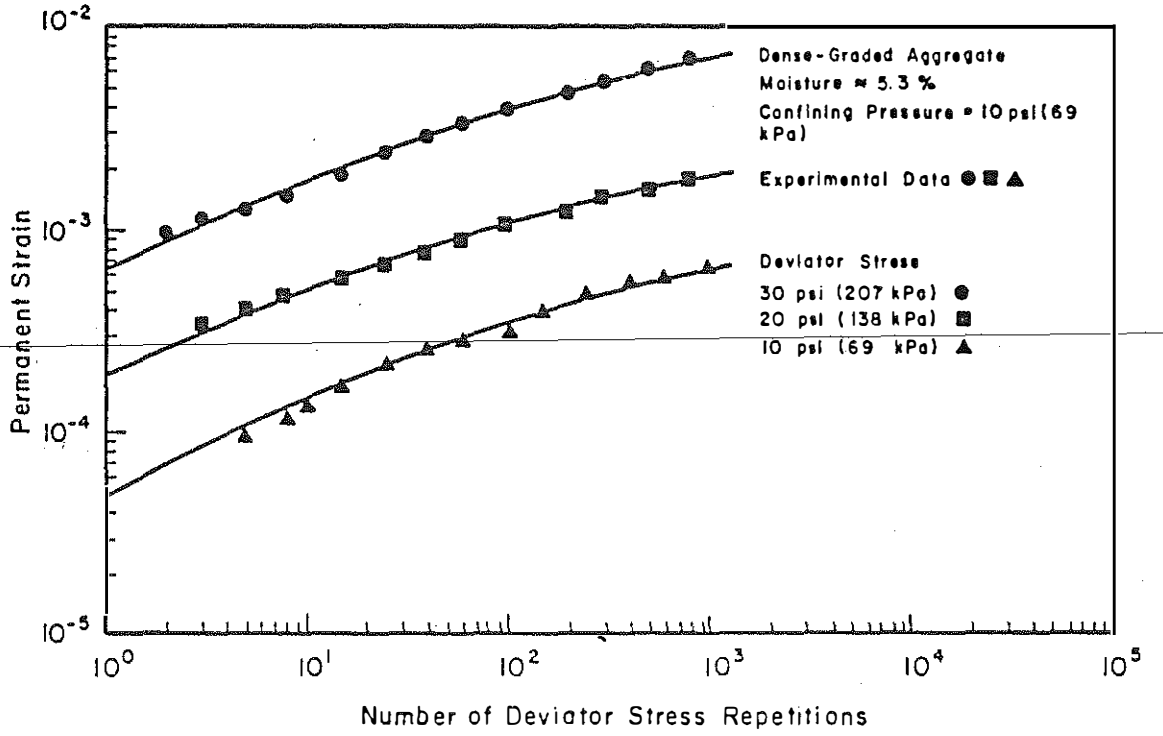


Figure 5. Permanent Strain as a Function of Number of Load Cycles (Dense-Graded Aggregate).

Subroutine DGARUT accumulates the permanent deformation from the repeated service loads in each "typical" hour of the year in the same manner as that described in the section on Subroutine ACRUT.

Although confining pressure and moisture content can be read into the program as data, this subroutine will automatically default to preprogrammed values for these variables when the user chooses not to assign values. In this case, confining pressure will be given a value of 35 percent of the vertical stress and moisture content is set equal to three percent for every month of the year except March and April. The value of moisture content for March and April is 4.5 percent.

SUBROUTINE SUBRUT

SUBRUT calculates the permanent deformations in subgrade materials. As in the case of the asphaltic concrete and dense-graded aggregate, the algorithm in this subroutine was developed from a series of repeated-load tests on laboratory compacted specimens.

Two series of specimens were tested: one at 8.2 percent moisture and the other at 9.4 percent. Three confining pressures [5 psi (34 kPa), 10 psi (69 kPa), and 15 psi (103 kPa)] were used in each series. At least three specimens were tested at each confining pressure with deviator stresses of 2.5 psi (17 kPa), 5 psi (34 kPa), and 10 psi (69 kPa). Further details of testing are reported in Reference (1).

There was considerable scatter in the data, and results were not always repeatable. This was attributed largely to the high degree of variability of the material. An example of the repeated-load tests data is shown in Figure 6. Because of scatter, each curve in this figure is an average of two or more tests; and for that reason, no data points are shown. A permanent deformation model was derived for the subgrade material using a linear-regression analysis on points taken from these average curves. The result is the following equation:

$$\log E_p = C_0 + C_1(\log N) + C_2(\log N)^2 + C_3(\log N)^3 \qquad (3)$$

in which E_p = permanent strain,

$C_3 = 0.007 + 0.001\ W$,

$C_2 = 0.018\ W$,

$C_1 = 10^{(-1.1+0.1\ W)}$,

$C_0 = [(-6.5 + 0.38\ W) - (1.1 \log \sigma_3)] + [1.86 \log \sigma_1]$,

W = moisture content (percent),

σ_1 = deviator stress (psi), and

σ_3 = confining pressure (psi).

Permanent deformations from each "typical" hour of the year are accumulated as in the two previous subroutines.

If confining pressure and moisture content for the subgrade are

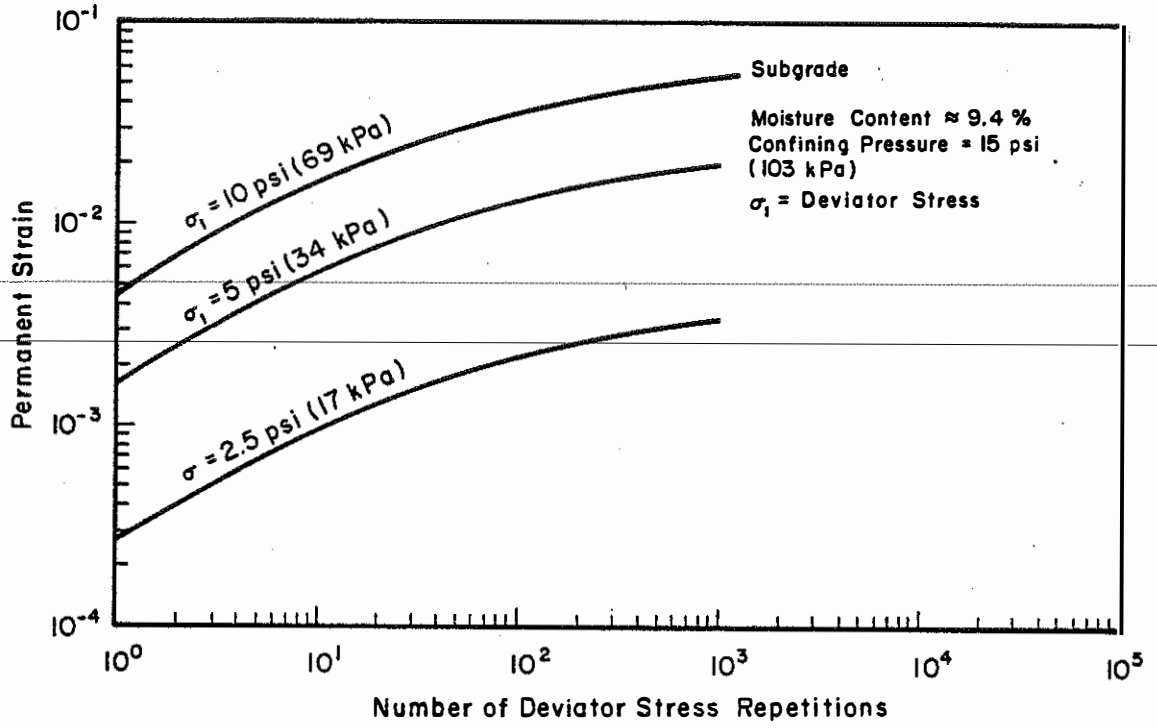


Figure 6. Permanent Strain as a Function of Number of Load Cycles (Subgrade).

assigned a value of zero when the data are read into the program, SUBRUT will default to a value of 35 percent of the vertical stress for the confining pressure and a value of 8.0 percent moisture for the months of March and April and 7.0 percent for the remaining months. To use CBR as well as moisture content in determining rutting for the subgrade, repeated-loads tests were run on four materials with different CBR values. Those rutting values were correlated with various moisture contents of the material tested in the original laboratory testing program, and the following relationship was developed:

$$\log W = 0.8633 - 0.05645 \log (CBR). \quad (4)$$

Therefore, CBR or moisture content can be used for calculating rutting of the subgrade.

SUBROUTINE POLYRT

As stated previously, Subroutines ACRUT, DGARUT, and SUBRUT all use this subroutine to solve for the roots of a third-degree polynomial (see Equations 1, 2, and 3). POLYRT employs Newton's method of iteration (4) to accomplish this task.

Let x_n be the arbitrarily chosen initial value of the root of the third-degree polynomial, with n = 0 for the first iteration, then Newton's equation for the root of the polynomial is the following:

$$X_{n+1} = X_n - [(C_3X_n^3 + C_2X_n^2 + C_1X_n + C_0) / (3C_3X_n^2 + 2C_2X_n + C_1)]. \quad (5)$$

In other words, the polynomial divided by its derivatives and subtracted from X_n equals the new root, X_{n+1}. The value of X_{n+1} is then substituted for X_n in Equation 5, and a new value for X_{n+1} is calculated. This process is repeated until convergence is reached ($X_{n+1} = X_n$). The value at which this occurs is the desired root of the polynomial. Equation 5 should normally converge in five or six iterations.

When solving for the roots of Equations 1, 2 , or 3, Equation 5 takes the following form:

$$(\log N)_{n+1} = (\log N)_n - [C_3(\log N)_n^3 + C_2(\log N)_n^2 + C_1(\log N)_n + C_0] / [3C_3(\log N)_n^2 + 2C_2(\log N)_n + C_1] . \quad (6)$$

In Subroutine POLYRT, $(\log N)_n$ for the first iteration is always set equal to 1.0. The maximum number of iterations allowed is ten. If Equation 6 does not converge in ten iterations, the program is aborted and an error message is printed.

SUBROUTINE TEMP

Subroutine TEMP is used to calculate the temperature of the asphaltic concrete at any depth for any typical hour of the year. This temperature is used in Subroutine ACRUT to calculate strain in the asphaltic concrete and also in Subroutine EMOD to calculate the modulus of elasticity of the asphaltic concrete.

In 1968, Southgate (5) published a report describing an in-depth analysis of temperature-versus-depth data collected by Kallas (3) in 1964-1965 at The Asphalt Institute laboratory at College Park, Maryland. Southgate presented a number of charts similar to the one shown in Figure 7. In those charts (Southgate presented a total of 28), pavement temperature at some depth is plotted as a function of depth and the pavement surface temperature plus the mean air temperature for the previous five days. Southgate developed those charts by running a regression analysis on data from Kallas (3) to give the zero intercepts and the slopes of the depth curves shown in Figure 7, for most hours of the day (one chart for each hour).

To use the information presented in Southgate's charts in the program, it was necessary to develop a mathematical model describing the relationship between the dependent variable (pavement temperature at some depth) and the independent variables (slope and zero intercept of the depth curves from all of Southgate's charts and pavement surface temperature plus the five-day mean air-temperature history). As illustrated in Figure 7, the depth curves are straight lines; therefore, an equation of the following form should describe the relationship:

in which $T = A + BX$, (7)

T = temperature at some depth (°F),
A = zero intercept of depth curves,
B = slope of depth curves and,
X = pavement surface temperature plus five-day mean air-temperature history (°F).

However, Variables A, B, and X are, in themselves, very complicated functions. As can be noted in Figure 7, Variables A and B are dependent upon hour of the day and depth in the pavement. Variable X is dependent upon month of the year and hour of the day.

To define Variables A and B, all values for A and B reported by Southgate were plotted as functions of hour and depth. Linear-regression analyses were performed, yielding functions that were fifth-degree polynomials in hour of the day and third-degree polynomials in depth in pavement. The following two equations describe Variables A and B:

$$A = [-0.8882061 - 5.409584H + 1.419966H^2 - 0.1436045H^3 + 0.006001302H^4 - 0.000087823H^5] + [-2.312872 + 3.643902H - 1.000187H^2 + 0.1082190H^3 - 0.004867211H^4 + 0.00007657193H^5][D] +$$

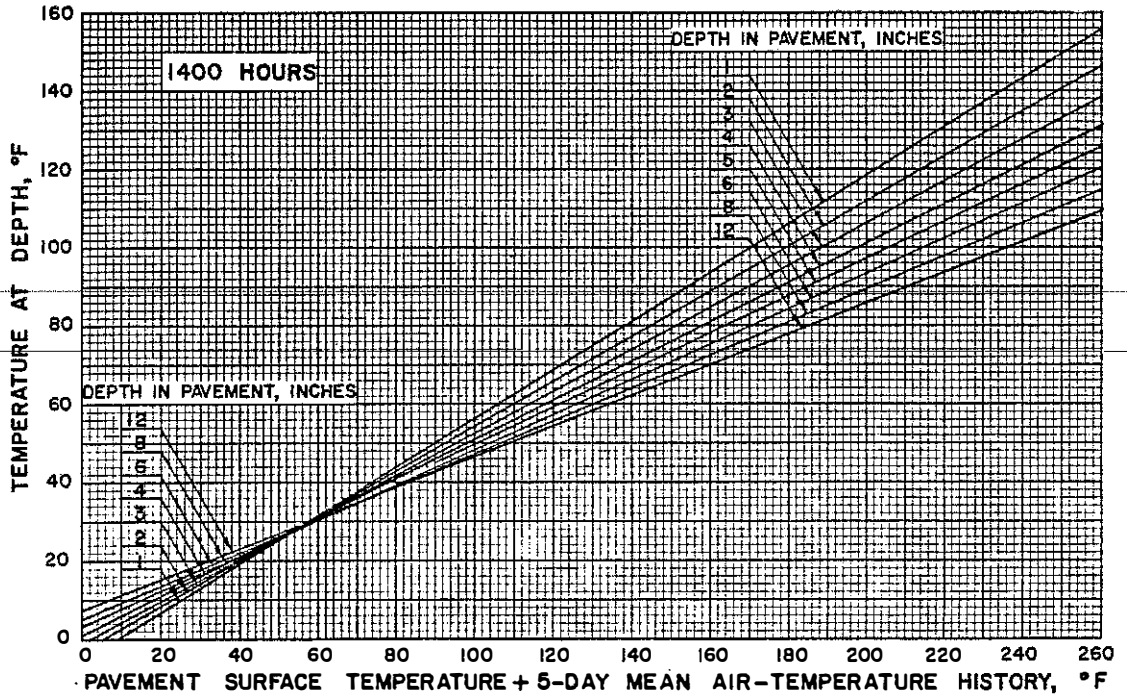


Figure 7. Pavement Temperature at Depth as a Function of Pavement Surface Temperature Plus 5-Day Mean Air-Temperature History.

$$[0.3188233 - 0.4041188H + 0.1103354H^2 - 0.01201035H^3 + 0.0005488345H_4 - 0.000008829082H^5][D]^2 + [-0.01064115 + 0.01438466H - 0.00390228H^2 + 0.00042378H^3 - 0.0000194274H^4 + 0.0000003144042H^5][D]^3, \quad (8)$$

and

$$B = [0.5449503 + 0.01836149H - 0.01005689H^2 + 0.00157948H^3 - 0.00008601361H^4 + 0.000001517039H^5] + [-0.004002625 + 0.0112879H - 0.001222558H^2 - 0.0001705093H^3 + 0.00001952838H^4 - 0.0000004628811H^5][D] + [0.0007371035 - 0.001401982H + 0.0002543963H^2 + 0.000001147628H^3 - 0.000001274846H^4 + 0.00000003690588H^5][D]^2 + [-0.00007334696 + 0.00007449587H - 0.00001665841H^2 + 0.0000008755230H^3 + 0.000000001938508H^4 - 0.000000000617645 1H^5][D]^3, \quad (9)$$

in which H = hour of the day and

D = depth in the pavement (inches).

Variable X in Equation 7 was also defined from data reported by Southgate (5). Figure 8, derived from Figure 4 of Southgate's report, shows the relationship between pavement surface temperature and hour of the day. It should be noted that the data have been normalized with 132°F equal to 1.0 (the average temperature at 1300 hours for the month of July). A regression analysis on those data yielded the following "best-fit" equation:

$$T_n = -0.316 + 0.0814H + 0.0125H^2 + 0.00155H^3 + 0.0000230H^4, \quad (10)$$

in which T_n = normalized pavement surface temperature.

However, Equation 10 does not adequately describe the "linear" portion of the curve, from hour one to hour six. Therefore, a correction factor must be applied to Equation 10. A factor was derived from a graphical solution:

$$C_n = 10^{\left\{[-0.0757-0.0221(H)^2]-[10^{(-2.96+0.0582(H)^2)}]\right\}} \quad (11)$$

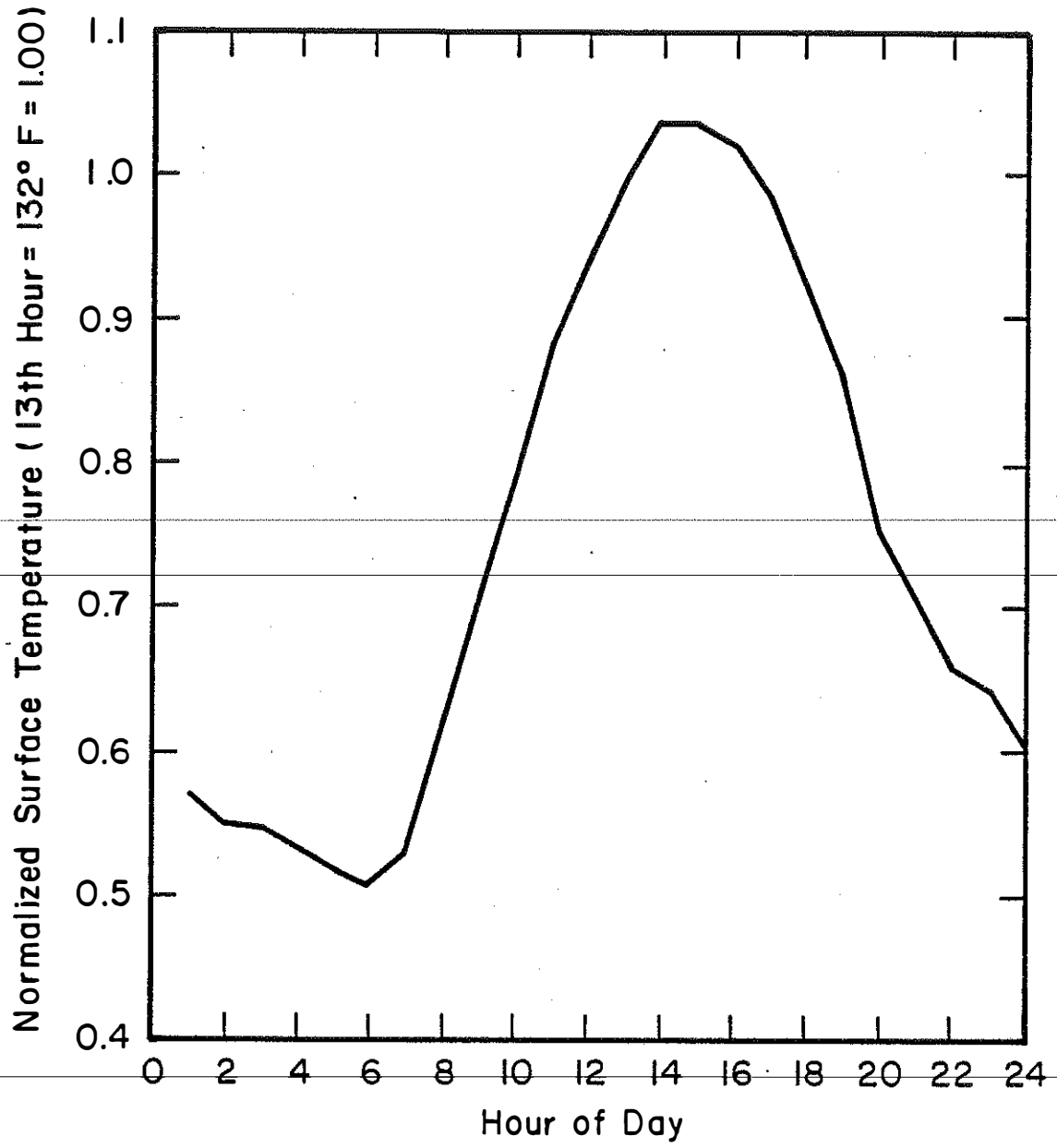


Figure 8. Normalized Pavement Surface Temperature as a Function of Hour of Day (1).

Adding Equations 10 and 11 gives the corrected pavement surface temperature in degrees Fahrenheit;

$$T_c = (T_n + C_n) \times 132. \tag{12}$$

As previously stated, Equation 12 is based upon temperatures for the month of July. Therefore, it must be corrected for each month. Figure 9, which was derived from Figure 22 of Southgate's report (5), shows the relationship between normalized pavement surface temperature at 1300 hours (°F) and month of the year. As in Figure 9, the average pavement surface temperature at 1300 hours for the month of July (132 °F) is equal to 1.0. A regression analysis on that data gave the following result:

$$T_{nm} = 0.603192 - 0.35332(M) + 0.152582(M)^2 - 0.017904(M)^3 + 0.00062937(M)^4, \tag{13}$$

in which T_{nm} = normalized pavement surface temperature as a function of month, and

M = month of the year (January = 1, December = 12).

Equation 12 can now be corrected for month of the year:

$$ST = T_c \times T_{nm} \tag{14}$$

in which ST = pavement surface temperature for any month and hour of the year.

The five-day mean air-temperature history is the last factor to be considered when defining Variable X in Equation 7. Figure 10 is a plot of the average daily temperature for each month, for the years 1970 through 1977. This was developed for locations with latitudes around 39 degrees North. Two linear "fits" were made to approximate the data. The first equation calculates the mean daily temperature for the months of January through August:

$$T_{DA} = 7.46\ M + 25.0. \tag{15}$$

The second equation calculates the same variable for September through December:

$$T_{DA} = -12.42\ M + 184. \tag{16}$$

As noted earlier, Southgate's charts were based upon the five-day mean air-temperature history. However, in making the previous analysis, it was assumed that the average daily temperature of any five-day period in the month would be reasonably close to the monthly mean. Although Southgate (5) has shown that this is not entirely true, it appeared that the error introduced would not be significant (see Figure 11).

Variable X of Equation 6 has now been defined and can be written as

$$X = ST + T_{DA} \tag{17}$$

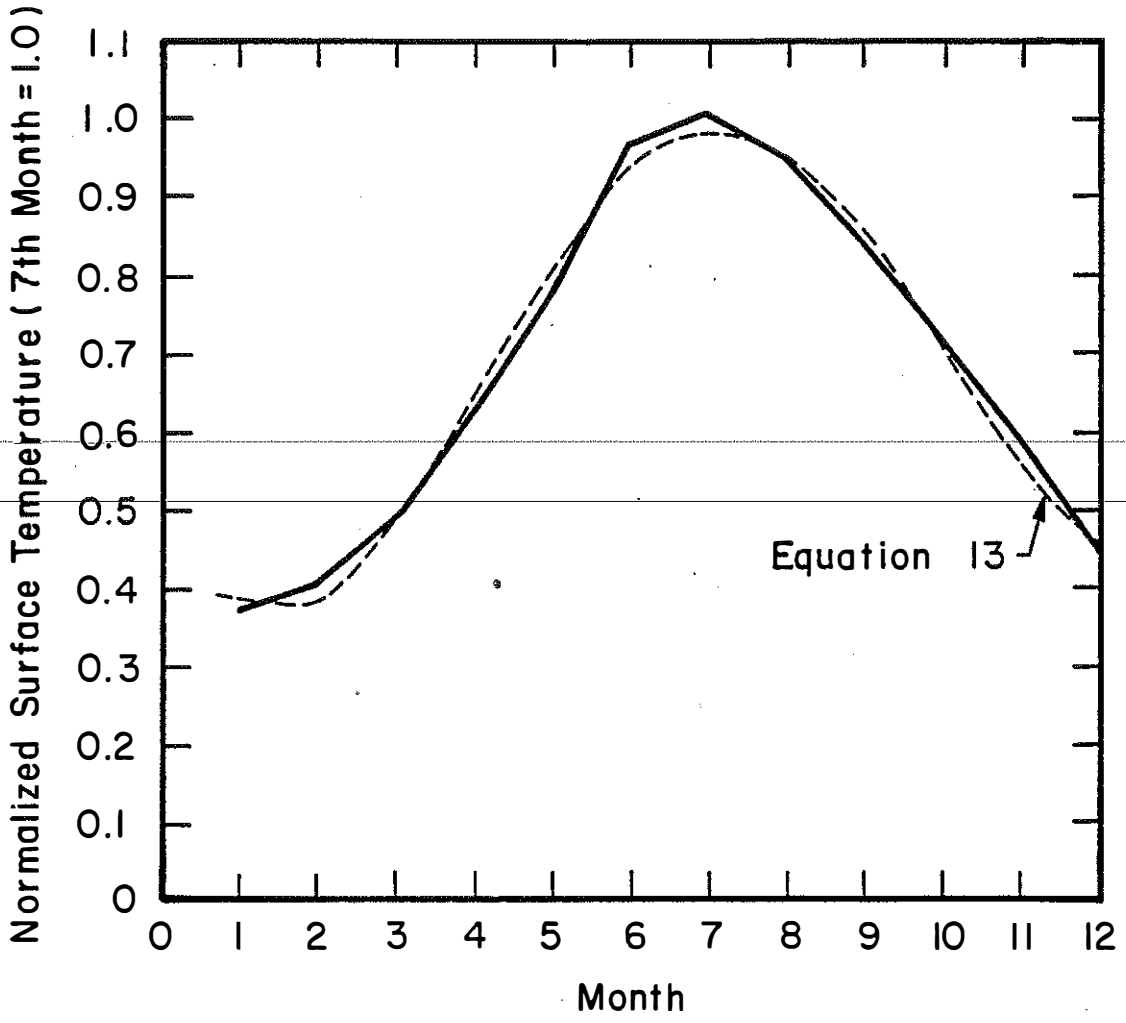


Figure 9. Normalized Pavement Surface Temperature as a Function of Month of Year (1).

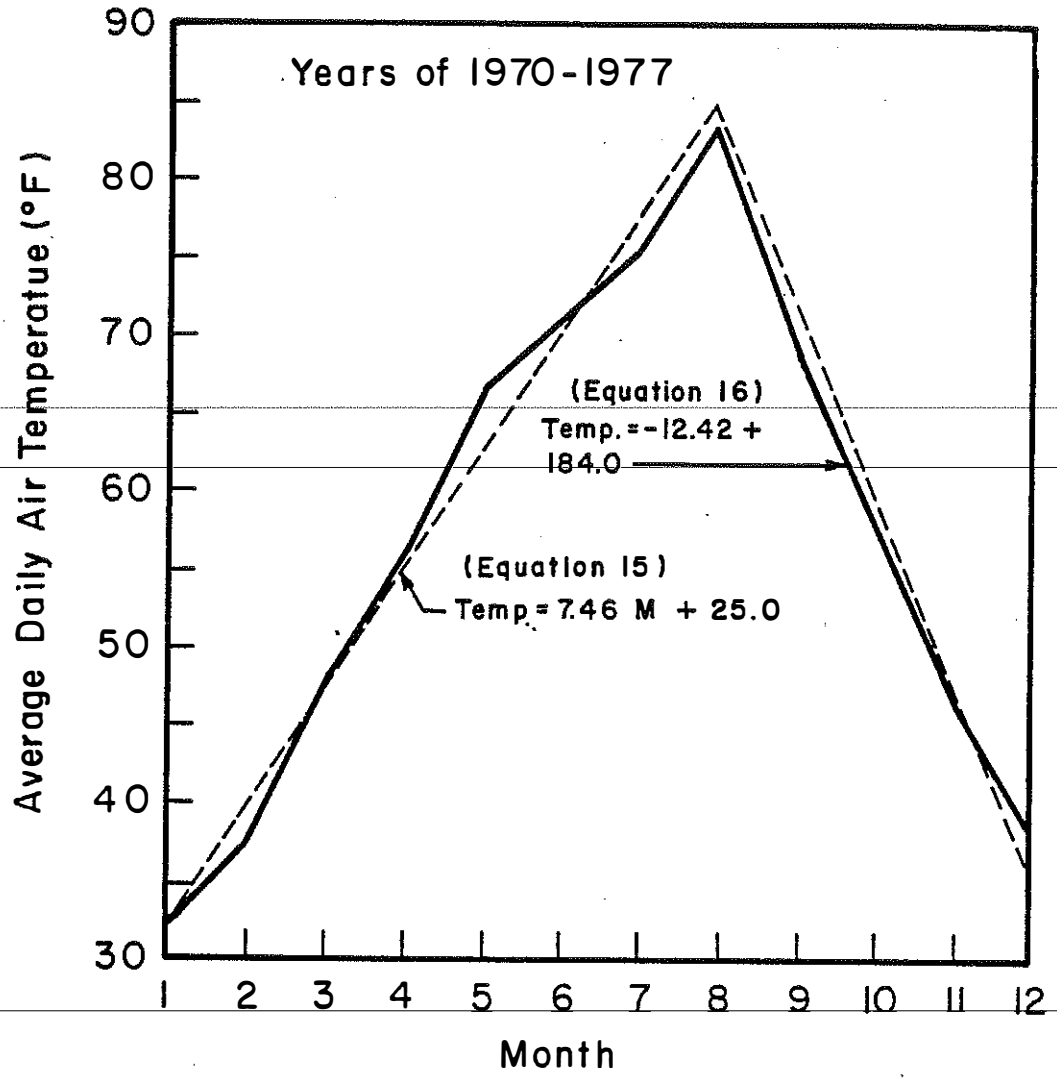


Figure 10. Average Daily Air-Temperature as a Function of Month of Year.

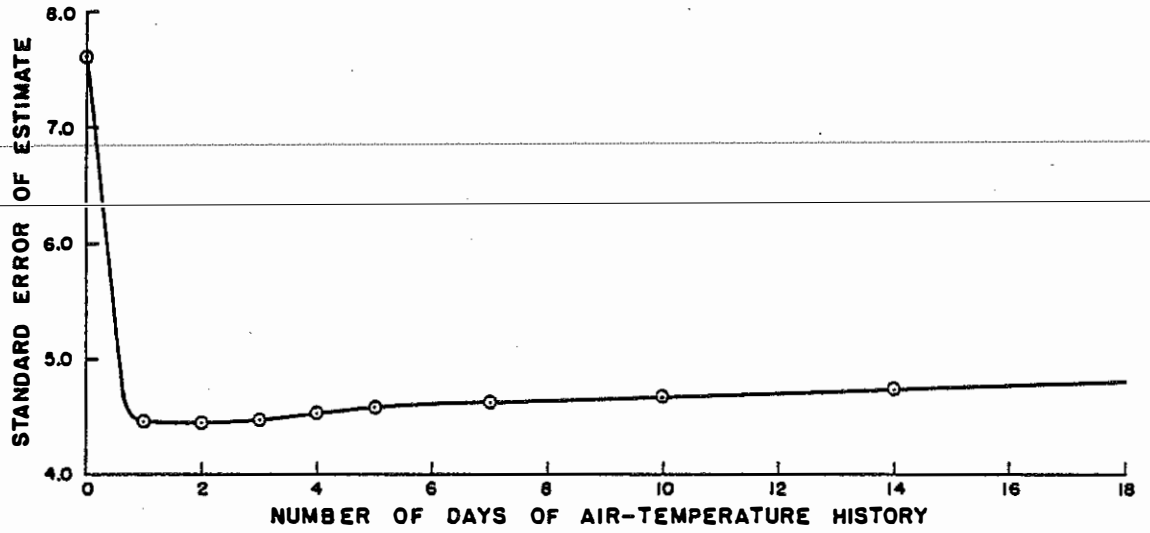


Figure 11. Standard Error of Estimate versus Number of Days of Antecedent Air Temperatures for 6-Inch Depth at 1300 hours.

SUBROUTINE EMOD

Subroutine EMOD calculates the moduli of the three material types. The modulus of elasticity of asphaltic concrete was derived from Figure 19 of Southgate's report (5). A regression analysis was performed on that data, yielding the following result:

$$\text{Log } E = 10.46 - 2.676 \text{ Log } T \quad (18)$$

in which E = modulus of elasticity (psi) and
T = pavement temperature (°F), calculated from Equation 7.

The modulus calculated for dense-graded aggregate is actually a resilient modulus obtained from the repeated-load tests. Definition of the resilient modulus, how it was obtained, and the effects of confining pressure and moisture content on its magnitude are explained in detail in Reference 1. Again, regression analyses on the laboratory data gave the following equation for resilient modulus:

$$\text{Log } M_r = (5.4624 - 2.729 \log W) + (0.175 + 1.10 \log W)(\log \sigma_3) \quad (19)$$

in which M_r = resilient modulus (psi),

W = moisture content (percent), and

σ_3 = confining pressure (psi).

The equation describing the modulus of the subgrade material as a function of moisture content and confining pressure was developed from regression analyses on data obtained from resonant column tests on the material (see Reference 1):

$$\log E_r = 5.331 + 0.00070\sigma_3 + (0.11246 - 0.010060\sigma_3 + (0.000310\sigma_3^2)W - (0.02496 - 0.001880\sigma_3 + 0.00005490\sigma_3^2)W^2 \quad (20)$$

in which E_r = modulus of elasticity (psi) from the resonant column.

If moisture content for dense-graded aggregate and subgrade material is not input as data, an assumed value is used. For dense-graded aggregate, moisture content is assumed to be 3.0 percent for each month except March and April when a value of 4.5 percent is used. For subgrade materials, the assumed values are 7.0 and 8.0 percent, respectively.

The moduli calculated in this subroutine are used in Subroutine STRESS for calculating stresses in the pavement structure.

BLOCK DATA

The traffic data that served as a model for loading patterns is stored in the section labelled BLOCK DATA. The traffic model is stored as data, as opposed to a mathematical analog, because of difficulty in developing reasonable functions that adequately described traffic patterns.

Traffic volumes by month and by hour of the day for rural roads in Kentucky were reported by Herd et al. (2). Figures 12 and 13 were developed from their data. Figure 12 shows the percentage of total annual volume that occurs in each month, and Figure 13 illustrates the percentage of daily volume that occurs in any hour for a "typical" day. Although it is not entirely correct, for the sake of simplicity, it was assumed that the traffic pattern was the same for all days of any particular month.

To determine the volume for a particular hour of a particular month, it is necessary to multiply the percentage value in Figure 12 by the percentage value in Figure 13. It is this product that is stored in BLOCK DATA for 288 "typical" hours of the year. To obtain volume, it is necessary to multiply the stored value by number of days in the month (30 is assumed) and then by the annual volume. The latter two multiplications are made in the MAIN program.

The total number of vehicles, however, is not the primary concern; the number of wheel-passes is the major factor to be considered. To determine this, it is imperative to classify the traffic stream as to type of vehicle. File data compiled by the Department of Highways indicate that approximately 20 percent of the traffic stream for rural roads is truck traffic. Furthermore, the same data show the average truck has 3.92 axles. Therefore, to obtain wheel-passes, 80 percent of the hourly volume is multiplied by 2.0 for automobiles and 20 percent is multiplied by 3.92 to obtain the total number of wheel-passes per hour.

When using axleloads to calculate rut depth, the number of axleloads are read in using variable ANVOL. However, this variable is a vehicle volume of all of the corrections of the previous paragraph would be applied to the axleloads that were input, making the number of axleloads greater than anticipated. For example, if 1,000,000 axleloads were desired and that number was input without any corrections, the program would multiply 80 percent of 1,000,000 by 2.0 and 20 percent of 1,000,000 by 3.92 (800,000 times 2.0 plus 200,000 times 3.92 equals 2,384,000) to give a number of axleloads that is 2.384 times greater than what was desired. Therefore, the desired number of axleloads should always be divided by 2.384 before inputing into the program. Also, when using axleloads, variable TRUCK should always be 0.0.

All wheel-passes do not occur at the same spot on the pavement. It has been shown (6) that, in general, the distribution of wheel-passes across any section of pavement will approximate a normal distribution pattern (bell-shaped curve) or a sinusoidal function. This broadens the rut while reducing the depth. To account for this pattern, the number of wheel-passes was reduced to an amount equal to the root mean square of the sinusoidal curve (0.707).

All of the above calculations concerning number of wheel-passes are made in the MAIN program.

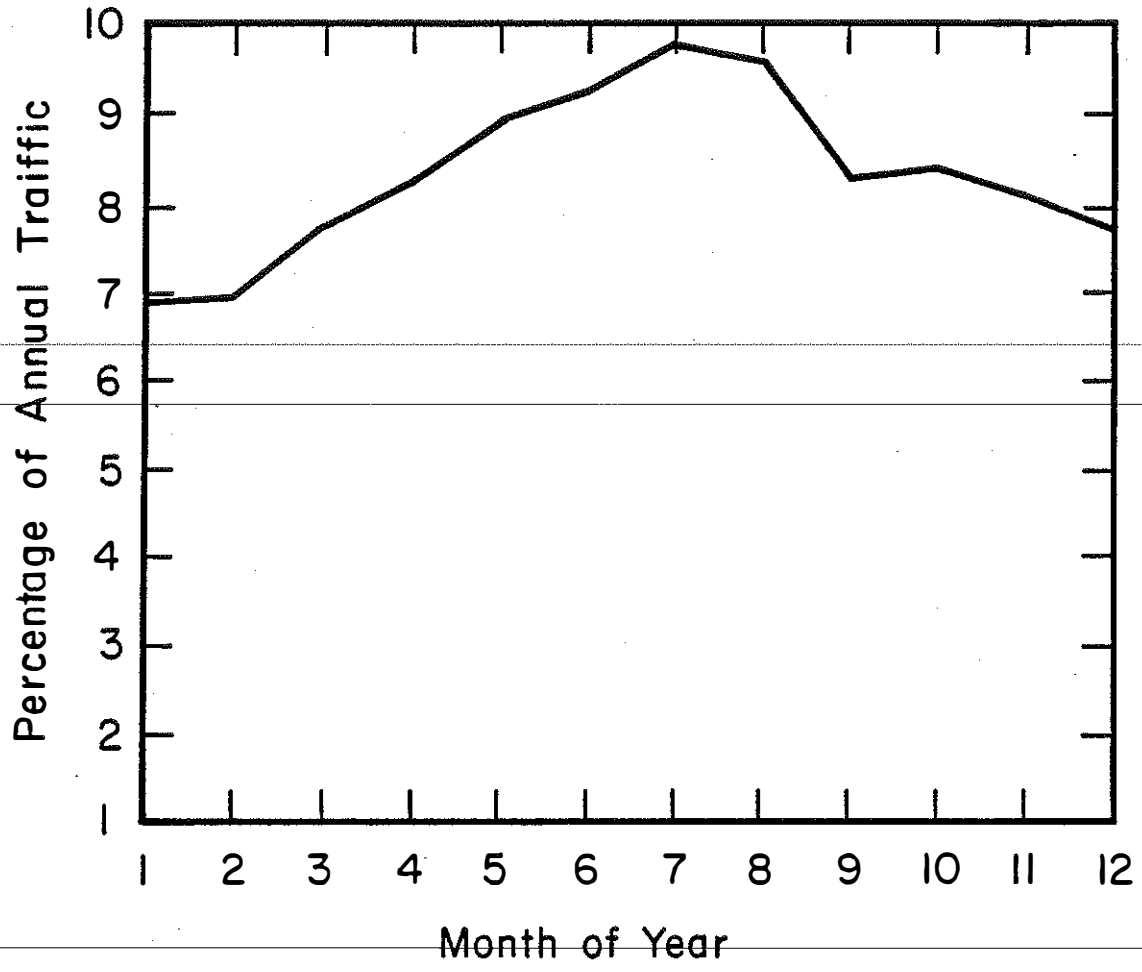


Figure 12. Percentage of Annual Traffic Volume Occurring in Each Month of the Year.

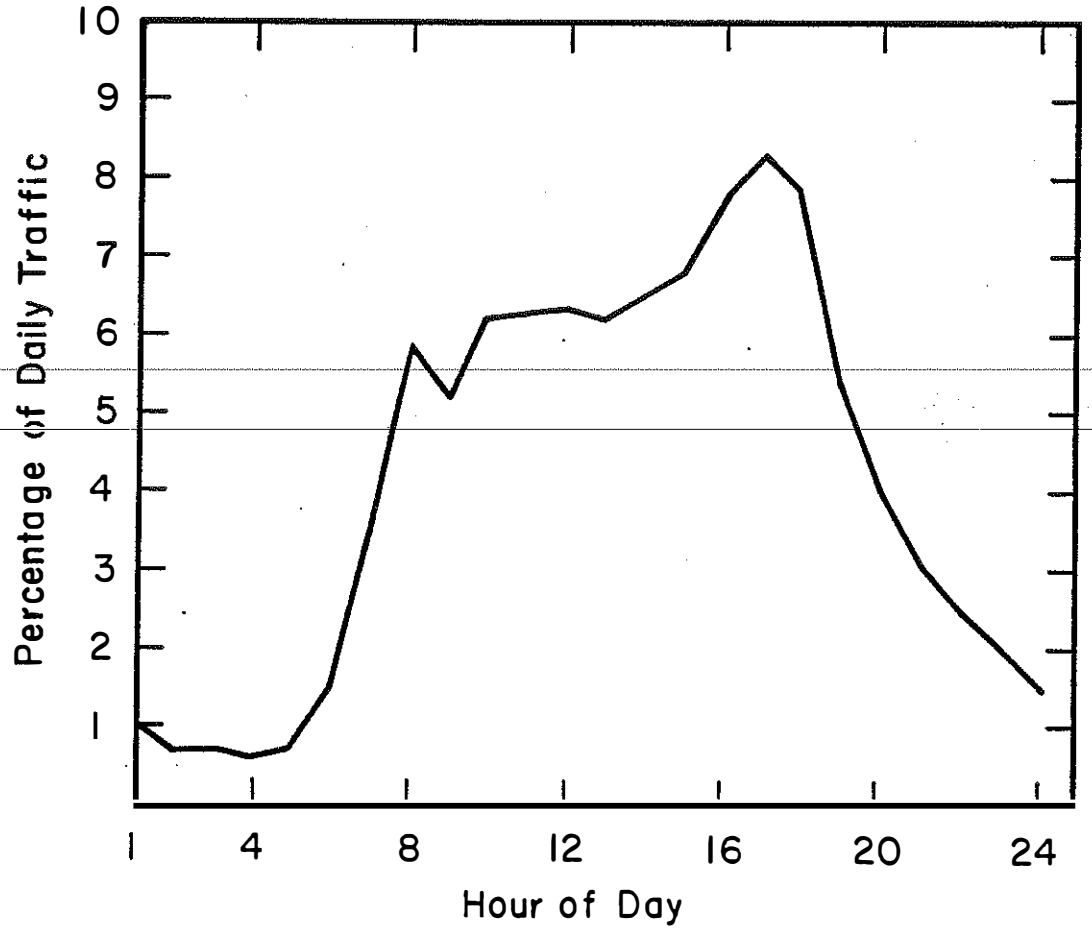


Figure 13. Percentage of Daily Traffic Volume Occurring in Any Hour of a "Typical" Day.

SUBROUTINE STRESS

This subroutine calculates the vertical stresses at various depths in the pavement structure. With some modifications, the subroutine was taken from a program entitled CHEVRON written by the Chevron Oil Company. Linear elastic theory is used to solve for the stresses.

IMPLEMENTATION

In order to illustrate the use and implementation of the rutting charts in a "real-life" analysis, six sections of rehabilitated and reconstructed Interstate 65 in Hart, LaRue, and Hardin Counties in Kentucky were analyzed for rutting. From this analysis, recommendations have been made as to the apparent best design when rutting is considered.

The six sections were identified on the design sheet as follows:

South of Elizabethtown, Kentucky,
(1) M.P. 61.149 to M.P. 76.096 (14.947 miles),
(2) M.P. 76.096 to M.P. 90.596 (14.5 miles),
North of Elizabethtown, Kentucky,
(3) Section 4-1,
(4) Section 4-2, 4.54 miles, including previous section),
(5) Section 4-3, (1.34 miles)
(6) Section 4-4, (2.45 miles)

It should be noted that the rut depths reported in the following analyses have been calculated using linear interpolation to obtain values that occur between successive charts.

The cost analyses are based upon the following unit bid prices:

DGA Base (Limestone)	$ 6.75/ton
Bituminous Concrete Base	$ 21.00/ton
Bituminous Concrete Surface	$ 24.00/ton
Pavement Milling	$ 11.00/ton

The costs associated with inflation have not been considered . When a number of thin overlays have been added to a pavement, their effects on the structural capabilities of that pavement have been ignored. When comparing two alternates for a particular section, the shoulder design was assumed to be the same for each alternate; therefore, costs of the shoulders have not been added to the total costs. Each of the sections are discussed seperately.

MILEPOST 61.149 to MILEPOST 76.096

Existing pavement--7.5 in. AC on 13 in. DGA
Estimated Subgrade CBR = 6.3
Design EAL = 5.5×10^6

The existing pavement is to have 0.5 inch milled off, leaving 7.0 inches of AC on 13 inches of DGA. Ignoring the structural patches that are to be added, it appears this section will receive approximately 3.5 inches of overlay.

From the rutting charts, the new rehabilitated structure will

develop 0.43 inch of rut by the end of its design life. If 0.5 inch of rut is considered the maximum allowed, then the pavement will not have to be overlaid during its design life. If 0.25 inch of rut is the maximum allowed, (as recommended by FHWA), then one overlay would be required during the design life. (The overlay was considered to be a 0.50-inch levelling course and a final course of 1.0-inch surface.) The total estimated cost of the additional overlay is $57,000 per mile. This is the additional cost required to insure depths of 0.25 inch or less as opposed to permitting depths up to 0.5 inch.

A second alternative to overlaying with 1.5 inches would be to mill off 0.5 inch and overlay with only 1.0 inch. This alternate would cost approximately $47,000 per mile.

For this particular section, it appears that the 3.5-inch overlay was a good choice in design, when considering rutting. However, if a rut depth of 0.25 inch is to be the maximum permissible, it is recommended that milling be used with an overlay of only 1.0 inch for any future rehabilitation that is rutting related.

Stage construction might be considered for this section, if the criterion of 0.25-inch maximum rut depth is used. Instead of placing 3.5 inches of overlay, and then milling and adding another 1.0 inch after approximately 2.9 million EAL, add only 1.75 inches initially and at 3.1 million EAL mill and add the additional 1.75 inches of overlay. This procedure could save approximately $30,000 per mile. However, the structural effects of this procedure were not evaluated.

MILEPOST 76.096 to MILEPOST 90.596

Existing pavement--10 in. PCC on 6 in. DGA
Estimated Subgrade CBR = 6.3
Design EAL = 5.2×10^6

The 10-inch concrete pavement is to be broken into pieces 18 to 24 inches in size and an overlay of 7.25 inches of AC is to be placed. When estimating rutting, a problem arises concerning the behavior of the broken concrete pavement. Some have indicated that it probably behaves as a DGA base. If that is true, then this particular section would be analyzed as 7.25 inches of AC on 16 inches of DGA. The rut depth at the end of the design period would be 1.4 inches.

However it seems the broken PCC pavement would more closely behave as a rock subgrade. If an analysis is made assuming that this rock subgrade has a minimum CBR of 20, then the rut depth at the end of the design life would be 0.64 inch. This seems to be a more reasonable estimate.

For the 0.5-inch maximum permissible rut depth criterion, the pavement would require one overlay at an estimated cost of $57,000 per mile (assuming a 1.5-inch overlay). For the 0.25-inch maximum permissible rut depth criterion, two overlays would be required at a total cost of $114,000 per mile.

Again, milling would appear to be a better alternative to simply overlaying, because of lower costs per mile, and the thinner overlays would accumulate rutting at a slower rate. The cost per mile per overlay would be $47,000.

Stage construction for this section was not analyzed because of uncertainty regarding the possibilty of reflection cracking propogating through the thinner overlay. In view of this uncertainty, a thinner overlay would not be recommended for this section.

SECTIONS 4-1 and 4-2

ALTERNATE 1 (Conventional Design)- under construction
8.75 in AC on 16 in. DGA
Subgrade CBR = 5
Design EAL = 1.5×10^7

ALTERNATE 2 (Full-Depth Design)
16.75 in. AC
Subgrade CBR = 5
Design EAL = 1.5×10^7

The conventional design (Alternate 1) will have approximately 1.1 inches of rut at the end of the design life. Therefore, the pavement will have to be overlaid during its service life. Using the 0.5-inch maximum allowable rut depth criterion, the pavement would receive two 1.5-inch overlays at a total cost of $168,000 per mile for both overlays. For the 0.25-inch rut criterion, there would be six 1.5-inch overlays at a total cost of $505,000 per mile.

If 0.5-inch of the surface were milled off and only a 1.0-inch overlay were placed, two overlays would be required for the 0.5-inch rut depth criterion, but the total cost for the two overlays would be only $138,000 per mile. This is a savings of over $20,000 per mile when compared to adding two 1.5-inch overlays.

For the 0.25-inch criterion, the number of overlays would be reduced from six to four, if the pavement were milled. This would be a total cost of $276,000 per mile for the four overlays and a savings of $228,676 per mile, when compared to six 1.5-inch overlays.

The full-depth design (Alternate 2) would develop 1.4 inches of rut during its design service life. Three 1.5-inch overlays would be required during the design life of these two sections to maintain ruts depths at 0.5 inches or less for the full-depth design. The total cost for the three overlays would be $252,576 per mile.

Eight additional 1.5-inch overlays would be required on the full-depth alternate to meet the 0.25-inch maximum allowable rut depth criterion. The total cost for these overlays would be $674,000 per mile.

Again, milling would be a better alternative to overlaying alone. For the 0.5-inch depth criterion, one overlay could be saved at a savings of approximately $114,000 per mile. When using the 0.25-inch criterion, only six overlays would be required instead of eight, if the pavement were milled before laying each overlay. This would save $259,000 per mile when compared to eight 1.5-inch overlays.

In summarizing these sections, the best design is Alternate 1 (33 percent AC), as it is less susceptible to rutting. This design is also better than the 50 percent or 75 percent AC designs. They would have developed rut depths between 1.1 inches (33 percent AC) and 1.4 inches (100 percent AC). Also, it appears that milling is the best progam to follow in rutting rehabilitation. The cost savings per mile

when using milling with Alternate 1 instead of milling with Alternate 2 is $155,000, for the 0.5-inch criterion. For the 0.25-inch criterion, the savings per mile for the same program is $293,000. These last two figures include the intial cost difference per mile between the two alternatives. At September 1983 prices, the construction cost per mile is more for full-depth than for conventional design (in the Elizabethtown area).

SECTION 4-3

ALTERNATE 1 (Conventional)--under construction,
8.75 in. AC on 9 in. of DGA
Subgrade CBR = 15 (assumed)--cement stabilized
Design EAL = 1.5×10^7

ALTERNATE 2 (Full Depth)--Using a design submitted to FHWA on May 24, 1983, for 100% AC, based on 480-ksi curves.

14.75 in. AC
Subgrade CBR = 15 (assumed)--cement stabilized
Design EAL = 1.5×10^7

It is estimated that Alternate 1 (conventional design) will rut approximately 1.0 inch during its design life. Alternate 1 is a 50-percent AC design; however, a 33-percent design would have worked as well, when considering rutting. In this case, both designs would have developed 1.0-inch of rut; therefore, the number of overlays for both designs would be the same. The number and type of overlays are the same as those listed for the conventional design in Sections 2 and 4.

It appears the 50-percent design is the better design for this section because of lower intial cost. The 33-percent design would cost $575,000 per mile while the 50-percent design would cost $545,000 per mile.

Alternate 2 (full-depth design) for this section would develop approximately 1.3 inches of rut during its design life. The initial cost for this alternate would be $718,000 per mile, which is $174,000 per mile greater than for the 50-percent design.

The number, type, and cost of overlays for this section are the same as for the full-depth design on Sections 1 and 2. Therefore, the recommended design for this section is the 50-percent design with two future overlays where 0.5 inch of material is milled off and a 1.0-inch surface course is put down for each overlay. The total cost for this design and rehabilitation program would be $683,000 per mile. The total cost for the 33-percent design would be $714,000 per mile. For the full-depth design, the total cost would be $787,000 per mile. These figures are based upon the 0.5-inch maximum allowable rut depth. The cost difference between the full-depth design and the two conventional designs would increase by an additional $138,000 per mile if the 0.25-inch rut depth criterion were used.

SECTION 4-4

ALTERNATE 1 (Full Depth)--under construction
17.5 in. AC
Subgrade CBR = 3
Design EAL = 6.2×10^6

ALTERNATE 2 (Conventional)--50 percent AC
11.0 in. AC on 12 in. of DGA
Subgrade CBR = 3
Design EAL = 6.2×10^6

Alternate 2 is the best design for this section. This alternate is a 50-percent AC design. Although the rutting behavior is approximately the same as for a 33-percent conventional design (0.87 inch for the design life), the initial cost of this design would be less. The 50-percent AC conventional design would cost approximately $649,000 per mile while the 33-percent AC design would cost $757,000 per mile.

Alternate 2 also would cost less than Alternate 1 (rut depth of 1.07 inches for the design life). The initial cost for Alternate 1 would be approximately $238,000 more per mile than Alternate 2.

Only one overlay would be required for Alternate 2. Again, milling would be recommended with a 1.0-inch overlay at a cost of $69,000 per mile. Alternate 2 would require two overlays at a total cost of $138,000 per mile (using the 0.5-inch rut depth criterion). Two overlays would be required for Alternate 2, and three overlays would be required for Alternate 1 under the 0.25-inch criterion.

REMARKS

In every instance analyzed, the conventional designs accumulated rut depths at a slower rate than did the full-depth designs. The 33-percent and 50-percent AC designs behaved nearly the same when considering rutting; however, from the unit bid prices used in this study, the 50-percent design had a lower initial cost per mile than the 33-percent design. Also, the full-depth design was the most expensive, considering initial cost.

As would be expected, it was much more expensive to maintain rut depths at 0.25 inch or less than permitting rut depths up to 0.5 inch.

When considering rutting, milling appears to be the better choice. The cost appears to be less initially when compared to adding a levelling course and then a thin riding surface. Also, the thinner overlays that can be added when the pavement is milled accumulate rutting at slower rates.

Although stage construction was considered for only one of these sections, it appears this strategy might have been a viable alternative under a more in-depth analysis. Therefore, it is suggested that further study and analysis in this area should be undertaken to determine the cost-effectiveness and serviceability of stage construction.

CONCLUSIONS AND RECOMMENDATIONS

In the one case tested, the rut depth charts gave a good estimate. However, it is recommended that more comparisons be made.

It is recommended that more types of asphalts be tested in the laboratory to develop more general rutting models. It is recommended that the testing program be expanded to include more soil types and a larger range of CBR values.

REFERENCES

1. Allen, D. L., "Determination of Rutting in Asphaltic Concrete Pavements: Field Instrumentation and Laboratory Characterizations," Research Report 502, Kentucky Department of Transportation, Division of Research, August 1978.

2. Herd, D. R., Agent, K. R., and Rizenbergs, R. L., "Traffic Accidents: Day Versus Night," Research Report 471, Kentucky Department of Transportation, Division of Research, May 1977.

3. Kallas, B. F., "Asphalt Pavement Temperatures," Record No. 150, Highway Research Board, 1966.

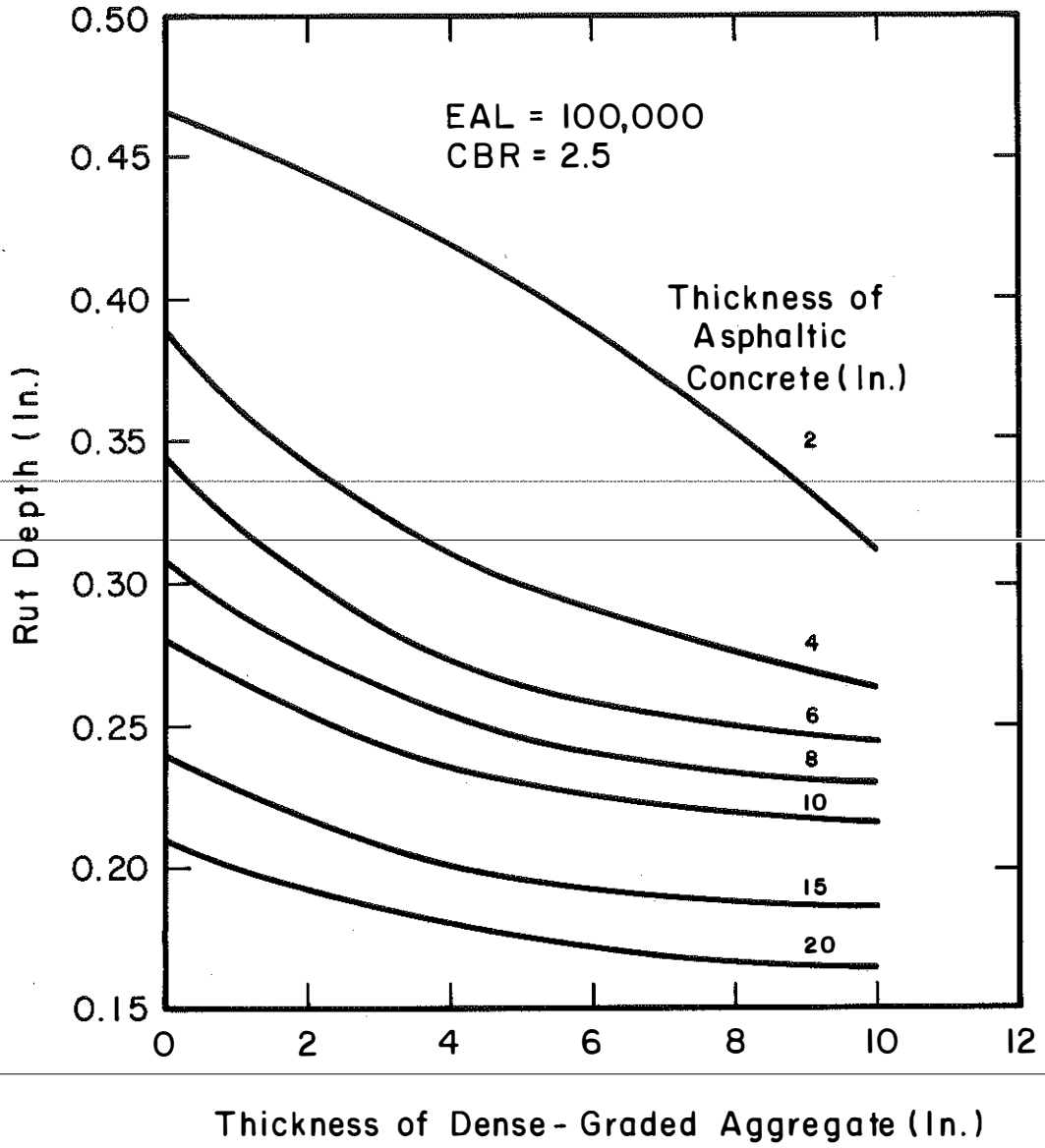
4. Kreysziq, E., Advance Engineering Mathematics, Fourth Edition, John Wiley and Sons, Inc., New York, 1979.

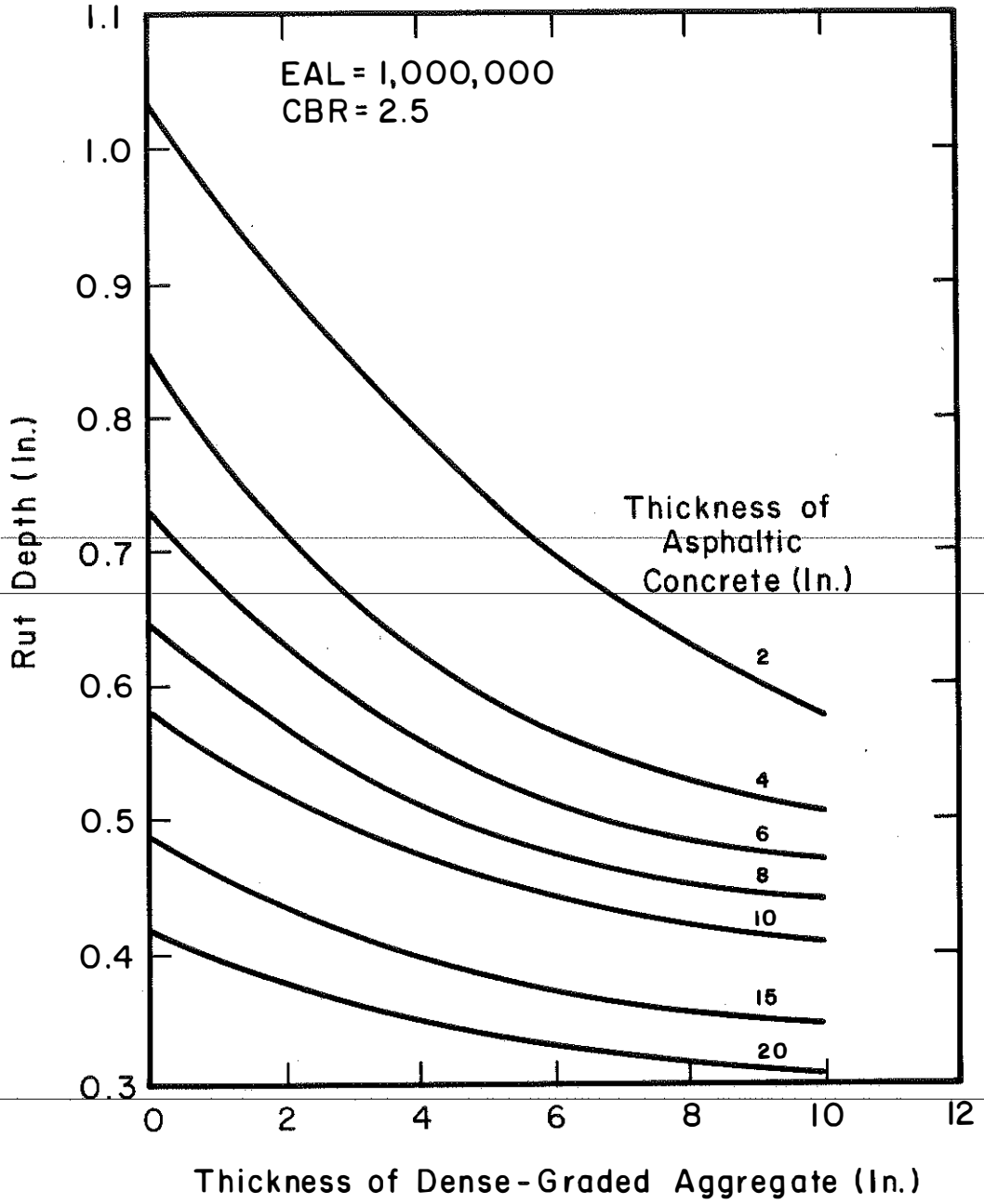
5. Southgate, H. F., "An Evaluation of Temperature Distribution Within Asphalt Pavements and Its Relationship to Pavement Deflection," Research Report 253, Kentucky Department of Highways, Division of Research, April 1968.

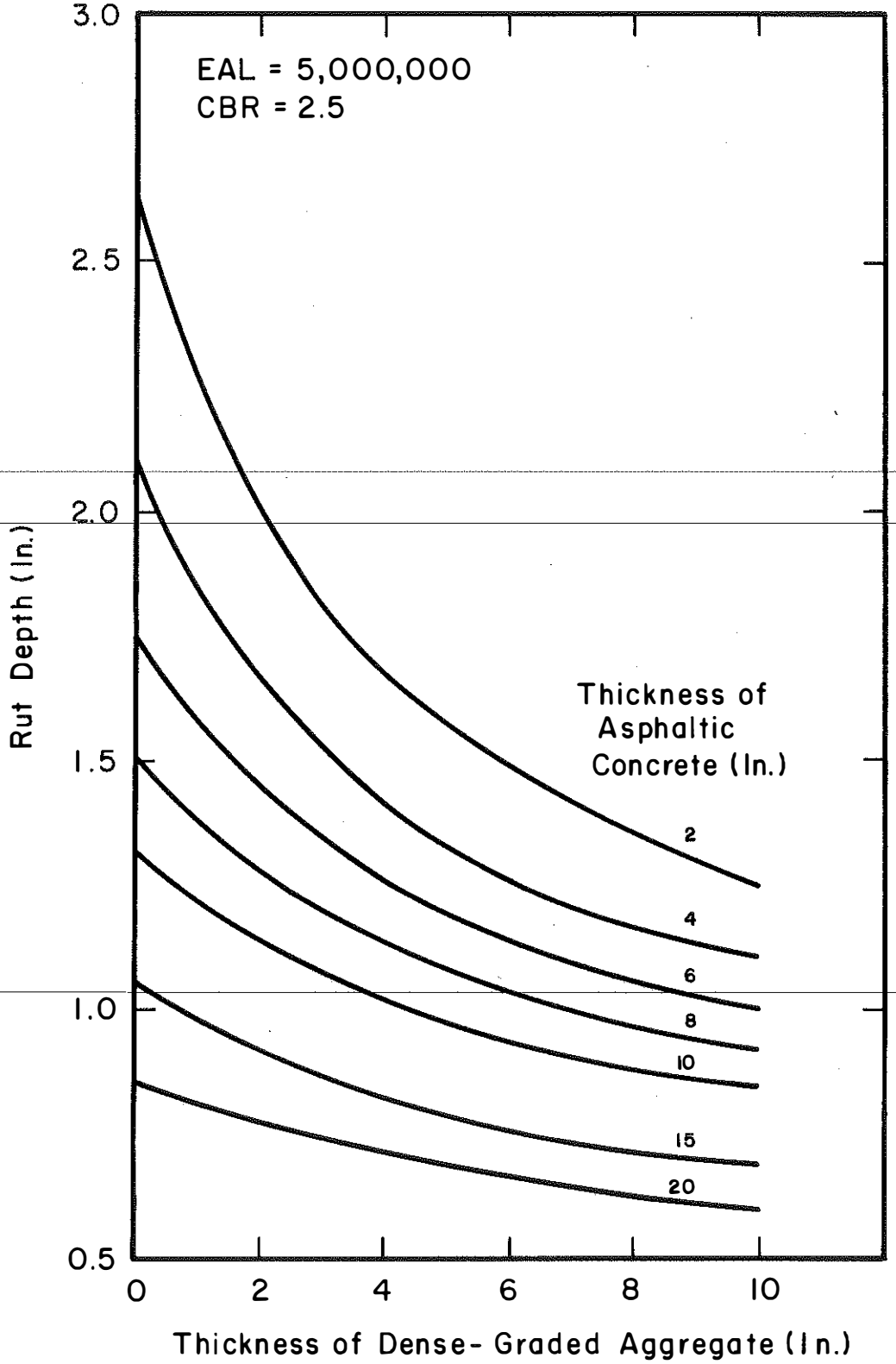
6. Van Der Loo, P. J., "A Practical Approach to the Prediction of Rutting in Asphalt Pavements: The Shell Method," Record No. 616, Transportation Research Board, 1976.

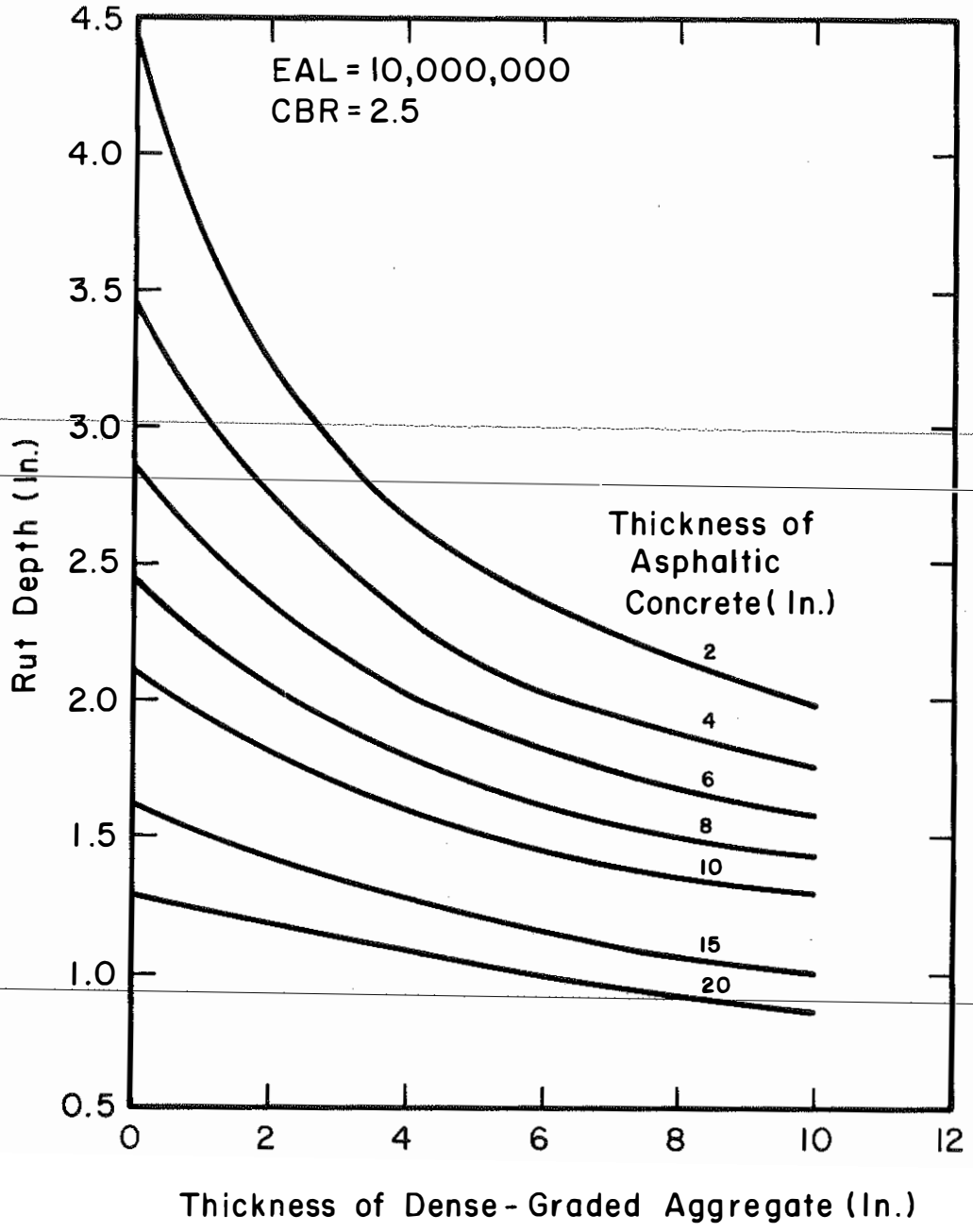
APPENDIX A

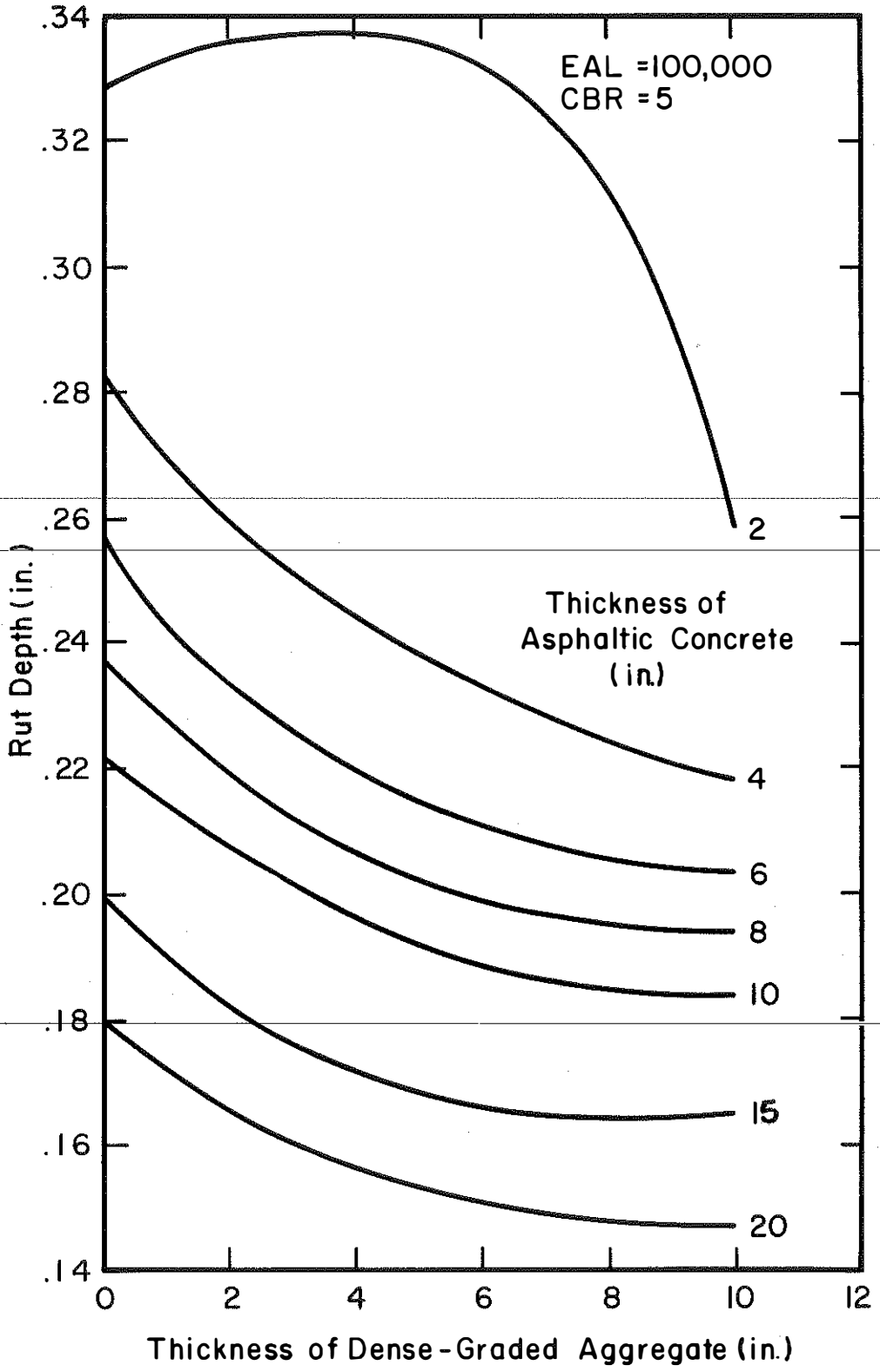
RUT DEPTH CHARTS

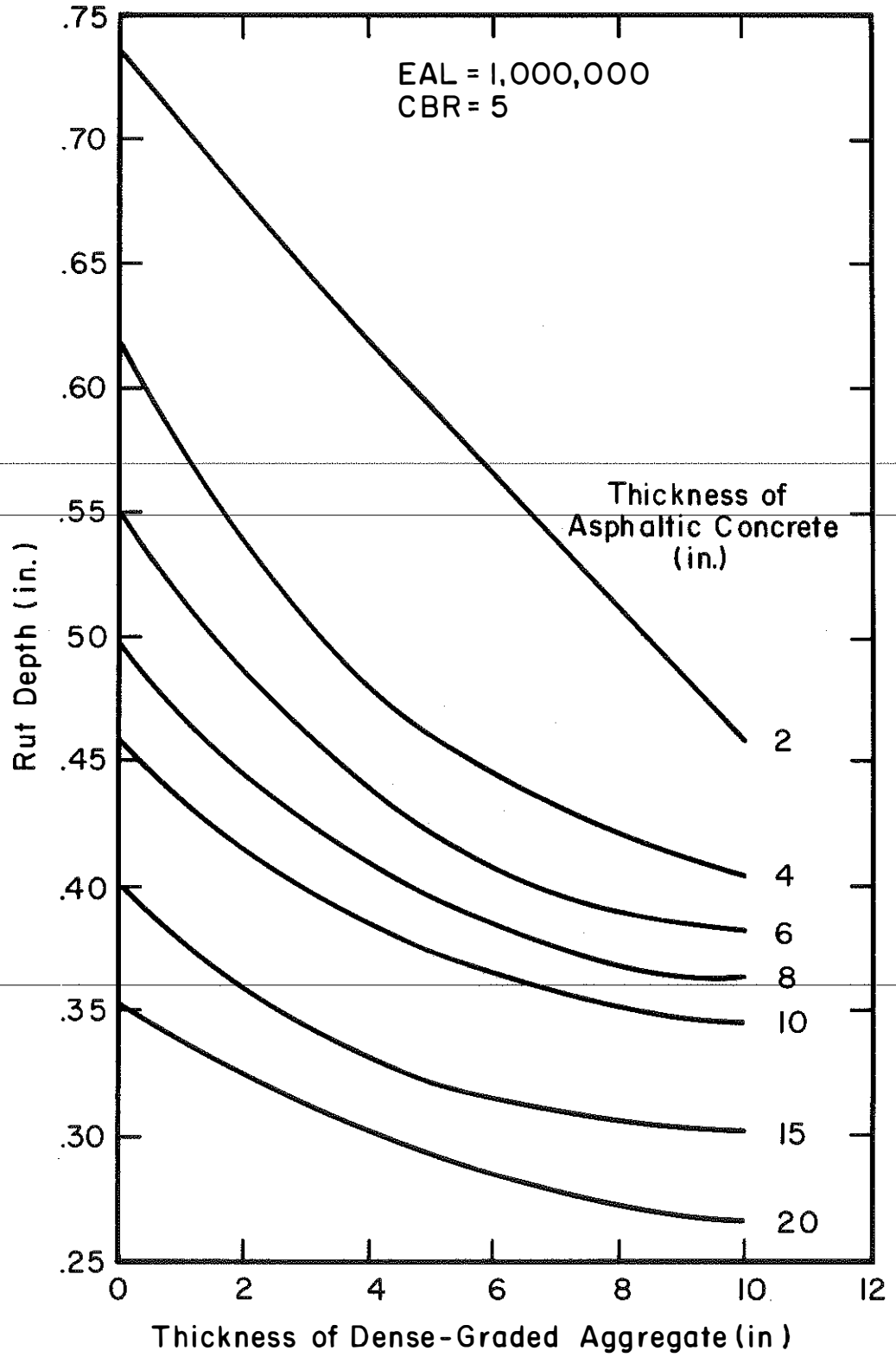

0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
Rut Depth (In.)
EAL = 100,000
CBR = 2.5
Thickness of
Asphaltic
Concrete (In.)
2
4
6
8
10
15
20
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (In.)

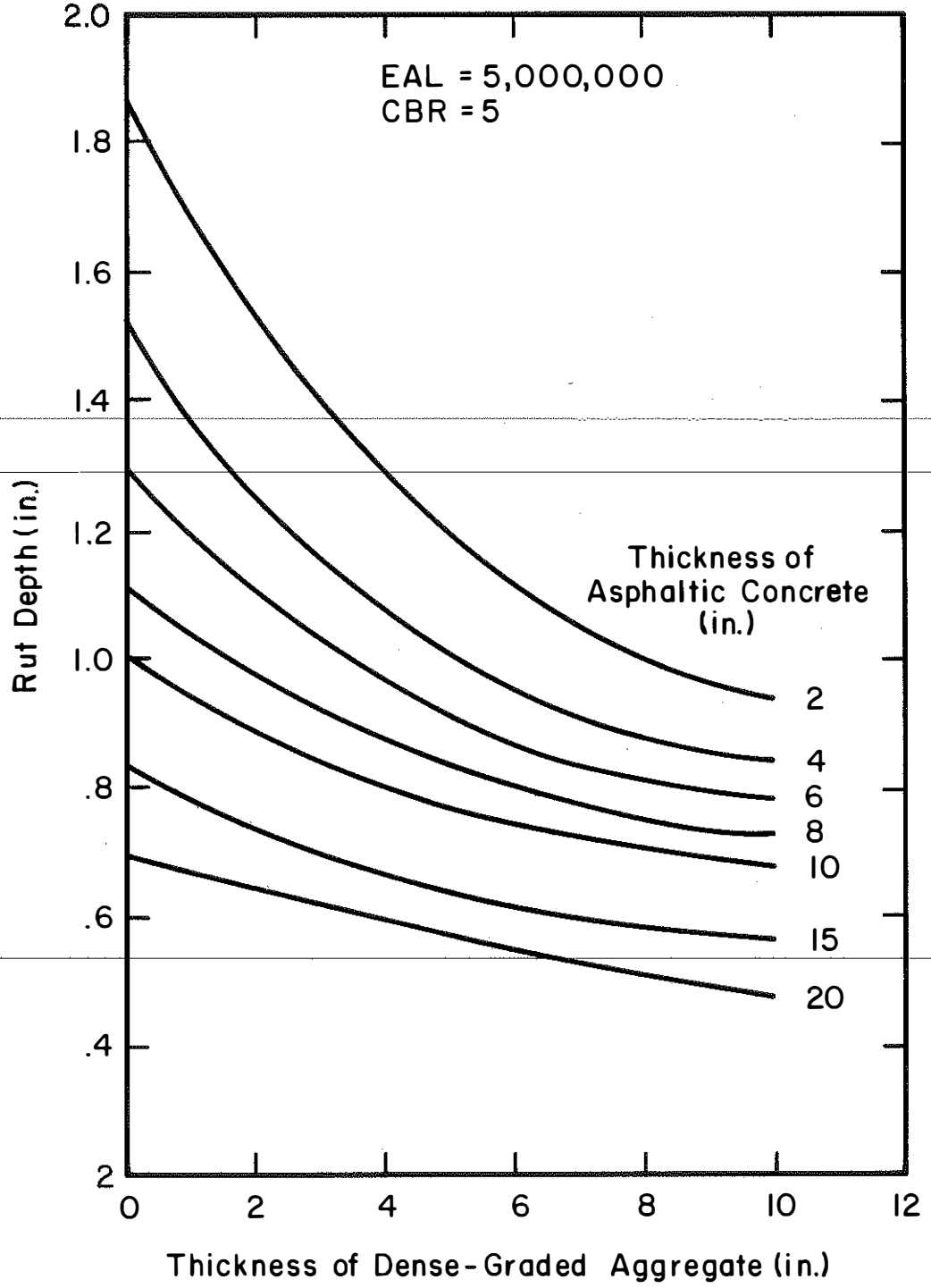

EAL = 1,000,000
CBR = 2.5
Thickness of Asphaltic Concrete (In.)
2
4
6
8
10
15
20
Rut Depth (In.)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (In.)

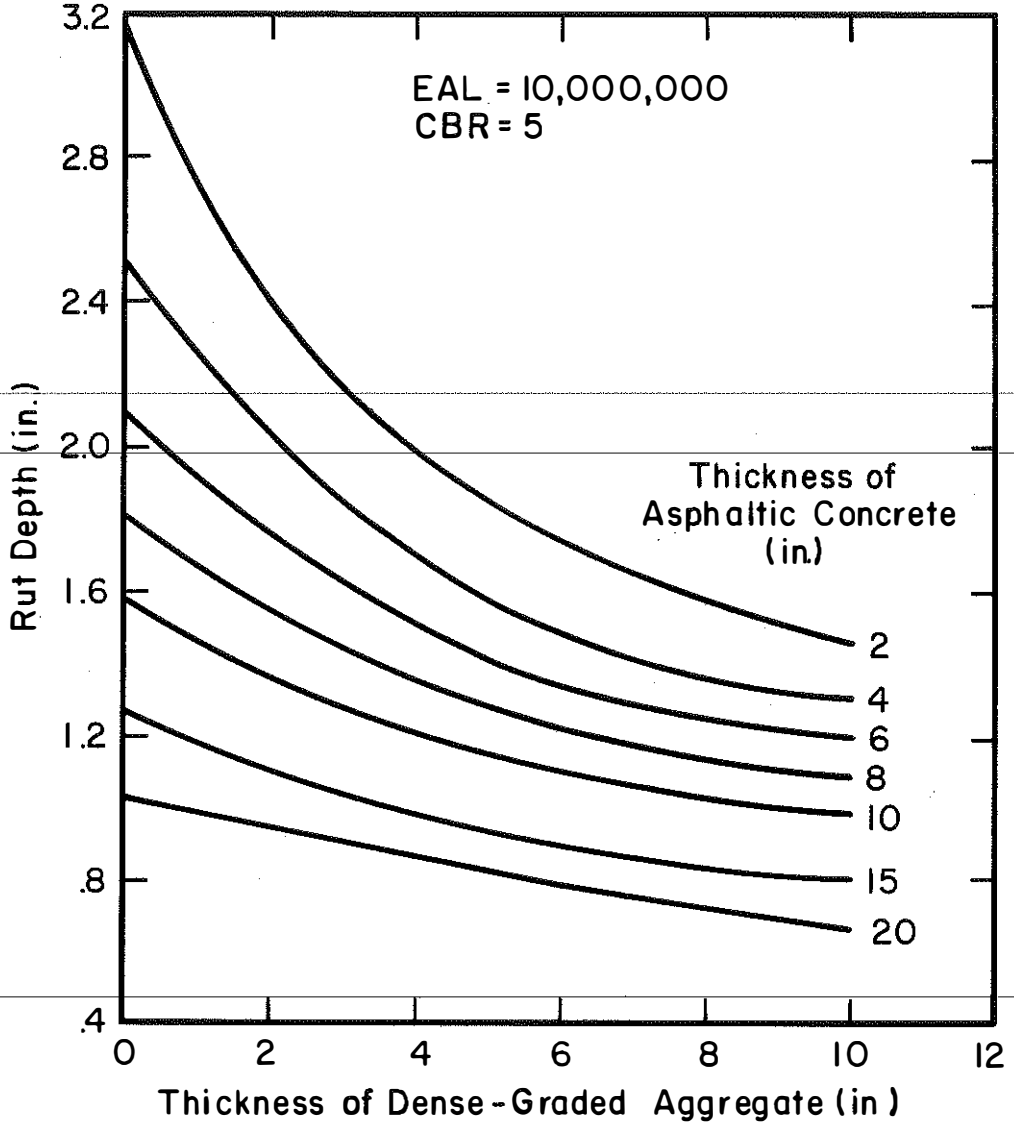

EAL = 5,000,000
CBR = 2.5
Rut Depth (In.)
3.0
2.5
2.0
1.5
1.0
0.5
0
2
4
6
8
10
Thickness of Dense-Graded Aggregate (In.)
Thickness of Asphaltic Concrete (In.)
2
4
6
8
10
15
20

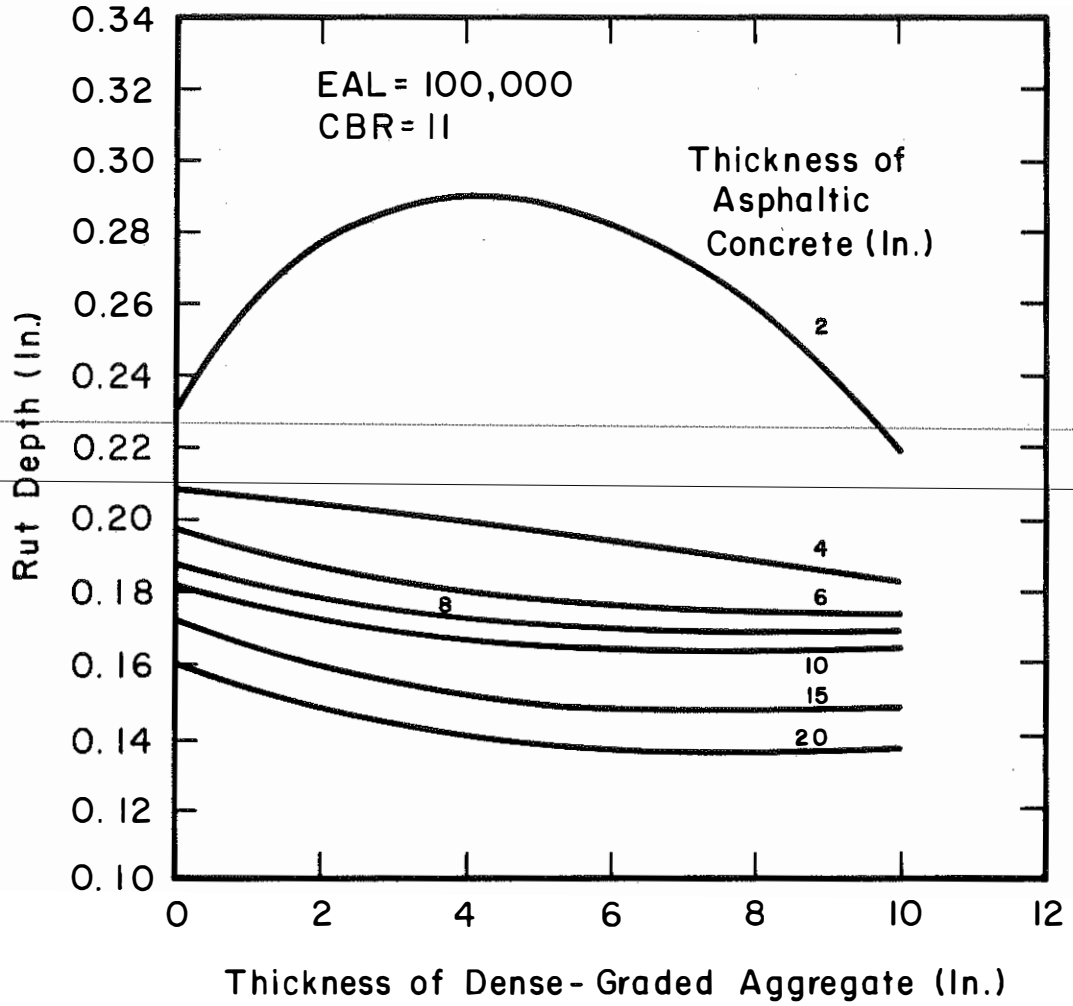

EAL = 10,000,000
CBR = 2.5
Thickness of Asphaltic Concrete (In.)
2
4
6
8
10
15
20
Rut Depth (In.)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
2
4
6
8
10
12
Thickness of Dense - Graded Aggregate (In.)

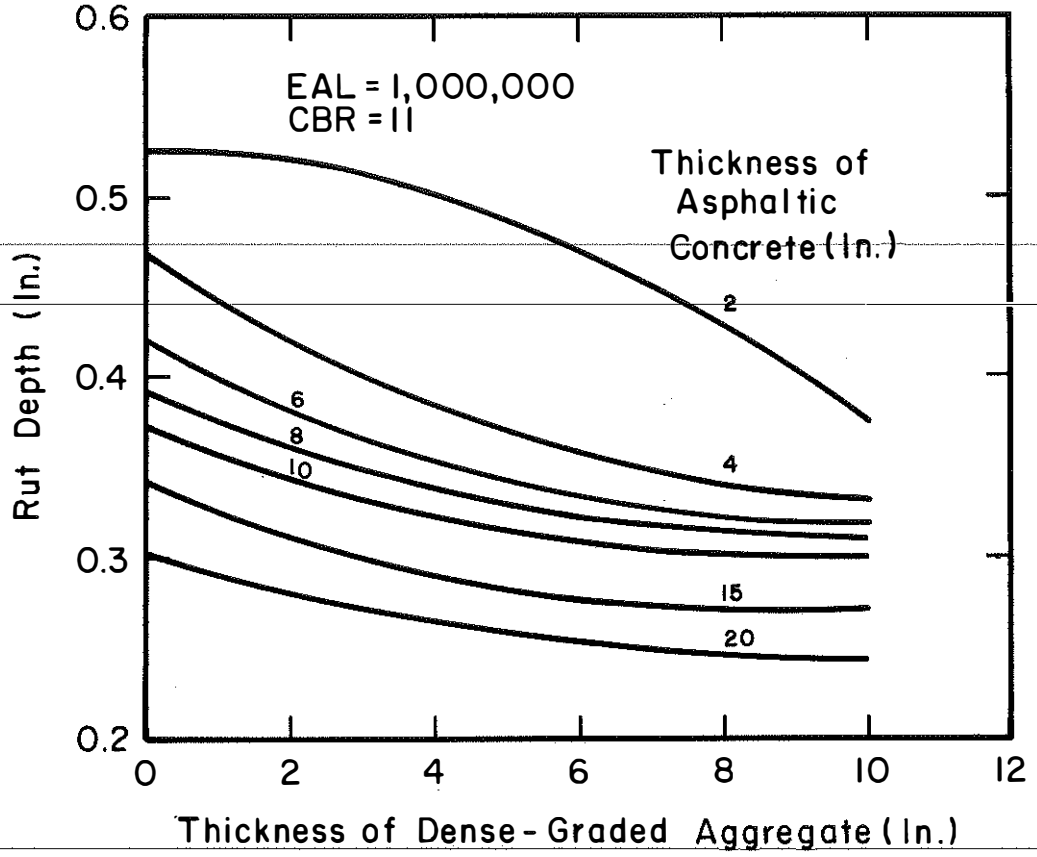

EAL =100,000
CBR = 5
Thickness of
Asphaltic Concrete
(in.)
2
4
6
8
10
15
20
Rut Depth (in.)
.34
.32
.30
.28
.26
.24
.22
.20
.18
.16
.14
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (in.)

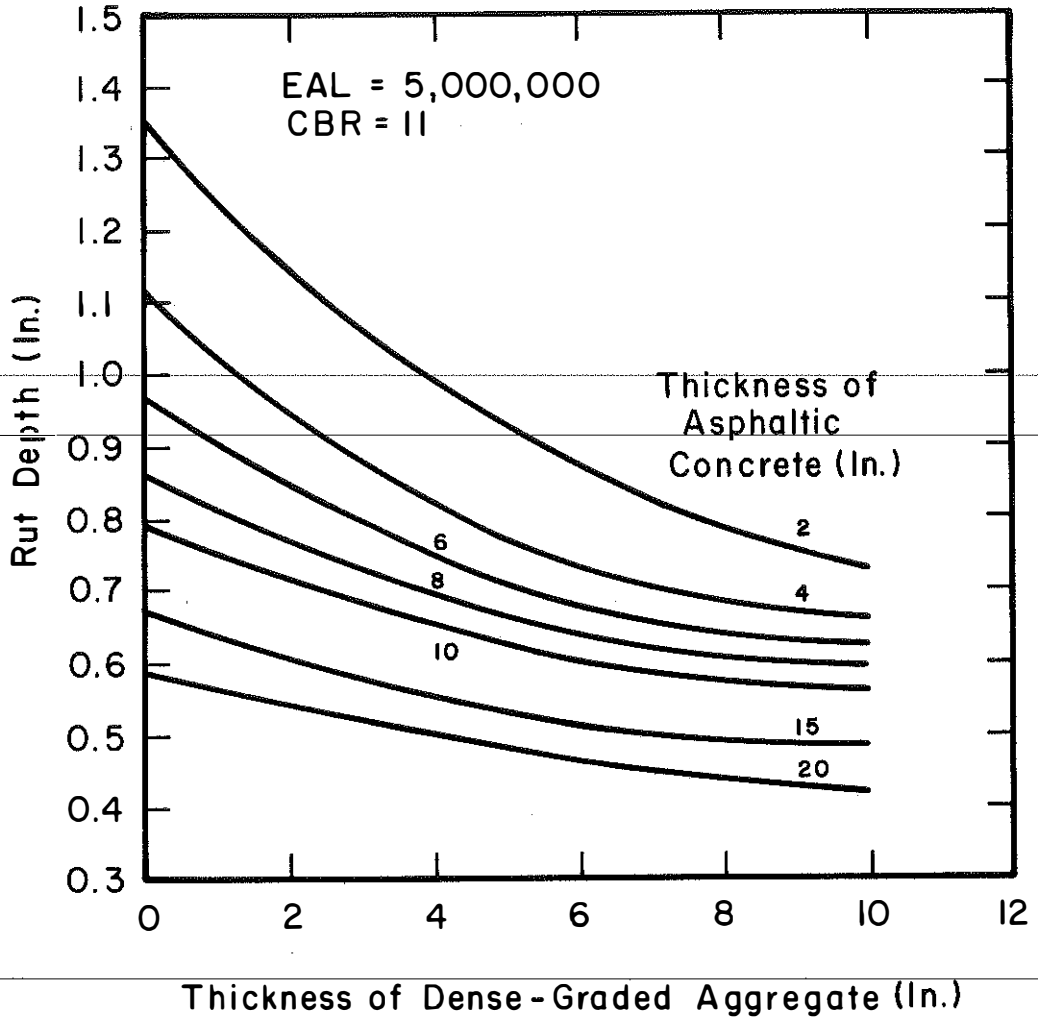

EAL = 1,000,000
CBR = 5
Thickness of
Asphaltic Concrete
(in.)
2
4
6
8
10
15
20
Rut Depth (in.)
.75
.70
.65
.60
.55
.50
.45
.40
.35
.30
.25
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (in)

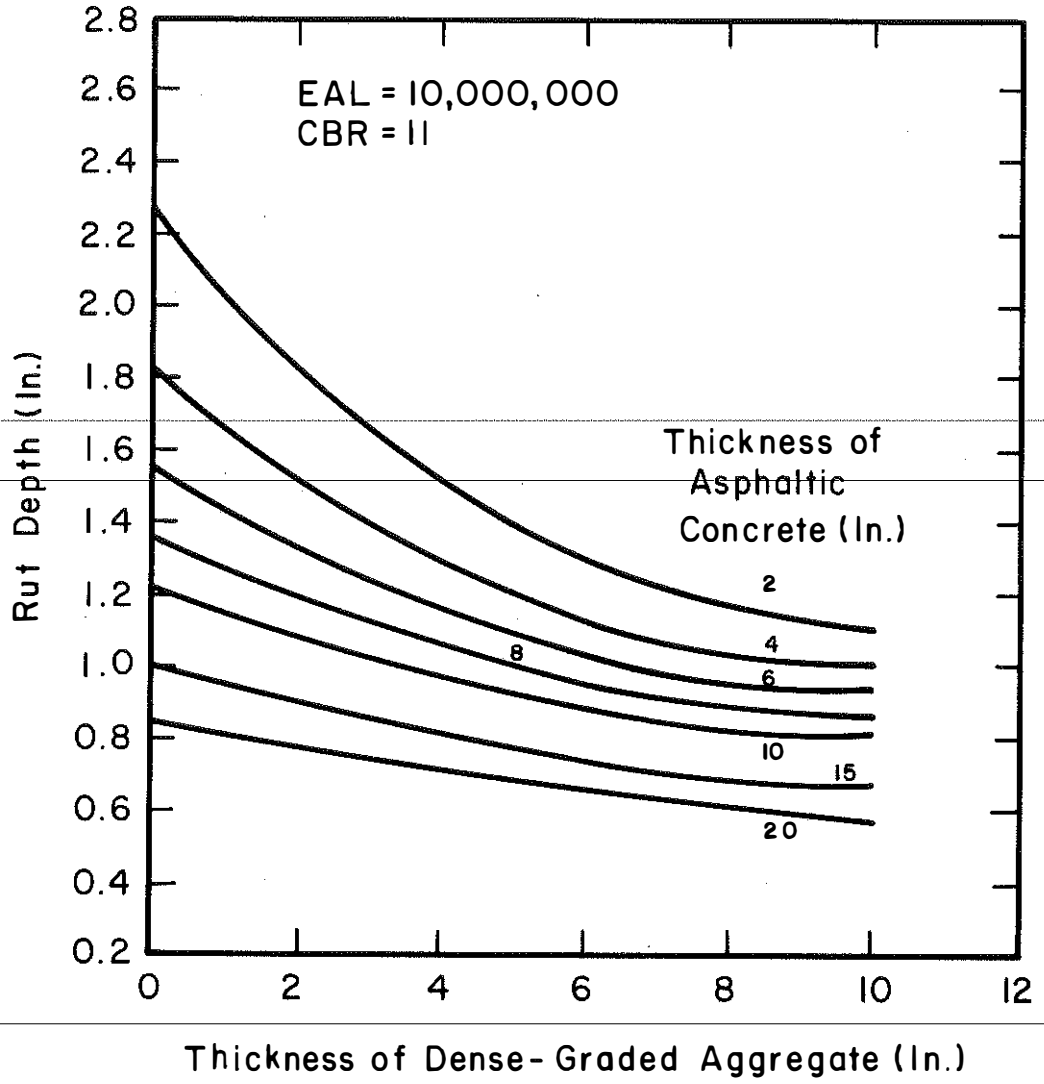

EAL = 5,000,000
CBR = 5
Rut Depth (in.)
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
2
Thickness of
Asphaltic Concrete
(in.)
2
4
6
8
10
15
20
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (in.)

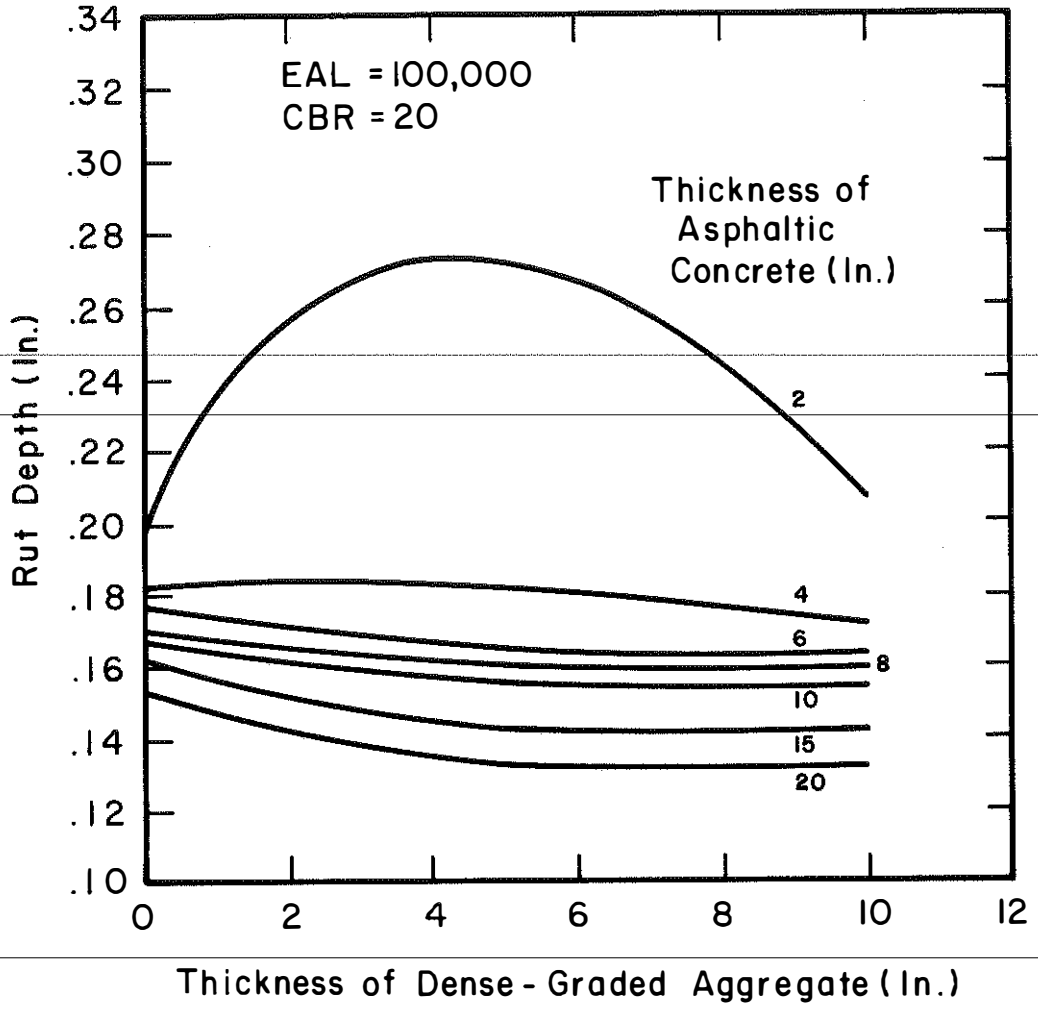

EAL = 10,000,000
CBR = 5
Thickness of
Asphaltic Concrete
(in.)
2
4
6
8
10
15
20
Rut Depth (in.)
3.2
2.8
2.4
2.0
1.6
1.2
.8
.4
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (in)

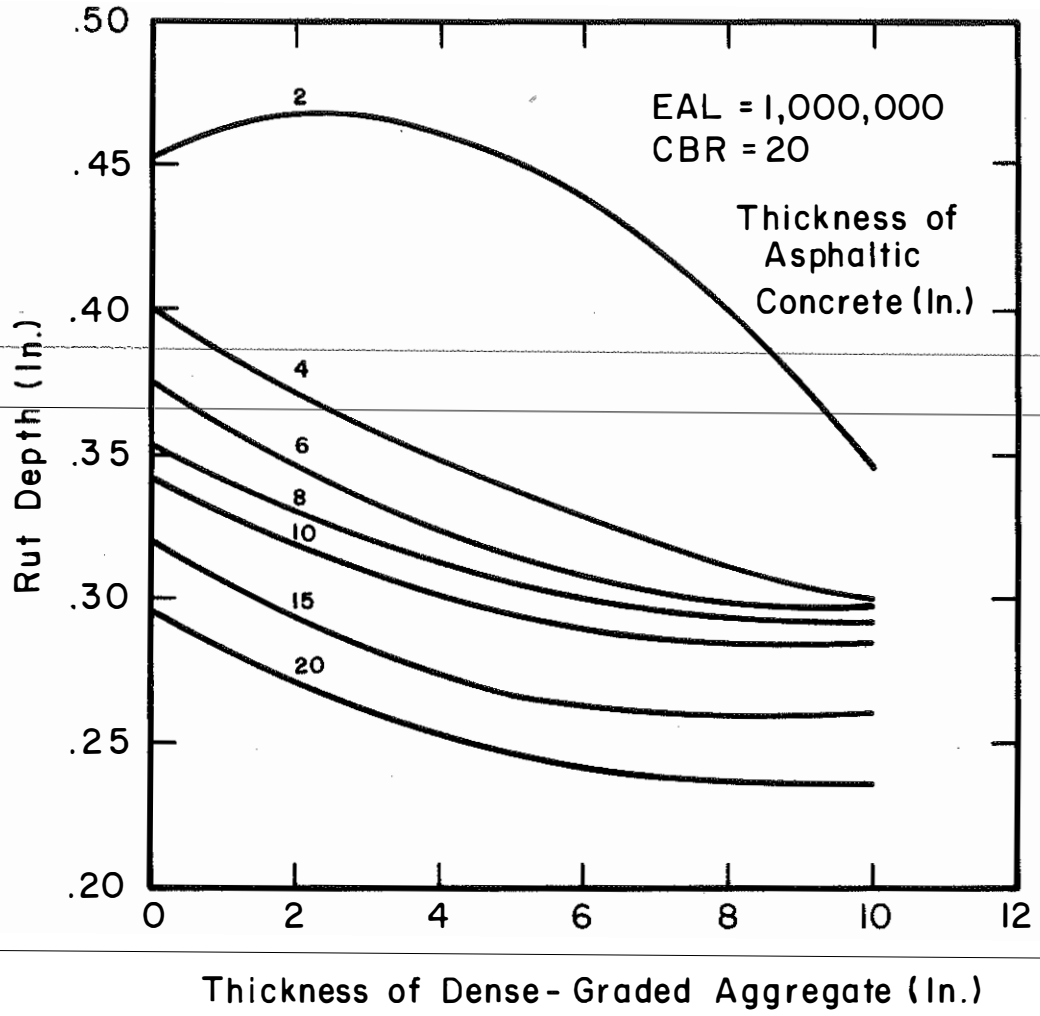

EAL = 100,000
CBR = 11
Thickness of Asphaltic Concrete (In.)
2
4
6
8
10
15
20
Rut Depth (In.)
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (In.)

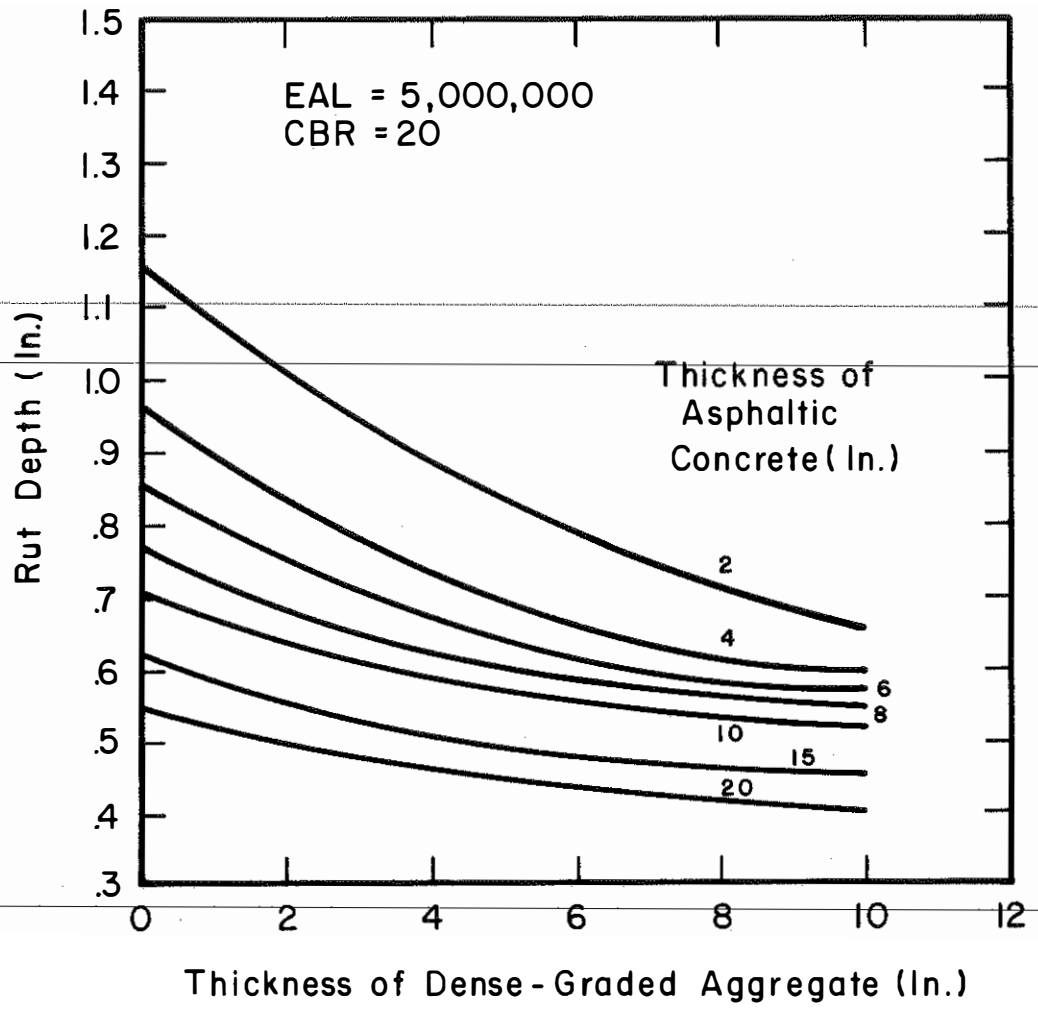

EAL = 1,000,000
CBR = 11
Thickness of Asphaltic Concrete (In.)
2
4
6
8
10
15
20
Rut Depth (In.)
0.6
0.5
0.4
0.3
0.2
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (In.)

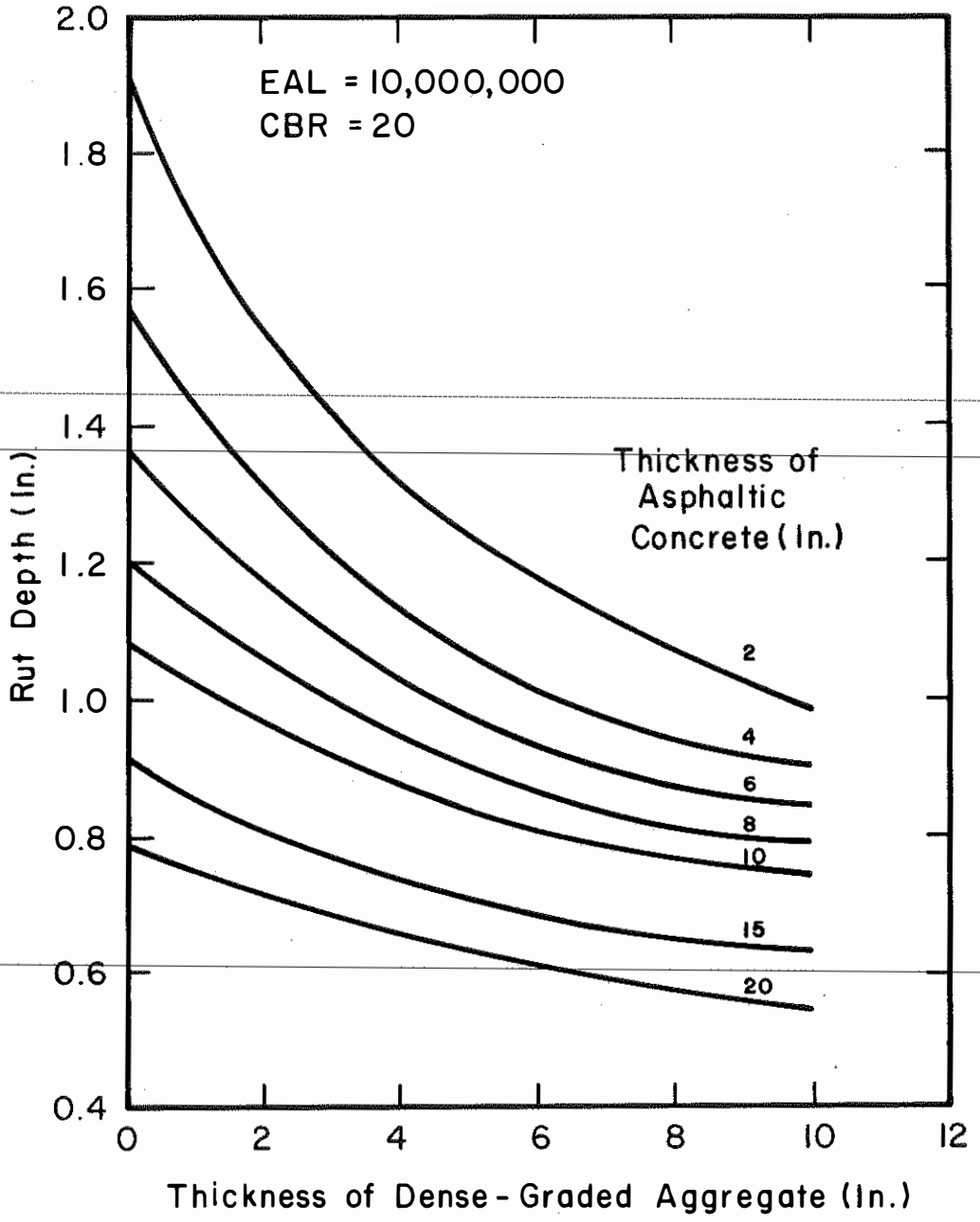

EAL = 5,000,000
CBR = 11
Thickness of Asphaltic Concrete (In.)
2
4
6
8
10
15
20
Rut Depth (In.)
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (In.)

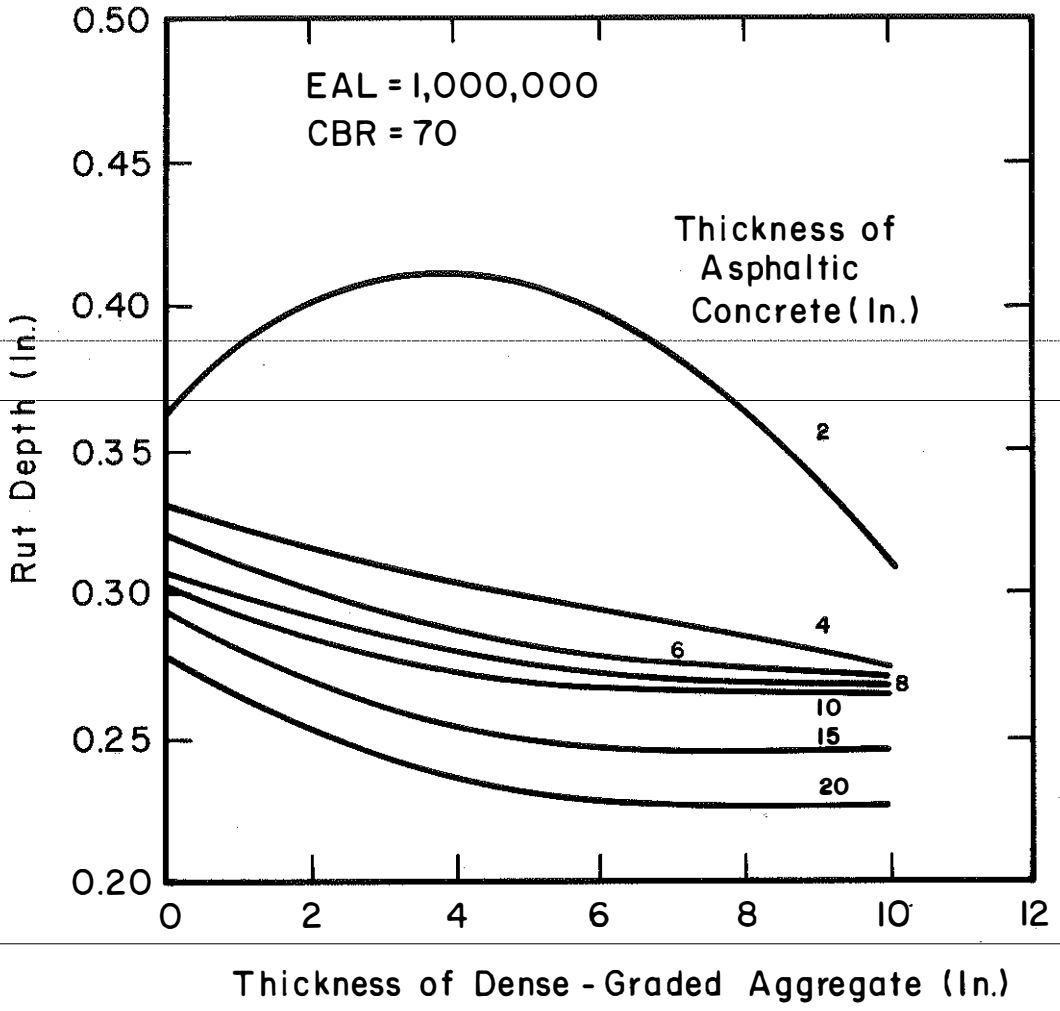

EAL = 10,000,000
CBR = 11
Thickness of Asphaltic Concrete (In.)
2
4
6
8
10
15
20
Rut Depth (In.)
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (In.)

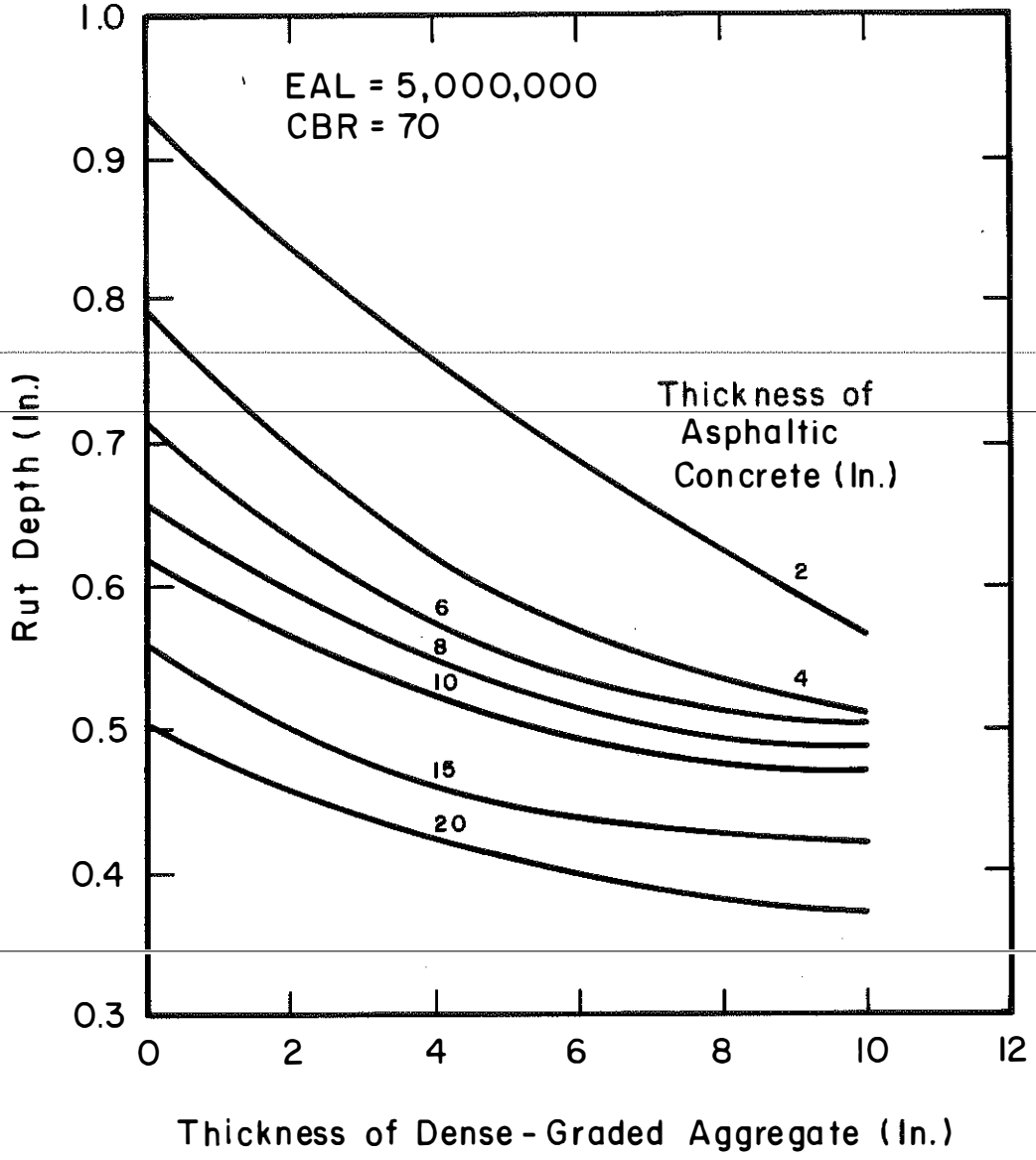

EAL = 100,000
CBR = 20
Thickness of Asphaltic Concrete (In.)
2
4
6
8
10
15
20
Rut Depth (In.)
.34
.32
.30
.28
.26
.24
.22
.20
.18
.16
.14
.12
.10
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (In.)

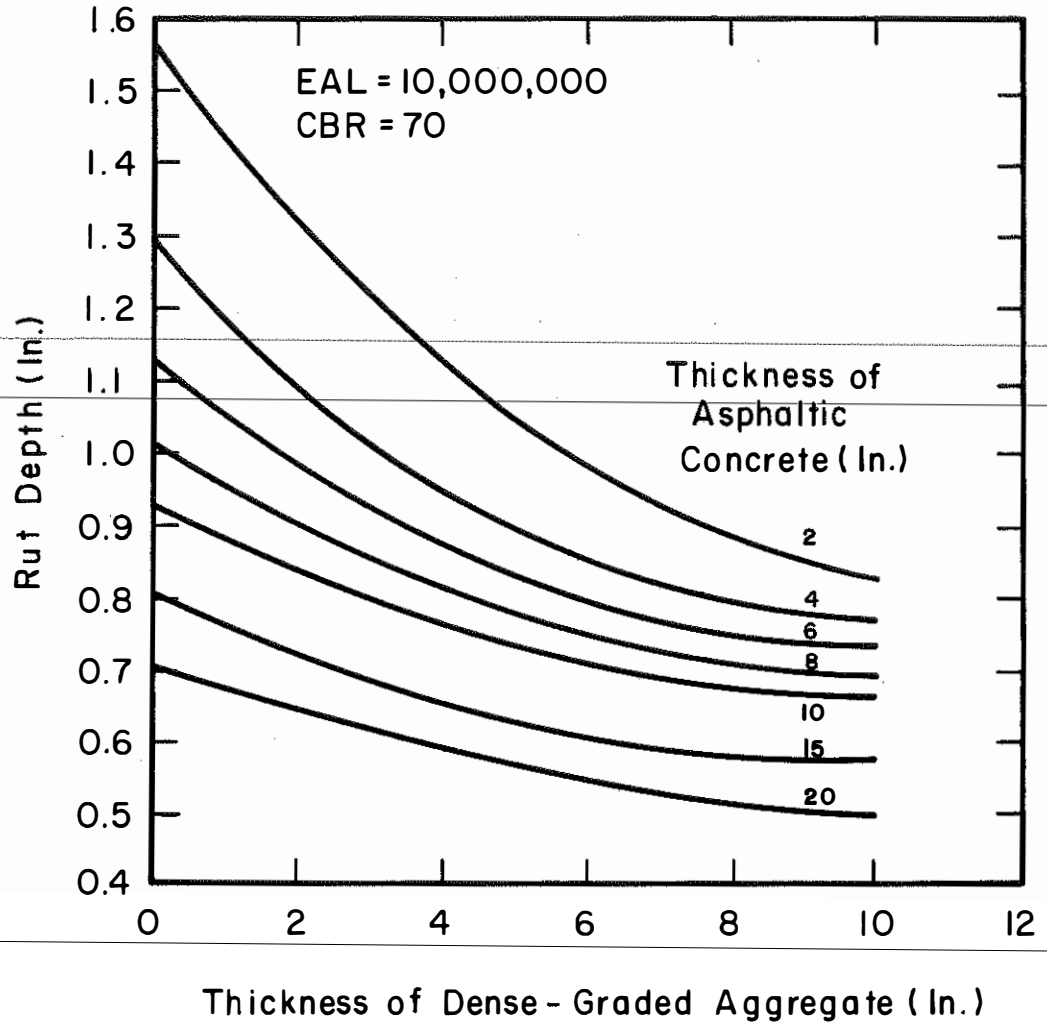

.50
.45
.40
.35
.30
.25
.20
Rut Depth (In.)
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (In.)
EAL = 1,000,000
CBR = 20
Thickness of Asphaltic Concrete (In.)
2
4
6
8
10
15
20


EAL = 5,000,000
CBR = 20
Thickness of Asphaltic Concrete (In.)
2
4
6
8
10
15
20
Rut Depth (In.)
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (In.)


EAL = 10,000,000
CBR = 20
Thickness of Asphaltic Concrete (In.)
2
4
6
8
10
15
20
Rut Depth (In.)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (In.)


EAL = 1,000,000
CBR = 70
Thickness of Asphaltic Concrete (In.)
2
4
6
8
10
15
20
Rut Depth (In.)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (In.)


EAL = 5,000,000
CBR = 70
Thickness of Asphaltic Concrete (In.)
2
4
6
8
10
15
20
Rut Depth (In.)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (In.)


EAL = 10,000,000
CBR = 70
Thickness of Asphaltic Concrete (In.)
2
4
6
8
10
15
20
Rut Depth (In.)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
2
4
6
8
10
12
Thickness of Dense-Graded Aggregate (In.)

APPENDIX B

INPUT INSTRUCTIONS FOR PAVRUT AND AN EXAMPLE OUTPUT

USER'S GUIDE FOR PAVRUT

1. CONTROL CARDS

A) TITLE CARD (80A1)

1-80 TITLE - TITLE CARD FOR PROGRAM IDENTIFICATION

B) PROGRAM CONSTANT CARD 1 (F15.0,F5.0,F3.0,2I2)

1-15 ANVOL - ANNUAL VOLUME OF VEHICLES

16-20 SPEED - AVERAGE SPEED OF VEHICLES

21-23 TRUCK - INPUT AS 1.0 OR 0.0,DEPENDING ON WHETHER TRUCKS ARE TO BE TREATED SEPARATELY FROM CARS

24-25 IGIMIC - INPUT AS 1 OR 0, IT IS ONE IF STRESSES ARE TO BE CALCULATED AT EACH NEW TEMPERATURE AND IT IS ZERO IF STRESSES ARE TO BE CALCULATED AT ONLY ONE TEMPERATURE

26-27 ICON - INPUT AS 1 OR 0, IT IS 1 IF THE PROBLEM INVOLVES AN OVERLAY ON A CONCRETE SLAB

C) PROGRAM CONSTANT CARD 2 (I3,2(F5.1,F6.0))

1-3 NS - NUMBER OF LAYERS (MAXIMUM OF 15)

4-8 PSIC - TIRE PRESSURE FOR CARS (PSI)

9-14 WGTC - WHEEL LOAD FOR CARS (POUNDS)

15-19 PSIT - TIRE PRESSURE FOR TRUCKS (PSI)
(IF VARIABLE TRUCK IS 0, THIS VARIABLE WILL BE ZERO)

20-25 WGTT - WHEEL LOAD FOR TRUCKS (POUNDS)
(IF VARIABLE TRUCK IS 0, THIS VARIABLE WILL BE ZERO)

2. DATA CARDS

A) PAVEMENT CHARACTERISTICS 1 (2(I3,2F5.2),F5.1) (MAXIMUM OF 15)

1-3 LYN - LAYER NUMBER

4-8 HH - LAYER THICKNESS (INCHES)

9-13 ANSDPT - ANSWER DEPTH : DEPTH FOR WHICH ANSWER IS CALCULATED (INCHES FROM TOP OF SURFACE)

14-16 MATYP - MATERIAL TYPE (1=ASPHALT CONCRETE,2=DENSE-GRADED AGGREGATE, 3=SUBGRADE)

17-21 W - MOISTURE CONTENT (IF THIS VARIABLE IS NOT ASSIGNED A VALUE, THE PROGRAM WILL ASSUME ONE)

22-26 SIGMA3 - CONFINING PRESSURE FOR DENSE-GRADED AGGREGATE AND SUBGRADE (IF THIS VARIABLE IS NOT ASSIGNED A VALUE, THE PROGRAM WILL ASSUME ONE)

27-31 CBR - CALIFORNIA BEARING RATIO FOR SUBGRADE (THIS VARIABLE IS LEFT BLANK WHEN READING DATA FOR ASPHALT CONCRETE AND DENSE-GRADED AGGREGATE)

B) PAVEMENT CHARACTERISTICS 2 (15F4.3)

1-4 V - POISSON'S RATIO FOR LAYER 1

5-8 V - POISSON'S RATIO FOR LAYER 2

9-12 V - POISSON'S RATIO FOR LAYER 3

13-16 V - POISSON'S RATIO FOR LAYER 4

17-20 V - POISSON'S RATIO FOR LAYER 5

21-24 V - POISSON'S RATIO FOR LAYER 6

25-28 V - POISSON'S RATIO FOR LAYER 7

29-32 V - POISSON'S RATIO FOR LAYER 8

33-36 V - POISSON'S RATIO FOR LAYER 9

37-40 V - POISSON'S RATIO FOR LAYER 10

41-44 V - POISSON'S RATIO FOR LAYER 11

45-48 V - POISSON'S RATIO FOR LAYER 12

49-52 V - POISSON'S RATIO FOR LAYER 13

53-56 V - POISSON'S RATIO FOR LAYER 14

57-60 V - POISSON'S RATIO FOR LAYER 15

EXAMPLE OUTPUT

```
**************************************************************************
*                                                                        *
*            10,000,000 EAL - RUN 21 - 20 10 18 CBR-7.5                  *
*                                                                        *
**************************************************************************
```

LAYER NUMBER 1	ASPHALT CONCRETE	
----------	LAYER THICKNESS	20.00
	FIRST STRESS	22.60
	ANSWER DEPTH	10.00
	LAYER DEFLECTION	0.3098E 00
LAYER NUMBER 2	DENSE-GRADED AGGREGATE	
----------	LAYER THICKNESS	10.00
	FIRST STRESS	1.79
	ANSWER DEPTH	25.00
	MOISTURE CONTENT	3.00
	LAYER DEFLECTION	0.3240E-01
LAYER NUMBER 3	SUBGRADE	
----------	LAYER THICKNESS	18.00
	FIRST STRESS	1.07
	ANSWER DEPTH	39.00
	MOISTURE CONTENT	7.00
	LAYER DEFLECTION	0.1967E 00

TOTAL PAVEMENT DEFLECTION 0.5389E 00

APPENDIX C

SOURCE LISTING OF PAVRUT

```
C*****************************************************************C
C               *                                       *         C
C               *                                       *         C
C               *                PAVRUT                 *         C
C               *                                       *         C
C               *                                       *         C
C               *     FIRST VERSION  JANUARY 1983       *         C
C               *                                       *         C
C               *        UPDATE, VERSIONS: NONE         *         C
C               *                                       *         C
C               *****************************************         C
C               *                                       *         C
C               *                                       *         C
C               *         COMPUTERIZED ANALYSIS         *         C
C               *                                       *         C
C               *                OF                     *         C
C               *                                       *         C
C               *  FLEXIBLE PAVEMENT RUTTING BEHAVIOR   *         C
C               *                                       *         C
C               *                                       *         C
C               *                USING                  *         C
C               *                                       *         C
C               *         ALGORITHMS DEVELOPED          *         C
C               *         FROM LABORATORY DATA          *         C
C               *                                       *         C
C               *                BY                     *         C
C               *                                       *         C
C               *            DAVID L. ALLEN             *         C
C               *                                       *         C
C               *                                       *         C
C               *****************************************         C
C               *                                       *         C
C               *       THE PROGRAM WAS DEVELOPED       *         C
C               *       UNDER THE AUSPICES OF THE       *         C
C               *                                       *         C
C               *        KENTUCKY TRANSPORTATION        *         C
C               *           RESEARCH PROGRAM            *         C
C               *                                       *         C
C               *          COLLEGE OF ENGINEERING       *         C
C               *                                       *         C
C               *        UNIVERSITY OF KENTUCKY         *         C
C               *                                       *         C
C               *          LEXINGTON KENTUCKY           *         C
C               *                                       *         C
C               *                                       *         C
C               *                                       *         C
C*****************************************************************C
C                                                                   C
C                                                                   C
C                        INPUT VARIABLES                            C
C                                                                   C
C                                                                   C
C*****************************************************************C
C                                                                   C
```

```
C  TITLE - PROBLEM TITLE                                                C
C                                                                       C
C  ANVOL - VOLUME OF VEHICLES                                           C
C                                                                       C
C  SPEED - AVERAGE SPEED OF VEHICLES                                    C
C                                                                       C
C  TRUCK - INPUT AS 1.0 OR 0.0 DEPENDING ON WHETHER TRUCKS ARE TO BE    C
C          TREATED SEPARATELY FROM CARS                                 C
C                                                                       C
C  IGIMIC - INPUT AS 1 OR 0, IT IS ONE IF STRESSES ARE TO BE            C
C           CALCULATED AT EACH NEW TEMPERATURE AND IT IS ZERO IF        C
C           STRESSES ARE TO BE CALCULATED AT ONLY ONE TEMPERATURE       C
C                                                                       C
C  ICON - INPUT AS 1 OR 0, IT IS 1 IF THE PROBLEM INVOLVES AN OVERLAY   C
C         ON A CONCRETE SLAB                                            C
C                                                                       C
C  NS   - NUMBER OF LAYERS                                              C
C                                                                       C
C  PSIC - TIRE PRESSURE FOR CARS                                        C
C                                                                       C
C  WGTC - WHEEL LOAD FOR CARS                                           C
C                                                                       C
C  PSIT - TIRE PRESSURE FOR TRUCKS (IF VARIABLE TRUCK IS 0, THIS        C
C         VARIABLE WILL BE ZERO)                                        C
C                                                                       C
C  WGTT - WHEEL LOAD FOR TRUCKS (IF VARIABLE TRUCK IS 0, THIS VARIABLE  C
C         WILL BE ZERO)                                                 C
C                                                                       C
C  LYN  - LAYER NUMBER                                                  C
C                                                                       C
C  HH   - LAYER THICKNESS                                               C
C                                                                       C
C  ANSDPT - ANSWER DEPTH (FROM THE SURFACE)                             C
C                                                                       C
C  MATYP - MATERIAL TYPE (1=ASPHALT CONCRETE, 2=DENSE-GRADED AGGREGATE, C
C          3=SUBGRADE)                                                  C
C                                                                       C
C  W     - MOISTURE CONTENT (IF THIS VARIABLE IS NOT ASSIGNED A VALUE,  C
C          THE PROGRAM WIL ASSUME ONE)                                  C
C                                                                       C
C  SIGMA3 - CONFINING PRESSURE FOR DENSE-GRADED AGGREGATE AND SUBGRADE  C
C           (IF THIS VARIABLE IS NOT ASSIGNED A VALUE, THE PROGRAM      C
C           WILL ASSUME ONE)                                            C
C                                                                       C
C  CBR   - CALIFORNIA BEARING RATIO FOR SUBGRADE (THIS VARIABLE IS      C
C          LEFT BLANK WHEN READING DATA FOR ASPHALT CONCRETE AND        C
C          DENSE-GRADED AGGREGATE)                                      C
C                                                                       C
C  V     - POISSON'S RATIO FOR EACH LAYER                               C
C                                                                       C
C                                                                       C
C***********************************************************************C
      COMMON /SPSCOM/ E(15),V(15),H(14),AZ(396),A(396,15),B(396,15),C(39
     16,15),D(396,15),AJ(396),BZ(100),X(15,4,4),SC(14),FM(4),PM(14,4,4),
```

```
     2Z,AR,NS,N,L,ITN,RSZ,SF,CSZ,I,ITN4,LC,PA,P,EP,T1P,T1,T2,T3,T4
     3,T5,T6,T2M,WA,ZF,SZ1,SZ2,SG1,SG2,PH,PH2,VK2,VKP2,VK4,VKP4,VKK8,
     4HH(15),SIGMA3(15),W(15),MATYP(15),ANSDPT(15)
      DIMENSION LYN(15),RLYT(15),DEF(15)
      DIMENSION TITLE(80)
      COMMON /VOLUME/ COHRV(24,12)
  10 READ(5,30,END=999) TITLE
  30 FORMAT(80A1)
      WRITE(6,75)
  75 FORMAT(1H1,'**********************************************************
     1***********************************')
      WRITE(6,74)
  74 FORMAT(1X,'*',88X,'*')
      WRITE(6,31) TITLE
  31 FORMAT(1X,'*',3X,80A1,5X,'*')
      WRITE(6,74)
      WRITE(6,76)
  76 FORMAT(1X,'**********************************************************
     1***********************************'//)
      READ(5,45) ANVOL, SPEED,TRUCK,IGIMIC,ICON
  45 FORMAT(F15.0,F5.0,F3.0,2I2)
      READ(5,81) NS,PSIC,WGTC,PSIT,WGTT
  81 FORMAT(I3,F5.1,F6.0,F5.1,F6.0)
      DO 705 LL=1,NS,1
      READ(5,105) LYN(LL), HH(LL), ANSDPT(LL), MATYP(
     1LL), W(LL), SIGMA3(LL),CBR
 105 FORMAT(I3,F5.2,F5.2,I3,F5.2,F5.2,F5.1)
 705 CONTINUE
      READ(5,963) (V(LL),LL=1,NS)
 963 FORMAT(15F4.3)
      DO 27 LL=1,NS,1
      ANSDP1=ANSDPT(LL)
      MA=MATYP(LL)
      STNLG=0.0
      DO 107 M=1,12,1
      DO 108 KK=1,24,1
      IF(MATYP(LL).EQ.1) CALL TEMP(M,KK,ANSDP1,TM)
      RTM=TM
      DO 109 KKK=1,2
      W1=W(LL)
      SIG3=SIGMA3(LL)
      IF(KKK.EQ.2.AND.TRUCK.EQ.0.0) GO TO 108
      IF(KKK.EQ.2.AND.TRUCK.GT.0.0) GO TO 299
      IF(TRUCK.EQ.0.0) HRV=COHRV(KK,M)*ANVOL*.0068*2.384
      IF(TRUCK.GT.0.0) HRV=COHRV(KK,M)*ANVOL*.00544*2.0
      PSI=PSIC
      WGT=WGTC
      CALL STRESS(RTM,M,PSI,WGT,ANSDP1,ADP,KK,IGIMIC,ICON,CSZ1)
      CORSTR=CSZ1*(1.0-0.32*(ANSDP1/AR))
      ASTRS=CSZ1
      STRS1=-ASTRS
      IF(STRS1.GT.PSI) STRS1=-CORSTR
      IF(STRS1.LT.1.0) STRS1=1.0
      GO TO 300
```

```
  299 HRV=COHRV(KK,M)*ANVOL*.00136*3.92
      PSI=PSIT
      WGT=WGTT
      CALL STRESS(RTM,M,PSI,WGT,ANSDP1,ADP,KK,IGIMIC,ICON,CSZ2)
      CORSTR=CSZ2*(1.0-0.32*(ANSDP1/AR))
      TSTRS=CSZ2
      STRS1=-TSTRS
      IF(STRS1.GT.PSI) STRS1=-CORSTR
      STRS2=STRS1
  300 GO TO(301,302,303), MA
  301 CALL ACRUT(STRS1,HRV,SPEED,RTM,STNLG)
      GO TO 109
  302 CALL DGARUT (M,STRS1,HRV,W1,SIG3,STNLG)
      GO TO 109
  303 CALL SUBRUT (M,STRS1,HRV,W1,SIG3,CBR,ICON,STNLG)
      GO TO 109
  109 CONTINUE
  108 CONTINUE
  107 CONTINUE
      IF(MATYP(LL).EQ.1) WRITE(6,41) LYN(LL)
   41 FORMAT(6X,'LAYER NUMBER',3X,I2,5X,'ASPHALT CONCRETE')
      IF(MATYP(LL).EQ.2) WRITE(6,42) LYN(LL)
   42 FORMAT(6X,'LAYER NUMBER',3X,I2,5X,'DENSE-GRADED AGGREGATE')
      IF(MATYP(LL).EQ.3) WRITE(6,43) LYN(LL)
   43 FORMAT(6X,'LAYER NUMBER',3X,I2,5X,'SUBGRADE')
      WRITE(6,56) HH(LL)
   56 FORMAT(6X,'----------------',5X,'LAYER THICKNESS',4X,F6.2)
      WRITE(6,57) STRS1
   57 FORMAT(28X,'FIRST STRESS',7X,F6.2)
      IF(TRUCK.GT.0.0) WRITE(6,58) STRS2
   58 FORMAT(28X,'SECOND STRESS',6X,F6.2)
      WRITE(6,59) ANSDPT(LL)
   59 FORMAT(28X,'ANSWER DEPTH',7X,F6.2)
      IF(MATYP(LL).NE.1) WRITE(6,61) W1
   61 FORMAT(28X,'MOISTURE CONTENT',3X,F6.2)
      DEF(LL)=(10.**STNLG)*(HH(LL))
      IF(ICON.EQ.1.AND.MA.EQ.3) DEF(LL)=0.0
      WRITE(6,445) DEF(LL)
  445 FORMAT(1H0,27X,'LAYER DEFLECTION',3X,E10.4//)
      IF(STNLG.GE.(-0.30103)) WRITE(6,55)
   55 FORMAT(3X,'WARNING--DEFLECTION VALUE FOR PREVIOUS LAYER APPEARS TO
     1BE EXCESSIVE.  IS THIS VALUE REALISTIC?'//)
   27 CONTINUE
      TOTDFL=0.0
      DO 507 LL=1,NS
  507 TOTDFL=TOTDFL+DEF(LL)
      WRITE(6,508) TOTDFL
  508 FORMAT(6X,'TOTAL PAVEMENT DEFLECTION',3X,E10.4,/,1H1)
      GO TO 10
  999 CONTINUE
      STOP
      END
C
C
```

```
C     ******************************************************************
C
C                        BLOCK DATA
C
C     ******************************************************************
C
C
      BLOCK DATA
      COMMON /VOLUME/ COHRV(24,12)
      DIMENSION A(24,6),B(24,6)
      EQUIVALENCE (A(1,1),COHRV(1,1)),(B(1,1),COHRV(1,7))
      DATA A/.23,2*.16,.14,.16,.35,.78,1.4,1.2,4*1.4,1.5,1.6,1.8,1.9,
     11.8,1.2,.92,.71,.57,.48,.35,.23,3*.16,.14,.35,.79,1.4,1.2,1.4,
     22*1.5,1.4,1.5,1.6,1.8,1.9,1.8,1.2,.93,.72,.58,.49,.35,.26,
     32*.18,.16,.18,.39,.88,1.5,1.3,4*1.6,1.7,1.8,2.0,2.1,2.0,1.4,
     41.0,.80,.65,.54,.39,.27,2*.19,.16,.19,.41,.93,1.6,1.4,4*1.7,1.8,
     51.9,2.1,2.3,2.1,1.5,1.1,.85,.68,.58,.41,.30,2*.21,.18,.21,.45,
     61.0,1.8,1.5,1.8,2*1.9,1.8,1.9,2.0,2.3,2.5,2.3,1.6,2.2,.92,.74,
     7.62,.45,.31,.22,.22,.19,.22,.46,1.0,1.8,1.6,3*1.9,1.9,2.0,2.1,
     82.4,2.6,2.4,1.6,1.2,.96,.77,.65,.46/
      DATA B/.33,2*.23,.20,.23,.49,1.1,1.9,1.7,2.0,2*2.1,2.0,2.1,2.2,
     12.5,2.7,2.5,1.7,1.3,1.0,.82,.69,.49,.32,2*.22,.19,.22,.48,1.1,
     21.9,1.7,4*2.0,2.1,2.2,2.5,2.7,2.5,1.7,1.3,.99,.80,.67,.48,.28,
     32*.19,.17,.19,.42,.94,1.6,1.4,4*1.7,1.8,1.9,2.1,2.3,2.2,1.5,1.1,
     4.86,.69,.58,.42,.28,2*.20,.17,.20,.42,.96,1.7,1.5,1.7,2*1.8,
     51.7,1.8,1.9,2.2,2.3,2.2,1.5,1.1,.87,.70,.59,.42,.27,2*.18,.16,
     6.18,.40,.92,1.5,1.4,1.6,2*1.7,1.6,1.7,1.8,2.0,2.2,2.1,1.4,1.0,
     7.83,.67,.56,.40,.25,2*.18,.15,.18,.38,.87,1.5,1.3,3*1.6,2*1.6,
     81.7,1.9,2.1,2.0,1.3,1.0,.80,.64,.54,.38/
      END
C
C
C     ******************************************************************
C
C                        SUBROUTINE ACRUT
C
C     ******************************************************************
C
C
      SUBROUTINE ACRUT(STRS1,HRV,SPEED,RTM,STNLG)
      REAL STRS1,HRV,SPEED,STNLG,RTM
      RNRP=HRV*(1./((SPEED*5280.)/3600.))
      IF(RNRP.LT.1.0) RNRP=1.0
      A=.00938
      B=-.10392
      C=.63974
      D=((-.000663*RTM**2)+(.1521*RTM-13.304))+((1.46-.00572*RTM)*ALOG10
     1(STRS1))
      IF(STNLG.EQ.0.0) GO TO 12
      CALL POLYRT (A,B,C,D,STNLG,ADNM)
      CRNRP=RNRP+ADNM
      STNLG=(A*ALOG10(CRNRP)*ALOG10(CRNRP)*ALOG10(CRNRP))+(B*ALOG10(CRNR
     1P)*ALOG10(CRNRP))+(C*ALOG10(CRNRP))+D
      GO TO 43
```

```
   12 STNLG=(A*ALOG10(RNRP)*ALOG10(RNRP)*ALOG10(RNRP))+(B*ALOG10(RNRP)*A
     1LOG10(RNRP))+(C*ALOG10(RNRP))+D
   43 RETURN
      END
C
C
C     ****************************************************************
C
C                        SUBROUTINE DGARUT
C
C     ****************************************************************
C
C
      SUBROUTINE DGARUT (M,STRS,HRV,W1,SIG3,STNLG)
      REAL STRS,HRV,STNLG,W1,SIG3
      INTEGER M
      IF(W1.LT..001.AND.(M.NE.3.AND.M.NE.4)) W1=3.0
      IF(W1.LT..001.AND.(M.EQ.3.0R.M.EQ.4)) W1=4.5
      IF(SIG3 .EQ.5.0) SIG3=.35*STRS
      A=.0066-.004*ALOG10(W1)
      B=-.142+.092*ALOG10(W1)
      C=.72
      D=(-4.41+(.0173+.003*W1)*(STRS))-((.00075+.0029*W1)*(SIG3))
      IF(STNLG.EQ.0.0) GO TO 21
      CALL POLYRT(A,B,C,D,STNLG,ADNM)
      CHRV=HRV+ADNM
      STNLG=(A*ALOG10(CHRV)*ALOG10(CHRV)*ALOG10(CHRV))+(B*ALOG10(CHRV)*A
     1LOG10(CHRV))+(C*ALOG10(CHRV))+D
      GO TO 47
   21 STNLG=(A*ALOG10(HRV)*ALOG10(HRV)*ALOG10(HRV))+(B*ALOG10(HRV)*ALOG1
     10(HRV))+(C*ALOG10(HRV))+D
   47 RETURN
      END
C
C
C     ****************************************************************
C
C                        SUBROUTINE SUBRUT
C
C     ****************************************************************
C
C
      SUBROUTINE SUBRUT (M,STRS,HRV,W1,SIG3,CBR,ICON,STNLG)
      REAL STRS,HRV,STNLG,W1,SIG3
      INTEGER M
      IF(SIG3.EQ.3.0) SIG3=.35*STRS
      IF(CBR.EQ.0.0)GO TO 57
      IF (CBR.NE.0.0) W3=0.0.8633-0.05645*ALOG10(CBR)
      W1=10**W3
   57 A=.007+.001*W1
      B=-.018*W1
      C=10**(-1.1+.1*W1)
      D=((-6.5+.38*W1)-(1.1*ALOG10(SIG3)))+(1.86*ALOG10(STRS))
      IF(STNLG.EQ.0.0) GO TO 38
```

```
      CALL POLYRT (A,B,C,D,STNLG,ADNM)
      CHRV=HRV+ADNM
      STNLG=(A*ALOG10(CHRV)*ALOG10(CHRV)*ALOG10(CHRV))+(B*ALOG10(CHRV)*A
     1LOG10(CHRV))+(C*ALOG10(CHRV))+D
      GO TO 42
   38 STNLG=(A*ALOG10(HRV)*ALOG10(HRV)*ALOG10(HRV))+(B*ALOG10(HRV)*ALOG1
     10(HRV))+(C*ALOG10(HRV))+D
   42 RETURN
      END
C
C
C     ****************************************************************
C
C                        SUBROUTINE TEMP
C
C     ****************************************************************
C
C
      SUBROUTINE TEMP(RMN,HR,DP,TM)
      INTEGER RMN, HR
      REAL DP, TM
      CAZEZE=-0.8882061D+00
      CAZEV1=-0.5409584D+01
      CAZEV2=0.1419966D+01
      CAZEV3=-0.1436045D+00
      CAZEV4=0.6001302D-02
      CAZEV5=-0.8782359D-04
      CAP1ZE=-0.2312872D+01
      CAP1V1=0.3643902D+01
      CAP1V2=-0.1000187D+01
      CAP1V3=0.1082190D+00
      CAP1V4=-0.4867211D-02
      CAP1V5=0.7657193D-04
      CAP2ZE=0.3188233D+00
      CAP2V1=-0.4041188D+00
      CAP2V2=0.1103354D+00
      CAP2V3=-0.1201035D-01
      CAP2V4=0.5488345D-03
      CAP2V5=-0.8829082D-05
      CAP3ZE=-0.1064115D-01
      CAP3V1=0.1438466D-01
      CAP3V1=0.1438466D-01
      CAP3V2=-0.3902280D-02
      CAP3V3=0.4237800D-03
      CAP3V4=-0.1942740D-04
      CAP3V5=0.3144042D-06
      CNAP1=CAZEV1*HR
      CNAP2=CAZEV2*HR**2
      CNAP3=CAZEV3*HR**3
      CNAP4=CAZEV4*HR**4
      CNAP5=CAZEV5*HR**5
      CNAP11=CAP1V1*HR
      CNAP12=CAP1V2*HR**2
      CNAP13=CAP1V3*HR**3
```

```
CNAP14=CAP1V4*HR**4
CNAP15=CAP1V5*HR**5
CNAP21=CAP2V1*HR
CNAP22=CAP2V2*HR**2
CNAP23=CAP2V3*HR**3
CNAP24=CAP2V4*HR**4
CNAP25=CAP2V5*HR**5
CNAP31=CAP3V1*HR
CNAP32=CAP3V2*HR**2
CNAP33=CAP3V3*HR**3
CNAP34=CAP3V4*HR**4
CNAP35=CAP3V5*HR**5
AZERO=CAZEZE+CNAP1+CNAP2+CNAP3+CNAP4+CNAP5
AONE=(CAP1ZE+CNAP11+CNAP12+CNAP13+CNAP14+CNAP15)*DP
ATWO=(CAP2ZE+CNAP21+CNAP22+CNAP23+CNAP24+CNAP25)*DP**2
ATHREE=(CAP3ZE+CNAP31+CNAP32+CNAP33+CNAP34+CNAP35)*DP**3
CONSTA=AZERO+AONE+ATWO+ATHREE
CBZEZE=0.5449503D+00
CBZEV1=0.1836149D-01
CBZEV2=-0.1005689D-01
CBZEV3=0.1579478D-02
CBZEV4=-0.8601361D-04
CBZEV5=0.1517039D-05
CBP1ZE=-0.4002625D-02
CBP1V1=0.1128790D-01
CBP1V2=-0.1222558D-02
CBP1V3=-0.1705093D-03
CBP1V4=0.1952838D-04
CBP1V5=-0.4628811D-06
CBP2ZE=0.7371035D-03
CBP2V1=-0.1401982D-02
CBP2V2=0.2543963D-03
CBP2V3=0.1147628D-05
CBP2V4=-0.1274846D-05
CBP2V5=0.3690588D-07
CBP3ZE=-0.7334696D-04
CBP3V1=0.7449587D-04
CBP3V2=-0.1665841D-04
CBP3V3=0.8755230D-06
CBP3V4=0.1938508D-08
CBP3V5=-0.6176451D-09
CFBP1=CBZEV1*HR
CFBP2=CBZEV2*HR**2
CFBP3=CBZEV3*HR**3
CFBP4=CBZEV4*HR**4
CFBP5=CBZEV5*HR**5
CFBP11=CBP1V1*HR
CFBP12=CBP1V2*HR**2
CFBP13=CBP1V3*HR**3
CFBP14=CBP1V4*HR**4
CFBP15=CBP1V5*HR**5
CFBP21=CBP2V1*HR
CFBP22=CBP2V2*HR**2
CFBP23=CBP2V3*HR**3
```

```
      CFBP24=CBP2V4*HR**4
      CFBP25=CBP2V5*HR**5
      CFBP31=CBP3V1*HR
      CFBP32=CBP3V2*HR**2
      CFBP33=CBP3V3*HR**3
      CFBP34=CBP3V4*HR**4
      CFBP35=CBP3V5*HR**5
      BZERO=CBZEZE+CFBP1+CFBP2+CFBP3+CFBP4+CFBP5
      BONE=(CBP1ZE+CFBP11+CFBP12+CFBP13+CFBP14+CFBP15)*DP
      BTWO=(CBP2ZE+CFBP21+CFBP22+CFBP23+CFBP24+CFBP25)*DP**2
      BTHREE=(CBP3ZE+CFBP31+CFBP32+CFBP33+CFBP34+CFBP35)*DP**3
      COEFFB=BZERO+BONE+BTWO+BTHREE
      ADD1=-.0757-.0221*HR**2
      ADD2=10**(-2.96+.0582*HR**2)
      ADD3=ADD1-ADD2
      IF (ADD3 .LT. -.300E+01) ADD3=-.300E+01
      SUTPML=10**ADD3
      SUFOUR=-.316+.0814*HR+.0125*HR**2-.00115*HR**3+.000023*HR**4
      SUTPHR=SUFOUR+SUTPML
      SRTPMN=.603-.353*RMN+.153*RMN**2-.0179*RMN**3+.000629*RMN**4
      SURTEM=SUTPHR*SRTPMN*132.
      IF (RMN .LE. 8) ARTEMP=7.46*RMN+25.3
      IF (RMN .GT. 8) ARTEMP=-12.42*RMN+184.
      HORVAR=SURTEM+ARTEMP
      PVTP=COEFFB*HORVAR+CONSTA
      IF(PVTP.LT.20.0) PVTP=20.0
      TM=PVTP
      RETURN
      END
C
C
C     ****************************************************************
C
C                        SUBROUTINE POLYRT
C
C     ****************************************************************
C
C
      SUBROUTINE POLYRT (A,B,C,D,STNLG,ADNM)
      DIMENSION X(10)
      N=1
      X(N)=1.0
      TS=D-STNLG
   10 X1=X(N)-(A*X(N)**3+B*X(N)**2+C*X(N)+TS)/(3*A*X(N)**2+2*B*X(N)+C)
      IF(ABS(X(N)-X1).GT.0.005) Z=X1
      IF(ABS(X(N)-X1).LT.0.005) GO TO 40
      N=N+1
      IF(N.EQ.10) GO TO 30
      X(N)=Z
      GO TO 10
   30 WRITE(6,35)
   35 FORMAT(' ','MAXIMUM NUMBER OF ITERATIONS EXCEEDED- ERROR IN
     1DATA',///)
      GO TO 50
```

```
   40 ROOT=X1
      ADNM=10.**ROOT
   50 RETURN
      END
C
C     ****************************************************************
C
C                        SUBROUTINE EMOD
C
C     ****************************************************************
C
C
      SUBROUTINE EMOD(M,ICON,NNT)
      COMMON /SPSCOM/ E(15),V(15),H(14),AZ(396),A(396,15),B(396,15),C(39
     16,15),D(396,15),AJ(396),BZ(100),X(15,4,4),SC(14),FM(4),PM(14,4,4),
     2Z,AR,NS,N,L,ITN,RSZ,SF,CSZ,I,ITN4,LC,PA,P,EP,T1P,T1,T2,T3,T4
     3,T5,T6,T2M,WA,ZF,SZ1,SZ2,SG1,SG2,PH,PH2,VK2,VKP2,VK4,VKP4,VKK8,
     4HH(15),SIGMA3(15),W(15),MATYP(15),ANSDPT(15)
      DO 45 NN=1,NS
      MA=MATYP(NN)
      GO TO (98,99,100), MA
   98 ADP=ANSDPT(NN)
      CALL TEMP(M,NNT,ADP,TM)
      RTM2=TM
      ACMOD=10.**(10.46-2.676*ALOG10(RTM2))
      IF(ACMOD.GT.6000000.0) ACMOD=6000000.0
      IF(ACMOD.LT.20000.0) ACMOD=20000.0
      E(NN)=ACMOD
      GO TO 45
   99 IF(SIGMA3(NN).EQ.0.0) SIGMA3(NN)=5.0
      IF (W(NN).EQ.0.0.AND.(M.NE.3.AND.M.NE.4)) W(NN)=3.0
      IF(W(NN).EQ.0.0.AND.(M.EQ.3.OR.M.EQ.4)) W(NN)=4.5
      DGAMOD=10.**((5.4624-2.729*ALOG10(W(NN)))+(0.175+1.19*ALOG10(W(NN)
     3))*(ALOG10(SIGMA3(NN))))
      IF(DGAMOD.GT.300000.) DGAMOD=300000.
      IF(DGAMOD.LT.1000.) DGAMOD=1000.
      E(NN)=DGAMOD
      GO TO 45
  100 IF(SIGMA3(NN).EQ.0.0) SIGMA3(NN)=3.0
      IF(W(NN).EQ.0.0.AND.(M.NE.3.AND.M.NE.4)) W(NN)=7.0
      IF(W(NN).EQ.0.0.AND.(M.EQ.3.OR.M.EQ.4)) W(NN)=8.0
      SUBMOD=10.**((5.331+.0007*SIGMA3(NN))+(.11246-.01006*SIGMA3(NN)+
     1.00031*SIGMA3(NN)**2)*W(NN)-(.02496-.00188*SIGMA3(NN)+.0000549*
     2SIGMA3(NN)**2)*W(NN)**2)
      IF(SUBMOD.GT.220000.) SUBMOD=220000.
      IF(SUBMOD.LT.50.) SUBMOD=50.
      E(NN)=SUBMOD
      IF (ICON.EQ.1) E(NN)=6000000.0
   45 CONTINUE
   47 RETURN
      END
C
C
C     ****************************************************************
```

```
C
C                        SUBROUTINE STRESS
C
C     ****************************************************************
C
C
      SUBROUTINE STRESS(RTM,M,PSI,WGT,ANSDP1,ADP,KK,IGIMIC,ICON,CSZ1)
      REAL*8 W2(4)/0.34785485,2*0.65214515,0.34785485/
      REAL*8 G1/0.86113631/,G2/0.33998104/
      COMMON /SPSCOM/ E(15),V(15),H(14),AZ(396),A(396,15),B(396,15),C(39
     16,15),D(396,15),AJ(396),BZ(100),X(15,4,4),SC(14),FM(4),PM(14,4,4),
     2Z,AR,NS,N,L,ITN,RSZ,SF,CSZ,I,ITN4,LC,PA,P,EP,T1P,T1,T2,T3,T4
     3,T5,T6,T2M,WA,ZF,SZ1,SZ2,SG1,SG2,PH,PH2,VK2,VKP2,VK4,VKP4,VKK8,
     4HH(15),SIGMA3(15),W(15),MATYP(15),ANSDPT(15)
      DIMENSION TEST(11)
      IF(KK.GT.1.AND.IGIMIC.EQ.0) GO TO 777
      NNT=10
      BZ(1)=0.0
      BZ(2)=1.0
      BZ(3)=2.4048
      BZ(4)=3.8317
      BZ(5)=5.5201
      BZ(6)=7.0156
      N=NS-1
      ITN=46
      ITN4=184
      K=ITN+1
      DO 2 I=7,K,2
      T=I/2
      TD=4.0*T-1.0
    2 BZ(I)=3.1415927*(T-0.25+0.0506661/TD-0.053041/TD**3+.262051/TD**5)
      DO 3 I=8,ITN,2
      T=(I-2)/2
      TD=4.0*T+1.0
    3 BZ(I)=3.1415927*(T+0.25-0.151982/TD+0.015399/TD**3-0.245270/TD**5)
      AR=SQRT(WGT/(3.14159*PSI))
      ZF=AR
      K=1
      ZF=2.0*ZF
      SZ2=0.0
      DO 28 I=1,ITN
      SZ1=SZ2
      SZ2=BZ(I+1)/ZF
      SF=SZ2-SZ1
      TT=SZ2+SZ1
      SG1=SF*G1
      SG2=SF*G2
      AZ(K)=TT-SG1
      AZ(K+1)=TT-SG2
      AZ(K+2)=TT+SG2
      AZ(K+3)=TT+SG1
      K=K+4
   28 CONTINUE
      CALL EMOD(M,ICON,NNT)
```

```
      H(1)=HH(1)
      DO 25 I=2,N
   25 H(I)=H(I-1)+HH(I)
      DO 125 I=1,ITN4
      P=AZ(I)
      CALL COFE(I,PSI)
      PA=AR*P
      CALL BESSEL(1,PA,Y)
      AJ(I)=Y
  125 CONTINUE
      Z=ANSDP1
      DO 44 J1=1,N
      J=NS-J1
      IF(Z-H(J)) 44,45,45
   44 CONTINUE
      L=1
      GO TO 46
   45 L=J+1
   46 CONTINUE
      VL=2.0*V(L)
      VL1=1.0-VL
      CSZ=0.0
      NTEST=2
      NTS1=NTEST+1
      ITS=1
      ARP=AR*PSI
   10 DO 40 I=1,ITN
      RSZ=0.0
      MMM=4*(I-1)
      DO 30 J=1,4
      J1=MMM+J
      P=AZ(J1)
      EP=EXP(P*Z)
      T2=D(J1,L)/EP
      T1=B(J1,L)*EP
      T1P=T1+T2
      T1=(A(J1,L)+B(J1,L)*Z)*EP
      T2=(C(J1,L)+D(J1,L)*Z)/EP
      T2M=P*(T1-T2)
      WA=AJ(J1)*W2(J)
      PP=P*P
      RSZ=RSZ+WA*PP*(VL1*T1P-T2M)
   30 CONTINUE
      SF=(AZ(M+4)-AZ(M+1))/1.7222726
      CSZ=CSZ+RSZ*SF
      RSZ=2.0*RSZ*AR*SF
      TESTH=ABS(RSZ)-10.0**(-4)
      IF(ITS-NTS1) 31,32,32
   31 CONTINUE
      TEST(ITS)=TESTH
      ITS=ITS+1
      GO  TO 40
   32 CONTINUE
      TEST(NTS1)=TESTH
```

```
      DO 33 J=1,NTEST
      IF(TESTH-TEST(J)) 35,36,36
   35 CONTINUE
      TESTH=TEST(J)
   36 CONTINUE
      TEST(J)=TEST(J+1)
   33  CONTINUE
       IF(TESTH) 50,50,40
   40 CONTINUE
   50 CSZ1=CSZ*ARP
  777 RETURN
      END
      SUBROUTINE COFE(KIN,PSI)
      COMMON /SPSCOM/ E(15),V(15),H(14),AZ(396),A(396,15),B(396,15),C(39
     16,15),D(396,15),AJ(396),BZ(100),X(15,4,4),SC(14),FM(4),PM(14,4,4),
     2Z,AR,NS,N,L,ITN,RSZ,SF,CSZ,I,ITN4,LC,PA,P,EP,T1P,T1,T2,T3,T4
     3,T5,T6,T2M,WA,ZF,SZ1,SZ2,SG1,SG2,PH,PH2,VK2,VKP2,VK4,VKP4,VKK8,
     4HH(15),SIGMA3(15),W(15),MATYP(15),ANSDPT(15)
      REAL*4 Q(2,2)
      LC=KIN
    1 DO 10 K=1,N
      T1=E(K)*(1.0+V(K+1))/(E(K+1)*(1.0+V(K)))
      T1M=T1-1.0
      PH=P*H(K)
      PH2=PH*2.0
      VK2=2.0*V(K)
      VKP2=2.0*V(K+1)
      VK4=2.0*VK2
      VKP4=2.0*VKP2
      VKK8=8.0*V(K)*V(K+1)
C
      X(K,1,1)=VK4-3.0-T1
      X(K,2,1)=0.0
      X(K,3,1)=T1M*(PH2-VK4+1.0)
      X(K,4,1)=-2.0*T1M*P
C
      T3=PH2*(VK2-1.0)
      T4=VKK8+1.0-3.0*VKP2
      T5=PH2*(VKP2-1.0)
      T6=VKK8+1.0-3.0*VK2
C
      X(K,1,2)=(T3+T4-T1*(T5+T6))/P
      X(K,2,2)=T1*(VKP4-3.0)-1.0
      X(K,4,2)=T1M*(1.0-PH2-VKP4)
C
      X(K,3,4)=(T3-T4-T1*(T5-T6))/P
C
      T3=PH2*PH-VKK8+1.0
      T4=PH2*(VK2-VKP2)
C
      X(K,1,4)=(T3+T4+VKP2-T1*(T3+T4+VK2))/P
      X(K,3,2)=    (-T3+T4-VKP2+T1*(T3-T4+VK2))/P
C
      X(K,1,3)=T1M*(1.0-PH2-VK4)
```

```
      X(K,2,3)=2.0*T1M*P
      X(K,3,3)=VK4-3.0-T1
      X(K,4,3)=0.0
C
      X(K,2,4)=T1M*(PH2-VKP4+1.0)
      X(K,4,4)=T1*(VKP4-3.0)-1.0
C     K = K
   10 CONTINUE
C     COMPUTE THE PRODUCT MATRICES PM
      SC(N)=4.0*(V(N)-1.0)
      IF (N-2) 13,11,11
   11 DO 12 K1=2,N
      M=NS-K1
      SC(M)=SC(M+1)*4.0*(V(M)-1.0)
   12 CONTINUE
   13 CONTINUE
C
      Q(1,1)=1.
      Q(2,2)=1.
      Q(1,2)=0.
      QQ    =P*2.*H(N)
      IF (QQ-172.) 15,15,16
   15 CONTINUE
      Q(1,2)=EXP(-QQ)
C     Q(2,1) IS NOT NEEDED FOR INITIALIZING THE PM MATRIX
   16 CONTINUE
C      20 LOOP INITIALIZES PM(N,,)
      DO 20 M=1,4
      LL=(M+1)/2
      DO 20 J=3,4
      PM(N,M,J)= X(N,M,J) *     Q(LL,2)
   20 CONTINUE
      DO 26 K1=2,N
      K=NS-K1
      KK=K+1
      QQ    =P*2.*H(K)
      IF (QQ-172.) 22,22,23
   22 CONTINUE
      Q(2,1)=EXP(QQ)
      Q(1,2)=1./Q(2,1)
      GO TO 24
   23 CONTINUE
      Q(1,2)=0.
      Q(2,1)=1.E20
   24 CONTINUE
      DO 25 M=1,4
      LL=(M+1)/2
      DO 25 J=3,4
      PM(K,M,J)=( X(K,M,1) * PM(KK,1,J)
     2           +X(K,M,2) * PM(KK,2,J) ) * Q(LL,1)
     3         +( X(K,M,3) * PM(KK,3,J)
     4           +X(K,M,4) * PM(KK,4,J) ) * Q(LL,2)
   25 CONTINUE
   26 CONTINUE
```

```
C     SOLVE FOR C(NS) AND D(NS)
      T3=2.0*V(1)
      T4 =T3-1.0
      FM(1)= P*(PM(1,1,3)+PM(1,3,3)) + T3*(PM(1,2,3)-PM(1,4,3))
      FM(2)= P*(PM(1,1,3)-PM(1,3,3)) + T4*(PM(1,2,3)+PM(1,4,3))
      FM(3)= P*(PM(1,1,4)+PM(1,3,4)) + T3*(PM(1,2,4)-PM(1,4,4))
      FM(4)= P*(PM(1,1,4)-PM(1,3,4)) + T4*(PM(1,2,4)+PM(1,4,4))
      DFAC=SC(1)/((FM(1)*FM(4)-FM(3)*FM(2))*P*P)
          A(LC,NS) = 0.0
          B(LC,NS) = 0.0
          C(LC,NS) = -FM(3)*DFAC
          D(LC,NS) =  FM(1)*DFAC
C     BACKSOLVE FOR THE OTHER A,B,C,D
      DO 91 K1=1,N
      A(LC,K1)=(PM(K1,1,3)*C(LC,NS)+PM(K1,1,4)*D(LC,NS))/SC(K1)
      B(LC,K1)=(PM(K1,2,3)*C(LC,NS)+PM(K1,2,4)*D(LC,NS))/SC(K1)
      C(LC,K1)=(PM(K1,3,3)*C(LC,NS)+PM(K1,3,4)*D(LC,NS))/SC(K1)
   91 D(LC,K1)=(PM(K1,4,3)*C(LC,NS)+PM(K1,4,4)*D(LC,NS))/SC(K1)
  100 CONTINUE
      RETURN
      END
      SUBROUTINE BESSEL(NI,XI,Y)
      REAL*8 PZ(6)/1.0D0,-1.125D-4,2.8710938D-7,-2.3449658D-9,
     A3.9806841D-11,-1.1536133D-12/,  QZ(6)/-5.0D-3,4.6875D-6,
     B-2.3255859D-8, 2.8307087D-10, -6.3912096D-12,  2.3124704D-12/,
     CP1(6)/ 1.0D0,  1.875D-4,      -3.6914063D-7,   2.7713232D-9,
     D-4.5114421D-11,1.2750463D-12/, Q1(6)/1.5D-2,  -6.5625D-6,
     E 2.8423828D-8,-3.2662044D-10,  7.1431166D-12, -2.5327056D-13/,
     F PI/3.1415927/
      DIMENSION  D(20)
C
C
    9 N=NI
      X=XI
      IF (X-7.0) 10,10,160
C
   10 X2=X/2.0
      FAC=-X2*X2
      IF  (N)  11,11,14
   11 C=1.0
      Y=C
      DO  13 I=1,34
      T=1
      C=FAC*C/(T*T)
      TEST=ABS (C) - 10.0**(-8)
      IF (TEST) 17,17,12
   12 Y=Y+C
   13 CONTINUE
   14 C=X2
      Y=C
      DO 16 I=1,34
      T=I
      C=FAC*C/(T*(T+1.0))
      TEST=ABS (C) - 10.0**(-8)
```

```
      IF (TEST) 17,17,15
   15 Y=Y+C
   16 CONTINUE
   17 RETURN
  160 IF (N) 161,161,164
C
C
  161 DO 162 I=1,6
      D(I) = PZ(I)
      D(I+10) = QZ(I)
  162 CONTINUE
      GO  TO  163
C
  164 DO 165 I=1,6
      D(I)= P1(I)
      D(I+10) = Q1(I)
  165 CONTINUE
  163 CONTINUE
      T1 = 25.0/X
      T2 = T1*T1
      P=D(6)*T2+D(5)
      DO 170 I=1,4
      J=5-I
      P=P*T2+D(J)
  170 CONTINUE
      Q=D(16)*T2+D(15)
      DO 171 I=1,4
      J=5-I
      Q=Q*T2+D(J+10)
  171 CONTINUE
      Q=Q*T1
C
      T4=DSQRT (X*PI)
      T6=SIN (X)
      T7=COS  (X)
C
      IF (N) 180,180,185
C
  180 T5=((P-Q)*T6+(P+Q)*T7)/T4
      GO TO  99
  185 T5=((P+Q)*T6-(P-Q)*T7)/T4
   99 Y=T5
      RETURN
      END
/*
```