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**STRUCTURAL CAPACITY  
OF IN-PLACE ASPHALTIC CONCRETE PAVEMENTS  
FROM DYNAMIC DEFLECTIONS**

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# STRUCTURAL CAPACITY OF IN-PLACE ASPHALTIC CONCRETE PAVEMENTS FROM DYNAMIC DEFLECTIONS

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## ABSTRACT

The proper design of asphaltic overlay thicknesses involves four major factors: the in-place modulus of the subgrade, an estimate of the structural capacity of the existing pavement, estimates of the future traffic expressed as equivalent axleloads and required or desired design levels, and a thickness design procedure. This paper deals with estimating the in-place subgrade modulus and the remaining load-carrying capacity of the existing pavement. The method presented herein is valid for any Road Rater or other dynamic tester such as the Dynaflect. This procedure was based upon a 600-pound (272.4-kg) peak-to-peak dynamic load applied at a rate of 25 Hz. The steady-state deflections have to be adjusted for load, dynamic frequency, and location of sensors. This method should be applied only to those testers that use a constant vibratory load.

## INTRODUCTION

In a 1979 Transportation Research Board symposium (1) on "Pavement Evaluation and Overlay Design" a graphical procedure to evaluate in-place conditions was presented. Herein are refinements to that graphical procedure. Equations have been developed and programmed so they can be processed using hand calculators or larger computers.

The major steps of the evaluation procedure are:

1. Development of theoretical relationships between pavement deflection, subgrade modulus, and asphaltic concrete thickness (this is a straight-forward method based upon elastic theory);
2. Adjustment of the test data to reference conditions (temperature, frequency of loading, location of sensors, percent voids, percent asphalt content in the mix, and modulus of the asphaltic concrete);
3. Determination of the in-place subgrade modulus and equivalent or "effective" asphaltic concrete thickness; and
4. Selection of input design parameters for an overlay design procedure.

Step 1 involves theoretical relationships between deflections of an original pavement of reference-quality materials and deflections of an existing pavement with the same crushed stone thickness, but with decreased thicknesses of asphaltic concrete (to account for a partial use of the fatigue life of the pavement) for each of the three sensors of the Road Rater. The two more-remote sensors are used to determine which portion of the pavement structure is exhibiting distress.

In Step 2, equations are used to adjust measured deflections for load, frequency, temperature, location of sensors, percent voids, percent asphalt content, and asphaltic concrete modulus. Deflections obtained by other dynamic testers (such as the Dynaflect) under various test conditions can be analyzed using the technique and relationships summarized in this paper.

In Step 3, the existing pavement is assumed to perform as a pavement of "x" thickness of reference-quality asphaltic concrete over the as-built thickness of crushed stone base (zero thickness for full-depth asphalt pavements). This portion of the analysis may involve a single test to represent a section of pavement, or as many test points as desired may be evaluated. If more than just a few deflection measurements are involved, the data should be subjected to the analyses of Step 4.

Step 4 is a statistical and/or graphical analysis of the subgrade moduli and the behavioral thicknesses of the asphaltic concrete layer determined in Step 3. The mean and standard error of estimate should be calculated so that an appropriate behavioral thickness can be chosen. The thickness selected in this portion of the analysis to represent the structural capacity of the existing pavement is related to the risk of failure to be assumed with the overlay design. Appropriate choices of behavioral thicknesses and design methods are discussed.

## THEORETICAL ANALYSIS

Construction records provide as-constructed thicknesses of the layers in the pavement structure. All layers below the asphaltic concrete are assumed to have remained as constructed. Deterioration and fatigue reduce the effectiveness of the asphaltic concrete to some equivalent, thinner thickness of reference-quality material. Vibratory testers, such as the Road Rater and Dynaflect, induce vibrations in the pavement structure that can be detected by velocity sensors or accelerometers. The electronics of the testers process the signal to yield surface deflections. These measured deflections are used to estimate the in-place condition of the pavement.

For an existing pavement, the effective thickness of the dense-graded aggregate layer is assumed to be equal to the as-constructed thickness. The remaining variables that influence the behavior of the pavement are the subgrade modulus and the effective thickness of the asphaltic concrete layers, defined as the equivalent thickness of reference-quality materials that matches measured behavior.

The Chevron N-layer computer program requires layer thicknesses, their respective moduli and Poisson's ratios, load, contact pressure, and geometry of load and sensor locations. A matrix of structures and input values were utilized to calculate deflections associated with the Road Rater loading. Procedures used in simulating Road Rater loadings and deflections are discussed in great detail elsewhere (1). These calculated deflections are the basis of the equations developed in this paper.

Analyses indicated surface deflections for a given pavement structure are a function of the subgrade modulus as given in

$$\log \Delta = K \log E_s + L \quad 1$$

in which  $\Delta$  = Road Rater deflection (0.00001 inches),

$K$  = slope of the log-log line,

$L$  = constant, and

$E_s$  = modulus of the subgrade (psi).

Both  $K$  and  $L$  are dependent upon the thicknesses of the asphaltic concrete and the dense-graded aggregate layers, as described by the third-degree polynomials

$$K = N_1 (AC)^3 + N_2 (AC)^2 + N_3 (AC) + N_4 \quad 2$$

and

$$L = N_5 (AC)^3 + N_6 (AC)^2 + N_7 (AC) + N_8 \quad 3$$

in which  $AC$  = thickness of the asphaltic concrete (inches) and

$N$  = eight constants determined by the fourth-degree polynomial,

$$N_i = A_i(DGA)^4 + B_i(DGA)^3 + C_i(DGA)^2 + D_i(DGA) + E_i, \quad 4$$

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in which  $N_1$  through  $N_4$  are associated with the slope  $K$  and  $N_5$  through  $N_8$  are associated with the constant  $L$ ,  
 DGA = thickness of the unbound layer (inches), and  
 A, B, C, D, E, = constants determined by regression analyses.

Values for each of the constants are listed in Table 1.

**Type of Distress**

The theoretical deflections for No.-2 and No.-3 Sensors (Equation 1) are used to calculate

$$\log \text{No.-1 Projection} = 2 \log (\text{No.-2 } \Delta) - \log (\text{No.-3 } \Delta) \quad 5$$

Equation 5 is a mathematical representation of a semilog line through the magnitudes of No.-2 and No.-3 Sensors projected to the position of the No.-1 Sensor. The slope of the relationship in Equation 5, the difference in magnitude between the No.-1 Projection and the No.-1 Sensor deflections, and the magnitudes of all deflections are indicative of the shape of the deflection bowl.

For a given combination of layer thicknesses, asphaltic concrete modulus, and subgrade modulus, each pavement will have a calculated deflection bowl. There is a difference between the No.-1 Projection and the No.-1 Sensor for theoretical deflec-

tions (Figure 1). There also will be a difference between these values for field-measured deflections.

Normally, the differences between the No.-1 Projected deflection and the No.-1 Sensor deflection for both theoretical and field values are similar. Slab deterioration is indicated when measured No.-1 Sensor deflections are greater than No.-1 Projections (Figure 2) and when the differences between these values are greater than the differences for corresponding theoretical deflections. A foundation problem or lack of supporting capability is indicated by increased magnitudes of all field deflections and No.-1 Projection greater than the No.-1 Sensor deflections (Figure 3).

Log-log plots of No.-1 Projections versus No.-1 Sensor deflections can be used to identify variations in pavement structure (see Figure 4A). The solid line shows the theoretical relationship between No.-1 Projections and No.-1 Sensor deflections for a constant structure and asphaltic concrete modulus. Subgrade modulus varies along the line. The points about the line represent measured deflections. The variation in position of the theoretical line due to changes in the magnitudes of deflections by +/- one unit (0.00001 in. (0.000254 mm)) and the associated changes in theoretical No.-1 Projections are indicated by the two dashed lines. The zone within these lines represents a normal variation

TABLE 1. COEFFICIENTS FOR ROAD RATER DEFLECTION EQUATIONS

$$N = A_i \text{ DGA}^4 + B_i \text{ DGA}^3 + C_i \text{ DGA}^2 + D_i \text{ DGA} + E_i$$

$$K = N_1 \text{ AC}^3 + N_2 \text{ AC}^2 + N_3 \text{ AC} + N_4$$

$$L = N_5 \text{ AC}^3 + N_6 \text{ AC}^2 + N_7 \text{ AC} + N_8$$

$$\log \Delta = K \log E_s + L$$

in which DGA = thickness of dense-graded aggregate base layer,  
 AC = thickness of asphaltic concrete layer,  
 $E_s$  = modulus of elasticity of subgrade, and  
 $\Delta$  = deflection

i	A <sub>i</sub>	B <sub>i</sub>	C <sub>i</sub>	D <sub>i</sub>	E <sub>i</sub>
<b>No. 1 Sensor</b>					
1	-8.0276712E-09	4.4637935E-07	-7.8334349E-06	4.3700774E-05	0.00015920
2	2.2880623E-07	-1.2956090E-05	0.00023168	-0.00126428	-0.00603433
3	-2.0069119E-06	0.00011636	-0.00213561	0.01152101	0.07053069
4	5.3511621E-06	-0.00032005	0.00617403	-0.03601869	-0.94738380
5	3.8112800E-08	-2.1142292E-06	3.6712485E-05	-0.00019713	-0.00079876
6	-1.0927940E-06	6.1604764E-05	-0.00108663	0.00564980	0.03181695
7	9.6888879E-06	-0.00055752	0.01004067	-0.05039463	-0.42286904
8	-2.6361517E-05	0.00155888	-0.02921499	0.14909581	6.27491080
<b>No. 2 Sensor</b>					
1	-1.9422702E-08	1.0770627E-06	-1.8518686E-05	9.5507480E-05	8.9416760E-05
2	5.2579366E-07	-2.9137271E-05	0.00049930	-0.00251336	-0.00416610
3	-4.2869807E-06	0.00023786	-0.00407118	0.01974778	0.07009015
4	9.8983780E-06	-0.00055346	0.00958628	-0.04540810	-1.12011456
5	6.1453952E-08	-3.3927169E-06	5.7851557E-05	-0.00028477	-0.00038341
6	-1.9486070E-06	0.00010728	-0.00180868	0.00847179	0.01804679
7	1.5831303E-05	-0.00087303	0.01469200	-0.06471592	-0.34277031
8	-3.6284025E-05	0.00202136	-0.03448633	0.13878339	6.61774653
<b>No. 3 Sensor</b>					
1	2.1333448E-08	-1.2598323E-06	2.4207689E-05	-0.00016422	4.6358157E-05
2	-6.1003392E-07	3.6138955E-05	-0.00069872	0.00483808	-0.00319426
3	5.4277510E-06	-0.00032212	0.00626602	-0.04474861	0.07028740
4	-1.5081292E-05	0.00089525	-0.01749993	0.13007837	-1.27529337
5	-1.0456648E-07	6.1644249E-06	-0.00011799	0.00078800	-0.00010359
6	2.9858350E-06	-0.00017641	0.00339148	-0.02303053	0.01019562
7	-2.6465435E-05	0.00156508	-0.03021266	0.21073267	-0.28067328
8	7.2699360E-05	-0.00429505	0.08308389	-0.60401394	6.84595514

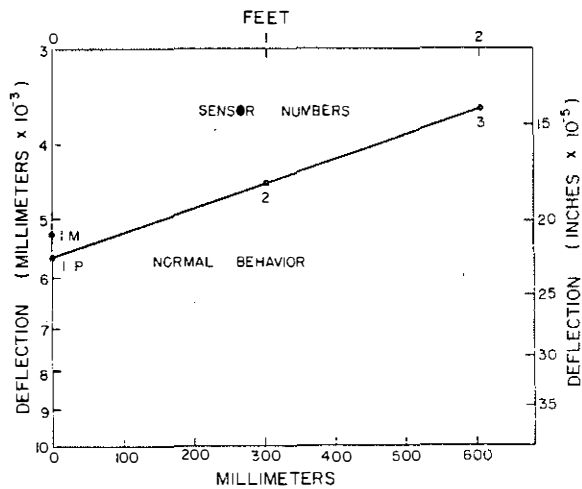


Figure 1. Relationship between Deflection and Distance from Point of Load and Determination of No.-1 Projected Deflection for Pavement Exhibiting Normal Behavior.

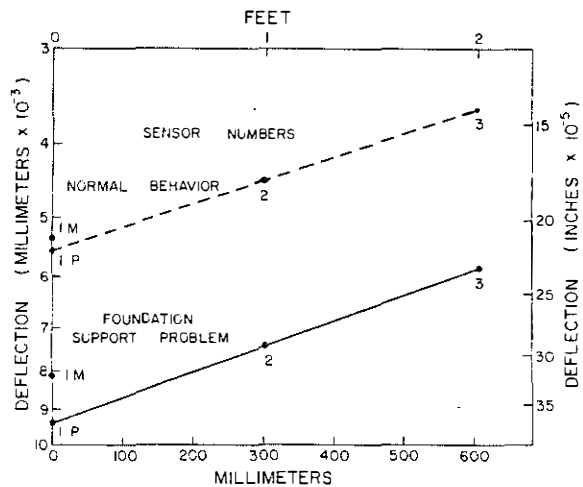


Figure 3. Relationship between Deflection and Distance from Point of Load and Determination of No.-1 Projected Deflection for Pavement With Foundation Support Problem.

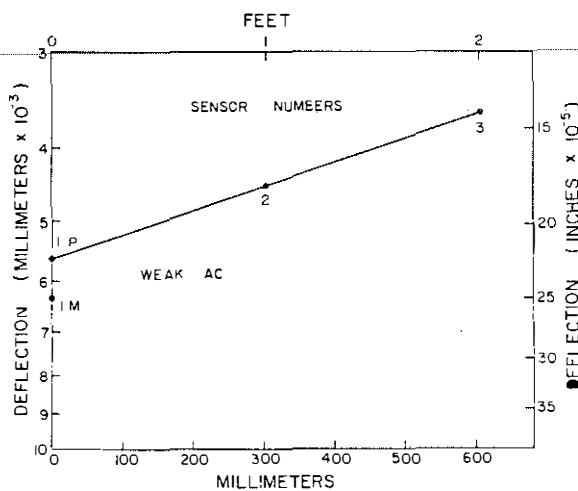


Figure 2. Relationship between Deflection and Distance from Point of Load and Determination of No.-1 Projected Deflection for Pavement With Weak Asphaltic Concrete Layer.

factor contributing to this condition. This condition and pattern of deflections were confirmed by data obtained in Huntington Beach, California (1, 2). There, Road Rater tests were performed, the pavements were cored, subgrade samples were obtained, and the moisture contents of the subgrade were determined. In those locations that had high water contents (possibly free water), the differences between the No.-1 Projected and measured deflections was considerably greater than the theoretical analyses would have indicated. One possible explanation is that water is a better conductor of sound or vibrations than normal subgrades. Therefore, the No.-2 and No.-3 Sensors measure higher deflections for soils containing excess water than for soils having normal water contents.

#### Deflection Equations

Equation 1 is solved for the eight constants  $N_i$  for a particular dense-graded aggregate thickness. For a given asphaltic concrete thickness,  $K$  and  $L$  remain constant. Thus, deflections are a function of the elastic modulus of the subgrade. Likewise, other asphaltic concrete thicknesses substituted into Equations 2 and 3 yield a family of curves (Figure 4B). The constants  $K$  and  $L$  for each thickness of asphaltic concrete are retained for use in evaluating the test data.

#### ADJUSTMENT OF DEFLECTIONS TO REFERENCE CONDITIONS

The five primary variables affecting deflections other than layer thicknesses and subgrade modulus are load, temperature, frequency of the dynamic loading, modulus of elasticity of the asphaltic concrete, and the location of the sensors. Pavement behavior can match more than one combination of subgrade modulus and thickness of asphaltic concrete. Thus, it is necessary to select an appropriate combination that matches measured deflections. The No.-2 and No.-3 Sensors can have quite different deflections but yield the same No.-1 Projected deflection by Equation 5; on the other hand, the No.-1 Sensor deflections may be nearly equal.

#### Load

A relationship to adjust a measured deflection induced by a load of any known magnitude to a reference load is given by

$$AF_L = \Delta \text{ at 600 pounds} \div \Delta \text{ at X pounds.} \quad 6$$

Thus, the adjusted deflection is expressed in terms of the matrices of calculations for Kentucky's Road Rater. Normal operation for the Kentucky Road Rater uses a 600-pound (272.4 kg) peak-to-peak dynamic force.

due to reading the meters.

The following situations have been observed from field evaluations:

1. Test data that lie within the zone of normal variation and show relatively low deflections are indicative of a structure of high-quality materials in which all layers are acting in concert with one another.

2. Test data on the upper side of the zone of normal variation are indicative of a pavement in which the subgrade has remained in good condition but in which cracking or some other problem has caused deterioration of the asphaltic concrete.

3. Test data that plot in the higher range of the zone of normal variation are indicative of either of two conditions: a) changes in the condition of the subgrade with the pavement remaining in good condition and the layers acting in concert or b) a deteriorated slab coupled with excessive water content in the subgrade (reduced subgrade modulus) and, again, the layers acting in concert.

4. Test data that plot below the zone of normal variation are indicative of subgrades not providing adequate support. Excessive water contents in the subgrade have been identified as a

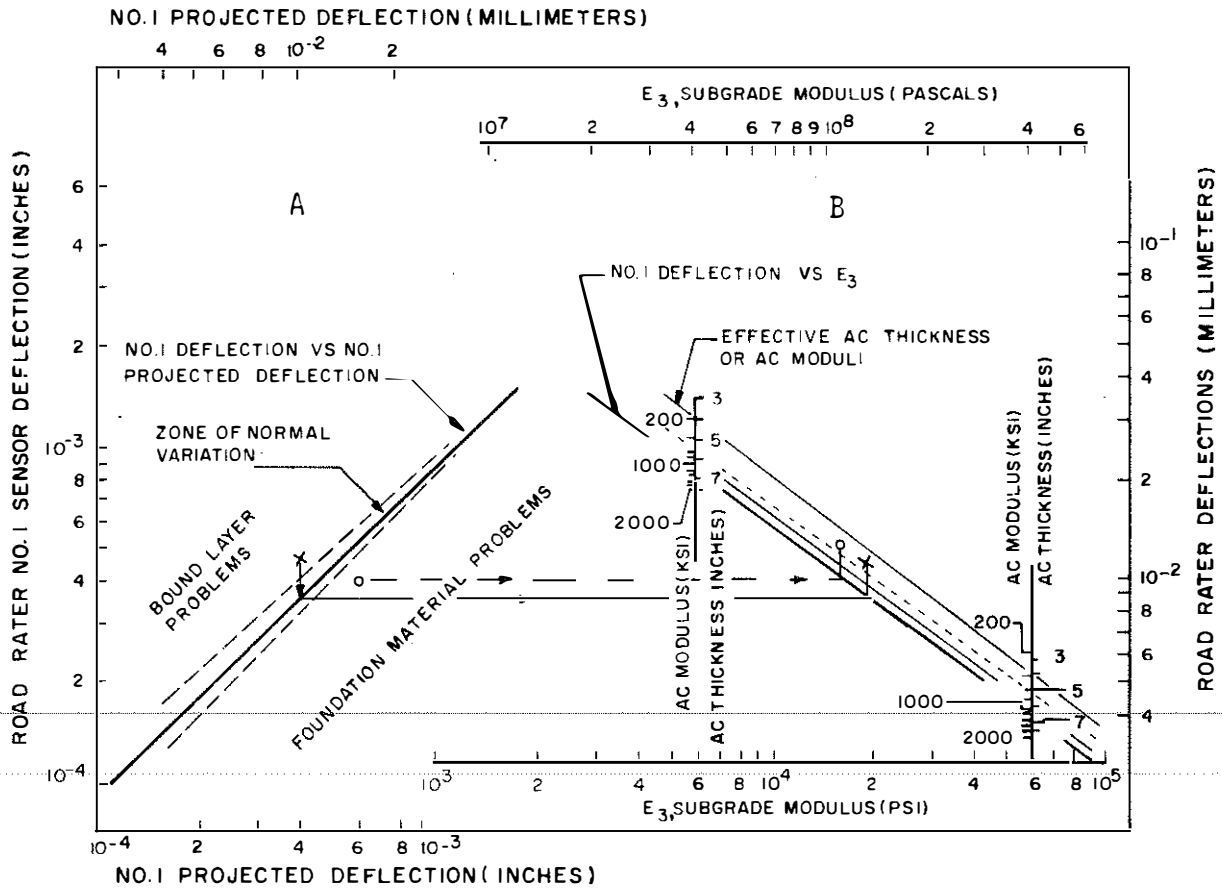


Figure 4. No.1 Deflection as a Function of No.1 Projected Deflection and Subgrade Modulus Illustrating a Method for Estimating Subgrade Modulus and Effective Behavior.

#### Temperature

The temperature distribution within the asphaltic concrete can be estimated (3). The average of the temperature at the surface, mid-depth, and bottom of the asphaltic concrete layer provides the basis for a reasonable approximation of the average modulus of elasticity of the asphaltic concrete.

#### Frequency of Loading and Modulus of Asphaltic Concrete

In testing asphaltic concrete pavements, Kentucky's Road Rater is operated at 25 Hz. This frequency was chosen because resonance was detected at 20 Hz and 30 Hz but not at 25 Hz. Figure 5 illustrates the relationships between temperature, frequency of the applied load, and the modulus of elasticity of asphaltic concrete as reported by Kallas and Riley (4). The equation in Figure 5 yields a very close approximation of their data. From that data, the mean annual temperature in Kentucky of approximately 70°F (21.1°C) corresponds very closely to 1,200 ksi (8.27 GPa) at 25 Hz.

#### Percent Voids and Asphalt Content

Shook and Kallas (5) reported the effects of asphalt content and voids upon the elastic modulus. An analysis for reference conditions of 70° F (21.1°C), five percent asphalt content, and four percent voids yielded

$$\log W = R + S(V) + T(V)^2 \quad 7$$

in which  $R = -7.21517 + 3.05790(\%AC) - 0.31182(\%AC)^2$ ,  
 $S = 2.03197 - 0.82952(\%AC) - 0.08186(\%AC)^2$ ,  
 $T = 0.12485 + 0.05020(\%AC) - 0.00504(\%AC)^2$ ,  
 $\%AC$  = percent asphalt content, and  
 $V$  = percent voids in the asphaltic concrete.

The development of these adjustment factors  $W$  is presented elsewhere (6).

Equation 7 should be used when the percentages of asphalt and void contents are known or can be estimated. Equation 7 illustrates the influence of construction quality control, or the lack thereof, upon expected behavior of the pavement. Equation 7 is the best least-squares fit of the  $W$  values for 4 Hz, 16 Hz, and 25 Hz, producing a standard error of estimate of 0.01 for this set of data. Thus,  $W$  holds true for any frequency within the range used by most dynamic testers. A word of caution is necessary. Equation 7 was developed from limited laboratory test data using one source of aggregates and asphalt cements. Others are encouraged to attempt similar laboratory test and analysis procedures.

#### Adjusting Deflections for Moduli Other than Reference

Because of the significant effects of temperature on modulus of elasticity of asphaltic concretes, a system was developed to adjust deflection measurements to a reference temperature and modulus (1). The adjustment scheme used ratios of deflections at reference conditions to deflections resulting from arrayed variables of layer thicknesses and moduli (1, 4, 7-9). The procedure to adjust deflections is based upon the assumed "reference" of 70° F (21.1°C), 25 Hz dynamic frequency, a 600-pound (272.4-kg) peak-to-peak load applied sinusoidally, and sensors located as for Kentucky's Road Rater. Conditions at the time of testing typically will be different, and the measured deflections must be adjusted to values at the reference conditions. Each Road Rater sensor requires its unique set of factors. The relationship of asphaltic concrete moduli, the asphaltic concrete thickness, and the deflection adjustment factor is expressed as

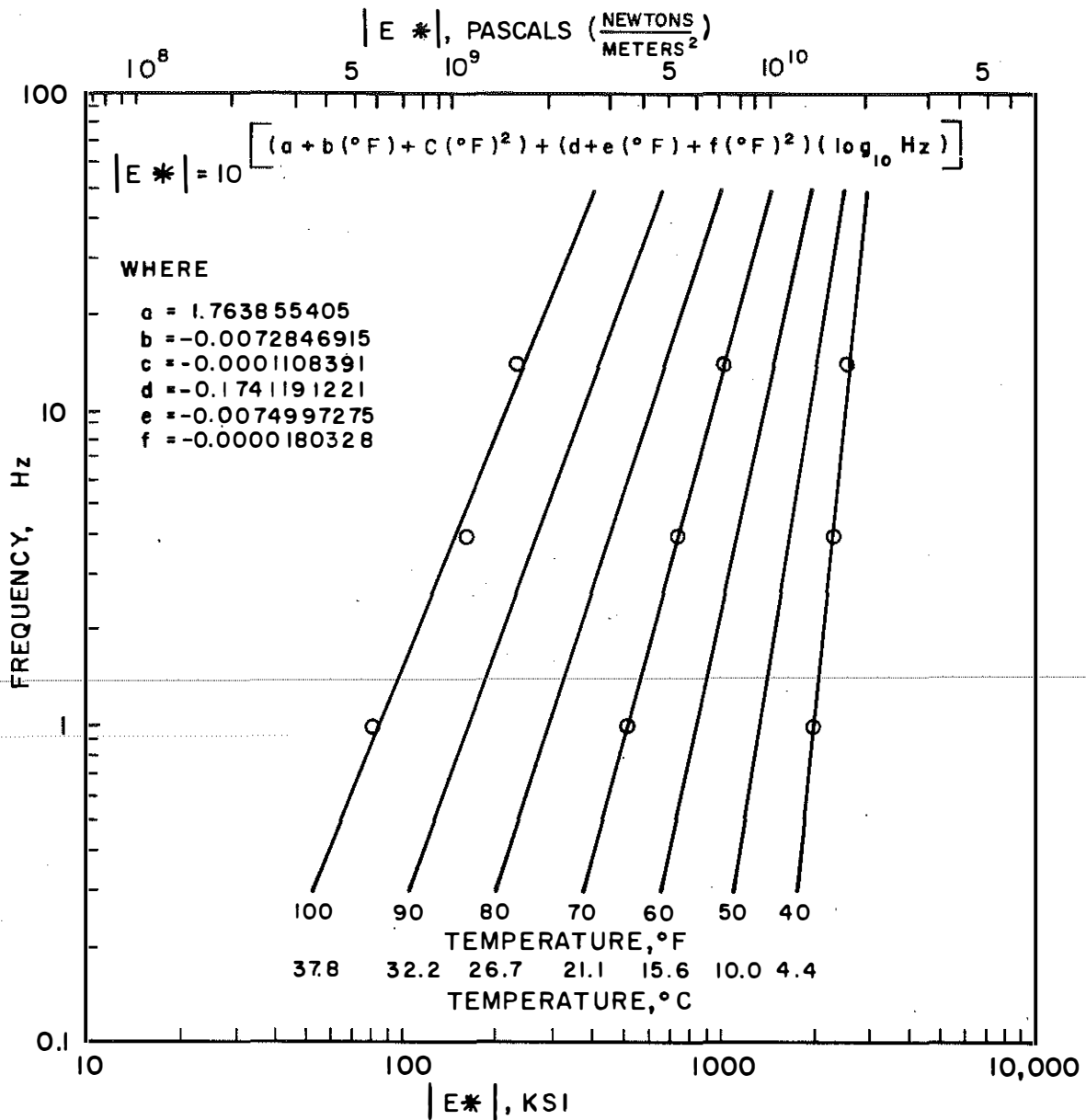


Figure 5. Relationship of Temperature, Frequency of Loading, and Modulus of Asphaltic Concrete.

$$\log AF_j = [\log AC \cdot (H_1 E_{AC}^3 + H_2 E_{AC}^2 + H_3 E_{AC} + H_4)] [M_1 E_{AC}^3 + M_2 E_{AC}^2 + M_3 E_{AC} + M_4]; \quad 8$$

in which  $M_1, M_2, M_3, M_4, H_1, H_2, H_3, H_4$  = constants (Table 2),  
 $E_{AC}$  = mean asphaltic concrete modulus,  
 $AC$  = thickness of asphaltic concrete pavement, and  
 $j$  = Road Rater sensor number.

- Statistical analyses of the differences between the calculated deflection ratio (1) and the adjustment factors resulting from Equation 8 indicated that the equation fitted the original deflection ratio within  $\pm 0.02$  for No.-1 Sensor deflections, and  $\pm 0.01$  for No.-2 and No.-3 Sensor deflections.

The adjusted deflections, as measured by the Road Rater, include the effects of pavement temperature and the resulting change of modulus, frequency of the sinusoidally applied load, effects of asphalt content and voids upon the modulus, and the magnitude of the load. The relationship between the locations of

the sensors and the shape of the deflection bowl is given by Equation 9:

$$\Delta = AA + BB r + CC r^2 \quad 9$$

in which  $\Delta$  = deflection,  
 $r$  = radius from the center of one loaded foot, and  
 $AA, BB, CC$  = constants determined by a least-square fit.

The parabolic equation accurately describes the deflection bowl up to a radius of 37 inches (940 mm).

Deflections measured by the Dynaflect can be adjusted for load and frequency as mentioned earlier. The adjusted deflections for the first three sensors of the Dynaflect can be used to determine the constants of Equation 9 by a least-squares fit. When the constants  $AA, BB$ , and  $CC$  have been determined, the radius for each Road Rater sensor can be substituted for  $r$  to calculate an equivalent deflection compatible with the remainder of this procedure.

TABLE 2. CONSTANTS FOR DEFLECTION ADJUSTMENT FACTORS FOR THE KENTUCKY ROAD RATER

$$\log AF_J = (\log AC - (H_1 E_{AC}^3 + H_2 E_{AC}^2 + H_3 E_{AC} + H_4)) / (M_1 E_{AC}^3 + M_2 E_{AC}^2 + M_3 E_{AC} + M_4)$$

in which AF= deflection adjustment factor  
 AC= asphaltic concrete thickness  
 E<sub>AC</sub>= mean modulus of elasticity for asphaltic concrete

J= Road Rater sensor number (1, 2, 3)

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 Three Layered Pavements

DGA Less Than 8 Inches

J	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>
1	1.0225763E-19	-4.4990262E-13	7.0628626E-07	-0.37155742
2	4.3336498E-20	-2.2091077E-13	4.5988841E-07	-0.30474423
3	3.3403716E-20	-1.6395133E-13	3.4805071E-07	-0.23820381

J	H <sub>1</sub>	H <sub>2</sub>	H <sub>3</sub>	H <sub>4</sub>
1	-2.0312535E-19	7.1127654E-13	-8.4587020E-07	0.25466949
2	7.2614981E-20	-1.0302809E-13	-1.3874220E-07	0.46069097
3	1.6419243E-19	-3.3570986E-13	-4.2060526E-08	0.66081522

DGA Greater Than or Equal to 8 Inches

J	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>
1	8.6110078E-20	-3.8725065E-13	6.2848481E-07	-0.34173343
2	3.5850121E-20	-1.8167083E-13	3.8532939E-07	-0.25976352
3	2.1116466E-20	-1.0783377E-13	2.5034102E-07	-0.18049747

J	H <sub>1</sub>	H <sub>2</sub>	H <sub>3</sub>	H <sub>4</sub>
1	-2.3472762E-20	1.1931522E-13	-2.9552194E-07	0.15345469
2	8.6274124E-20	-1.3810588E-13	-8.8295169E-08	0.42052283
3	1.1280263E-19	1.7456748E-13	-1.3783142E-07	0.60022647

Two Layered Pavements

J	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>
1	1.0486807E-19	-4.5399608E-13	6.6726565E-07	-0.32106577
2	1.0429773E-19	-4.7586726E-13	7.9423008E-07	-0.44438965
3	9.6133265E-20	-3.9709184E-13	6.8153597E-07	-0.41509883

J	H <sub>1</sub>	H <sub>2</sub>	H <sub>3</sub>	H <sub>4</sub>
1	-1.1966613E-18	3.6419900E-12	-3.3712189E-06	0.40220812
2	8.4194518E-20	-1.0803309E-13	-2.9750845E-07	0.63921054
3	2.8337843E-19	-6.0413664E-13	6.2056443E-08	0.84294820

ANALYSIS OF THE ADJUSTED DEFLECTIONS

For a given structure, Equations 1-4 and the constants of Table 1 are used to calculate the theoretical deflections for Road Rater Sensors 1, 2, and 3. The No.-1 Projected deflection is calculated by Equation 5. Deflections should be calculated for a subgrade modulus of 6,000 psi (0.041 GPa) and 60,000 psi (0.410 GPa), permitting the development of the relationship between the No.-1 Sensor deflections and the No.-1 Projected deflections for a given structure (Figure 4A) over the range of subgrade moduli, from the following equation:

$$y = y_1 + (y_2 - y_1)(x - x_1) / (x_2 - x_1) \quad 10$$

in which y = log(No.-1 Sensor deflection),  
 x = log(No.-1 Projected deflection),  
 x<sub>1</sub>, y<sub>1</sub> = log(deflections for subgrade modulus of 60,000 psi) and

x<sub>2</sub>, y<sub>2</sub> = log(deflections for subgrade modulus of 6,000 psi).

Rearranging Equation 10 gives

$$\log \text{No.-1 Sensor} = [\log(\text{No.-1 Projection}) + Z] \div P, \quad 11$$

in which P = (y<sub>2</sub> - y<sub>1</sub>) / (x<sub>2</sub> - x<sub>1</sub>) and  
 Z = a constant.

For each test, Equation 11 is used to determine the equivalent No.-1 Sensor theoretical deflection to compare to the measured deflection at the No.-1 Sensor. Earlier work (1, 7) showed that this comparison indicates which portion of the pavement structure is experiencing difficulty, if at all. A limit of +/- 0.00001 inches (one unit on the Road Rater meter scale) of measured-versus-calculated deflections from Equation 11 is within the expected error of the operator reading the meters; and all layers are performing as would be expected from elastic theory (Condition 1). However, if the calculated deflection (Equation 11) is less than the measured No.-1 Sensor deflection, then the asphaltic

concrete layer is in a weakened condition and the deflection bowl is relatively narrow and deep (Figure 2, Condition 2). If the deflection by Equation 11 is greater than the measured No.-1 Sensor deflection, the subgrade or the portion of the structure below the asphaltic concrete is weak, and the asphaltic concrete is attempting the bridge the weak area by "slab action". The weakness may be due to excessive water in the subgrade (1, 2)(Condition 3).

### APPLICATION OF TEST DATA TO OVERLAY DESIGN

To facilitate the following discussion, the term "measured deflections" will be assumed to mean all deflections have been adjusted to the "reference" modulus of 1,200 ksi (8.27 GPa), 25 Hz, and 70° F (21.1°C). Values of the in-place subgrade moduli and the equivalent thicknesses of the asphaltic concrete are retained for statistical or graphical analyses to determine the design modulus of the subgrade and the design effective thickness of the existing asphaltic concrete as input to an overlay design procedure.

#### Condition 1

Rearranging Equation 1 permits solving directly for subgrade modulus:

$$\log E_s = (\log \Delta + L) \div K. \quad 12$$

The modulus of the subgrade is obtained by substituting the deflection of the No.-1 Sensor. Values of the in-place subgrade modulus and effective thickness are retained for statistical or graphical analyses.

#### Condition 2

The deflection calculated by Equation 11 would correspond to the proper deflection had the asphaltic concrete been in good condition and exhibited the reference modulus. The calculated deflection is substituted into Equation 12 to determine the in-place subgrade modulus. The equivalent thickness of asphaltic concrete having the reference modulus of elasticity remains to be determined.

Constants K and L (Equations 2 and 3) and the in-place subgrade modulus determined above are substituted into Equation 5. A close approximation can be obtained by fitting a second-degree polynomial to the logarithm of the calculated deflections versus their respective thicknesses of asphaltic concrete for the in-place subgrade modulus:

$$AC = JJ + KK (\log \Delta) + LL (\log (\Delta))^2 \quad 13$$

in which JJ, KK, LL = constants obtained by regression analysis and

$$AC = \text{thickness of asphaltic concrete (inches).}$$

Substituting the measured deflection into Equation 13 yields the equivalent thickness of asphaltic concrete having the reference modulus of elasticity. In-place subgrade modulus and the equivalent thickness of asphaltic concrete are retained for statistical or graphical analyses later.

#### Condition 3

When the asphaltic concrete is behaving as a slab over a weakened substructure, the asphaltic layer is having to "work" harder than normal and its "life" will be expended faster. Therefore, there is more potential damage, requiring an additional overlay thickness to carry the anticipated future traffic. To obtain the compatible combination of in-place subgrade modulus and asphaltic concrete thickness, the No.-1 measured deflection is used in Equation 12 to determine the subgrade modulus for that test data. The No.-1 Projected deflection is used in Equation 11 to calculate its equivalent and compatible No.-1 measured deflection. This equivalent No.-1 Sensor deflection corresponds to a thinner asphaltic concrete layer.

### Adequacy of the Existing Pavement

Several methods (9, 10) have been used to analyze and utilize the in-place values of existing structures. One valuable method has been to create a plot of in-place subgrade modulus versus distance (Figure 6) along the proposed resurfacing project. Subgrade modulus (psi) is converted to CBR by dividing by 1500. Two advantages will be seen. First, those locations exhibiting unusually weak subgrades are easily identified. Special overlay thicknesses are designed for those locations. Second, the minimum subgrade modulus and the locations of significant changes in subgrade support are easy to determine.

Figure 7 illustrates the change in predicted subgrade moduli for the period of April to September based on Kentucky data taken during a one-year period. Such analyses permit adjusting fall deflection data to equivalent spring deflections when the subgrade is in its weakest condition. Analyses of Kentucky data have indicated that fall tests provide the most consistent long-term indicator of behavior. However, overlay designs are based upon the subgrade being in its weakest condition. Thus, Figure 7 permits an approximate conversion of test data at any time to springtime conditions.

A plot is made of the effective thickness of the asphaltic concrete versus distance (Figure 8) along the proposed resurfacing project. For the same location describing a general minimum value of the subgrade, determine the minimum thickness of the asphaltic concrete. Then, determine the overlay thickness for the expected future traffic. The overlay thickness is subtracted from the special overlay designs for the unusually weak subgrades to obtain the required thickness of a "structural patch or overlay". Judicious inspection of the data permits the placement of a designed overlay thickness as a structural patch only where needed, allowing the use of a reduced overlay thickness over the entire length of a proposed resurfacing project.

Another method (7) requires the determination of the mean and standard error of estimate of the data. The design engineer determines how many "standard errors" he requires in an overlay design criteria. With this concept, the designer can establish the percentage of failure that is acceptable.

Statistical analyses can be applied to either the measured No.-1 Sensor deflections, the predicted subgrade moduli, or the effective thicknesses of asphaltic concrete. It is recommended that any representation of pavement behavior encompass 90 percent of the data. Other investigators have selected similar levels (11-13). For example, if an effective structure that encompasses 90 percent of the deflection data is desired, the recommended effective thicknesses are equal to the mean effective thickness less the product of 1.28 and the standard error of estimate. Figure 9 illustrates the selection of the multiplier for the standard error. Note that the multiplier 1.28 corresponds to an 80-percent cumulative distribution but results in a 90th-percentile effective thickness because one tail of the normal distribution is not included (14, 15).

### SUMMARY

A procedure has been presented that allows the engineer to evaluate the in-place pavement using dynamic test equipment (such as the Road Rater or the Dynaflect) that impart a steady-state loading to the pavement. The procedure presented herein consists of a series of equations that may be incorporated into a computer program or used with small "hand" calculators. The method is based upon elastic theory and has been used successfully to evaluate pavements ranging from 3 inches (76 mm) of asphaltic concrete on 5 inches (127 mm) of crushed stone base to 18 inches (457 mm) of full-depth asphaltic concrete. Overlays have been designed using this method (9, 10, 16), and some have been constructed.



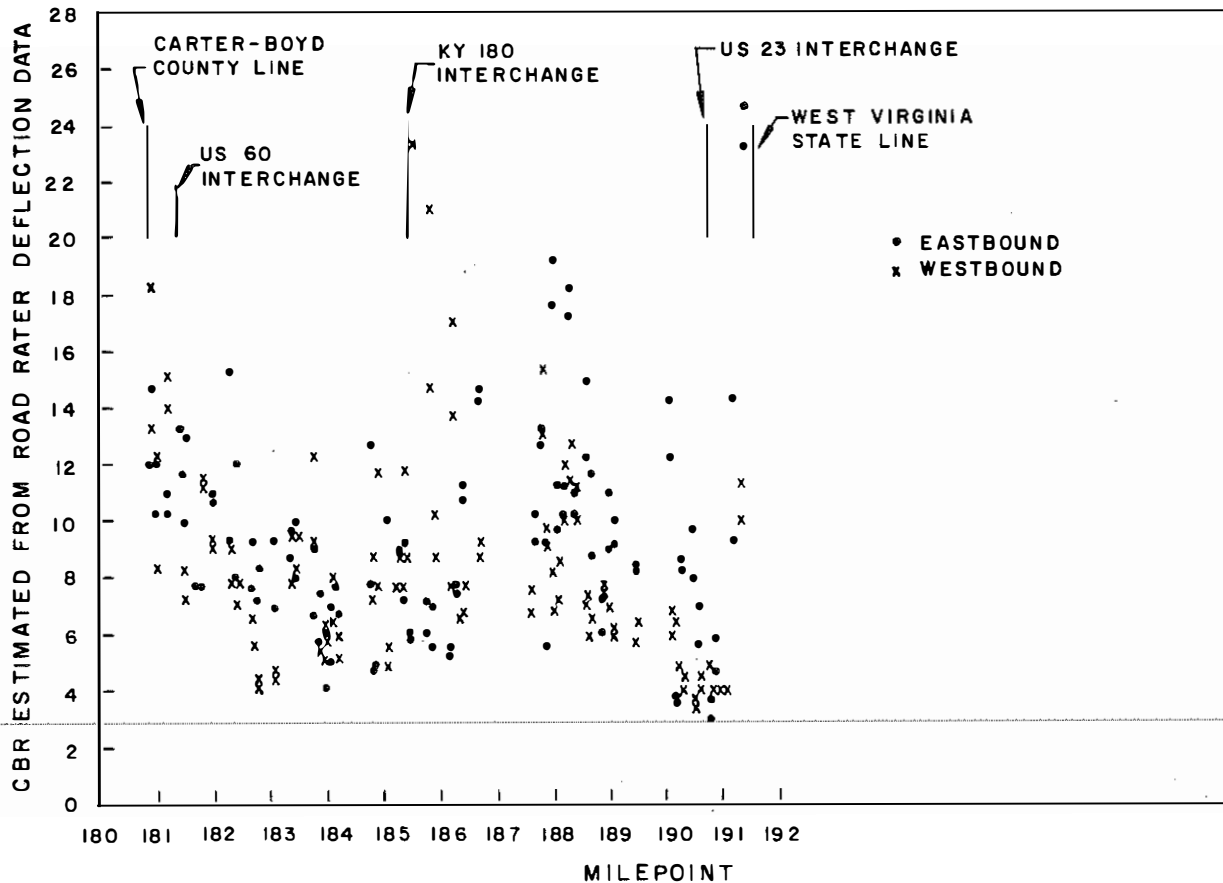


Figure 6. Estimated In-Place Subgrade Modulus versus Distance.

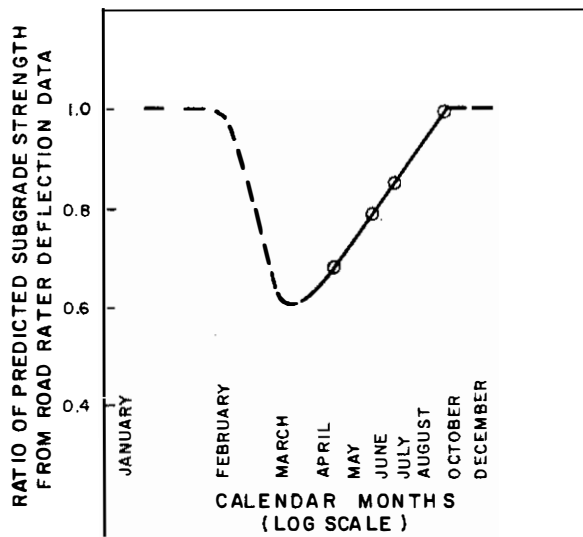


Figure 7. Change in Subgrade Modulus versus Time.

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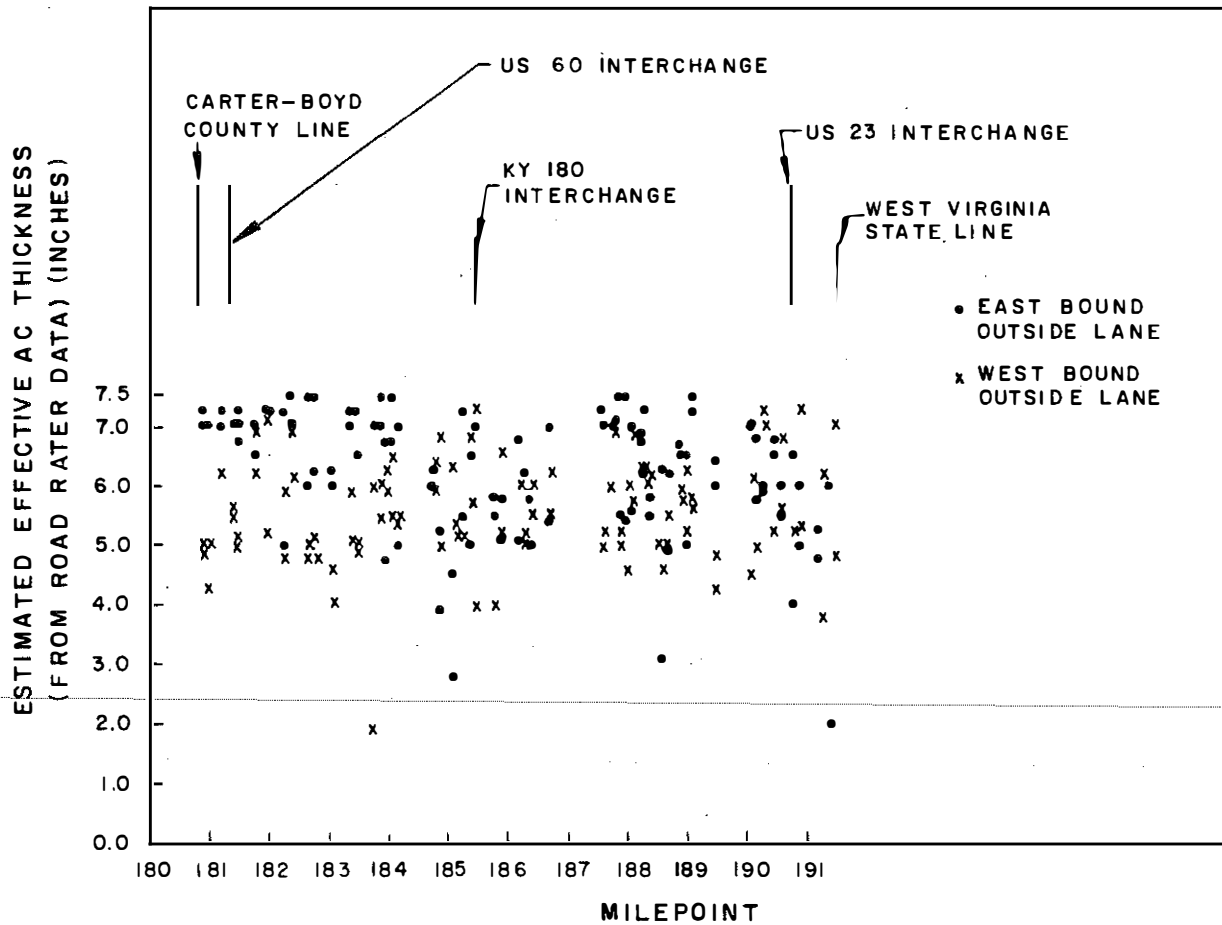


Figure 8. Estimated In-Place Equivalent Thickness of Asphaltic Concrete versus Distance.

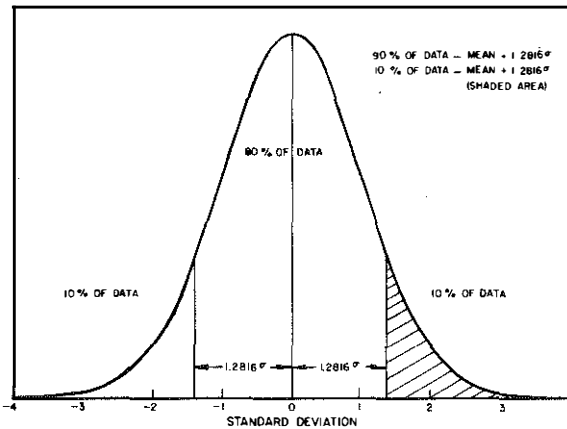


Figure 9. Illustration of 90th-Percentile Cumulative Distribution.

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**STRUCTURAL CAPACITY  
OF IN-PLACE ASPHALTIC CONCRETE PAVEMENTS  
FROM DYNAMIC DEFLECTIONS**

by

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August 1981

**STRUCTURAL CAPACITY OF IN-PLACE ASPHALTIC CONCRETE PAVEMENTS  
FROM DYNAMIC DEFLECTIONS**

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**ABSTRACT**

The proper design of asphaltic overlay thicknesses involves four major factors: the in-place modulus of the subgrade, an estimate of the structural capacity of the existing pavement, estimates of the future traffic expressed as equivalent axleloads and required or desired design levels, and a thickness design procedure. This paper deals with estimating the in-place subgrade modulus and the remaining load-carrying capacity of the existing pavement. The method presented herein is valid for any Road Rater or other dynamic tester such as the Dynaflect. This procedure was based upon a 600-pound (272.4-kg) peak-to-peak dynamic load applied at a rate of 25 Hz. The steady-state deflections have to be adjusted for load, dynamic frequency, and location of sensors. This method should be applied only to those testers that use a constant vibratory load.

**INTRODUCTION**

In a 1979 Transportation Research Board symposium (1) on "Pavement Evaluation and Overlay Design" a graphical procedure to evaluate in-place conditions was presented. Herein are refinements to that graphical procedure. Equations have been developed and programmed so they can be processed using hand calculators or larger computers.

The major steps of the evaluation procedure are:

1. Development of theoretical relationships between pavement deflection, subgrade modulus, and asphaltic concrete thickness (this is a straight-forward method based upon elastic theory);
2. Adjustment of the test data to reference conditions (temperature, frequency of loading, location of sensors, percent voids, percent asphalt content in the mix, and modulus of the asphaltic concrete);
3. Determination of the in-place subgrade modulus and equivalent or "effective" asphaltic concrete thickness; and
4. Selection of input design parameters for an overlay design procedure.

Step 1 involves theoretical relationships between deflections of an original pavement of reference-quality materials and deflections of an existing pavement with the same crushed stone thickness, but with decreased thicknesses of asphaltic concrete (to account for a partial use of the fatigue life of the pavement) for each of the three sensors of the Road Rater. The two more-remote sensors are used to determine which portion of the pavement structure is exhibiting distress.

In Step 2, equations are used to adjust measured deflections for load, frequency, temperature, location of sensors, percent voids, percent asphalt content, and asphaltic concrete modulus. Deflections obtained by other dynamic testers (such as the Dynaflect) under various test conditions can be analyzed using the technique and relationships summarized in this paper.

In Step 3, the existing pavement is assumed to perform as a pavement of "x" thickness of reference-quality asphaltic concrete over the as-built thickness of crushed stone base (zero thickness for full-depth asphalt pavements). This portion of the analysis may involve a single test to represent a section of pavement, or as many test points as desired may be evaluated. If more than just a few deflection measurements are involved, the data should be subjected to the analyses of Step 4.

Step 4 is a statistical and/or graphical analysis of the subgrade moduli and the behavioral thicknesses of the asphaltic concrete layer determined in Step 3. The mean and standard error of estimate should be calculated so that an appropriate behavioral thickness can be chosen. The thickness selected in this portion of the analysis to represent the structural capacity of the existing pavement is related to the risk of failure to be assumed with the overlay design. Appropriate choices of behavioral thicknesses and design methods are discussed.

**THEORETICAL ANALYSIS**

Construction records provide as-constructed thicknesses of the layers in the pavement structure. All layers below the asphaltic concrete are assumed to have remained as constructed. Deterioration and fatigue reduce the effectiveness of the asphaltic concrete to some equivalent, thinner thickness of reference-quality material. Vibratory testers, such as the Road Rater and Dynaflect, induce vibrations in the pavement structure that can be detected by velocity sensors or accelerometers. The electronics of the testers process the signal to yield surface deflections. These measured deflections are used to estimate the in-place condition of the pavement.

For an existing pavement, the effective thickness of the dense-graded aggregate layer is assumed to be equal to the as-constructed thickness. The remaining variables that influence the behavior of the pavement are the subgrade modulus and the effective thickness of the asphaltic concrete layers, defined as the equivalent thickness of reference-quality materials that matches measured behavior.

The Chevron N-layer computer program requires layer thicknesses, their respective moduli and Poisson's ratios, load, contact pressure, and geometry of load and sensor locations. A matrix of structures and input values were utilized to calculate deflections associated with the Road Rater loading. Procedures used in simulating Road Rater loadings and deflections are discussed in great detail elsewhere (1). These calculated deflections are the basis of the equations developed in this paper.

Analyses indicated surface deflections for a given pavement structure are a function of the subgrade modulus as given in

$$\log \Delta = K \log E_s + L \quad 1$$

in which  $\Delta$  = Road Rater deflection (0.00001 inches),

$K$  = slope of the log-log line,

$L$  = constant, and

$E_s$  = modulus of the subgrade (psi).

Both  $K$  and  $L$  are dependent upon the thicknesses of the asphaltic concrete and the dense-graded aggregate layers, as described by the third-degree polynomials

$$K = N_1 (AC)^3 + N_2 (AC)^2 + N_3 (AC) + N_4 \quad 2$$

and

$$L = N_5 (AC)^3 + N_6 (AC)^2 + N_7 (AC) + N_8 \quad 3$$

in which  $AC$  = thickness of the asphaltic concrete (inches) and  $N$  = eight constants determined by the fourth-degree polynomial,

$$N_i = A_i(DGA)^4 + B_i(DGA)^3 + C_i(DGA)^2 + D_i(DGA) + E_i, \quad 4$$

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in which  $N_1$  through  $N_4$  are associated with the slope  $K$  and  $N_5$  through  $N_8$  are associated with the constant  $L$ .

DGA = thickness of the unbound layer (inches), and  
A, B, C, D, E, = constants determined by regression analyses.

Values for each of the constants are listed in Table 1.

#### Type of Distress

The theoretical deflections for No.-2 and No.-3 Sensors (Equation 1) are used to calculate

$$\log \text{No.-1 Projection} = 2 \log (\text{No.-2 } \Delta) - \log (\text{No.-3 } \Delta) \quad 5$$

Equation 5 is a mathematical representation of a semilog line through the magnitudes of No.-2 and No.-3 Sensors projected to the position of the No.-1 Sensor. The slope of the relationship in Equation 5, the difference in magnitude between the No.-1 Projection and the No.-1 Sensor deflections, and the magnitudes of all deflections are indicative of the shape of the deflection bowl.

For a given combination of layer thicknesses, asphaltic concrete modulus, and subgrade modulus, each pavement will have a calculated deflection bowl. There is a difference between the No.-1 Projection and the No.-1 Sensor for theoretical deflec-

tions (Figure 1). There also will be a difference between these values for field-measured deflections.

Normally, the differences between the No.-1 Projected deflection and the No.-1 Sensor deflection for both theoretical and field values are similar. Slab deterioration is indicated when measured No.-1 Sensor deflections are greater than No.-1 Projections (Figure 2) and when the differences between these values are greater than the differences for corresponding theoretical deflections. A foundation problem or lack of supporting capability is indicated by increased magnitudes of all field deflections and No.-1 Projection greater than the No.-1 Sensor deflections (Figure 3).

Log-log plots of No.-1 Projections versus No.-1 Sensor deflections can be used to identify variations in pavement structure (see Figure 4A). The solid line shows the theoretical relationship between No.-1 Projections and No.-1 Sensor deflections for a constant structure and asphaltic concrete modulus. Subgrade modulus varies along the line. The points about the line represent measured deflections. The variation in position of the theoretical line due to changes in the magnitudes of deflections by +/- one unit (0.0001 in. (0.000254 mm)) and the associated changes in theoretical No.-1 Projections are indicated by the two dashed lines. The zone within these lines represents a normal variation

TABLE 1. COEFFICIENTS FOR ROAD  
RATER DEFLECTION EQUATIONS

$$N = A_i \text{ DGA}^4 + B_i \text{ DGA}^3 + C_i \text{ DGA}^2 + D_i \text{ DGA} + E_i$$

$$K = N_1 \text{ AC}^3 + N_2 \text{ AC}^2 + N_3 \text{ AC} + N_4$$

$$L = N_5 \text{ AC}^3 + N_6 \text{ AC}^2 + N_7 \text{ AC} + N_8$$

$$\log \Delta = K \log E_s + L$$

in which DGA = thickness of dense-graded aggregate base layer,  
AC = thickness of asphaltic concrete layer,  
 $E_s$  = modulus of elasticity of subgrade, and  
 $\Delta$  = deflection

i	$A_i$	$B_i$	$C_i$	$D_i$	$E_i$
<b>No. 1 Sensor</b>					
1	-8.0276712E-09	4.4637935E-07	-7.8334349E-06	4.3700774E-05	0.00015920
2	2.2880623E-07	-1.2956090E-05	0.00023168	-0.00126428	-0.00603433
3	-2.0069119E-06	0.00011636	-0.00213561	0.01152101	0.07053069
4	5.3511621E-06	-0.00032005	0.00617403	-0.03601869	-0.94738380
5	3.8112800E-08	-2.1142292E-06	3.6712485E-05	-0.00019713	-0.00079876
6	-1.0927940E-06	6.1604764E-05	-0.00108663	0.00564980	0.03181695
7	9.6888879E-06	-0.00055752	0.01004067	-0.05039463	-0.42286904
8	-2.6361517E-05	0.00155888	-0.02921499	0.14909581	6.27491080
<b>No. 2 Sensor</b>					
1	-1.9422702E-08	1.0770627E-06	-1.8518686E-05	9.5507480E-05	8.9416760E-05
2	5.2579366E-07	-2.9137271E-05	0.00049930	-0.00251336	-0.00416610
3	-4.2869807E-06	0.00023786	-0.00407118	0.01974778	0.07009015
4	9.8983780E-06	-0.00055346	0.00958628	-0.04540810	-1.12011456
5	6.1453952E-08	-3.3927169E-06	5.7851557E-05	-0.00028477	-0.00038341
6	-1.9486070E-06	0.00010728	-0.00180868	0.00847179	0.01804679
7	1.5831303E-05	-0.00087303	0.01469200	-0.06471592	-0.34277031
8	-3.6284025E-05	0.00202136	-0.03448633	0.13878339	6.61774653
<b>No. 3 Sensor</b>					
1	2.1333448E-08	-1.2598323E-06	2.4207689E-05	-0.00016422	4.6358157E-05
2	-6.1003392E-07	3.6138955E-05	-0.00069872	0.00483808	-0.00319426
3	5.4277510E-06	-0.00032212	0.00626602	-0.04474861	0.0728740
4	-1.5081292E-05	0.00089525	-0.01749993	0.13007837	-1.27529337
5	-1.0456648E-07	6.1644249E-06	-0.00011799	0.00078800	-0.00010359
6	2.9858350E-06	-0.00017441	0.00339148	-0.02303053	0.01019562
7	-2.6465435E-05	0.00156508	-0.03021266	0.21073267	-0.28067328
8	7.2699360E-05	-0.00429505	0.08308389	-0.60401394	6.84595514

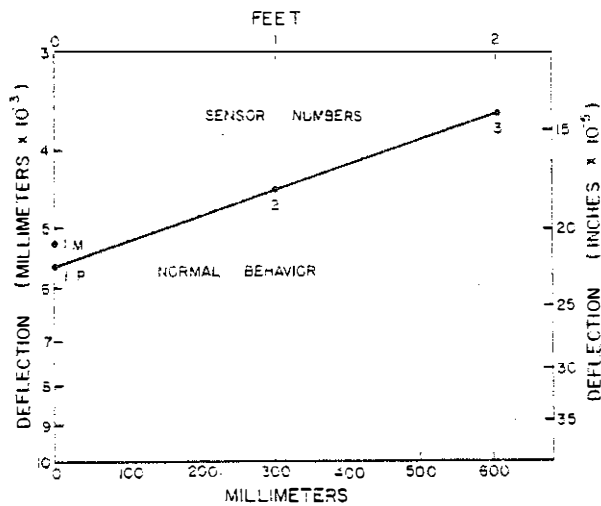


Figure 1. Relationship between Deflection and Distance from Point of Load and Determination of No.-1 Projected Deflection for Pavement Exhibiting Normal Behavior.

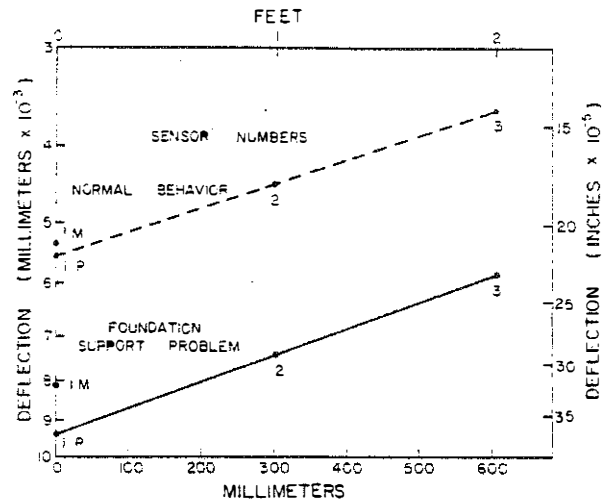


Figure 3. Relationship between Deflection and Distance from Point of Load and Determination of No.-1 Projected Deflection for Pavement With Foundation Support Problem.

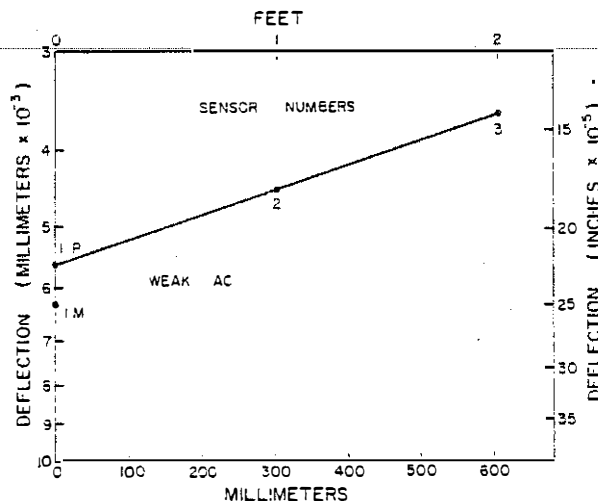


Figure 2. Relationship between Deflection and Distance from Point of Load and Determination of No.-1 Projected Deflection for Pavement With Weak Asphaltic Concrete Layer.

factor contributing to this condition. This condition and pattern of deflections were confirmed by data obtained in Huntington Beach, California (1, 2). There, Road Rater tests were performed, the pavements were cored, subgrade samples were obtained, and the moisture contents of the subgrade were determined. In those locations that had high water contents (possibly free water), the differences between the No.-1 Projected and measured deflections was considerably greater than the theoretical analyses would have indicated. One possible explanation is that water is a better conductor of sound or vibrations than normal subgrades. Therefore, the No.-2 and No.-3 Sensors measure higher deflections for soils containing excess water than for soils having normal water contents.

#### Deflection Equations

Equation 1 is solved for the eight constants  $N_i$  for a particular dense-graded aggregate thickness. For a given asphaltic concrete thickness,  $K$  and  $L$  remain constant. Thus, deflections are a function of the elastic modulus of the subgrade. Likewise, other asphaltic concrete thicknesses substituted into Equations 2 and 3 yield a family of curves (Figure 4B). The constants  $K$  and  $L$  for each thickness of asphaltic concrete are retained for use in evaluating the test data.

#### ADJUSTMENT OF DEFLECTIONS TO REFERENCE CONDITIONS

The five primary variables affecting deflections other than layer thicknesses and subgrade modulus are load, temperature, frequency of the dynamic loading, modulus of elasticity of the asphaltic concrete, and the location of the sensors. Pavement behavior can match more than one combination of subgrade modulus and thickness of asphaltic concrete. Thus, it is necessary to select an appropriate combination that matches measured deflections. The No.-2 and No.-3 Sensors can have quite different deflections but yield the same No.-1 Projected deflection by Equation 5; on the other hand, the No.-1 Sensor deflections may be nearly equal.

#### Load

A relationship to adjust a measured deflection induced by a load of any known magnitude to a reference load is given by

$$AF_L = \Delta \text{ at } 600 \text{ pounds} \div \Delta \text{ at } X \text{ pounds.} \quad 6$$

Thus, the adjusted deflection is expressed in terms of the matrices of calculations for Kentucky's Road Rater. Normal operation for the Kentucky Road Rater uses a 600-pound (272.4-kg) peak-to-peak dynamic force.

due to reading the meters.

The following situations have been observed from field evaluations:

1. Test data that lie within the zone of normal variation and show relatively low deflections are indicative of a structure of high-quality materials in which all layers are acting in concert with one another.
2. Test data on the upper side of the zone of normal variation are indicative of a pavement in which the subgrade has remained in good condition but in which cracking or some other problem has caused deterioration of the asphaltic concrete.
3. Test data that plot in the higher range of the zone of normal variation are indicative of either of two conditions: a) changes in the condition of the subgrade with the pavement remaining in good condition and the layers acting in concert or b) a deteriorated slab coupled with excessive water content in the subgrade (reduced subgrade modulus) and, again, the layers acting in concert.
4. Test data that plot below the zone of normal variation are indicative of subgrades not providing adequate support. Excessive water contents in the subgrade have been identified as a

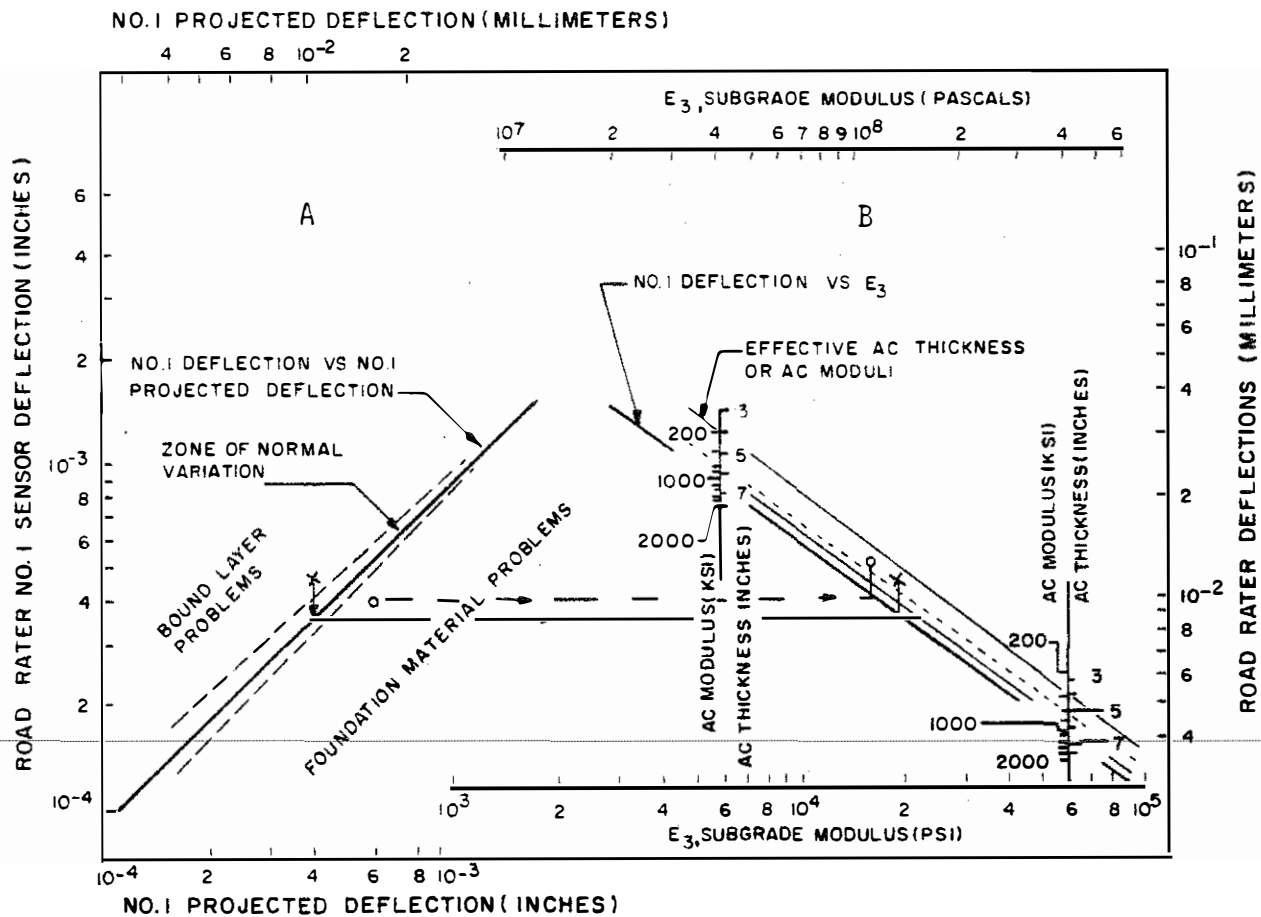


Figure 4. No.-1 Deflection as a Function of No.-1 Projected Deflection and Subgrade Modulus Illustrating a Method for Estimating Subgrade Modulus and Effective Behavior.

#### Temperature

The temperature distribution within the asphaltic concrete can be estimated (3). The average of the temperature at the surface, mid-depth, and bottom of the asphaltic concrete layer provides the basis for a reasonable approximation of the average modulus of elasticity of the asphaltic concrete.

#### Frequency of Loading and Modulus of Asphaltic Concrete

In testing asphaltic concrete pavements, Kentucky's Road Rater is operated at 25 Hz. This frequency was chosen because resonance was detected at 20 Hz and 30 Hz but not at 25 Hz. Figure 5 illustrates the relationships between temperature, frequency of the applied load, and the modulus of elasticity of asphaltic concrete as reported by Kallas and Riley (4). The equation in Figure 5 yields a very close approximation of their data. From that data, the mean annual temperature in Kentucky of approximately 70°F (21.1°C) corresponds very closely to 1,200 ksi (8.27 GPa) at 25 Hz.

#### Percent Voids and Asphalt Content

Shook and Kallas (5) reported the effects of asphalt content and voids upon the elastic modulus. An analysis for reference conditions of 70° F (21.1°C), five percent asphalt content, and four percent voids yielded

$$\log W = R + S(V) + T(V)^2 \quad 7$$

in which  $R = -7.21517 + 3.05790(\%AC) - 0.31182(\%AC)^2$ ,  
 $S = 2.03197 - 0.82952(\%AC) + 0.08186(\%AC)^2$ ,  
 $T = -0.12485 + 0.05020(\%AC) - 0.00504(\%AC)^2$ .  
 %AC = percent asphalt content, and  
 V = percent voids in the asphaltic concrete.

The development of these adjustment factors W is presented elsewhere (6).

Equation 7 should be used when the percentages of asphalt and void contents are known or can be estimated. Equation 7 illustrates the influence of construction quality control, or the lack thereof, upon expected behavior of the pavement. Equation 7 is the best least-squares fit of the W values for 4 Hz, 16 Hz, and 25 Hz, producing a standard error of estimate of 0.01 for this set of data. Thus, W holds true for any frequency within the range used by most dynamic testers. A word of caution is necessary. Equation 7 was developed from limited laboratory test data using one source of aggregates and asphalt cements. Others are encouraged to attempt similar laboratory test and analysis procedures.

#### Adjusting Deflections for Moduli Other than Reference

Because of the significant effects of temperature on modulus of elasticity of asphaltic concretes, a system was developed to adjust deflection measurements to a reference temperature and modulus (1). The adjustment scheme used ratios of deflections at reference conditions to deflections resulting from arrayed variables of layer thicknesses and moduli (1, 4, 7-9). The procedure to adjust deflections is based upon the assumed "reference" of 70° F (21.1°C), 25 Hz dynamic frequency, a 600-pound (272.4-kg) peak-to-peak load applied sinusoidally, and sensors located as for Kentucky's Road Rater. Conditions at the time of testing typically will be different, and the measured deflections must be adjusted to values at the reference conditions. Each Road Rater sensor requires its unique set of factors. The relationship of asphaltic concrete moduli, the asphaltic concrete thickness, and the deflection adjustment factor is expressed as

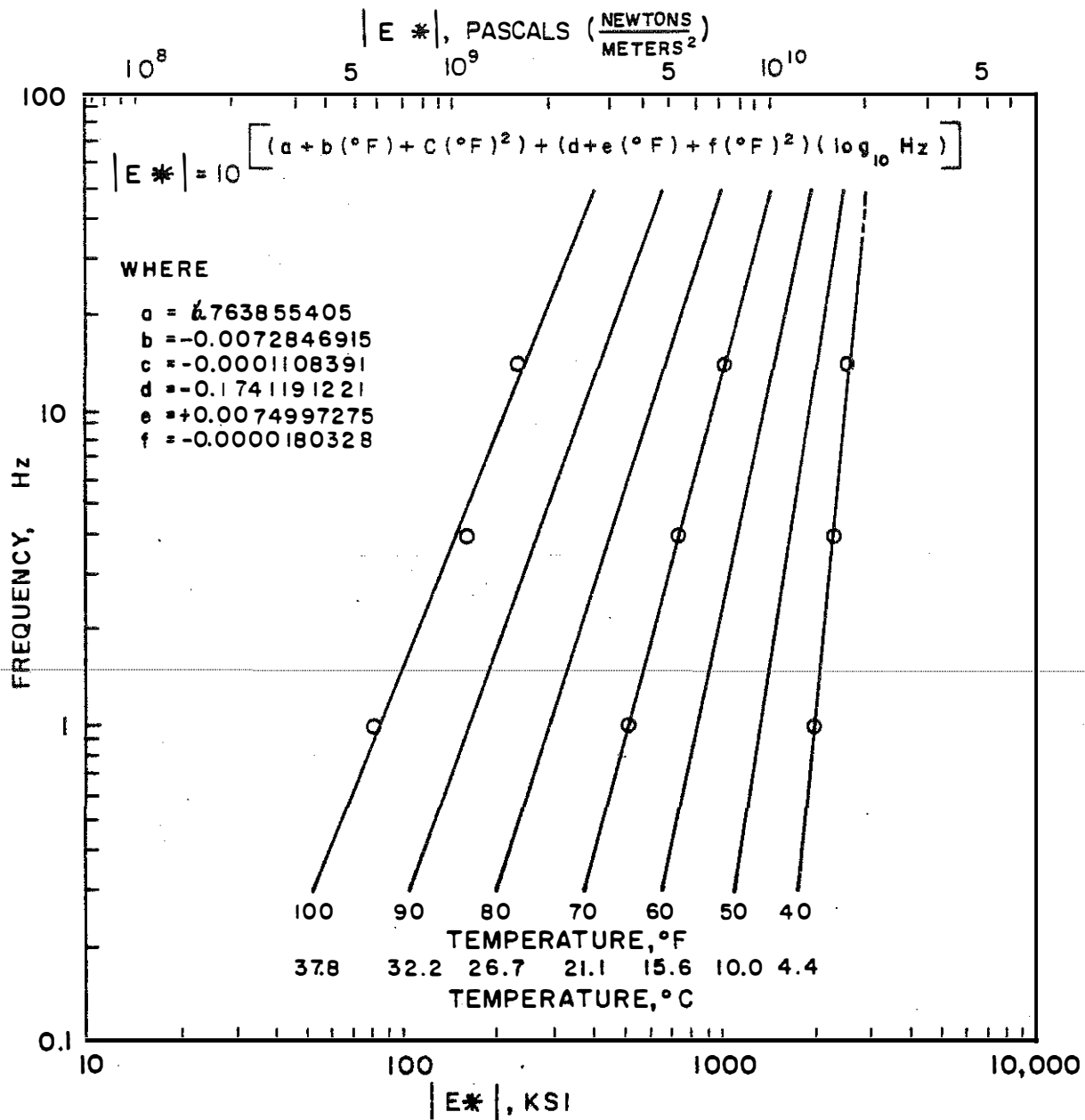


Figure 5. Relationship of Temperature, Frequency of Loading, and Modulus of Asphaltic Concrete.

$$\log AF_j = [\log AC \cdot (H_1 E_{AC}^3 + H_2 E_{AC}^2 + H_3 E_{AC} + H_4)] [M_1 E_{AC}^3 + M_2 E_{AC}^2 + M_3 E_{AC} + M_4]; \quad 8$$

in which  $M_1, M_2, M_3, M_4, H_1, H_2, H_3, H_4$  = constants (Table 2),  
 $E_{AC}$  = mean asphaltic concrete modulus,  
 $AC$  = thickness of asphaltic concrete pavement, and  
 $j$  = Road Rater sensor number.

Statistical analyses of the differences between the calculated deflection ratio (1) and the adjustment factors resulting from Equation 8 indicated that the equation fitted the original deflection ratio within  $\pm 0.02$  for No.-1 Sensor deflections, and  $\pm 0.01$  for No.-2 and No.-3 Sensor deflections.

The adjusted deflections, as measured by the Road Rater, include the effects of pavement temperature and the resulting change of modulus, frequency of the sinusoidally applied load, effects of asphalt content and voids upon the modulus, and the magnitude of the load. The relationship between the locations of

the sensors and the shape of the deflection bowl is given by Equation 9:

$$\Delta = AA + BB r + CC r^2 \quad 9$$

in which  $\Delta$  = deflection,  
 $r$  = radius from the center of one loaded foot, and  
 $AA, BB, CC$  = constants determined by a least-square fit.

The parabolic equation accurately describes the deflection bowl up to a radius of 37 inches (940 mm).

Deflections measured by the Dynaflect can be adjusted for load and frequency as mentioned earlier. The adjusted deflections for the first three sensors of the Dynaflect can be used to determine the constants of Equation 9 by a least-squares fit. When the constants  $AA, BB,$  and  $CC$  have been determined, the radius for each Road Rater sensor can be substituted for  $r$  to calculate an equivalent deflection compatible with the remainder of this procedure.



TABLE 2. CONSTANTS FOR DEFLECTION ADJUSTMENT FACTORS FOR THE KENTUCKY ROAD RATER

$$\log AF_J = (\log AC - (H_1 E_{AC}^3 + H_2 E_{AC}^2 + H_3 E_{AC} + H_4)) / (M_1 E_{AC}^3 + M_2 E_{AC}^2 + M_3 E_{AC} + M_4)$$

in which AF= deflection adjustment factor  
 AC= asphaltic concrete thickness  
 E<sub>AC</sub>= mean modulus of elasticity for asphaltic concrete

J= Road Rater sensor number (1, 2, 3)

-----  
 Three Layered Pavements

DGA Less Than 8 Inches

J	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>
1	1.0225763E-19	-4.4990262E-13	7.0628626E-07	-0.37155742
2	4.3336498E-20	-2.2091077E-13	4.5988841E-07	-0.30474423
3	3.3403716E-20	-1.6395133E-13	3.4805071E-07	-0.23820381

J	H <sub>1</sub>	H <sub>2</sub>	H <sub>3</sub>	H <sub>4</sub>
1	-2.0312535E-19	7.1127654E-13	-8.4587020E-07	0.25466949
2	7.2614981E-20	-1.0302809E-13	-1.3874220E-07	0.46069097
3	1.6419243E-19	-3.3570986E-13	-4.2060526E-08	0.66081522

DGA Greater Than or Equal to 8 Inches

J	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>
1	8.6110078E-20	-3.8725065E-13	6.2848481E-07	-0.34173343
2	3.5850121E-20	-1.8167083E-13	3.8532939E-07	-0.25976352
3	2.1116466E-20	-1.0783377E-13	2.5034102E-07	-0.18049747

J	H <sub>1</sub>	H <sub>2</sub>	H <sub>3</sub>	H <sub>4</sub>
1	-2.3472762E-20	1.1931522E-13	-2.9552194E-07	0.15345469
2	8.6274124E-20	-1.3810588E-13	-8.8295169E-08	0.42052283
3	1.1280263E-19	-1.7456748E-13	-1.3783142E-07	0.60022647

Two Layered Pavements

J	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>
1	1.0486807E-19	-4.5399608E-13	6.6726565E-07	-0.32106577
2	1.0429773E-19	-4.7586726E-13	7.9423008E-07	-0.44438965
3	9.6133265E-20	-3.9709184E-13	6.8153597E-07	-0.41509883

J	H <sub>1</sub>	H <sub>2</sub>	H <sub>3</sub>	H <sub>4</sub>
1	-1.1966613E-18	3.6419900E-12	-3.3712189E-06	0.40220812
2	8.4194518E-20	-1.0803309E-13	-2.9750845E-07	0.63921054
3	2.8337843E-19	-6.0413664E-13	6.2056443E-08	0.84294820

ANALYSIS OF THE ADJUSTED DEFLECTIONS

For a given structure, Equations 1-4 and the constants of Table 1 are used to calculate the theoretical deflections for Road Rater Sensors 1, 2, and 3. The No.-1 Projected deflection is calculated by Equation 5. Deflections should be calculated for a subgrade modulus of 6,000 psi (0.041 GPa) and 60,000 psi (0.410 GPa), permitting the development of the relationship between the No.-1 Sensor deflections and the No.-1 Projected deflections for a given structure (Figure 4A) over the range of subgrade moduli, from the following equation:

$$y = y_1 + (y_2 - y_1)(x - x_1) / (x_2 - x_1) \quad 10$$

in which y = log(No.-1 Sensor deflection),  
 x = log(No.-1 Projected deflection),  
 x<sub>1</sub>, y<sub>1</sub> = log(deflections for subgrade modulus of 60,000 psi) and

$$x_2, y_2 = \log(\text{deflections for subgrade modulus of 6,000 psi}).$$

Rearranging Equation 10 gives

$$\log \text{No.-1 Sensor} = \frac{P(x + Z)}{\log(\text{No.-1 Projection}) + Z} = P \quad 11$$

in which P = (y<sub>2</sub> - y<sub>1</sub>) / (x<sub>2</sub> - x<sub>1</sub>) and  
 Z = a constant.

For each test, Equation 11 is used to determine the equivalent No.-1 Sensor theoretical deflection to compare to the measured deflection at the No.-1 Sensor. Earlier work (1, 7) showed that this comparison indicates which portion of the pavement structure is experiencing difficulty, if at all. A limit of +/- 0.00001 inches (one unit on the Road Rater meter scale) of measured-versus-calculated deflections from Equation 11 is within the expected error of the operator reading the meters; and all layers are performing as would be expected from elastic theory (Condition 1). However, if the calculated deflection (Equation 11) is less than the measured No.-1 Sensor deflection, then the asphaltic

concrete layer is in a weakened condition and the deflection bowl is relatively narrow and deep (Figure 2, Condition 2). If the deflection by Equation 11 is greater than the measured No.-1 Sensor deflection, the subgrade or the portion of the structure below the asphaltic concrete is weak, and the asphaltic concrete is attempting the bridge the weak area by "slab action". The weakness may be due to excessive water in the subgrade (1, 2)(Condition 3).

## APPLICATION OF TEST DATA TO OVERLAY DESIGN

To facilitate the following discussion, the term "measured deflections" will be assumed to mean all deflections have been adjusted to the "reference" modulus of 1,200 ksi (8.27 GPa), 25 Hz. and 70° F (21.1°C). Values of the in-place subgrade moduli and the equivalent thicknesses of the asphaltic concrete are retained for statistical or graphical analyses to determine the design modulus of the subgrade and the design effective thickness of the existing asphaltic concrete as input to an overlay design procedure.

### Condition 1

Rearranging Equation 1 permits solving directly for subgrade modulus:

$$\log E_s = (\log \Delta \sqrt{L}) \div K. \quad 12$$

The modulus of the subgrade is obtained by substituting the deflection of the No.-1 Sensor. Values of the in-place subgrade modulus and effective thickness are retained for statistical or graphical analyses.

### Condition 2

The deflection calculated by Equation 11 would correspond to the proper deflection had the asphaltic concrete been in good condition and exhibited the reference modulus. The calculated deflection is substituted into Equation 12 to determine the in-place subgrade modulus. The equivalent thickness of asphaltic concrete having the reference modulus of elasticity remains to be determined.

Constants K and L (Equations 2 and 3) and the in-place subgrade modulus determined above are substituted into Equation 5. A close approximation can be obtained by fitting a second-degree polynomial to the logarithm of the calculated deflections versus their respective thicknesses of asphaltic concrete for the in-place subgrade modulus:

$$AC = JJ + KK (\log \Delta) + LL (\log (\Delta))^2 \quad 13$$

in which JJ, KK, LL = constants obtained by regression analysis and

$$AC = \text{thickness of asphaltic concrete (inches).}$$

Substituting the measured deflection into Equation 13 yields the equivalent thickness of asphaltic concrete having the reference modulus of elasticity. In-place subgrade modulus and the equivalent thickness of asphaltic concrete are retained for statistical or graphical analyses later.

### Condition 3

When the asphaltic concrete is behaving as a slab over a weakened substructure, the asphaltic layer is having to "work" harder than normal and its "life" will be expended faster. Therefore, there is more potential damage, requiring an additional overlay thickness to carry the anticipated future traffic. To obtain the compatible combination of in-place subgrade modulus and asphaltic concrete thickness, the No.-1 measured deflection is used in Equation 12 to determine the subgrade modulus for that test data. The No.-1 Projected deflection is used in Equation 11 to calculate its equivalent and compatible No.-1 measured deflection. This equivalent No.-1 Sensor deflection corresponds to a thinner asphaltic concrete layer.

## Adequacy of the Existing Pavement

Several methods (9, 10) have been used to analyze and utilize the in-place values of existing structures. One valuable method has been to create a plot of in-place subgrade modulus versus distance (Figure 6) along the proposed resurfacing project. Subgrade modulus (psi) is converted to CBR by dividing by 1500. Two advantages will be seen. First, those locations exhibiting unusually weak subgrades are easily identified. Special overlay thicknesses are designed for those locations. Second, the minimum subgrade modulus and the locations of significant changes in subgrade support are easy to determine.

Figure 7 illustrates the change in predicted subgrade moduli for the period of April to September based on Kentucky data taken during a one-year period. Such analyses permit adjusting fall deflection data to equivalent spring deflections when the subgrade is in its weakest condition. Analyses of Kentucky data have indicated that fall tests provide the most consistent long-term indicator of behavior. However, overlay designs are based upon the subgrade being in its weakest condition. Thus, Figure 7 permits an approximate conversion of test data at any time to springtime conditions.

A plot is made of the effective thickness of the asphaltic concrete versus distance (Figure 8) along the proposed resurfacing project. For the same location describing a general minimum value of the subgrade, determine the minimum thickness of the asphaltic concrete. Then, determine the overlay thickness for the expected future traffic. The overlay thickness is subtracted from the special overlay designs for the unusually weak subgrades to obtain the required thickness of a "structural patch or overlay". Judicious inspection of the data permits the placement of a designed overlay thickness as a structural patch only where needed, allowing the use of a reduced overlay thickness over the entire length of a proposed resurfacing project.

Another method (7) requires the determination of the mean and standard error of estimate of the data. The design engineer determines how many "standard errors" he requires in an overlay design criteria. With this concept, the designer can establish the percentage of failure that is acceptable.

Statistical analyses can be applied to either the measured No.-1 Sensor deflections, the predicted subgrade moduli, or the effective thicknesses of asphaltic concrete. It is recommended that any representation of pavement behavior encompass 90 percent of the data. Other investigators have selected similar levels (11-13). For example, if an effective structure that encompasses 90 percent of the deflection data is desired, the recommended effective thicknesses are equal to the mean effective thickness less the product of 1.28 and the standard error of estimate. Figure 9 illustrates the selection of the multiplier for the standard error. Note that the multiplier 1.28 corresponds to an 80-percent cumulative distribution but results in a 90th-percentile effective thickness because one tail of the normal distribution is not included (14, 15).

## SUMMARY

A procedure has been presented that allows the engineer to evaluate the in-place pavement using dynamic test equipment (such as the Road Rater or the Dynaflect) that impart a steady-state loading to the pavement. The procedure presented herein consists of a series of equations that may be incorporated into a computer program or used with small "hand" calculators. The method is based upon elastic theory and has been used successfully to evaluate pavements ranging from 3 inches (76 mm) of asphaltic concrete on 5 inches (127 mm) of crushed stone base to 18 inches (457 mm) of full-depth asphaltic concrete. Overlays have been designed using this method (9, 10, 16), and some have been constructed.

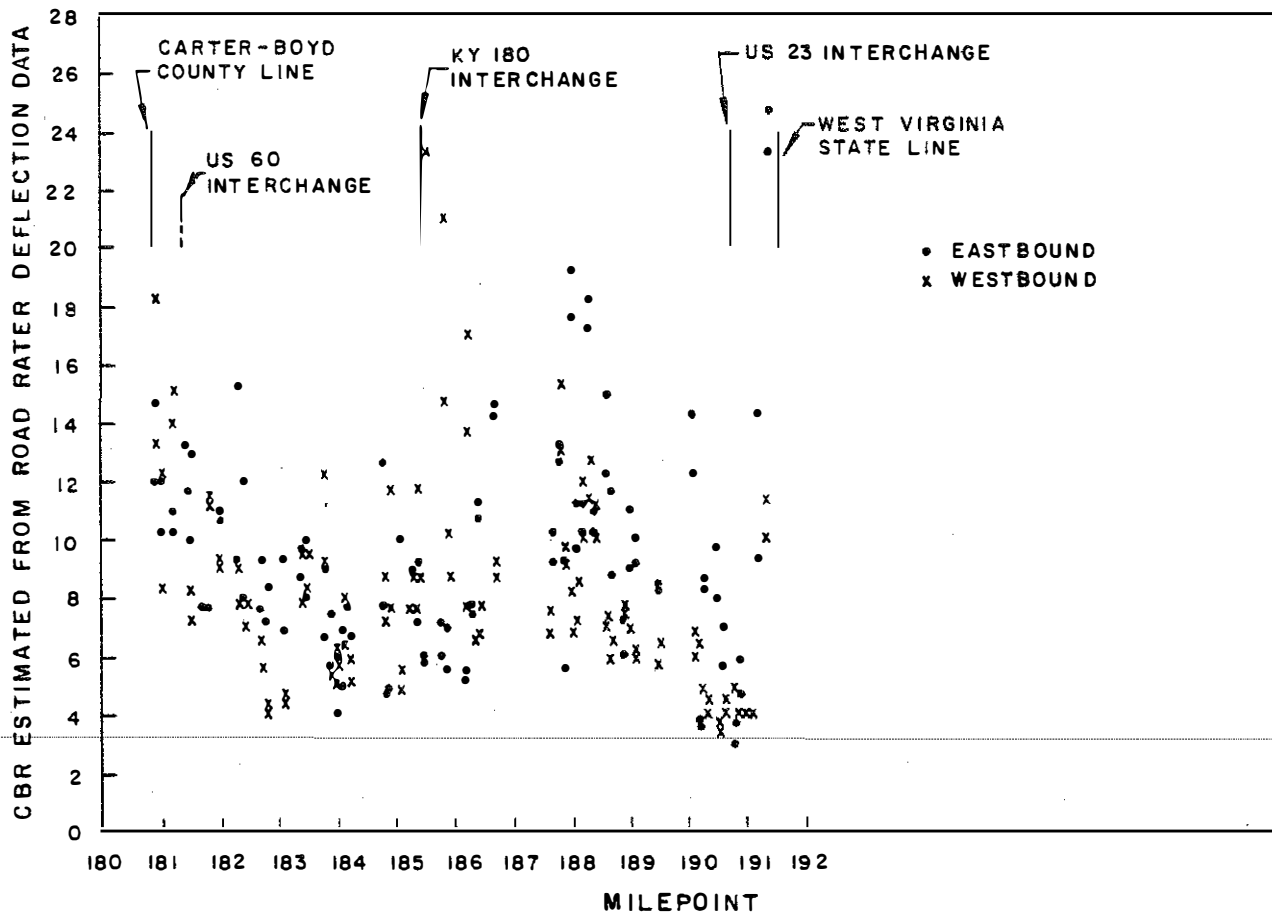


Figure 6. Estimated In-Place Subgrade Modulus versus Distance.

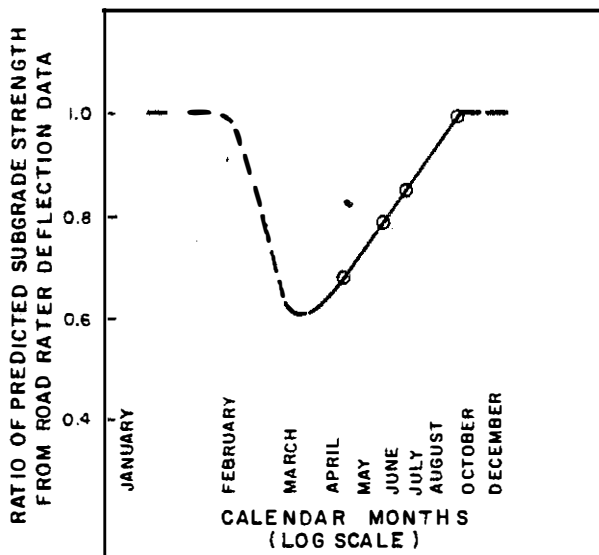


Figure 7. Change in Subgrade Modulus versus Time.

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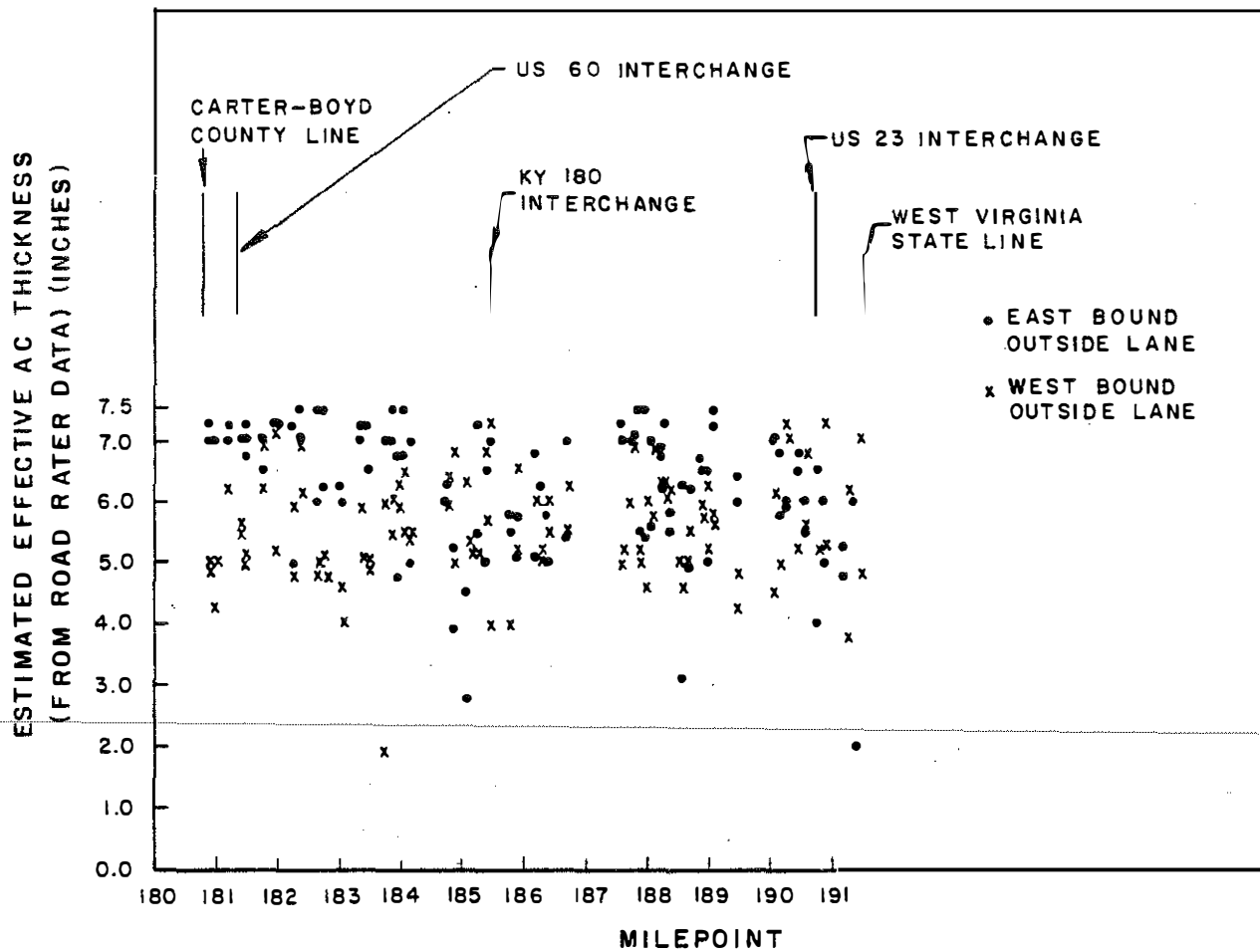


Figure 8. Estimated In-Place Equivalent Thickness of Asphaltic Concrete versus Distance.

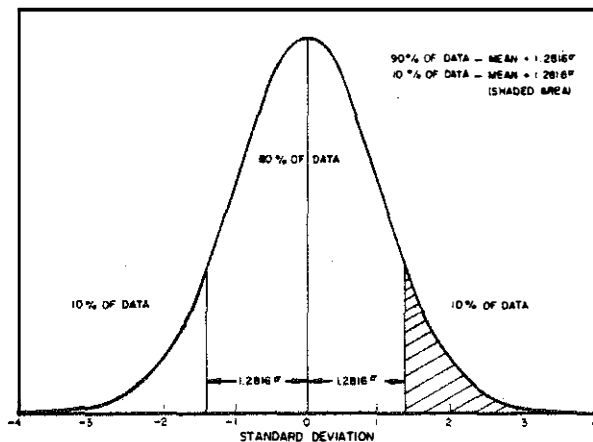


Figure 9. Illustration of 90th-Percentile Cumulative Distribution.

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# STRUCTURAL CAPACITY OF IN-PLACE ASPHALTIC CONCRETE PAVEMENTS FROM DYNAMIC DEFLECTIONS

H. F. Southgate,<sup>1</sup> G. W. Sharpe,<sup>2</sup> R. C. Deen,<sup>3</sup> and J. H. Havens<sup>4</sup>

## ABSTRACT

The proper design of asphaltic overlay thicknesses involves four major factors: the in-place modulus of the subgrade, an estimate of the structural capacity of the existing pavement, estimates of the future traffic expressed as equivalent axleloads and required or desired design levels, and a thickness design procedure. This paper deals with estimating the in-place subgrade modulus and the remaining load-carrying capacity of the existing pavement. The method presented herein is valid for any Road Rater or other dynamic tester such as the Dynaflect. This procedure was based upon a 600-pound (272.4-kg) peak-to-peak dynamic load applied at a rate of 25 Hz. The steady-state deflections have to be adjusted for load, dynamic frequency, and location of sensors. This method should be applied only to those testers that use a constant vibratory load.

## INTRODUCTION

In a 1979 Transportation Research Board symposium (1) on "Pavement Evaluation and Overlay Design" a graphical procedure to evaluate in-place conditions was presented. Herein are refinements to that graphical procedure. Equations have been developed and programmed so they can be processed using hand calculators or larger computers.

The major steps of the evaluation procedure are:

1. Development of theoretical relationships between pavement deflection, subgrade modulus, and asphaltic concrete thickness (this is a straight-forward method based upon elastic theory);
2. Adjustment of the test data to reference conditions (temperature, frequency of loading, location of sensors, percent voids, percent asphalt content in the mix, and modulus of the asphaltic concrete);
3. Determination of the in-place subgrade modulus and equivalent or "effective" asphaltic concrete thickness; and
4. Selection of input design parameters for an overlay design procedure.

Step 1 involves theoretical relationships between deflections of an original pavement of reference-quality materials and deflections of an existing pavement with the same crushed stone thickness, but with decreased thicknesses of asphaltic concrete (to account for a partial use of the fatigue life of the pavement) for each of the three sensors of the Road Rater. The two more-remote sensors are used to determine which portion of the pavement structure is exhibiting distress.

In Step 2, equations are used to adjust measured deflections for load, frequency, temperature, location of sensors, percent voids, percent asphalt content, and asphaltic concrete modulus. Deflections obtained by other dynamic testers (such as the Dynaflect) under various test conditions can be analyzed using the technique and relationships summarized in this paper.

In Step 3, the existing pavement is assumed to perform as a pavement of "x" thickness of reference-quality asphaltic concrete over the as-built thickness of crushed stone base (zero thickness for full-depth asphalt pavements). This portion of the analysis may involve a single test to represent a section of pavement, or as many test points as desired may be evaluated. If more than just a few deflection measurements are involved, the data should be subjected to the analyses of Step 4.

Step 4 is a statistical and/or graphical analysis of the subgrade moduli and the behavioral thicknesses of the asphaltic concrete layer determined in Step 3. The mean and standard error of estimate should be calculated so that an appropriate behavioral thickness can be chosen. The thickness selected in this portion of the analysis to represent the structural capacity of the existing pavement is related to the risk of failure to be assumed with the overlay design. Appropriate choices of behavioral thicknesses and design methods are discussed.

## THEORETICAL ANALYSIS

Construction records provide as-constructed thicknesses of the layers in the pavement structure. All layers below the asphaltic concrete are assumed to have remained as constructed. Deterioration and fatigue reduce the effectiveness of the asphaltic concrete to some equivalent, thinner thickness of reference-quality material. Vibratory testers, such as the Road Rater and Dynaflect, induce vibrations in the pavement structure that can be detected by velocity sensors or accelerometers. The electronics of the testers process the signal to yield surface deflections. These measured deflections are used to estimate the in-place condition of the pavement.

For an existing pavement, the effective thickness of the dense-graded aggregate layer is assumed to be equal to the as-constructed thickness. The remaining variables that influence the behavior of the pavement are the subgrade modulus and the effective thickness of the asphaltic concrete layers, defined as the equivalent thickness of reference-quality materials that matches measured behavior.

The Chevron N-layer computer program requires layer thicknesses, their respective moduli and Poisson's ratios, load, contact pressure, and geometry of load and sensor locations. A matrix of structures and input values were utilized to calculate deflections associated with the Road Rater loading. Procedures used in simulating Road Rater loadings and deflections are discussed in great detail elsewhere (1). These calculated deflections are the basis of the equations developed in this paper.

Analyses indicated surface deflections for a given pavement structure are a function of the subgrade modulus as given in

$$\log \Delta = K \log E_s + L \quad 1$$

in which  $\Delta$  = Road Rater deflection (0.00001 inches),

$K$  = slope of the log-log line,

$L$  = constant, and

$E_s$  = modulus of the subgrade (psi).

Both  $K$  and  $L$  are dependent upon the thicknesses of the asphaltic concrete and the dense-graded aggregate layers, as described by the third-degree polynomials

$$K = N_1 (AC)^3 + N_2 (AC)^2 + N_3 (AC) + N_4 \quad 2$$

and

$$L = N_5 (AC)^3 + N_6 (AC)^2 + N_7 (AC) + N_8 \quad 3$$

in which  $AC$  = thickness of the asphaltic concrete (inches) and  
 $N$  = eight constants determined by the fourth-degree polynomial,

$$N_i = A_i (DGA)^4 + B_i (DGA)^3 + C_i (DGA)^2 + D_i (DGA) + E_i \quad 4$$

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in which  $N_1$  through  $N_4$  are associated with the slope  $K$  and  $N_5$  through  $N_8$  are associated with the constant  $L$ ,  
 $DGA$  = thickness of the unbound layer (inches), and  
 $A, B, C, D, E,$  = constants determined by regression analyses.

Values for each of the constants are listed in Table 1.

#### Type of Distress

The theoretical deflections for No.-2 and No.-3 Sensors (Equation 1) are used to calculate

$$\log \text{No.-1 Projection} = 2 \log (\text{No.-2 } \Delta) - \log (\text{No.-3 } \Delta) \quad 5$$

Equation 5 is a mathematical representation of a semilog line through the magnitudes of No.-2 and No.-3 Sensors projected to the position of the No.-1 Sensor. The slope of the relationship in Equation 5, the difference in magnitude between the No.-1 Projection and the No.-1 Sensor deflections, and the magnitudes of all deflections are indicative of the shape of the deflection bowl.

For a given combination of layer thicknesses, asphaltic concrete modulus, and subgrade modulus, each pavement will have a calculated deflection bowl. There is a difference between the No.-1 Projection and the No.-1 Sensor for theoretical deflec-

tions (Figure 1). There also will be a difference between these values for field-measured deflections.

Normally, the differences between the No.-1 Projected deflection and the No.-1 Sensor deflection for both theoretical and field values are similar. Slab deterioration is indicated when measured No.-1 Sensor deflections are greater than No.-1 Projections (Figure 2) and when the differences between these values are greater than the differences for corresponding theoretical deflections. A foundation problem or lack of supporting capability is indicated by increased magnitudes of all field deflections and No.-1 Projection greater than the No.-1 Sensor deflections (Figure 3).

Log-log plots of No.-1 Projections versus No.-1 Sensor deflections can be used to identify variations in pavement structure (see Figure 4A). The solid line shows the theoretical relationship between No.-1 Projections and No.-1 Sensor deflections for a constant structure and asphaltic concrete modulus. Subgrade modulus varies along the line. The points about the line represent measured deflections. The variation in position of the theoretical line due to changes in the magnitudes of deflections by +/- one unit (0.00001 in. (0.000254 mm)) and the associated changes in theoretical No.-1 Projections are indicated by the two dashed lines. The zone within these lines represents a normal variation

TABLE 1. COEFFICIENTS FOR ROAD RATER DEFLECTION EQUATIONS

$$N = A_i DGA^4 + B_i DGA^3 + C_i DGA^2 + D_i DGA + E_i$$

$$K = N_1 AC^3 + N_2 AC^2 + N_3 AC + N_4$$

$$L = N_5 AC^3 + N_6 AC^2 + N_7 AC + N_8$$

$$\log \Delta = K \log E_s + L$$

in which  $DGA$  = thickness of dense-graded aggregate base layer,  
 $AC$  = thickness of asphaltic concrete layer,  
 $E_s$  = modulus of elasticity of subgrade, and  
 $\Delta$  = deflection

i	$A_i$	$B_i$	$C_i$	$D_i$	$E_i$
<b>No. 1 Sensor</b>					
1	-8.0276712E-09	4.4637935E-07	-7.8334349E-06	4.3700774E-05	0.00015920
2	2.2880623E-07	-1.2956090E-05	0.00023168	-0.00126428	-0.00603433
3	-2.0069119E-06	0.00011636	-0.00213561	0.01152101	0.07053069
4	5.3511621E-06	-0.00032005	0.00617403	-0.03601869	-0.94738380
5	3.8112800E-08	-2.1142292E-06	3.6712485E-05	-0.00019713	-0.00079876
6	-1.0927940E-06	6.1604764E-05	-0.00108663	0.00564980	0.03181695
7	9.6888879E-06	-0.00055752	0.01004067	-0.05039463	-0.42286704
8	-2.6361517E-05	0.00155888	-0.02921499	0.14909581	6.27491080
<b>No. 2 Sensor</b>					
1	-1.9422702E-08	1.0770627E-06	-1.8518686E-05	9.5507480E-05	8.9416760E-05
2	5.2579366E-07	-2.9137271E-05	0.00049930	-0.00251336	-0.00416610
3	-4.2869807E-06	0.00023786	-0.00407118	0.01974778	0.07009015
4	9.8983780E-06	-0.00055346	0.00958628	-0.04540810	-1.12011456
5	6.1453952E-08	-3.3927169E-06	5.7851557E-05	-0.00028477	-0.00038341
6	-1.9486070E-06	0.00010728	-0.00180868	0.00847179	0.01804679
7	1.5831303E-05	-0.00087303	0.01469200	-0.06471592	-0.34277031
8	-3.6284025E-05	0.00202136	-0.03448633	0.13878339	6.61774653
<b>No. 3 Sensor</b>					
1	2.1333448E-08	-1.2598323E-06	2.4207689E-05	-0.00016422	4.6358157E-05
2	-6.1003392E-07	3.6138955E-05	-0.00069872	0.00483808	-0.00319426
3	5.4277510E-06	-0.00032212	0.00626602	-0.04474861	0.07028740
4	-1.5081292E-05	0.00089525	-0.01749993	0.13007837	-1.27529337
5	-1.0456648E-07	6.1644249E-06	-0.00011799	0.00078800	-0.00010359
6	2.9858350E-06	-0.00017641	0.00339148	-0.02303053	0.01019562
7	-2.6465435E-05	0.00156508	-0.03021264	0.21073267	-0.28067328
8	7.2699360E-05	-0.00429505	0.08308389	-0.60401394	6.84595514



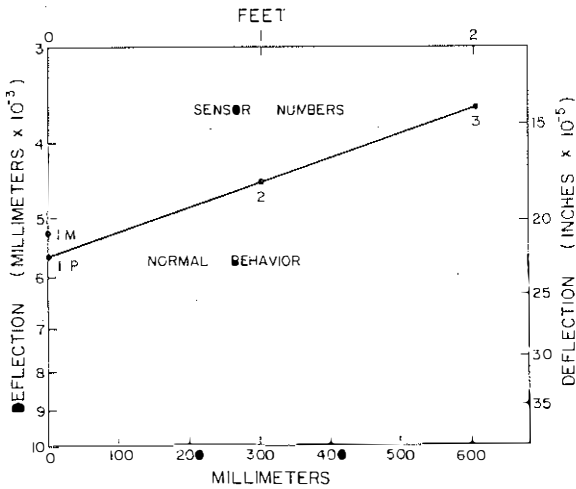


Figure 1. Relationship between Deflection and Distance from Point of Load and Determination of No.-1 Projected Deflection for Pavement Exhibiting Normal Behavior.

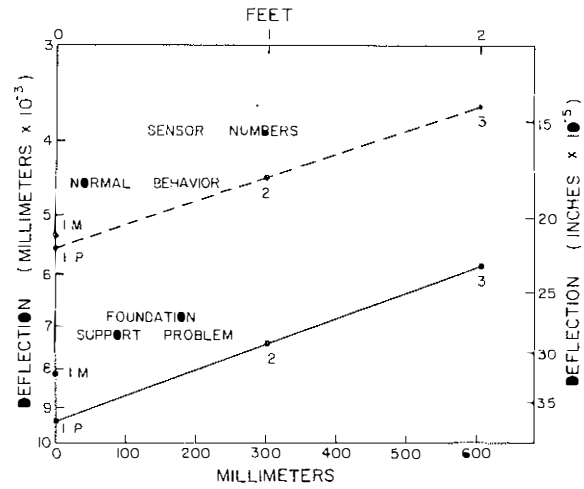


Figure 3. Relationship between Deflection and Distance from Point of Load and Determination of No.-1 Projected Deflection for Pavement With Foundation Support Problem.

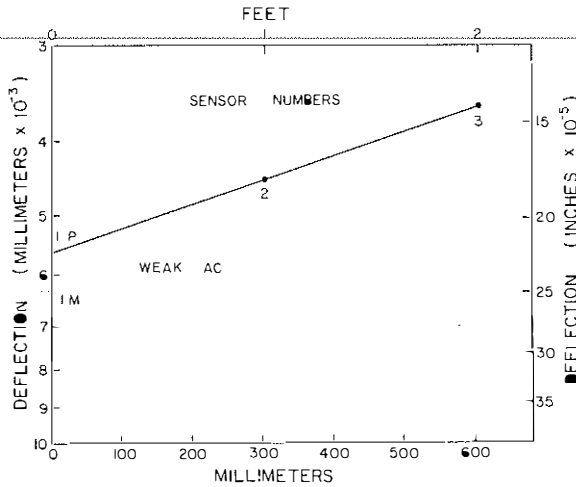


Figure 2. Relationship between Deflection and Distance from Point of Load and Determination of No.-1 Projected Deflection for Pavement With Weak Asphaltic Concrete Layer.

factor contributing to this condition. This condition and pattern of deflections were confirmed by data obtained in Huntington Beach, California (1, 2). There, Road Rater tests were performed, the pavements were cored, subgrade samples were obtained, and the moisture contents of the subgrade were determined. In those locations that had high water contents (possibly free water), the differences between the No.-1 Projected and measured deflections was considerably greater than the theoretical analyses would have indicated. One possible explanation is that water is a better conductor of sound or vibrations than normal subgrades. Therefore, the No.-2 and No.-3 Sensors measure higher deflections for soils containing excess water than for soils having normal water contents.

#### Deflection Equations

Equation 1 is solved for the eight constants  $N_i$  for a particular dense-graded aggregate thickness. For a given asphaltic concrete thickness,  $K$  and  $L$  remain constant. Thus, deflections are a function of the elastic modulus of the subgrade. Likewise, other asphaltic concrete thicknesses substituted into Equations 2 and 3 yield a family of curves (Figure 4B). The constants  $K$  and  $L$  for each thickness of asphaltic concrete are retained for use in evaluating the test data.

#### ADJUSTMENT OF DEFLECTIONS TO REFERENCE CONDITIONS

The five primary variables affecting deflections other than layer thicknesses and subgrade modulus are load, temperature, frequency of the dynamic loading, modulus of elasticity of the asphaltic concrete, and the location of the sensors. Pavement behavior can match more than one combination of subgrade modulus and thickness of asphaltic concrete. Thus, it is necessary to select an appropriate combination that matches measured deflections. The No.-2 and No.-3 Sensors can have quite different deflections but yield the same No.-1 Projected deflection by Equation 5; on the other hand, the No.-1 Sensor deflections may be nearly equal.

#### Load

A relationship to adjust a measured deflection induced by a load of any known magnitude to a reference load is given by

$$AF_L = \Delta \text{ at } 600 \text{ pounds} \div \Delta \text{ at } X \text{ pounds.} \quad 6$$

Thus, the adjusted deflection is expressed in terms of the matrices of calculations for Kentucky's Road Rater. Normal operation for the Kentucky Road Rater uses a 600-pound (272.4-kg) peak-to-peak dynamic force

due to reading the meters.

The following situations have been observed from field evaluations:

1. Test data that lie within the zone of normal variation and show relatively low deflections are indicative of a structure of high-quality materials in which all layers are acting in concert with one another.
2. Test data on the upper side of the zone of normal variation are indicative of a pavement in which the subgrade has remained in good condition but in which cracking or some other problem has caused deterioration of the asphaltic concrete.
3. Test data that plot in the higher range of the zone of normal variation are indicative of either of two conditions: a) changes in the condition of the subgrade with the pavement remaining in good condition and the layers acting in concert or b) a deteriorated slab coupled with excessive water content in the subgrade (reduced subgrade modulus) and, again, the layers acting in concert.
4. Test data that plot below the zone of normal variation are indicative of subgrades not providing adequate support. Excessive water contents in the subgrade have been identified as a

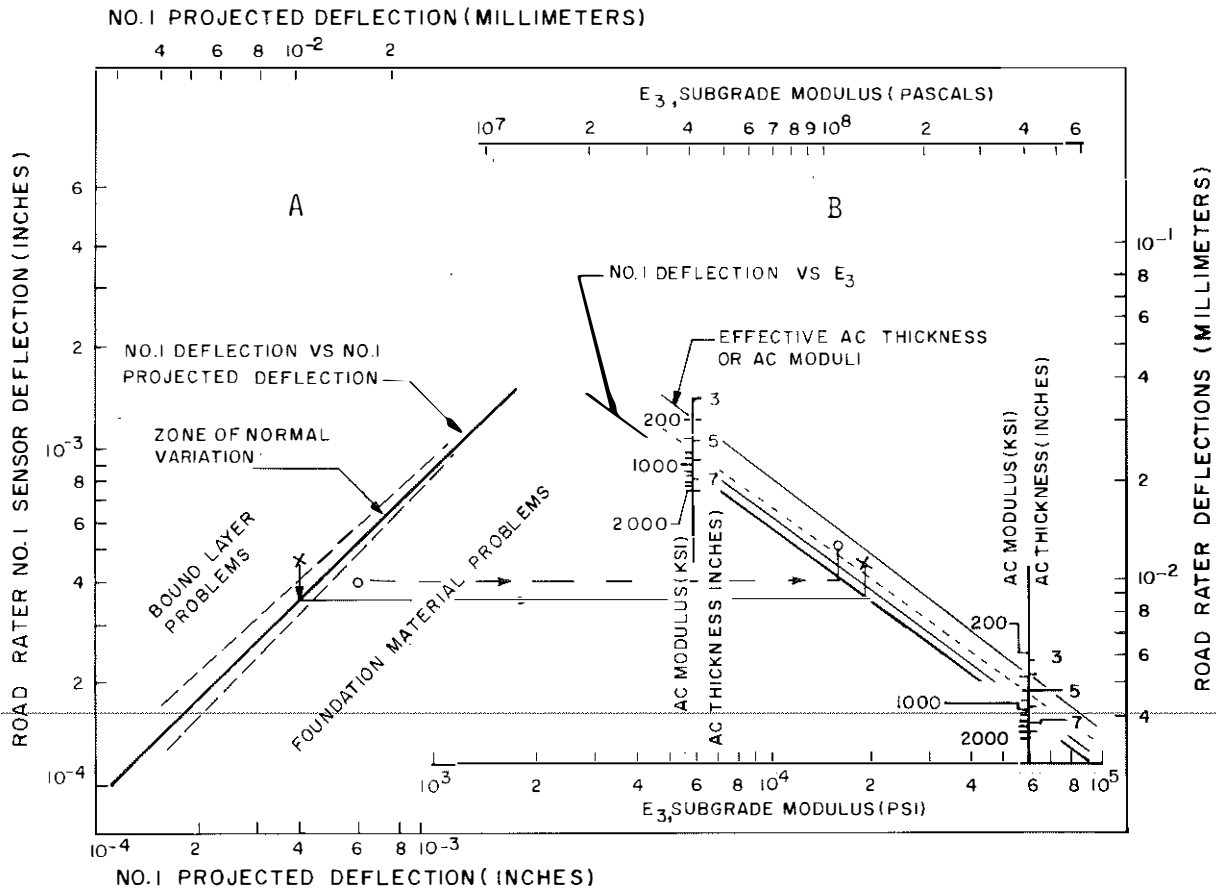


Figure 4. No.-1 Deflection as a Function of No.-1 Projected Deflection and Subgrade Modulus Illustrating a Method for Estimating Subgrade Modulus and Effective Behavior.

#### Temperature

The temperature distribution within the asphaltic concrete can be estimated (3). The average of the temperature at the surface, mid-depth, and bottom of the asphaltic concrete layer provides the basis for a reasonable approximation of the average modulus of elasticity of the asphaltic concrete.

#### Frequency of Loading and Modulus of Asphaltic Concrete

In testing asphaltic concrete pavements, Kentucky's Road Rater is operated at 25 Hz. This frequency was chosen because resonance was detected at 20 Hz and 30 Hz but not at 25 Hz. Figure 5 illustrates the relationships between temperature, frequency of the applied load, and the modulus of elasticity of asphaltic concrete as reported by Kallas and Riley (4). The equation in Figure 5 yields a very close approximation of their data. From that data, the mean annual temperature in Kentucky of approximately 70°F (21.1°C) corresponds very closely to 1,200 ksi (8.27 GPa) at 25 Hz.

#### Percent Voids and Asphalt Content

Shook and Kallas (5) reported the effects of asphalt content and voids upon the elastic modulus. An analysis for reference conditions of 70°F (21.1°C), five percent asphalt content, and four percent voids yielded

$$\log W = R + S(V) + T(V)^2 \quad 7$$

in which  $R = -7.21517 + 3.05790(\%AC) - 0.31182(\%AC)^2$ ,  
 $S = 2.03197 - 0.82952(\%AC) - 0.08186(\%AC)^2$ ,  
 $T = 0.12485 + 0.05020(\%AC) - 0.00504(\%AC)^2$ ,  
 $\%AC$  = percent asphalt content, and  
 $V$  = percent voids in the asphaltic concrete.

The development of these adjustment factors  $W$  is presented elsewhere (6).

Equation 7 should be used when the percentages of asphalt and void contents are known or can be estimated. Equation 7 illustrates the influence of construction quality control, or the lack thereof, upon expected behavior of the pavement. Equation 7 is the best least-squares fit of the  $W$  values for 4 Hz, 16 Hz, and 25 Hz, producing a standard error of estimate of 0.01 for this set of data. Thus,  $W$  holds true for any frequency within the range used by most dynamic testers. A word of caution is necessary. Equation 7 was developed from limited laboratory test data using one source of aggregates and asphalt cements. Others are encouraged to attempt similar laboratory test and analysis procedures.

#### Adjusting Deflections for Moduli Other than Reference

Because of the significant effects of temperature on modulus of elasticity of asphaltic concretes, a system was developed to adjust deflection measurements to a reference temperature and modulus (1). The adjustment scheme used ratios of deflections at reference conditions to deflections resulting from arrayed variables of layer thicknesses and moduli (1, 4, 7-9). The procedure to adjust deflections is based upon the assumed "reference" of 70°F (21.1°C), 25 Hz dynamic frequency, a 600-pound (272.4-kg) peak-to-peak load applied sinusoidally, and sensors located as for Kentucky's Road Rater. Conditions at the time of testing typically will be different, and the measured deflections must be adjusted to values at the reference conditions. Each Road Rater sensor requires its unique set of factors. The relationship of asphaltic concrete moduli, the asphaltic concrete thickness, and the deflection adjustment factor is expressed as

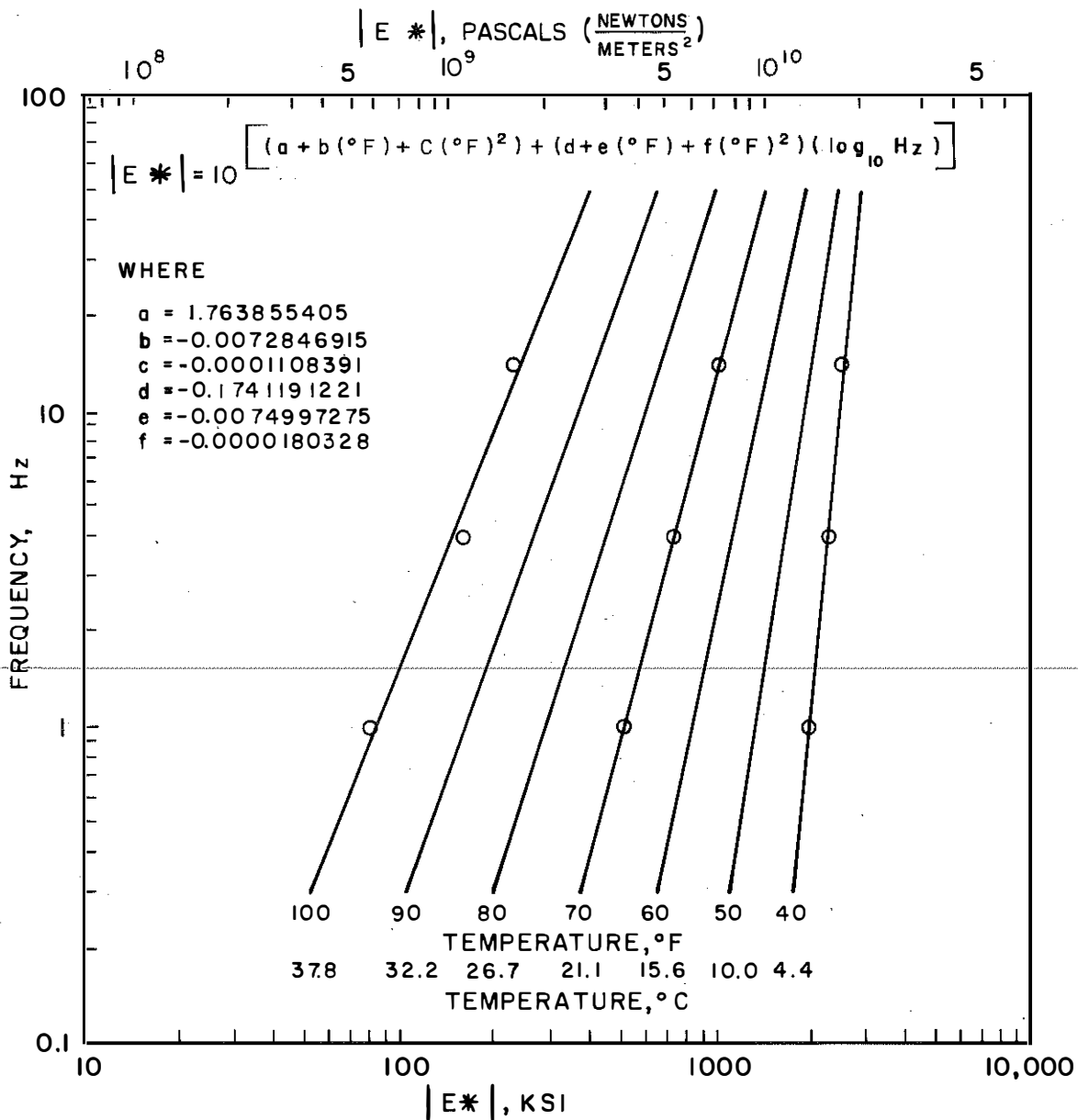


Figure 5. Relationship of Temperature, Frequency of Loading, and Modulus of Asphaltic Concrete.

$$\log AF_j = [\log AC - (H_1 E_{AC}^3 + H_2 E_{AC}^2 + H_3 E_{AC} + H_4)] [M_1 E_{AC}^3 + M_2 E_{AC}^2 + M_3 E_{AC} + M_4]; \quad 8$$

in which  $M_1, M_2, M_3, M_4, H_1, H_2, H_3, H_4$  = constants (Table 2),  
 $E_{AC}$  = mean asphaltic concrete modulus,  
 $AC$  = thickness of asphaltic concrete pavement, and  
 $j$  = Road Rater sensor number.

Statistical analyses of the differences between the calculated deflection ratio (1) and the adjustment factors resulting from Equation 8 indicated that the equation fitted the original deflection ratio within +/- 0.02 for No.-1 Sensor deflections, and +/- 0.01 for No.-2 and No.-3 Sensor deflections.

The adjusted deflections, as measured by the Road Rater, include the effects of pavement temperature and the resulting change of modulus, frequency of the sinusoidally applied load, effects of asphalt content and voids upon the modulus, and the magnitude of the load. The relationship between the locations of

the sensors and the shape of the deflection bowl is given by Equation 9:

$$\Delta = AA + BB r + CC r^2 \quad 9$$

in which  $\Delta$  = deflection,  
 $r$  = radius from the center of one loaded foot, and  
 $AA, BB, CC$  = constants determined by a least-square fit.

The parabolic equation accurately describes the deflection bowl up to a radius of 37 inches (940 mm).

Deflections measured by the Dynaflect can be adjusted for load and frequency as mentioned earlier. The adjusted deflections for the first three sensors of the Dynaflect can be used to determine the constants of Equation 9 by a least-squares fit. When the constants  $AA, BB,$  and  $CC$  have been determined, the radius for each Road Rater sensor can be substituted for  $r$  to calculate an equivalent deflection compatible with the remainder of this procedure.

TABLE 2. CONSTANTS FOR DEFLECTION ADJUSTMENT FACTORS FOR THE KENTUCKY ROAD RATER

$$\log AF_j = (\log AC - (H_1 E_{AC}^{-3} + H_2 E_{AC}^{-2} + H_3 E_{AC}^{-1} + H_4)) \\ (M_1 E_{AC}^3 + M_2 E_{AC}^2 + M_3 E_{AC} + M_4)$$

in which AF = deflection adjustment factor  
 AC = asphaltic concrete thickness  
 E<sub>AC</sub> = mean modulus of elasticity for asphaltic concrete

j = Road Rater sensor number (1, 2, 3)

-----  
 Three Layered Pavements

DGA Less Than 8 Inches

J	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>
1	1.0225763E-19	-4.4990262E-13	7.0628626E-07	-0.37155742
2	4.3336498E-20	-2.2091077E-13	4.5988841E-07	-0.30474423
3	3.3403716E-20	-1.6395133E-13	3.4805071E-07	-0.23820381

J	H <sub>1</sub>	H <sub>2</sub>	H <sub>3</sub>	H <sub>4</sub>
1	-2.0312535E-19	7.1127654E-13	-8.4587020E-07	0.25466949
2	7.2614981E-20	-1.0302809E-13	-1.3874220E-07	0.46069097
3	1.6419243E-19	-3.3570986E-13	-4.2060526E-08	0.66081522

DGA Greater Than or Equal to 8 Inches

J	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>
1	8.6110078E-20	-3.8725065E-13	6.2848481E-07	-0.34173343
2	3.5850121E-20	-1.8167083E-13	3.8532939E-07	-0.25976352
3	2.1116466E-20	-1.0783377E-13	2.5034102E-07	-0.18049747

J	H <sub>1</sub>	H <sub>2</sub>	H <sub>3</sub>	H <sub>4</sub>
1	-2.3472762E-20	1.1931522E-13	-2.9552194E-07	0.15345469
2	8.6274124E-20	-1.3810588E-13	-8.8295169E-08	0.42052283
3	1.1280263E-19	1.7456748E-13	-1.3783142E-07	0.60922647

Two Layered Pavements

J	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>
1	1.0486807E-19	-4.5399608E-13	6.6726565E-07	-0.32106577
2	1.0429773E-19	-4.7586726E-13	7.9423008E-07	-0.44438965
3	9.6133265E-20	-3.9709184E-13	6.8153597E-07	-0.41509383

J	H <sub>1</sub>	H <sub>2</sub>	H <sub>3</sub>	H <sub>4</sub>
1	-1.1966613E-18	3.6419900E-12	-3.3712189E-06	0.40220812
2	8.4194518E-20	-1.0803309E-13	-2.9750845E-07	0.63921054
3	2.8337843E-19	-6.0413664E-13	6.2056443E-08	0.84294820

ANALYSIS OF THE ADJUSTED DEFLECTIONS

For a given structure, Equations 1-4 and the constants of Table 1 are used to calculate the theoretical deflections for Road Rater Sensors 1, 2, and 3. The No.-1 Projected deflection is calculated by Equation 5. Deflections should be calculated for a subgrade modulus of 6,000 psi (0.041 GPa) and 60,000 psi (0.410 GPa), permitting the development of the relationship between the No.-1 Sensor deflections and the No.-1 Projected deflections for a given structure (Figure 4A) over the range of subgrade moduli, from the following equation:

$$y = y_1 + (y_2 - y_1)(x - x_1) / (x_2 - x_1) \quad 10$$

in which y = log(No.-1 Sensor deflection),  
 x = log(No.-1 Projected deflection),  
 x<sub>1</sub>, y<sub>1</sub> = log(deflections for subgrade modulus of 60,000 psi) and

x<sub>2</sub>, y<sub>2</sub> = log(deflections for subgrade modulus of 6,000 psi).

Rearranging Equation 10 gives

$$\log \text{No.-1 Sensor} = [\log (\text{No.-1 Projection}) + Z] \div P, \quad 11$$

in which P = (y<sub>2</sub> - y<sub>1</sub>) / (x<sub>2</sub> - x<sub>1</sub>) and  
 Z = a constant.

For each test, Equation 11 is used to determine the equivalent No.-1 Sensor theoretical deflection to compare to the measured deflection at the No.-1 Sensor. Earlier work (1, 7) showed that this comparison indicates which portion of the pavement structure is experiencing difficulty, if at all. A limit of +/- 0.00001 inches (one unit on the Road Rater meter scale) of measured-versus-calculated deflections from Equation 11 is within the expected error of the operator reading the meters; and all layers are performing as would be expected from elastic theory (Condition 1). However, if the calculated deflection (Equation 11) is less than the measured No.-1 Sensor deflection, then the asphaltic

concrete layer is in a weakened condition and the deflection bowl is relatively narrow and deep (Figure 2, Condition 2). If the deflection by Equation 11 is greater than the measured No.-1 Sensor deflection, the subgrade or the portion of the structure below the asphaltic concrete is weak, and the asphaltic concrete is attempting the bridge the weak area by "slab action". The weakness may be due to excessive water in the subgrade (1, 2)(Condition 3).

#### APPLICATION OF TEST DATA TO OVERLAY DESIGN

To facilitate the following discussion, the term "measured deflections" will be assumed to mean all deflections have been adjusted to the "reference" modulus of 1,200 ksi (8.27 GPa), 25 Hz, and 70° F (21.1°C). Values of the in-place subgrade moduli and the equivalent thicknesses of the asphaltic concrete are retained for statistical or graphical analyses to determine the design modulus of the subgrade and the design effective thickness of the existing asphaltic concrete as input to an overlay design procedure.

##### Condition 1

Rearranging Equation 1 permits solving directly for subgrade modulus:

$$\log E_s = (\log \Delta + L) \div K \quad 12$$

The modulus of the subgrade is obtained by substituting the deflection of the No.-1 Sensor. Values of the in-place subgrade modulus and effective thickness are retained for statistical or graphical analyses.

##### Condition 2

The deflection calculated by Equation 11 would correspond to the proper deflection had the asphaltic concrete been in good condition and exhibited the reference modulus. The calculated deflection is substituted into Equation 12 to determine the in-place subgrade modulus. The equivalent thickness of asphaltic concrete having the reference modulus of elasticity remains to be determined.

Constants K and L (Equations 2 and 3) and the in-place subgrade modulus determined above are substituted into Equation 5. A close approximation can be obtained by fitting a second-degree polynomial to the logarithm of the calculated deflections versus their respective thicknesses of asphaltic concrete for the in-place subgrade modulus:

$$AC = JJ + KK (\log \Delta) + LL (\log \Delta)^2 \quad 13$$

in which JJ, KK, LL = constants obtained by regression analysis and

$$AC = \text{thickness of asphaltic concrete (inches).}$$

Substituting the measured deflection into Equation 13 yields the equivalent thickness of asphaltic concrete having the reference modulus of elasticity. In-place subgrade modulus and the equivalent thickness of asphaltic concrete are retained for statistical or graphical analyses later.

##### Condition 3

When the asphaltic concrete is behaving as a slab over a weakened substructure, the asphaltic layer is having to "work" harder than normal and its "life" will be expended faster. Therefore, there is more potential damage, requiring an additional overlay thickness to carry the anticipated future traffic. To obtain the compatible combination of in-place subgrade modulus and asphaltic concrete thickness, the No.-1 measured deflection is used in Equation 12 to determine the subgrade modulus for that test data. The No.-1 Projected deflection is used in Equation 11 to calculate its equivalent and compatible No.-1 measured deflection. This equivalent No.-1 Sensor deflection corresponds to a thinner asphaltic concrete layer.

#### Adequacy of the Existing Pavement

Several methods (9, 10) have been used to analyze and utilize the in-place values of existing structures. One valuable method has been to create a plot of in-place subgrade modulus versus distance (Figure 6) along the proposed resurfacing project. Subgrade modulus (psi) is converted to CBR by dividing by 1500. Two advantages will be seen. First, those locations exhibiting unusually weak subgrades are easily identified. Special overlay thicknesses are designed for those locations. Second, the minimum subgrade modulus and the locations of significant changes in subgrade support are easy to determine.

Figure 7 illustrates the change in predicted subgrade modulus for the period of April to September based on Kentucky data taken during a one-year period. Such analyses permit adjusting fall deflection data to equivalent spring deflections when the subgrade is in its weakest condition. Analyses of Kentucky data have indicated that fall tests provide the most consistent long-term indicator of behavior. However, overlay designs are based upon the subgrade being in its weakest condition. Thus, Figure 7 permits an approximate conversion of test data at any time to springtime conditions.

A plot is made of the effective thickness of the asphaltic concrete versus distance (Figure 8) along the proposed resurfacing project. For the same location describing a general minimum value of the subgrade, determine the minimum thickness of the asphaltic concrete. Then, determine the overlay thickness for the expected future traffic. The overlay thickness is subtracted from the special overlay designs for the unusually weak subgrades to obtain the required thickness of a "structural patch or overlay". Judicious inspection of the data permits the placement of a designed overlay thickness as a structural patch only where needed, allowing the use of a reduced overlay thickness over the entire length of a proposed resurfacing project.

Another method (7) requires the determination of the mean and standard error of estimate of the data. The design engineer determines how many "standard errors" he requires in an overlay design criteria. With this concept, the designer can establish the percentage of failure that is acceptable.

Statistical analyses can be applied to either the measured No.-1 Sensor deflections, the predicted subgrade moduli, or the effective thicknesses of asphaltic concrete. It is recommended that any representation of pavement behavior encompass 90 percent of the data. Other investigators have selected similar levels (11-13). For example, if an effective structure that encompasses 90 percent of the deflection data is desired, the recommended effective thicknesses are equal to the mean effective thickness less the product of 1.28 and the standard error of estimate. Figure 9 illustrates the selection of the multiplier for the standard error. Note that the multiplier 1.28 corresponds to an 80-percent cumulative distribution but results in a 90th-percentile effective thickness because one tail of the normal distribution is not included (14, 15).

#### SUMMARY

A procedure has been presented that allows the engineer to evaluate the in-place pavement using dynamic test equipment (such as the Road Rater or the Dynaflect) that impart a steady-state loading to the pavement. The procedure presented herein consists of a series of equations that may be incorporated into a computer program or used with small "hand" calculators. The method is based upon elastic theory and has been used successfully to evaluate pavements ranging from 3 inches (76 mm) of asphaltic concrete on 5 inches (127 mm) of crushed stone base to 18 inches (457 mm) of full-depth asphaltic concrete. Overlays have been designed using this method (9, 10, 16), and some have been constructed.

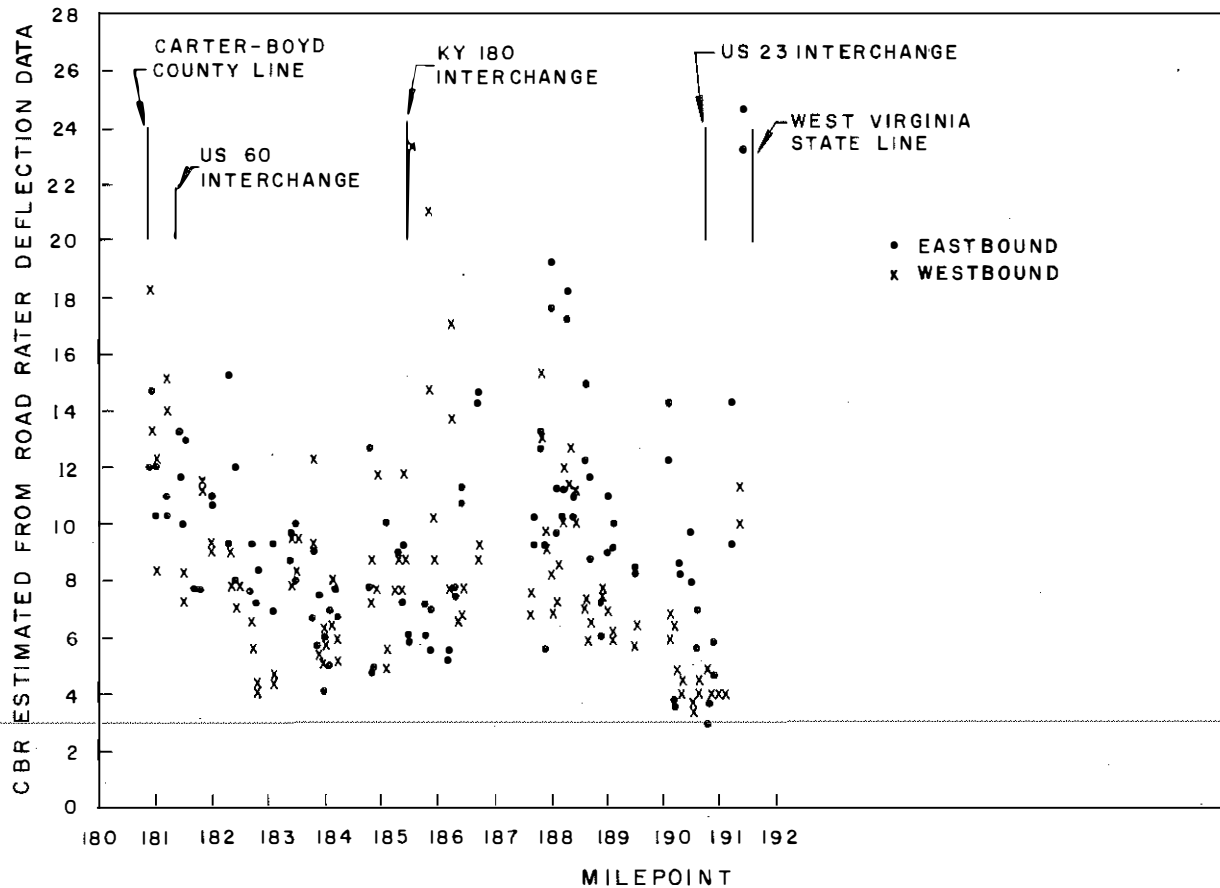


Figure 6. Estimated In-Place Subgrade Modulus versus Distance.

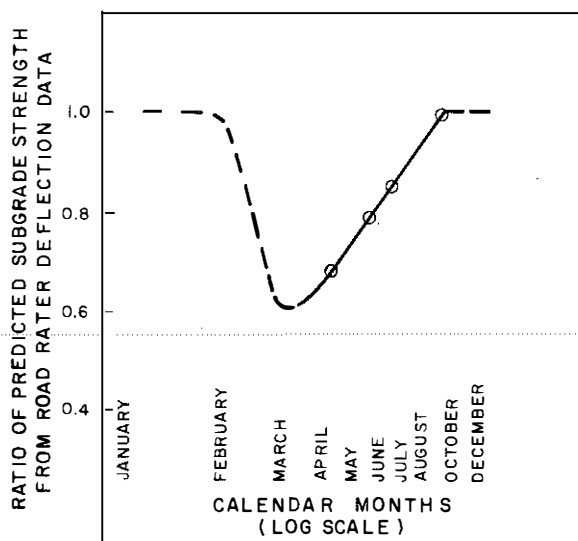


Figure 7. Change in Subgrade Modulus versus Time.

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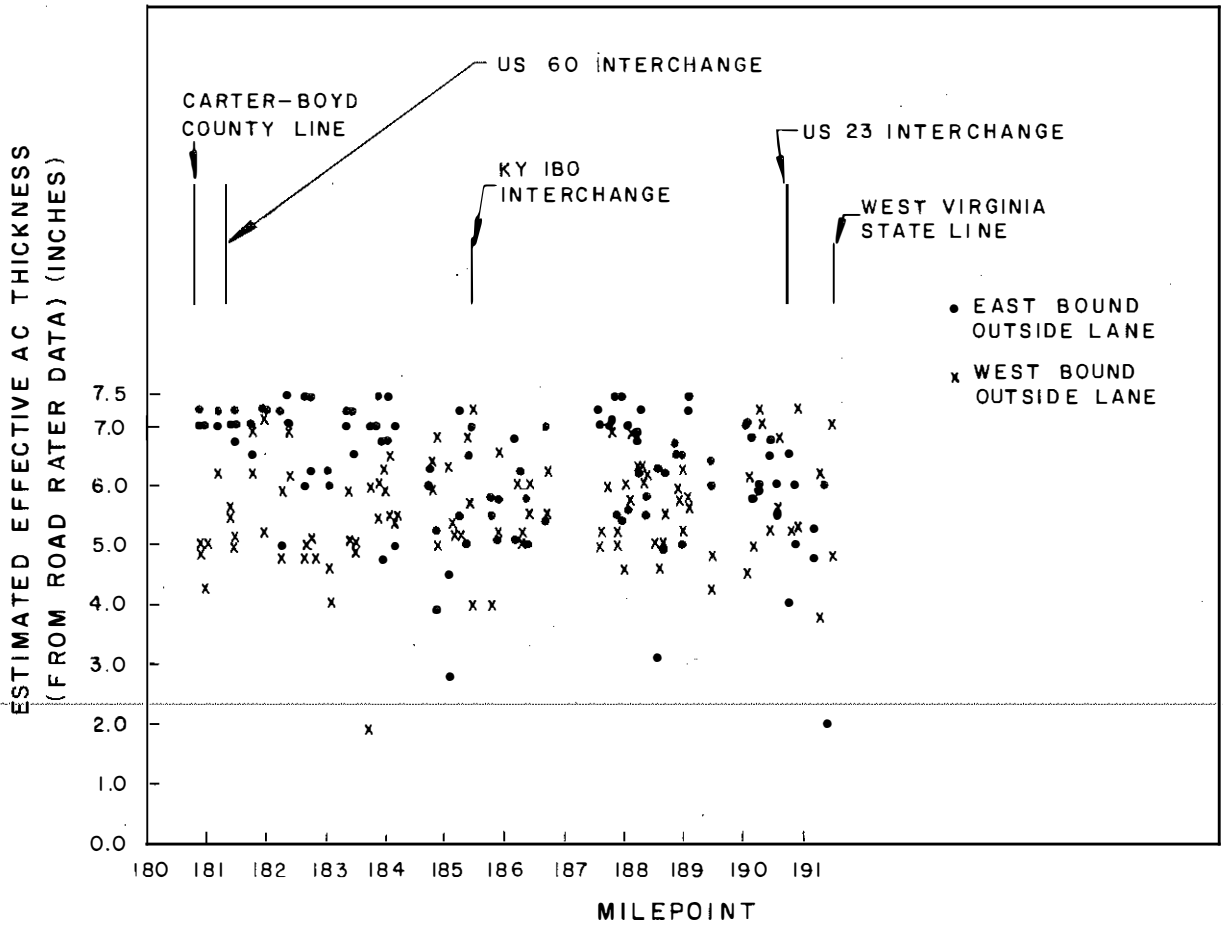


Figure 8. Estimated In-Place Equivalent Thickness of Asphaltic Concrete versus Distance.

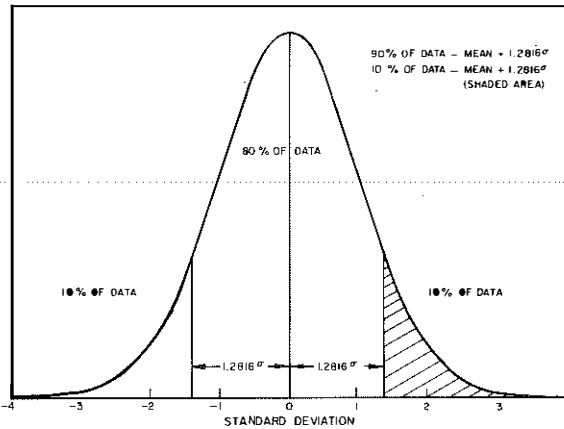


Figure 9. Illustration of 90th-Percentile Cumulative Distribution.

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