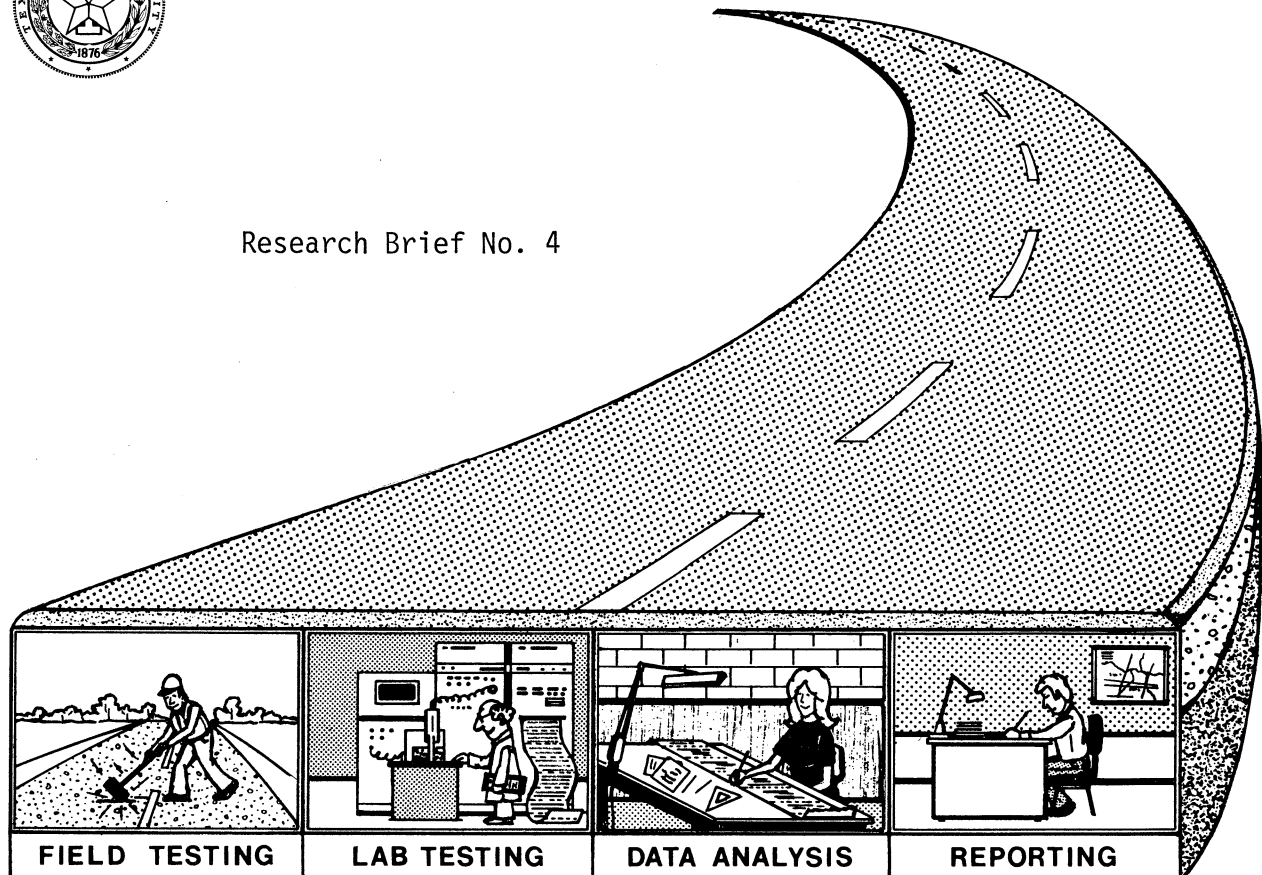


THE DUAL PARAMETRIC APPROACH TO THE ANALYSIS
OF SURFACE DEFLECTION DATA



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TO THE ANALYSIS OF SURFACE DEFLECTION DATA

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The Dual Parametric Approach To the Analysis of Surface Deflection Data

General

Evaluating in situ surface deflection measurements is a task plagued with overwhelming difficulties. This opening statement is purposefully ominous in order to effectively draw attention to the potential problem of pavement material characterization based on surface deflection data. In developing a reasonable technique to evaluate these data one must consider that:

1. Pavement materials are not linearly elastic, homogeneous or isotropic,
2. Environmental effects contribute as much to deflection as do loading conditions and
3. The general type of pavement structural cross-section affects the structural response of individual layers.

Researchers have long sought for a simple graphical technique with which to evaluate surface deflection data. Realistically such a technique must be based on linear layered elastic theory and as such does not consider the stress sensitivity of pavement layers, the effects of loading intensities (stress changes), structural layer thicknesses or seasonal effects on layer moduli. However, when these limitations are recognized the engineer can use a basic graphical analysis founded on linear layered elastic theory as a means of comparative analysis of pavement structural responses.

This report explains a graphical approach based on layered elastic

theory. More specifically the approach is based on the dual deflection parameters of maximum basin deflection and the ratio of the average basin deflection to the maximum deflection within the basin. This technique was originally developed by Vaswani (1) and allows one to comparatively evaluate pavements and to evaluate the effects of time on the structural integrity of the subgrade and structural pavement separately.

Explanation of the Method

Of all the methods by which to analyze Dynaflect deflection data the Vaswani method (1) offers the most graphic representation of the data. Basically Vaswani analyzed the pavement system underlying the Dynaflect by means of the maximum Dynaflect deflection and the ratio of the average deflection within the basin to the maximum deflection. This ratio is termed spreadability, S:

$$S = \frac{d_{\max} + d_1 + d_2 + d_3 + d_4}{5 d_{\max}} \times 100 \quad (1)$$

where

d_{\max} = maximum deflection of the pavement

d_1, d_2, d_3, d_4 = deflection recorded under sensors, 2, 3, 4 and 5, respectively.

Vaswani assumed that the deflection basin under a 9,000 pound (40 KN) wheel load with a tire pressure of 70 psi (0.49 MPa) could be realistically approximated directly from the Dynaflect Basin. He further assumed that the maximum deflection under the 9,000 pound (40 KN) wheel load could be directly calculated from the maximum Dynaflect deflection by multiplying this deflection by 28.6. This multiplication factor of

28.6 was arrived at through correlation studies between the Dynaflect and the Benkleman Beam in Virginia (2, 3).

Based on the two parameters of maximum deflection under a 9,000 pound (40 KN) single wheel load spreadability a pavement analysis scheme was developed using layered elastic theory. The materials in the layered system were assumed to be elastic, isotropic and homogeneous, and a perfect bond was assumed between contiguous layers. The Chevron computer program (4) was used for the evaluation.

Pavement systems with layers of decreasing strength from the top of the pavement toward the subgrade were considered. Neither the sandwich layer system nor the case of weaker layers over stronger layers were included in the evaluation because of their different properties. The effect of these variations in structural make up on this analysis will, however, be subsequently discussed.

The maximum deflection and spreadability parameters are used together with elastic theory to evaluate the subgrade and the structural pavement above the subgrade as two separate units. The theoretical evaluation of subgrade properties is based on Boussinesq's and Terzaghi's analyses. These analyses utilize the following simple relationship for displacements in a deflected basin of the top horizontal surface for a semi-infinite single-layer system:

$$d_r = \frac{p}{E_s} \frac{(1 - \mu_s^2)}{f(r)} \quad (2)$$

where d_r = deflection in the deflected basin at a distance r from
the load center
 p = applied load

μ_s = Poisson's ratio of the subgrade

E_s = modulus of elasticity of the subgrade

$f(r)$ = function of r , the distance from the center of the applied load.

Based on Equation 2, Vaswani found that, for all values of E_s and μ_s , the deflections at any point in terms of the maximum deflection within the basin, d_{\max} , were constant. The deflections for a 9,000 pound (40 KN) wheel load, a 70 psi (0.49 MPa) tire pressure and a radius of 6.4 inches (162.5 mm) at 1, 2, 3 and 4 feet (305, 610, 914 and 1219 mm) from the center of the applied load were found to be $0.277 d_{\max}$, $0.134 d_{\max}$, $0.089 d_{\max}$ and $0.067 d_{\max}$, respectively.

Thus the spreadability of a semi-infinite subgrade material from any value of E_s and μ_s for a 9,000 pound (40 KN) single wheel load was found to be constant as follows:

$$S = \frac{d_{\max} + 0.277 d_{\max} + 0.134 d_{\max} + 0.089 d_{\max} + 0.067 d_{\max}}{5 d_{\max}} \times 100 \quad (3)$$

$$= 31.35$$

Pavement layers over the subgrade increase the spreadability while reducing the deflection. Figure 1 is used to show how the structural pavement layer above the subgrade affects spreadability and maximum surface deflections. In this cross-section of an idealized layered elastic pavement system the pavement above the subgrade is characterized by a composite modulus of elasticity or as Vaswani (1) calls it an average modulus of elasticity, E_{av} , where

$$E_{av} = \frac{h_1 E_1 + h_2 E_2 + \dots}{h_1 + h_2 + \dots} \quad (4)$$

in which E_1, E_2 , etc. are elastic moduli of the various layers
and h_1, h_2 , etc. are the corresponding thicknesses of the
respective layers.

The composite modulus of the materials above the subgrade in Figure 1
is assigned a value of 500,000 psi (3,492 MPa).

First a 9,000 pound (40 KN) wheel load is applied directly to the
subgrade and the values of d_{max} and spreadability are calculated by
means of the Chevron layered elastic computer program. Next, the
thickness of the composite layer above the subgrade is increased in
segments two inches (50 mm) thick. The effects of d_{max} and spreadability
of the deflection basin measured at the pavement's surface can be seen
in Figure 2. For example, if the 9,000 pound (40 KN) wheel load is
applied to a semi-infinite subgrade with an elastic modulus of 15,000
psi (105 MPa) the maximum surface deflection is 0.047 inches (1.19 mm)
point A on Figure 2, and the spreadability is 31.35. If 4 inches
(102 mm) of pavement of $E_1 = 500,000$ psi (3,492 MPa) is applied over
this subgrade, point B represents the new maximum deflection and spread-
ability. For 8 inches (203 mm) of pavement point C represents the locus
of d_{max} as S. Note that although d_{max} becomes smaller and spreadability
becomes larger as the pavement over the subgrade becomes thicker, the
locus of these points is always along the same main curve, i.e., the
curve which originates from $d_{max} = 0.047$ inch (1.19 mm), which is d_{max}
for a 9,000 pound (40 KN) wheel load over a semi-infinite half space
with $E_s = 15,000$ psi (104.8 MPa). This is to say that, theoretically, a

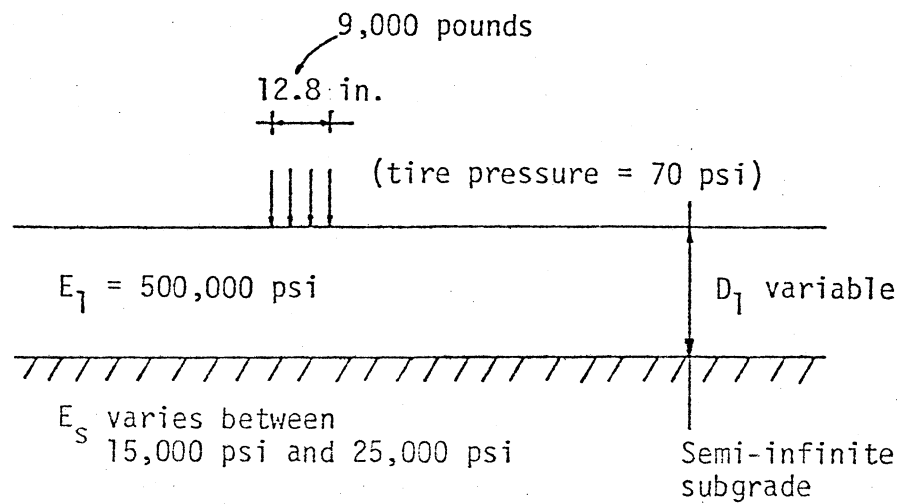


Figure 1. Two layer pavement cross section used in layered elastic development of Figure 80.

(1 psi = 6,894 Pa; 1 lb. = 4.448 N; 1 in. = 2.54 cm)

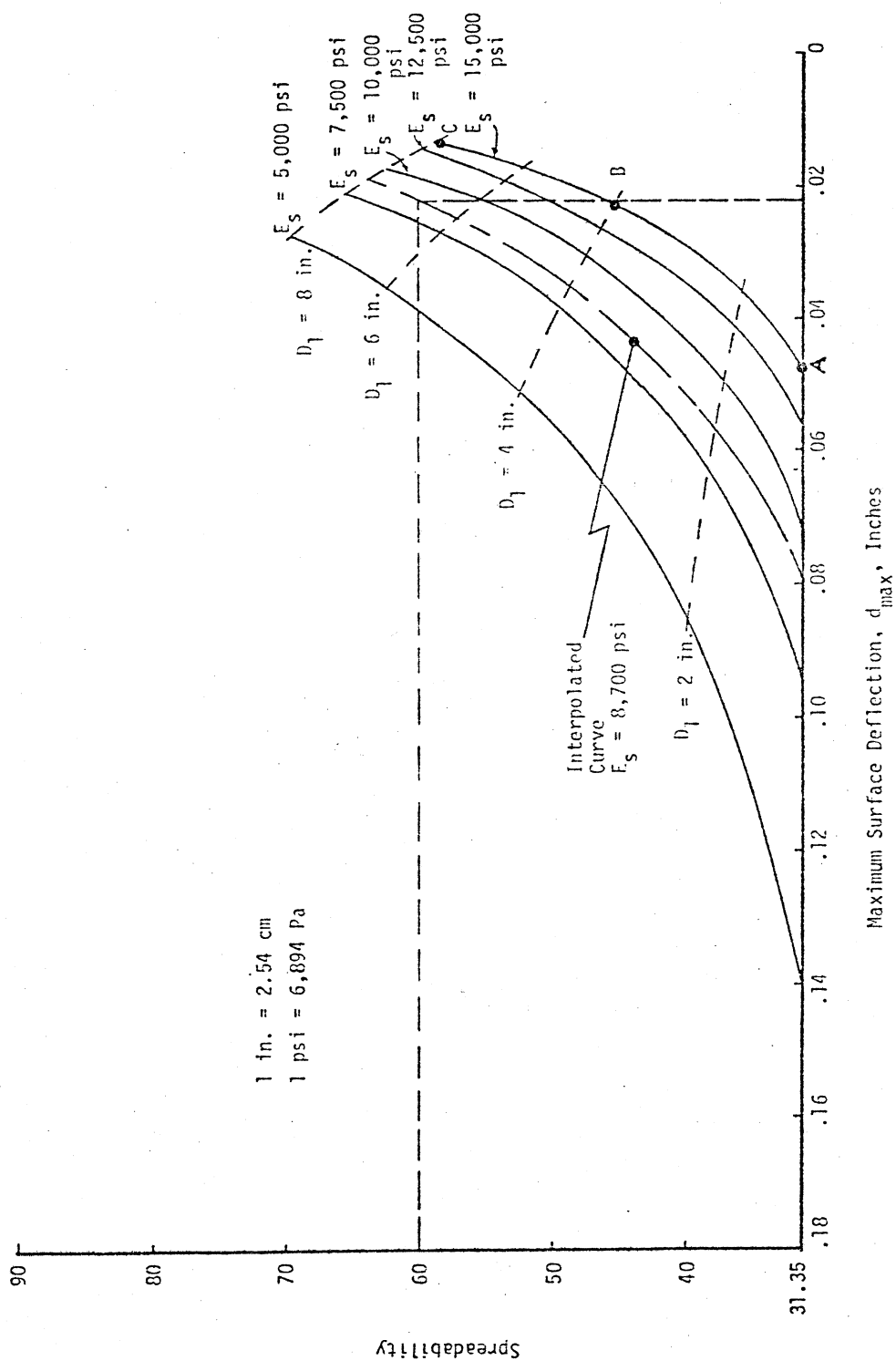


Figure 2. Dual parametric curve developed under a single 9,000 pound wheel load for the conditions shown.

figure such as Figure 2 can be used along with surface deflection parameters, i.e., d_{\max} and S , to not only evaluate the effective thickness of the pavement above the subgrade, but also the elastic modulus of the subgrade. This point will be discussed in more detail later.

To solidify the use of a chart like Figure 2, consider the following example. Let d_{\max} under 9,000 pound (40 kN) wheel load applied to the pavement cross-section in Figure 1 equal 0.022 inch (0.56 mm), and let $S = 60$. From Figure 2 it is found that $D_1 = 7.00$ inches (178 mm) and E_s is interpolated as being 8,700 psi (60.76 MPa) as the intersection of $d_{\max} = 0.022$ inch (0.56 mm) and $S = 60$ is midway between the curves representing $E_s = 10,000$ and $E_s = 7,500$ (68.9 and 51.7 MPa).

The curves shown in Figure 2 were, as previously stated, developed for a composite or average modulus of elasticity as defined in Equation 4. In practice the pavement consists of materials in layers with each layer having a different modulus of elasticity. Vaswani (1) illustrated that curves for pavements with more than two layers can be extrapolated in a general evaluation chart, such as Figure 3, by using the composite modulus in lieu of the individual layer moduli of elasticity.

In his illustration of the three-layered systems, Vaswani let the modulus of elasticity of the top layer equal 300,000 psi (2,095 MPa) and the modulus of elasticity E_2 of the second layer was taken as 30,000 psi (209.5 MPa). The subgrade modulus E_s was evaluated as 1,000 psi (6.89 MPa). Three cases were evaluated with the top layer thicknesses equal to 2, 4 and 6 inches (51, 102 and 152 mm), respectively. In each case the base thickness was varied from 0 or 2 inches (102 mm)

up to 8 inches (203 mm). These three cases are shown in Figure 3 by curves a, b and c. All three curves lie within subcurves 1A and 1B. These three curves show that, as the average modulus of elasticity of the pavement layers over the subgrade increases, the curves move from subcurve 1A toward subcurve 1B.

The Vaswani method of evaluating surface deflection data is attractive for four specific reasons in this research: (1) the parameter of spreadability, $d_{avg.}/d_{max}$, together with the maximum surface deflection, d_{max} , is (heuristically) acceptable as a means of characterizing the deflection basin shape in that information from the entire basin is considered; (2) the Dynaflect is a speedy, reliable and easy way to obtain the necessary data for this analysis, and Dynaflect surface deflection data has been successfully correlated with surface deflections under heavier loads, i.e., Benkleman Beam deflections; (3) the method allows a graphic evaluation of deflection data in which the structural contribution of the subgrade and the pavement overlying the subgrade can be separately evaluated; and (4) by employing the concept of the composite modulus or average elastic modulus of material above the subgrade the in-situ elastic moduli of pavement layers may be evaluated.

Reasons (1) and (2) will be evaluated in detail in the next section.

To illustrate the third reason listed above, consider the following example. Assume that surface deflection data is obtained from a newly constructed flexible pavement like the one characterized in Figure 1. From these data the spreadability is computed to be 60 and the maximum deflection 0.018 inch (0.46 mm). This is graphically shown by point A in Figure 4. This indicates that the subgrade has an elastic modulus of 10,000 psi (69.84 MPa) and the effective thickness of the pavement

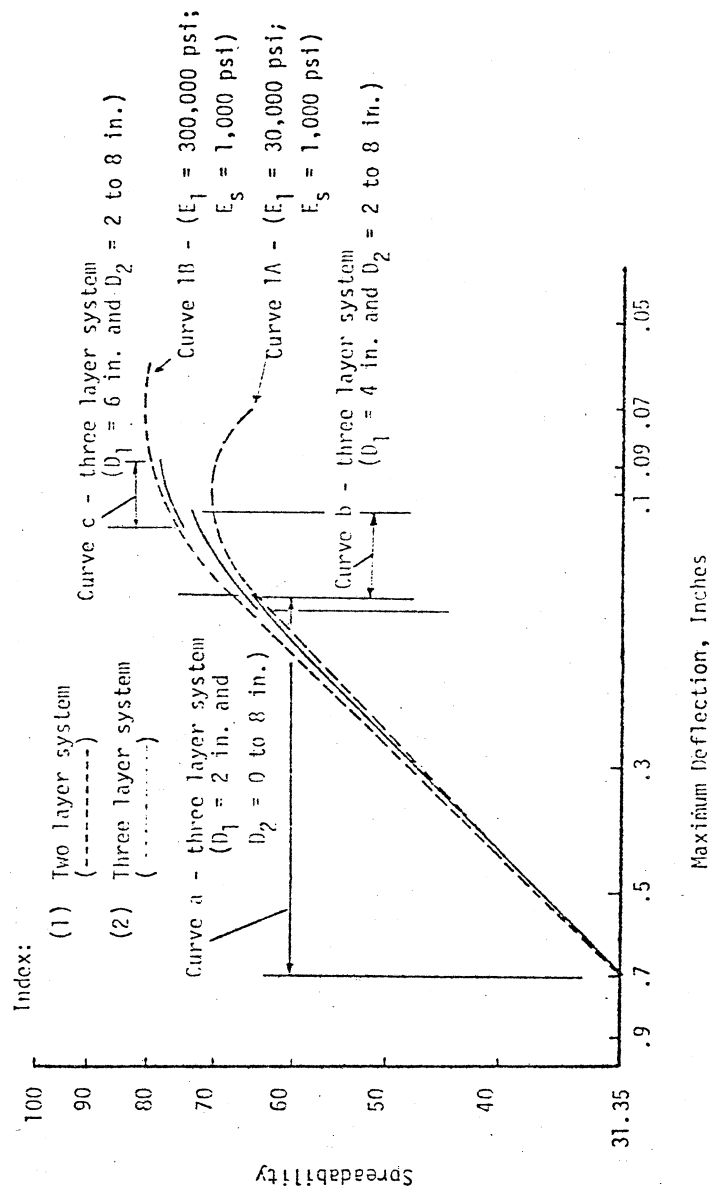


Figure 3. Approximating a three-layered system by the concept of one composite modulus above a semi-infinite subgrade [modified from Vaswani (1)].

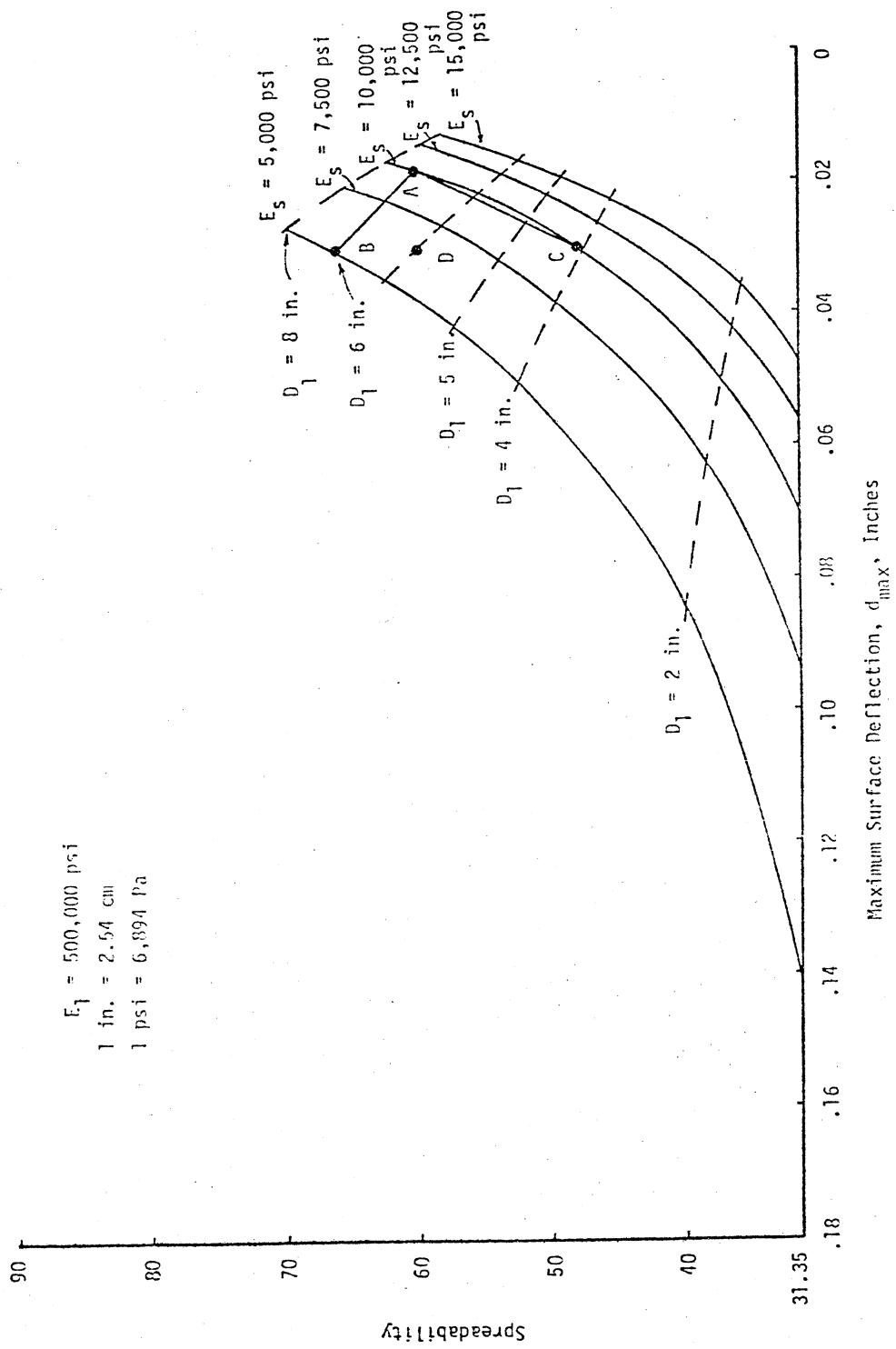


Figure 4. Illustrating the ability of the dual parametric analysis to differentiate between the contribution of the pavement and the subgrade.

above the subgrade having a composite elastic modulus of 500,000 psi (3,492 MPa) is approximately 7.5 inches (190 mm). Now suppose that the next surface deflections are recorded in the spring of the following year after a season of severe freeze-thaw degradation. These data are characterized by a spreadability of 66 and a maximum deflection of 0.03 inch (0.76 mm), point B on Figure 4. The line AB graphically depicts what has happened to the pavement during the one-year period between deflection readings. The pavement structure above the subgrade has retained its integrity and maintains an effective thickness of around 7.00 inches (17.78 cm). On the other hand, the large increase in maximum deflection is seen to be due to the loss of strength in the subgrade, i.e., the E_s was reduced by 50 percent. Such a subgrade strength reduction is not unusual in the silty subgrade of cold, wet climates.

If, on the other hand, the one year deflections were depicted by point C, $S = 48$ and $d_{\max} = 0.03$ (0.76 mm); it is evident that the loss in the strength of the pavement system is in the pavement above the subgrade.

If curves like those in Figure 4 are developed for the type of loading in question and developed for various composite elastic moduli and if the pavement layer thicknesses are known, in-situ elastic moduli can be evaluated. For example Figures 5 and 6 are identical to Figure 4 in their development except that they were developed from composite pavement elastic moduli of 200,000 and 100,000 psi (1,397 and 698 MPa), respectively. These three charts provide a tool with which to evaluate the elastic modulus of a given pavement layer. Consider the pavement in Figure 7. The elastic modulus of the asphalt emulsion base which has been curing for 30 days is required. The elastic moduli or

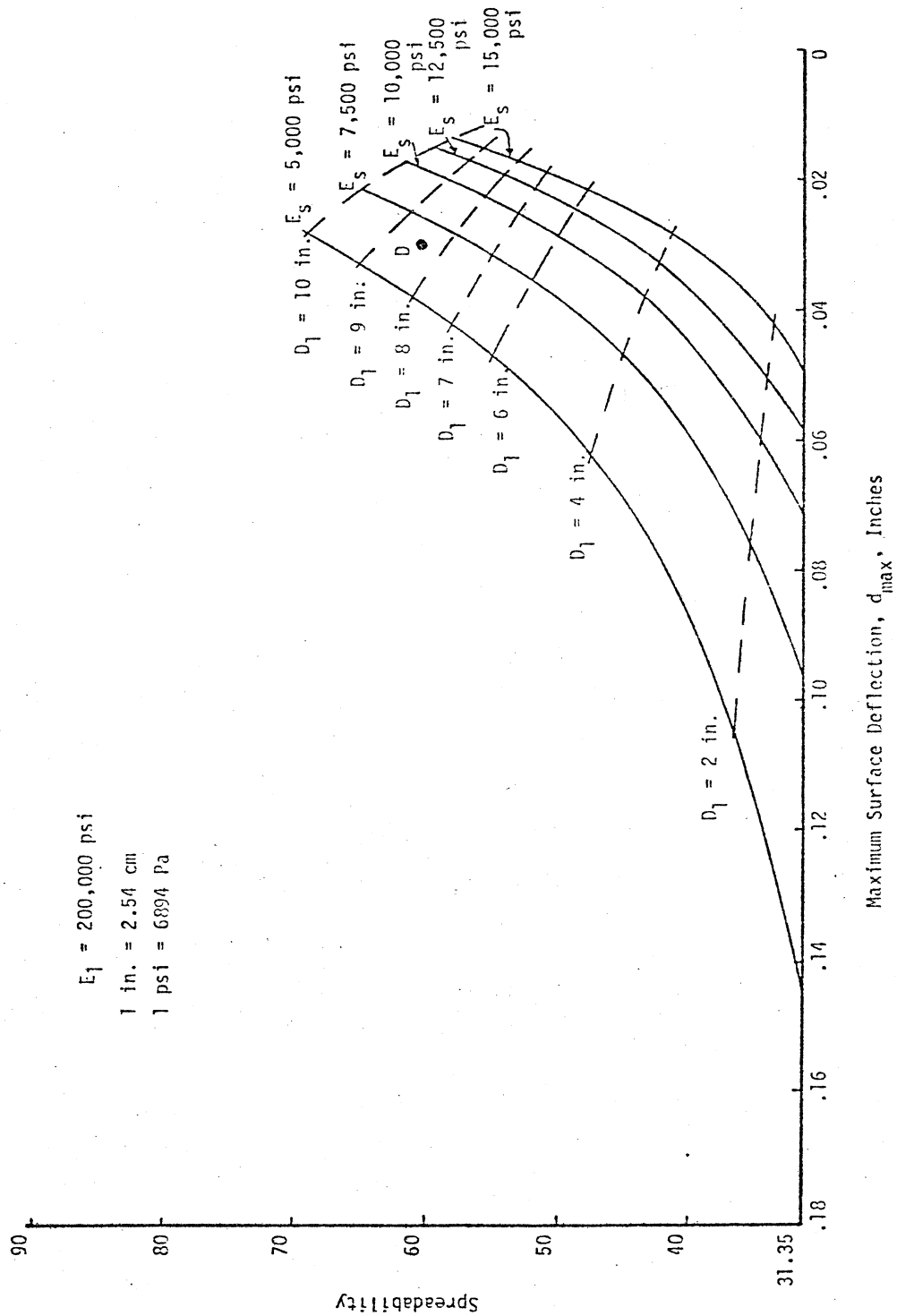


Figure 5. Dual parametric curve developed for a composite modulus of 200,000 psi.

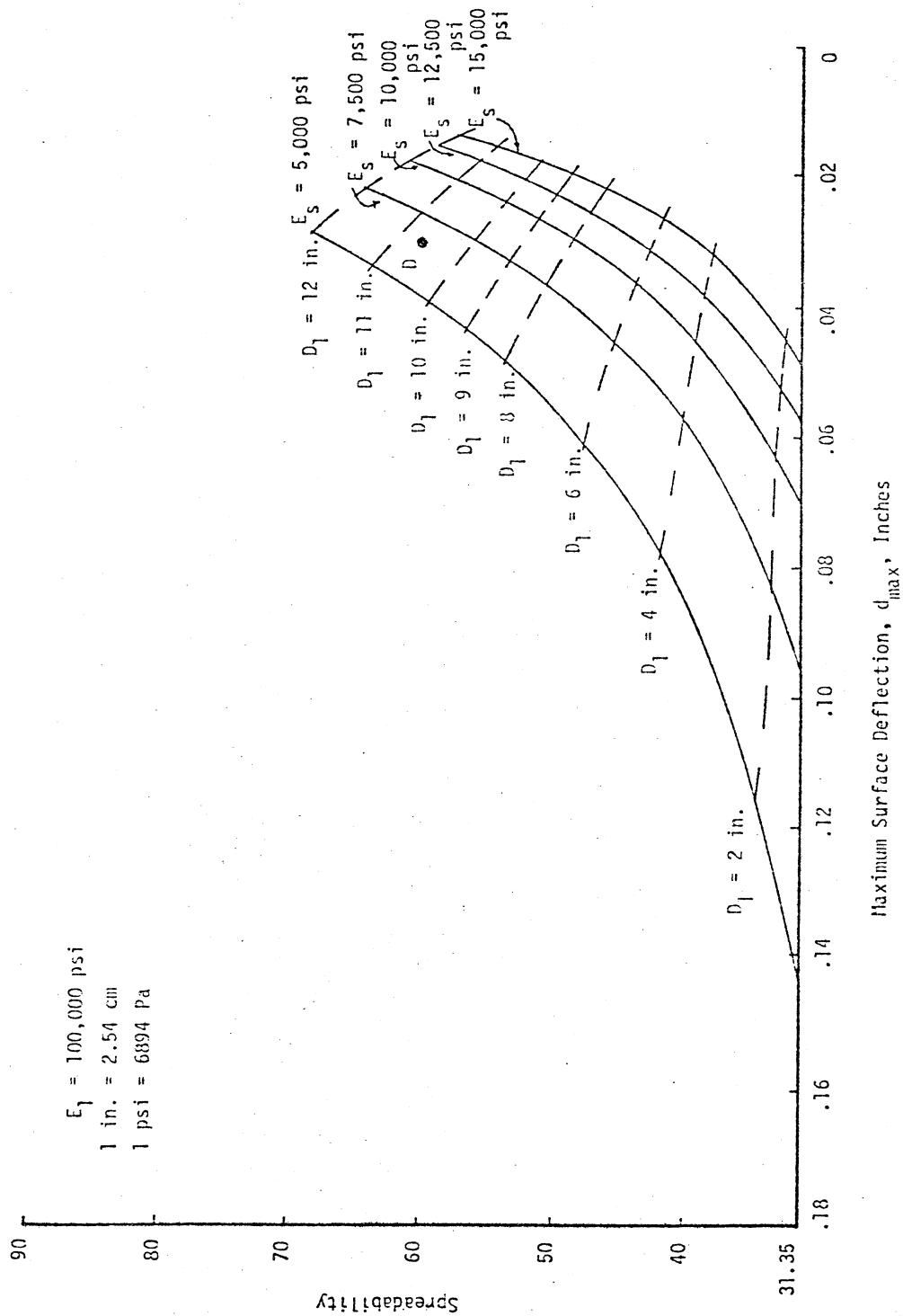


Figure 6. Dual parametric curve developed for a composite modulus of 100,000 psi.

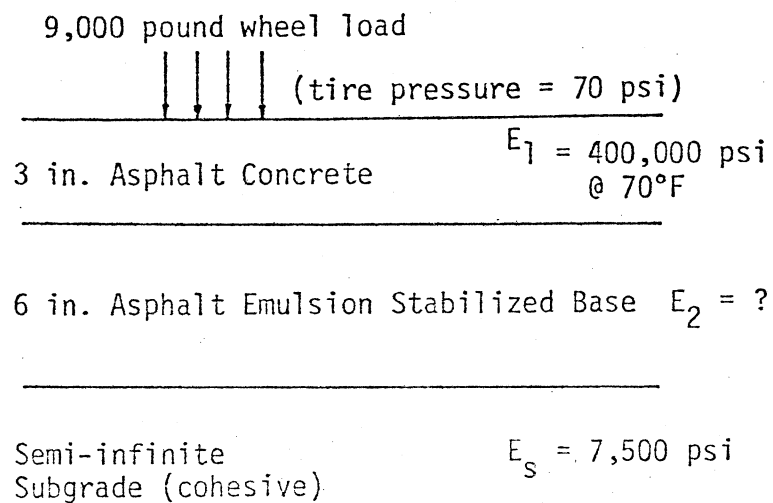


Figure 7. Pavement cross-section which yields a spreadability of 60 and a $d_{\max} = 0.03$ inches.

(1 in. = 2.54 cm; 1 psi = 6,894 Pa)

resilient moduli of the asphalt concrete and subgrade are known from laboratory testing.

If the deflection basin parameters are represented in Figures 4, 5 and 6 by point D, the effective composite thicknesses are 6.0 inches (152 mm), 8.3 inches (211 mm) and 10.7 inches (272 mm). These thicknesses are next plotted against the elastic moduli they represent, Figure 8. The composite modulus of the pavement in question is gotten by entering Figure 8 with the actual thickness of pavement above the subgrade, i.e., 9 inches (229 mm). The elastic modulus of the emulsion treated base is calculated as shown below:

$$E_{\text{comp}} = 155,000 \text{ psi} = \frac{E_{\text{AC}} (3") + E_{\text{ETB}} (6")}{9"}$$

$$155,000 = \frac{400,000 (3) + E_{\text{ETB}} (6)}{9}$$

$$E_{\text{ETB}} = 32,500 \text{ psi}$$

In this hypothetical case the elastic modulus of the asphalt emulsion treated base is very low at 32,500 psi (224 MPa). Such an evaluation of the elastic properties of asphalt bound bases may prove a valuable tool in evaluating the change in elastic properties of these layers with curing.

Using The Dynaflect Basin to Approximate Design Loads

Vaswani's aim in the development of the dual parametric technique was to predict the pavement response under a design wheel load instead of the light Dynaflect load. He did this by assuming that the spreada-

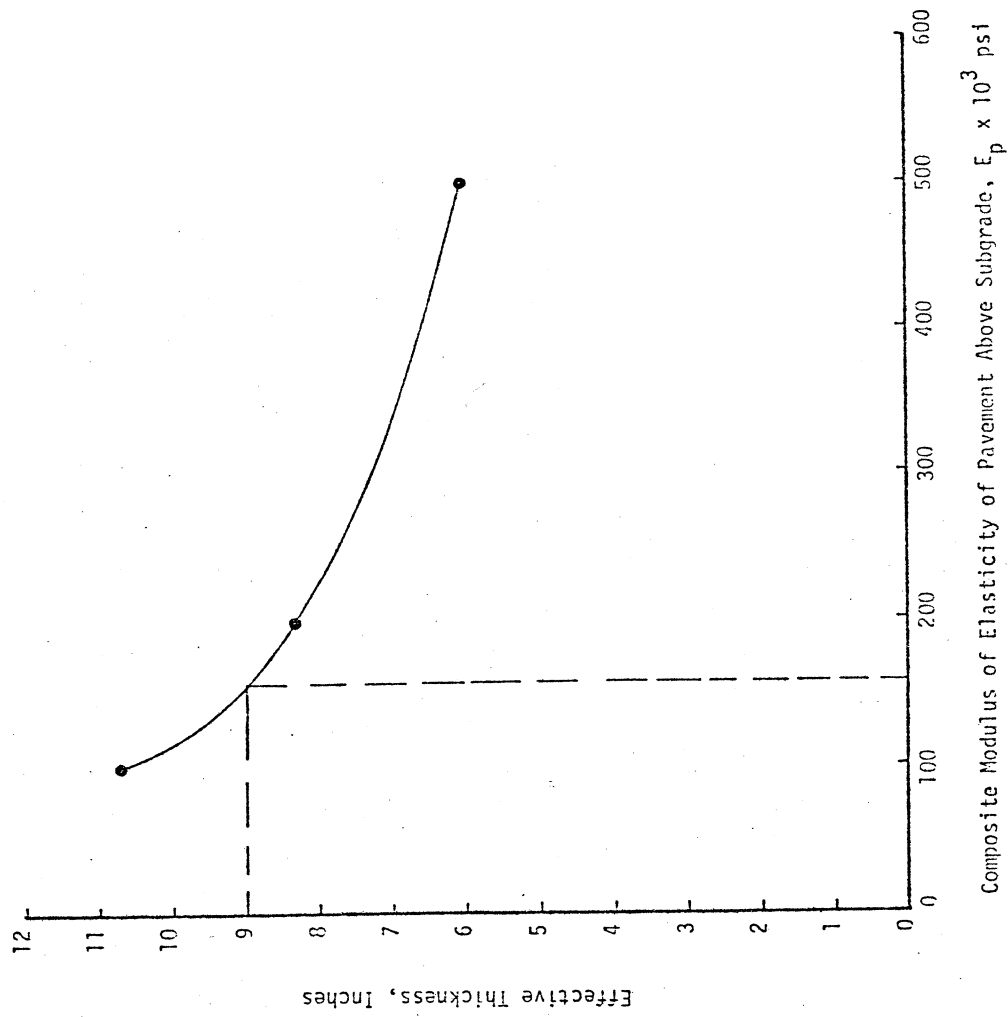


Figure 8. Graphical technique used to approximate the actual composite modulus of the pavement tested.

bility under the Dynaflect load and a 9000 lb. wheel load would be identical and that the design basin could be matched by simply shifting the basin by a factor derived through field experience.

The sections which follow analyze the validity of these assumptions.

Dynaflect Versus Benkelman Beam Deflection Basin

To begin with, the Dynaflect applies its steel wheel load to the pavement system over a rather small area, approximately four square inches (258 mm^2) per wheel. A dual wheel 4,500 pound (20 kN) load on the other hand, with a tire pressure of 70 psi (0.48 MPa), applies its load over an area of 64.3 square inches (415 mm^2) per wheel. In fact, researchers such as Swift (5) have approximated the Dynaflect load as a point load in developing layered elastic computer programs to compute elastic moduli and stiffness coefficients from Dynaflect results while the standard dual wheel load should be treated as uniformly distributed circular or elliptical load.

Secondly, the configuration of the first geophone in the Dynaflect is located between the two steel wheels or 10 inches (254 mm) from each wheel, Figure 9. The maximum deflection using the Benkelman Beam is taken between the dual wheels, but these wheels are on the order of twelve inches (305 mm) apart so that the deflection is recorded only six inches (152 mm) from the center of each wheel's contact area, Figure 9. The maximum deflection using the Dynaflect is then recorded at 8.86 radii from each wheel ($10 \text{ inches} \div 1.13 \text{ inches}$ or $254 \text{ mm} \div 29 \text{ mm}$) while the maximum Benkelman Beam deflection is recorded at 1.33 radii ($6 \text{ inches} \div 4.52 \text{ inches}$ or $152 \text{ mm} \div 11 \text{ mm}$) from each wheel, Figure 9. This results

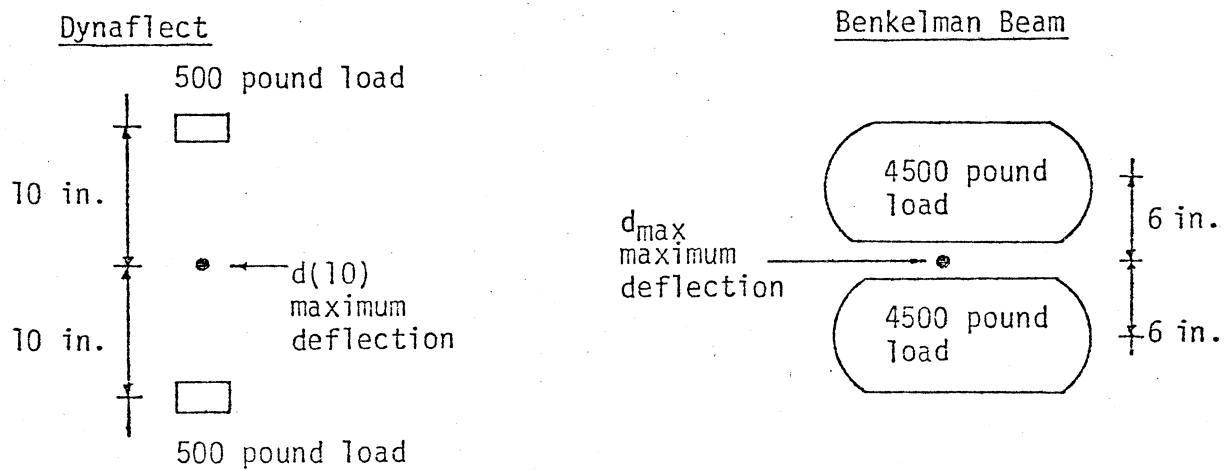


Figure 9. Comparison of the geometrics of the loading configuration of the Dynaflect and Benkelman Beam
(1 in. = 2.54 cm; 1 psi = 6,894 Pa)

in the maximum Benkelman Beam deflection being greater in proportion to the average deflection within its basin than is the case for the Dynaflect.

To investigate the effect of the difference in the measurement of maximum deflection between the Benkelman Beam and Dynaflect, the Chevron layered elastic computer program was used.

The sensor locations for the Dynaflect apparatus are 10, 15.6, 26, 37.4 and 49 inches (254, 396, 660, 950 and 124 mm) from the center of the area of each 500 pound (2.22 KN) load. Using the Chevron five layer computer program the spreadability was calculated for thicknesses of pavement above the subgrade of 4, 8 and 15 inches (102, 203 and 381 mm) and for subgrades with elastic moduli of 2,500, 7,500 and 15,000 psi (17.2, 51.7 and 103.4 MPa). The dual 4,500 pound (20 KN) wheel load configuration shown in Figure 9 was also input to the Chevron layered elastic program and the surface deflections were calculated at distances from the center of each loaded area of 10, 15.6, 26, 37.4 and 49 inches (254, 396, 660, 950 and 124 mm). The result of this analysis, Figure 10, shows that the spreadabilities are virtually identical as one would expect. So then, theoretically, the deflection basins developed by the two different load configurations are identical when the deflections are measured at the same absolute distances of 10, 15.6, 26, 37.4 and 49 inches (254, 396, 660, 950 and 124 mm) from the center of the load.

Next, the actual Dynaflect basin and a comparable Benkelman Beam deflection basin were evaluated. The Benkelman Beam deflection basin was calculated with the first or maximum deflection calculated at locations identical to Dynaflect geophone sensor locations 2 through 4 or at 15.6, 26, 37.4 and 49 inches (396, 660, 950, and 124 mm) from the center of each wheel's contact area. The results are

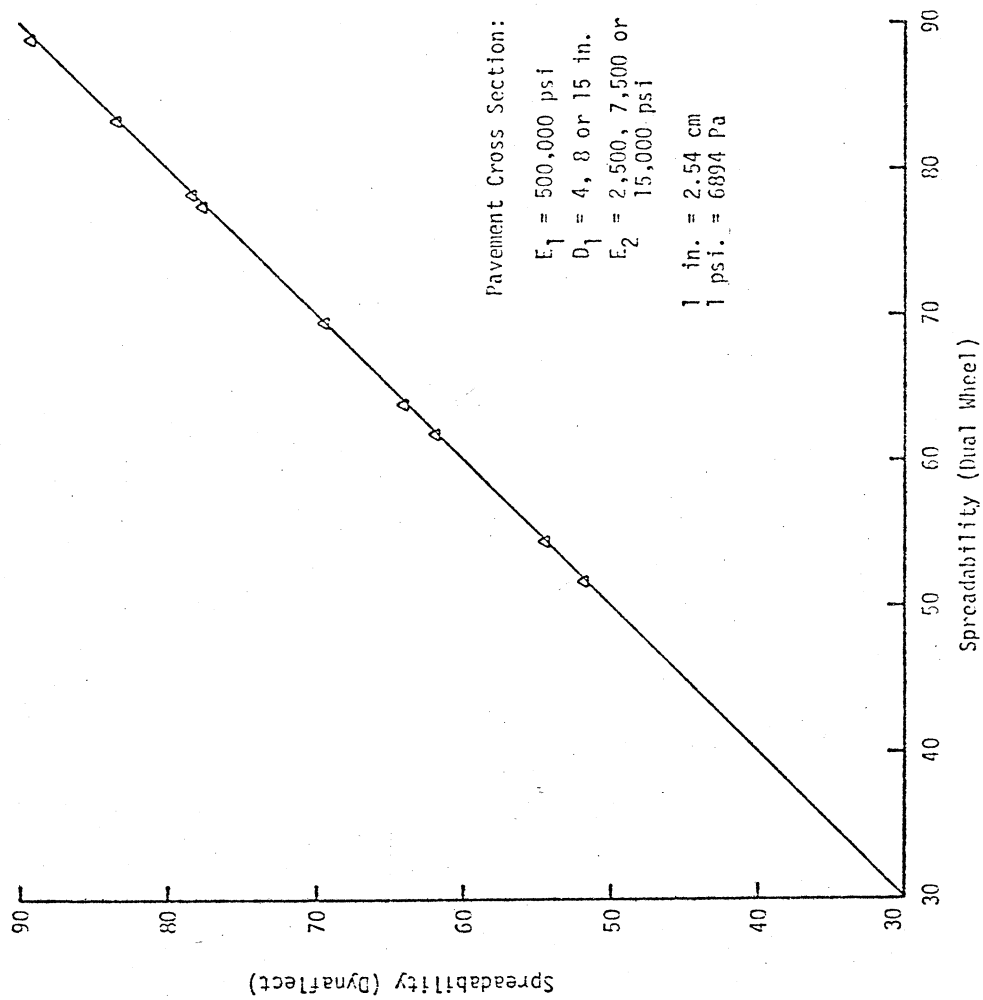


Figure 10. Comparison of spreadabilities of deflection basins under dual wheel (Benkelman Beam) and Dynaflect loading configurations with deflection sensors at 10, 15.6, 26, 37.2 and 49 inches from each load.

investigated for two subgrades: (1) a stress dependent fine grained subgrade in which the subgrade modulus is a function of the deviator stress and (2) a coarse-grained subgrade where the elastic subgrade modulus increases slightly with confining pressure but is relatively constant under typical highway loading conditions. The results of these analyses are shown in Figure 11.

In the case of fine grained subgrades, the subgrade was modeled to represent a typical fine grained soil which is highly stress dependent until a deviator stress of about six pounds per square inch (41.4 kPa) is reached. At this point the elastic modulus of most fine-grained soils is relatively constant with increase in deviator. The magnitude of the subgrade moduli chosen for the analysis represent a wide range of typical values. The fine-grained model represents the AASHTO Road Test subgrade. The range in magnitude of elastic moduli of the subgrade is due to the effect of the variation in deviator stresses transmitted to the subgrade due to the different possible thicknesses of the reinforcing pavement layer, i.e., pavement base and surface. Stress dependency within the pavement layers above the subgrade was not considered here. The result of this analysis is that the deflection basins shape as measured under the Dynaflect and Benkelman Beam are comparable above a spreadability of 50.

In the case of a stress independent subgrade, the deflection basin shape as measured by spreadability calculated under the Dynaflect is once again a quite acceptable predictor of that calculated under the Benkelman Beam above a spreadability of about 50.

The Dynaflect spreadability may then be theoretically used with confidence to predict the Benkelman Beam spreadability when the Dynaflect

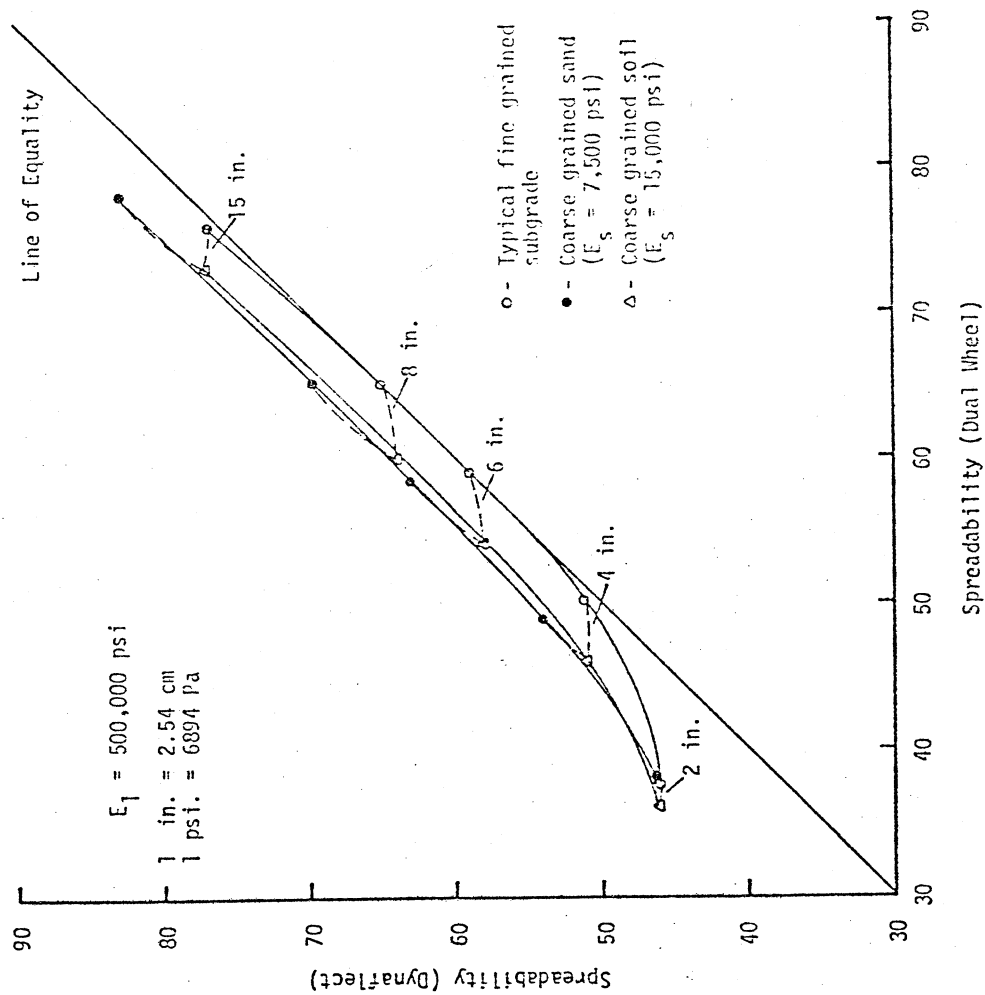


Figure 11. Comparison of spreadabilities with deflection sensors located at 10, 15.6, 26, 27.4 and 49 inches from the Dynaflect load and 6, 15.6, 26, 37.4 and 49 inches from the dual wheel load ($E_1 = 500,000$ psi).

spreadability is above 50. The reason for the breakdown in correlation below a Dynaflect reading of 50 is evident when we examine the elastic theory as the pavement thickness above the subgrade approaches zero and the spreadability decreases. In the case of the Dynaflect the load applied to an elastic semi-infinite subgrade can be approximated as two point loads of 500 pounds (2.22 kN) each, 20 inches (508 mm) apart. Applying Saint Venant's law and superposition the deflection basin may be calculated as follows:

$$d_z = \frac{P}{2\pi E} \cdot \frac{M+1}{M} \left[\frac{z^2}{R^3} + \frac{M-1}{M} \cdot \frac{2}{R} \right] \quad (6)$$

where $M = \text{Poisson's number} = \frac{1}{\mu}$

$\mu = \text{Poisson's ratio}$

$P = \text{the point load}$

$E = \text{subgrade's elastic modulus}$

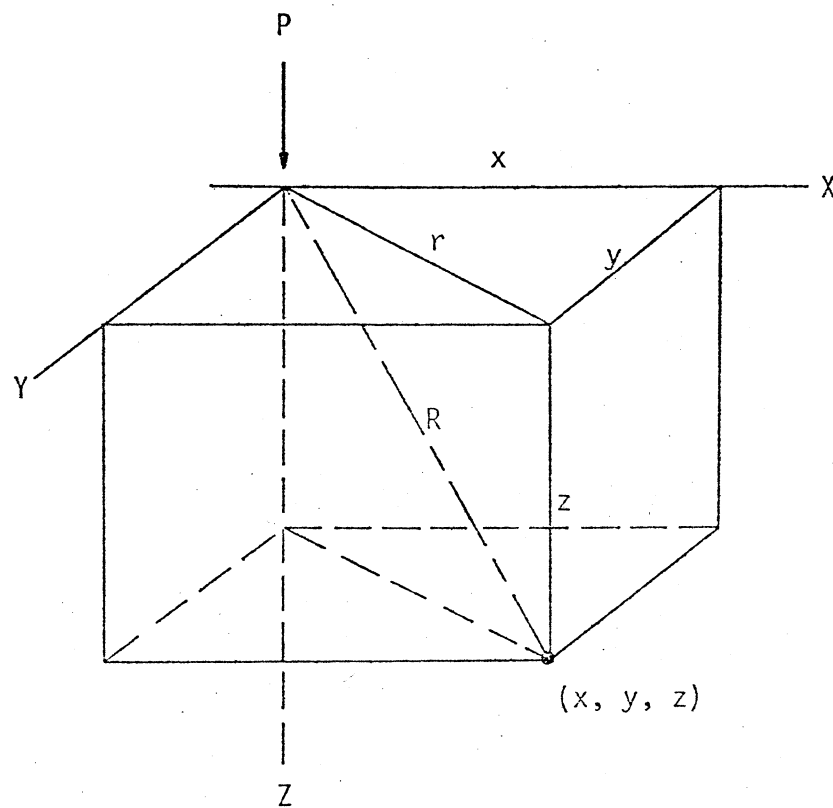
and R identified by the geometric relationship illustrated in Figure 12.

Assuming Poisson's ratio at 0.5 and $Z = 0$, Equation 6 reduces to

$$d = \frac{P}{2\pi E} \cdot 1.5 \left[\frac{2}{R} \right] \quad (7)$$

Solving for the vertical displacements at 10 inches, 15.6 inches, 26 inches, 37.4 inches and 49 inches (254, 369, 660, 950 and 125 mm) from the point loads yields a deflection basin spreadability

$$S = \frac{d_{z1} + d_{z2} + d_{z3} + d_{z4} + d_{z5}}{5(d_{z1})} \times 100 \quad (8)$$



$$x^2 + y^2 = r^2$$

$$x^2 + y^2 + z^2 = z^2 + r^2 = R^2$$

Figure 12. Geometric relationship applicable to equation 3-8 for computation of deflections due to a point load.

$$= \frac{d_{z1} + 0.640 d_{z1} + 0.3800 d_{z1} + 0.270 d_{z1} + 0.204 d_{z1}}{5 d_{z1}} \times 100 \quad (8 \text{ cont.})$$

$$= 49.9$$

On the other hand in the case of the dual wheel load below which the Benkelamn Beam is used to measure deflection, the vertical deflection may be approximated over a semi-infinite elastic half-space as,

$$d_z = \frac{p(1 + \mu)a}{E_1} \left[\frac{Z}{a} A + (1 - \mu)H \right] \quad (9)$$

where p = tire pressure (70 psi or 483 kPa)
 a = radius of the tire contact surface
 Z = depth below surface in radii
 μ = Poisson's ratio
 E_1 = elastic modulus of the subgrade
 A & H = functions of Z and a .

Assuming a Poisson's ratio of 0.5 and $Z = 0$, Equation 9 reduces to

$$d_z = \frac{0.75 pa}{E_1} (H) \quad (10)$$

Solving for the deflection basin spreadability at the effect distances of 6 inches, 15.6 inches, 26 inches, 37.4 inches and 49 inches (152, 369, 660, 950 and 124 mm) from the center of the tire contact surface we get,

$$S = \frac{d_{z1} + 0.346 d_{z1} + 0.207 d_{z1} + 0.185 d_{z1} + 0.108 d_{z1}}{5 d_{z1}} \times 100 \quad (11)$$

$$= 36.9$$

The spreadabilities of the Benkelman Beam and Dynaflect deflection basins are then substantially different, theoretically, when the loads are applied on the homogeneous, semi-infinite elastic subgrade. However, the spreadabilities become comparable, theoretically, when a reinforcing pavement layer of four or more inches (102 mm) is present. This is true even if the composite modulus of the reinforcing pavement varies over a wide range.

Theoretically the Dynaflect measured deflection basin can reliably predict a deflection basin under a dual 4,500 pound (20 kN) wheel load with a tire pressure of 70 psi (0.48 MPa) over a range of pavement thicknesses normally encountered in highway analysis.

Anomalies in the Spreadability Factor

Theoretically, as explained previously, the deflection basin spreadability for a uniform elastic subgrade using the Dynaflect was found to be constant at 49.9. However, credible test results yield values significantly lower than this even when the subgrade is overlain by a reinforcing pavement surface. This apparent anomaly can be explained by shortcomings in the ability of elastic layered theory to model the pavement system. For example, in a stress-sensitive subgrade or in a stress-sensitive layer within the pavement system above the subgrade, the lower stresses developed at the Dynaflect sensor locations out from the load develop different elastic moduli in the materials than are developed

directly under the load. The lateral variation in the actual moduli due to material stress sensitivity, which cannot be evaluated by layered elastic theory, could tend to lower the value of spreadability. However, this effect should be minimal and would most probably tend to increase rather than decrease deflection spreadability values.

A more plausible explanation is the action of a very poor subgrade or a subgrade which cannot be considered as semi-infinite due to moisture variation, the effects of poor compaction or simply a weak soil layer overlying a stronger soil (such as an organic layer overlying a hard clay or a loose sand layer over a dense sand). To evaluate this type of condition layered pavement models illustrated in Figure 13 were analyzed by the Chevron layered elastic computer program. Figure 13 depicts a pavement surface having a composite modulus of elasticity of 100,000 psi (6,894 MPa). Underlying the pavement are two layers of subgrade. The top layer has a modulus of elasticity of 1,000 psi (6,894 KPa) and is allowed to vary in thickness. The second and semi-infinite subgrade layer is assigned a modulus of elasticity of 15,000 psi (103.4 MPa). The net effect of the weak layer is clear when the deflection spreadability is computed. The factor is significantly lower than would be the case where the subgrade modulus of elasticity was uniform from the pavement to infinity. Figure 14 illustrates this point and reveals that as the middle layer becomes thicker it eventually acts as a semi-infinite subgrade with the lower modulus of 1,000 psi (6,894 KPa).

The question now arises as to how to evaluate the deflection spreadability when it is below the theoretical minimum. For example, how would one evaluate a Dynaflect derived deflection basin shape factor

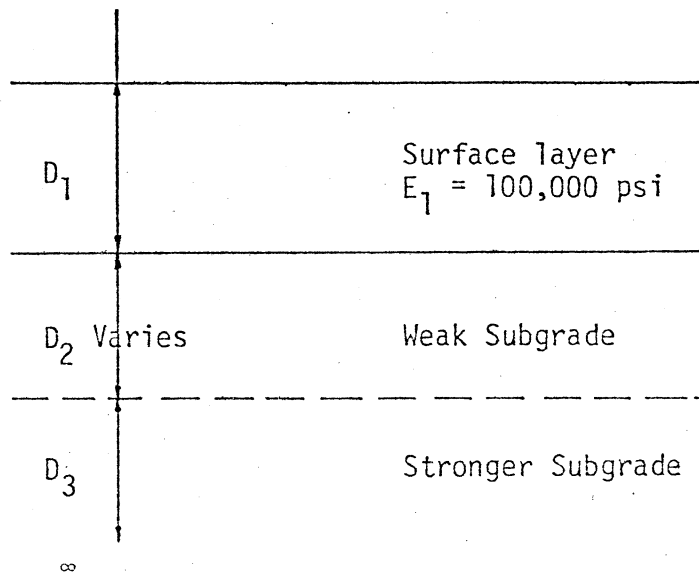


Figure 13. Cross section of a simplified pavement illustrating the "Sandwich layer effect."

(1 psi = 6,894 Pa)

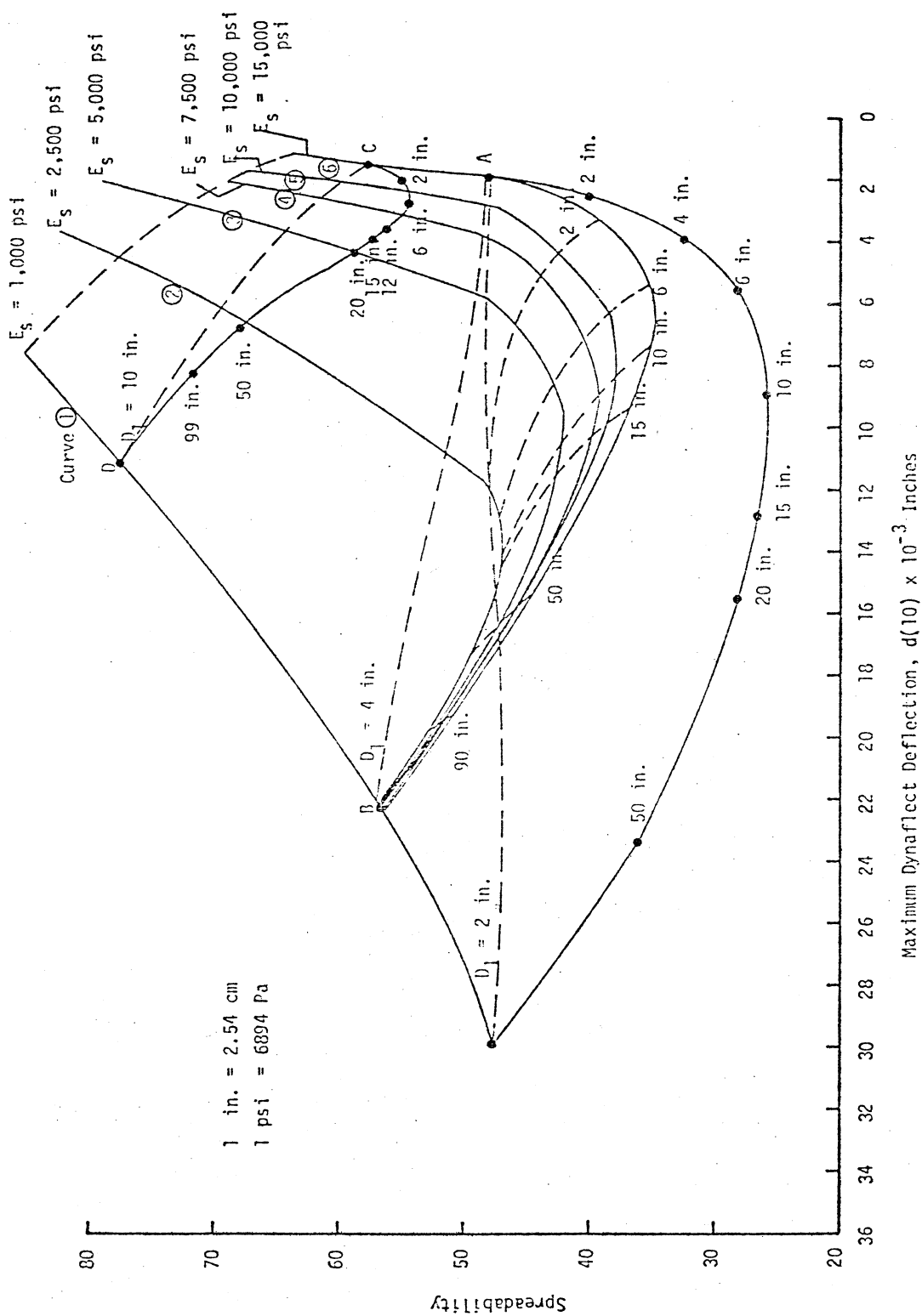


Figure 14. Dual parametric curves, developed for Dynaflect loading, illustrating the effects of a layer of lower elastic modulus between two stiffer layers.

of 40 when the theoretical minimum is 49.9. We have previously established that the deflection basin of the dual wheel load configuration can satisfactorily be approximated if the Dynaflect S is 50 or greater. But when the Dynaflect deflection spreadability is below 49.9 this approximation deteriorates.

Using the data from Figure 15, it is apparent that even for a low value of the deflection spreadability, the value of the semi-infinite subgrade modulus is in the same range as that found when the deflection spreadability factor is quite high, approaching 70 due to overlay. Therefore, this procedure is still quite valuable in estimating the subgrade modulus and in evaluating the difference between two pavements of the structural contribution of the pavement above the subgrade. For example, in this case of the Woodburn, Oregon, project, Figure 15, the 6 inch (152 mm) recycled overlay has contributed an effective thickness in terms of a composite elastic modulus of 400,000 psi (2,758 MPa) of about 4.5 inches (114 mm). Furthermore, the semi-infinite subgrade has retained a modulus of about 5,000 psi (34.5 MPa). Thus, a comparative analysis of Figure 15 is still possible though the spreadability values of the control pavement are below the theoretical minimum.

When the basin is reduced because of an intermediate or "sandwiched layer" of relatively low elastic modulus, one can only say that this reduces the total structural capability of the pavement system above the subgrade which is reflected by a lower deflection spreadability and higher maximum deflection. It would be extremely difficult and would require a very speculative analysis to actually pinpoint the structural reinforcing pavement thickness above the subgrade as well as

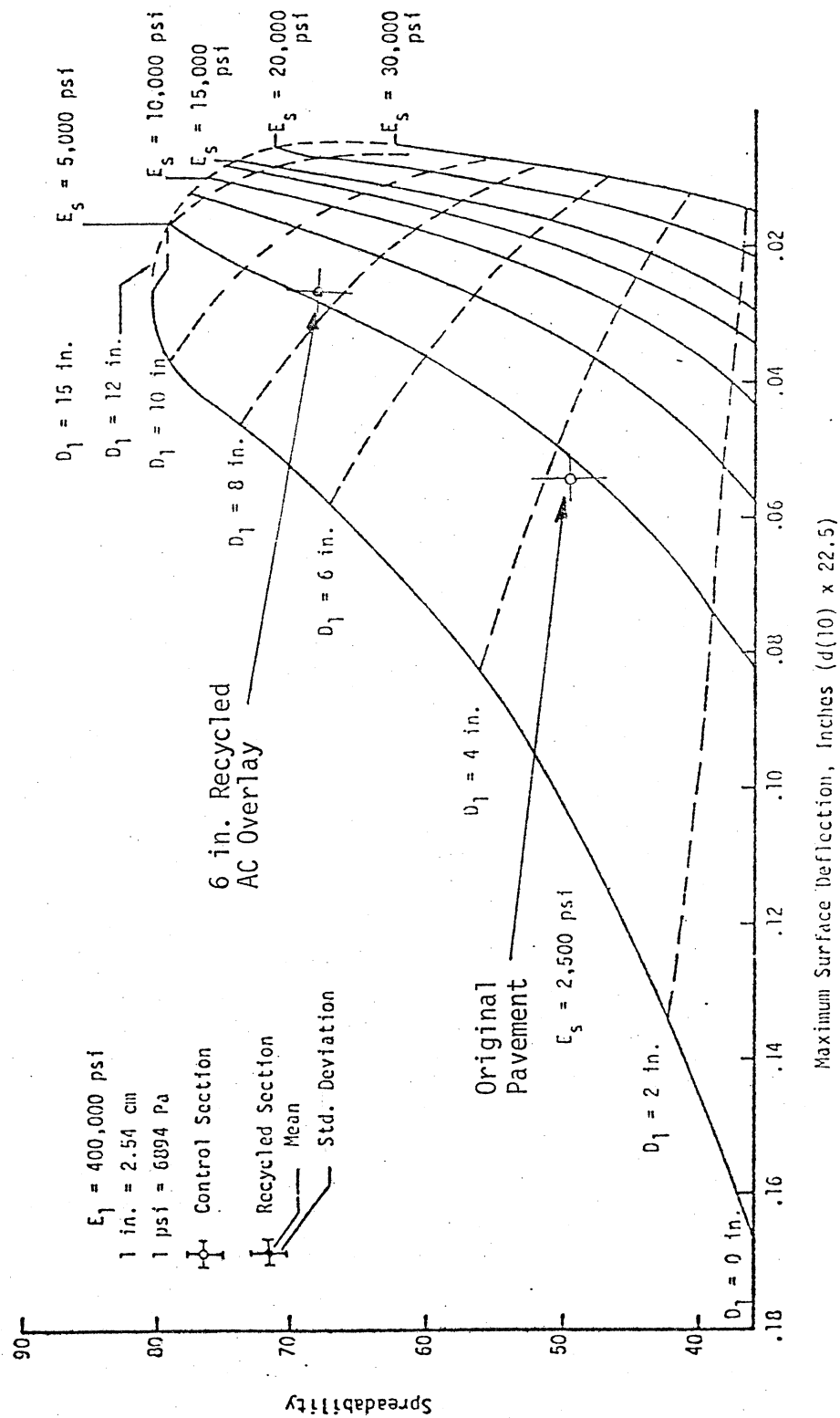


Figure 15. Dual parametric analysis of the Hillsboro to Silverton Highway, Woodburn, Oregon.

the properties and thickness of the weak layer between the reinforcing pavement and the semi-infinite subgrade. Therefore, although this may explain why the deflection spreadability may plunge below its theoretical limit, this method probably should only be used for comparative analysis in certain select circumstances

Figure 14 illustrates the effect of a weak layer which may be sandwiched between the semi-infinite subgrade and the reinforcing pavement layer. The main curves of this figure are labeled curves 1 through 6 and represent pavement systems which have a composite pavement modulus above the subgrade of 100,000 psi (6,894 MPa) underlain by semi-infinite subgrade of elastic moduli of 1,000, 2,500, 5,000, 7,500, 10,000 and 15,000 psi (6.89, 17.24, 34.5, 51.7, 68.9 and 103.4 MPa). As has been previously explained, the theoretical low value of the deflection spreadability is 49.9. The extension of the main curves below 49.9 are due to the effect of a sandwiched, weak layer with a modulus of elasticity of 1,000 psi (6,894 KPa) with varying thicknesses. The dotted contours represent the thicknesses of the sandwiched layer.

To more specifically illustrate the effect of this weak sandwiched layer consider the following examples. The effect of the sandwiched layer on the pavement cross-section in Figure 13 is illustrated by moving along subcurve 6 from main curve 6, Point A, to main curve 1, Point B. As D_2 increases up to a value of about eight inches (203 mm) the deflection spreadability decreases well below the 49.9 theoretical limit. As D_2 becomes larger it ultimately approaches the Point B which represents the pavement system whose semi-infinite subgrade is 1,000 psi (6,894 KPa). Similar situations are illustrated in Figure 16 as

the effect of the weak sandwiched layer is analyzed between the surface and subgrades of varying elastic moduli. The effect of the sandwiched layer below a thicker pavement, $D_1 = 10$ inches (254 mm) is shown by moving from Point C to Point D. The effects of the sandwiched layer is not as pronounced in altering the maximum deflection and spreadability as is the case for the thinner pavements. However, the effect is readily apparent.

The effect of the weak layer sandwiched between the semi-infinite elastic subgrade and the reinforcing surface pavement is not, however, too detrimental in the analysis for reinforcing pavement layers greater than four inches (102 mm) thick because the spreadability for both the Benkelman Beam and Dynaflect appears to be affected proportionally. For example, with a reinforcing layer over the subgrade of ten inches (254 mm) the sandwiched weak layer reduces the deflection spreadability for both Dynaflect and Benkelman Beam. This reduction is proportional as shown in Figures 14 and 16. Suppose that a 100,000 psi (6,894 MPa) asphaltic concrete surface ten inches (254 mm) thick is underlain by 12 inches (305 mm) of wet, silty, poorly compacted material which in turn overlies the semi-infinite elastic subgrade whose elastic modulus is relatively stress insensitive and is 15,000 psi (103.4 MPa). The deflection spreadability is recorded as 56 from the Dynaflect and 51 by means of the Benkelman Beam. The difference between these values is the same magnitude as for the ten inches (25.4 cm) of asphaltic concrete, $E_1 = 100,000$ psi (689.4 MPa), overlying the 15,000 psi (103.4 MPa) subgrade with the weak layer absent. In the latter case the shape factor differs by seven (57-50).

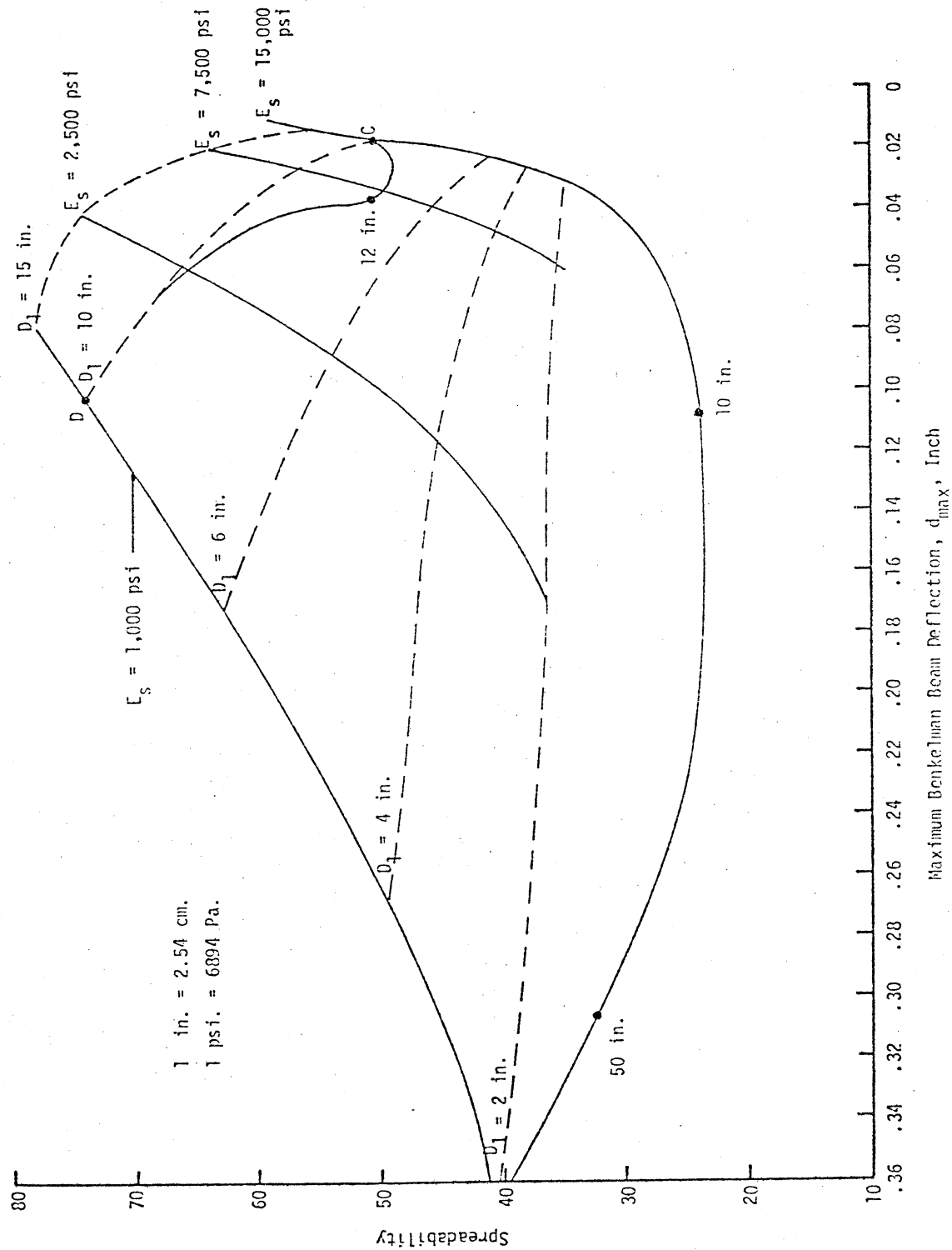


Figure 16. Dual parametric curves, developed for dual 4,500 pound wheel loading, illustrating the effect of a lower elastic modulus between two stiffer layers.

Virginia Research Council Field Tests

The Virginia Research Council (6) actually measured deflection basins with the Dynaflect and Benkelman Beam. The Benkelman Beam deflections were obtained at 0, 2, 4 and 9 feet (0, 0.62, 1.23 and 2.77 m) and the Dynaflect deflections at 0, 1, 2, 3 and 4 feet (0.31, 0.62, 0.92 and 1.23 m). In this case a distance of zero feet indicates a reading directly between the wheels, one foot (0.31 m) refers to one foot lateral distance from reading zero, etc. Figure 17, 18 and 19 are the results of this investigation. Since there is no straight-forward method to statistically analyze these curves for comparative purposes the analysis was based on visual inspection.

The relative position and shape of the curves in Figure 17 are similar since curves C are lower than A and B until a distance of three feet (0.92 m) is reached. Then they both cross curves B and at the four-foot (1.23 m) point are nearly the same magnitude as A. Also for both devices curve A lies above and essentially parallel to stabilized and unstabilized layers. The deflection spreadability was computed for each basin and is labeled on the respective curves. The agreement between deflection spreadabilities is quite good when compared to the theoretical correlation illustrated in Figure 11. In each case the Benkelman Beam deflection spreadability is slightly lower than that of the Dynaflect.

Figure 18 represents the deflection spreadabilities measured on cement treated soil and cement treated aggregate which form the base for a flexible pavement structural system. Curves A and B represent

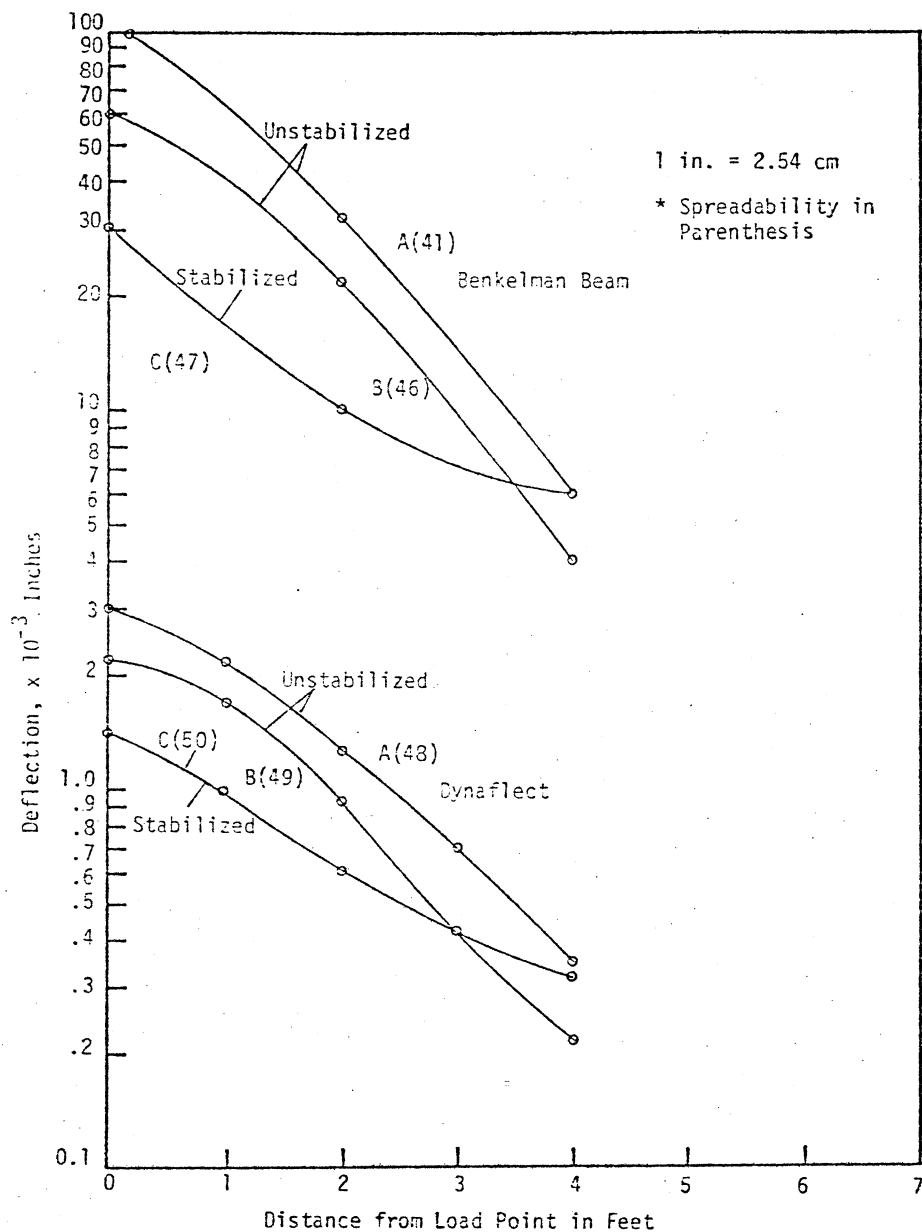


Figure 17. Measured deflection basins under Benkelman Beam and Dynaflect loadings for pavements with stabilized and unstabilized layers [after Hughes (6)].

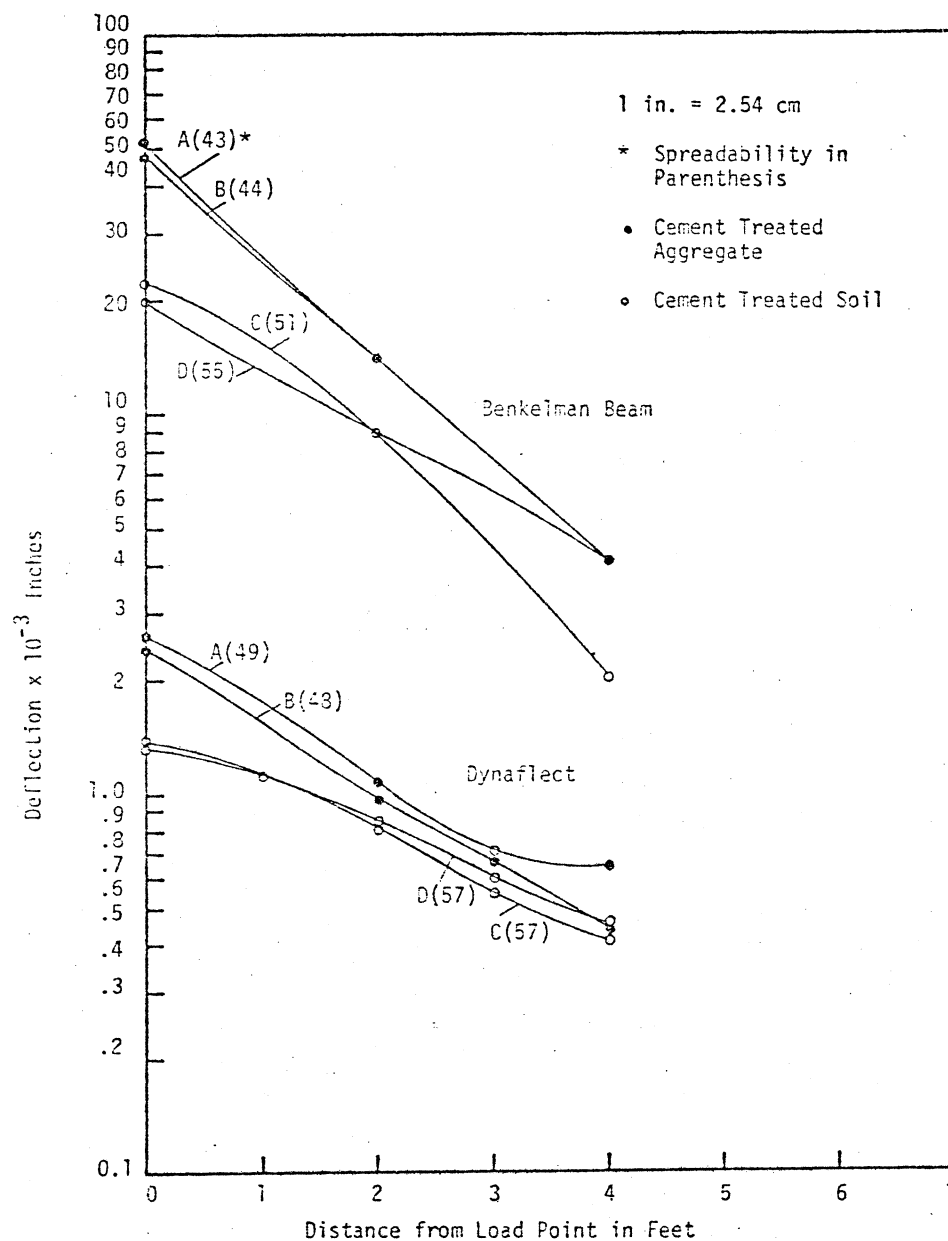


Figure 18. Measured deflection basins under Benkelman Beam and Dynaflect loadings for pavement containing cement treated aggregate bases and cement treated soil subgrades [after Hughes (6)].

the deflection basins on the cement treated soil and are seen to have very similar deflection spreadabilities of 43 and 44, respectively, for the Benkelman Beam. This compares quite favorably with the values of 49 and 48 calculated from the Dynaflect basins. Once again this agrees very well with the theoretical relationship as illustrated in Figure 11. Curves C and D are also quite closely associated in terms of deflection spreadabilities between Benkelman Beam and Dynaflect measurements. Here the spreadabilities are 51 and 55, respectively, for C and D under Benkelman Beam loading and 57 and 57, respectively, under Dynaflect loading.

Figure 19 represents the deflection basins for a flexible pavement with unstabilized bases and subgrades. The low values of the deflection spreadabilities indicates that the type of situation illustrated by Figure 13 may exist here. In each case the Dynaflect deflection spreadabilities are below the theoretical limit as are the Benkelman Beam deflection basin shape factors. It is also important that the magnitude of difference between the actual shape factors and the theoretical limits are comparable. For example, the Benkelman Beam measured deflection basin shape factor for curve A is 32 which is lower than the theoretical lower boundary of 36.9 for a homogenous semi-infinite half-space by 4.9. Similarly the Dynaflect measured deflection basin spreadability for curve A is 46 which is 3.9 lower than its theoretical lower limit of 49.9.

All this appears to substantiate the previous theoretical evaluation that for deflection basin shape factors above 50 the Dynaflect is a very good predictor of the Benkelman Beam. However, this may not be the case below 50 especially when dealing with thin pavements, four inches (102 mm) or less.

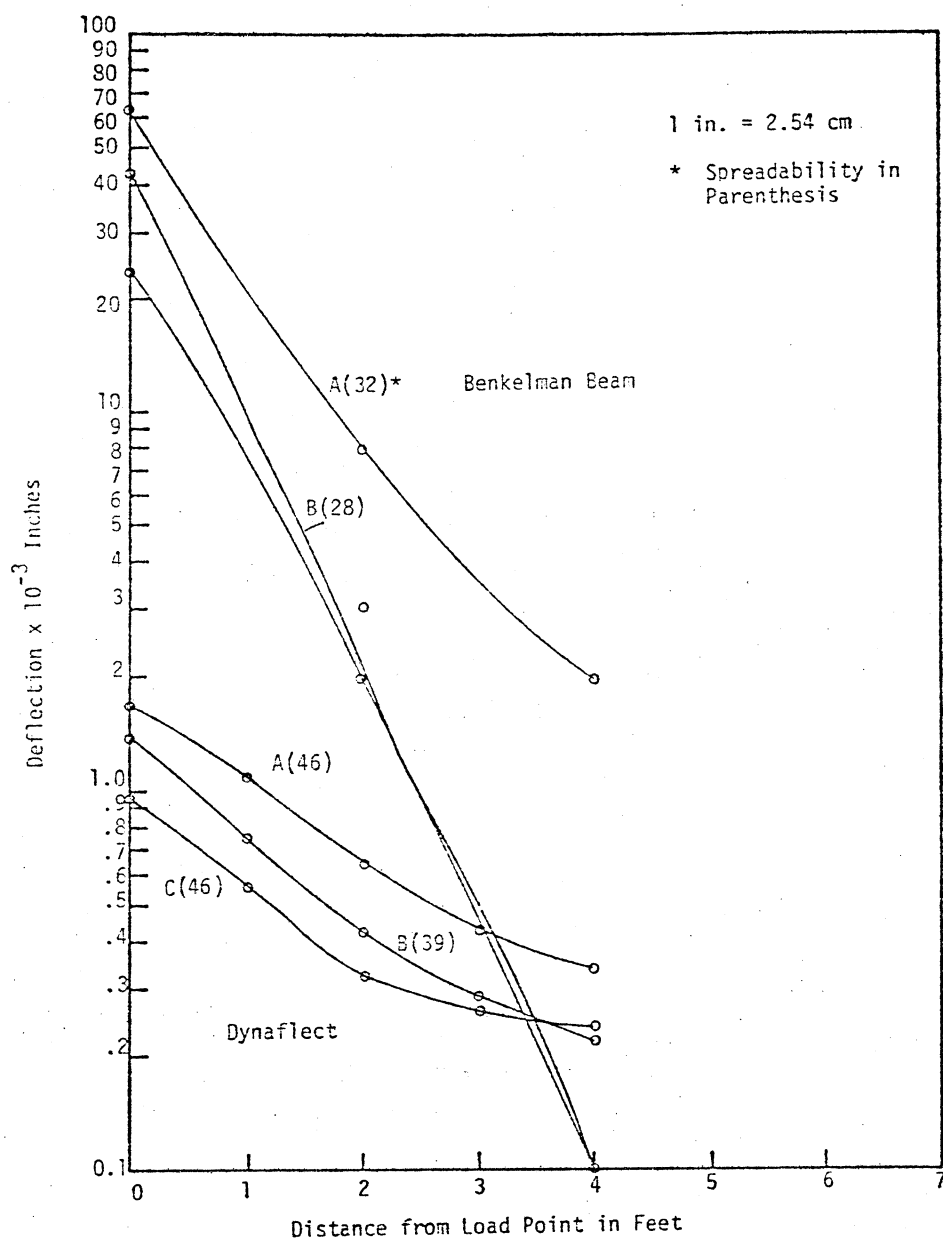


Figure 19. Measured deflection basins under Benkelman Beam and Dynaflect loadings for pavements with unstabilized bases and subgrades [after Hughes (6)].

Effects of Load Frequency and Magnitude

If the Dynaflect is to be used to evaluate structural pavement responses under wheel loads in the range normally designed for, one must consider the magnitude and type of loading initiated by the design wheels. The Benkelman Beam is commonly used to evaluate surface deflection under actual design wheel loads. The dual 4500 pound (20 KN) load is the standard. The Benkelman Beam deflection is not only caused by a much heavier load than the Dynaflect load, but also the Benkelman Beam measures an essentially static deflection whereas the Dynaflect loading is dynamic at 8 Hz.

Although the Dynaflect loading is more like actual highway loading, the magnitude of load, about 1000 pounds (4.4 KN) is far too low. Thus it would be prudent to establish a viable link between Dynaflect and Benkelman Beam deflection if such a link can be established based on existing empirical data.

The first step in such an analysis is to investigate whether or not the types of loading between the Dynaflect and Benkelman Beam are similar enough to compare, i.e., one is dynamic, the other static. Research has conclusively shown (1, 7) that the dynamic response of a pavement system approaches its static or elastic response at low frequencies. Furthermore, at frequencies less than 10 Hz the static and dynamic responses are essentially the same for all types of pavements and for both elastic and highly viscoelastic subgrades. Thus, it is valid to compare deflection between the Dynaflect and the Benkelman Beam.

Research by the Asphalt Institute (8), California (9), Utah (10) and Texas Transportation Institute (11) has verified that on the average

the Benkelman Beam deflection is approximately 22.5 times that of the corresponding Dynaflect deflection.

Possible Methods of Presenting Graphical Analysis

Two possibilities of dual parametric data presentation exist:

1. Based solely on Dynaflect parameters and
2. Using Dynaflect parameters to approximate the parameters under a design wheel load such as a dual 4500 pound (20 kN) load.

Both methods have advantages and limitations. If the design charts are based solely on Dynaflect parameters, the method is theoretically sound but suffers from practical limitation of the theory such as the spreadabilities of less than 49.9 which often are measured by Dynaflect analyses.

The author believes it is better to use the Dynaflect parameters to approximate the effects of a design wheel load. Practical experience has proved this approach to be very successful in the comparative evaluation of pavement structural responses (11).

Figure 20 is an illustration of dual parametric curves developed from layered elastic analysis for a dual 4500 pound (20 kN) load, 12 inches (305 mm) center to center. The locus of maximum deflection and spreadabilities for the control and recycled sections as represented by the open and closed circles, respectively, are from Dynaflect analysis. Recycled sections 2, 3, and 4 represent pavements identical to the control section but with a 2 inch overlay of recycled asphalt concrete whose laboratory determined elastic modulus was determined to be approximately 400,000 psi (2,758 MPa) at the temperature of Dynaflect testing.

Recycled Section 1 represents a 4.0 inch (12 mm) overlay.

It is evident in Figure 20 that the subgrade modulus remains the same as the overlay thickness increases and that the increase in effective pavement thickness is readily discernable by this graphical procedure.

Suggested Procedure

1. Develop charts for the standard design wheel load such as shown for a dual 4500 pound (20 KN) load in Figure 20.
2. Assume that the spreadability below the design load is successfully predicted by the Dynaflect.
3. Multiply the maximum Dynaflect deflection, $d(10)$, by 22.5 or by an established factor determined in the area of use to approximate the maximum deflection below the design load.
4. Use the analysis as a comparative evaluation of pavements.
5. Realize the limitations for thin pavements and the insensitivity of the analysis when stiff ($> 30,000$ psi) subgrades are encountered.

Results of Lime Fly-Ash Stabilized Bases

Figure 21 is a graphical dual parametric presentation of the Dynaflect deflection data for field tests of lime fly ash stabilized bases on project 2240. These data illustrate how this technique can be used to comparatively evaluate the section.

The change from point a and b represents the change in the structural pavement above the subgrade as 6 inches (152 mm) of flexible base

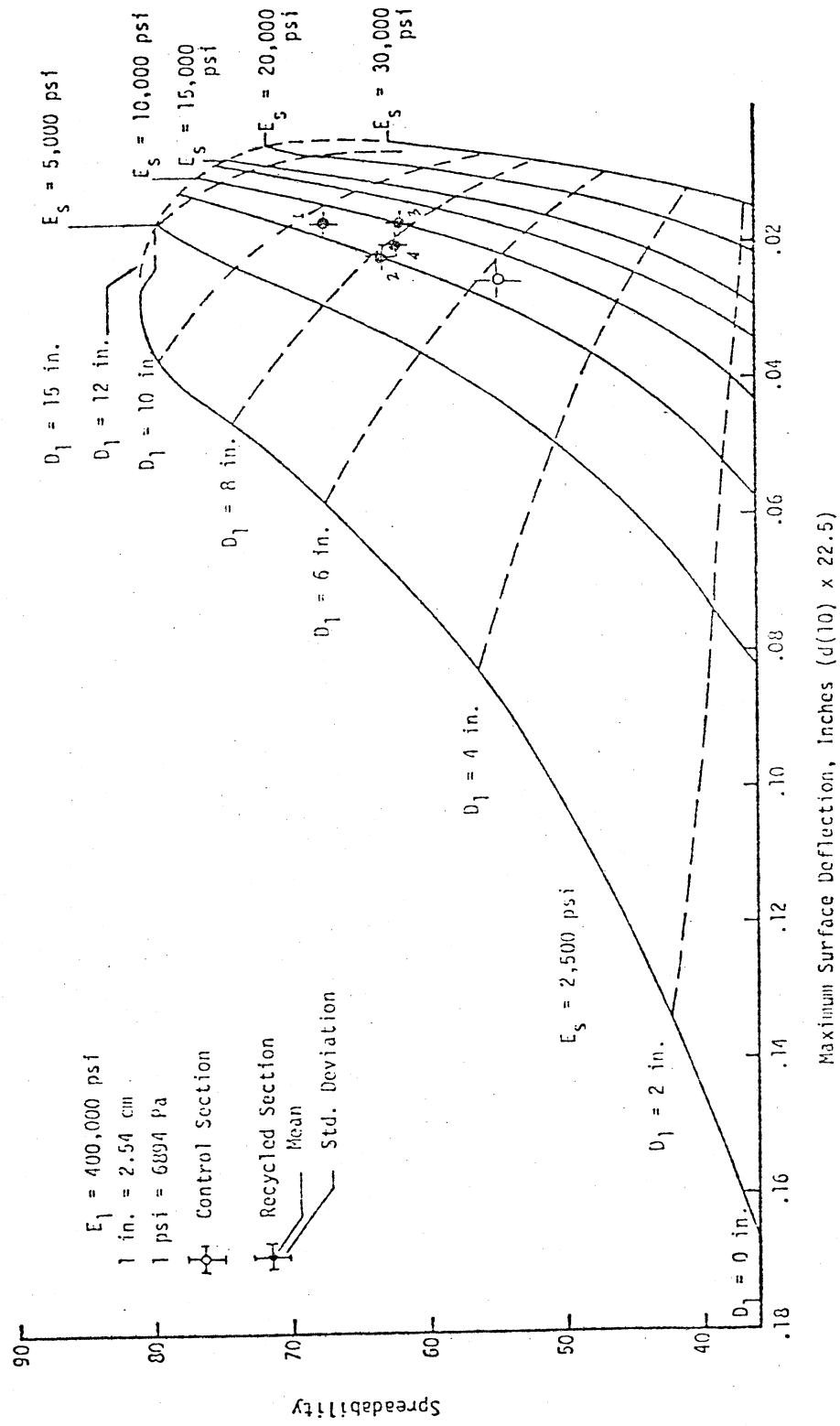


Figure 20. Dual parametric analysis of U.S. 84, Snyder, Texas.

TEST SITE 8 - SH 335
 TEST SECTION #5
 3% Lime 6% Fly Ash

*E = 300,000 psi

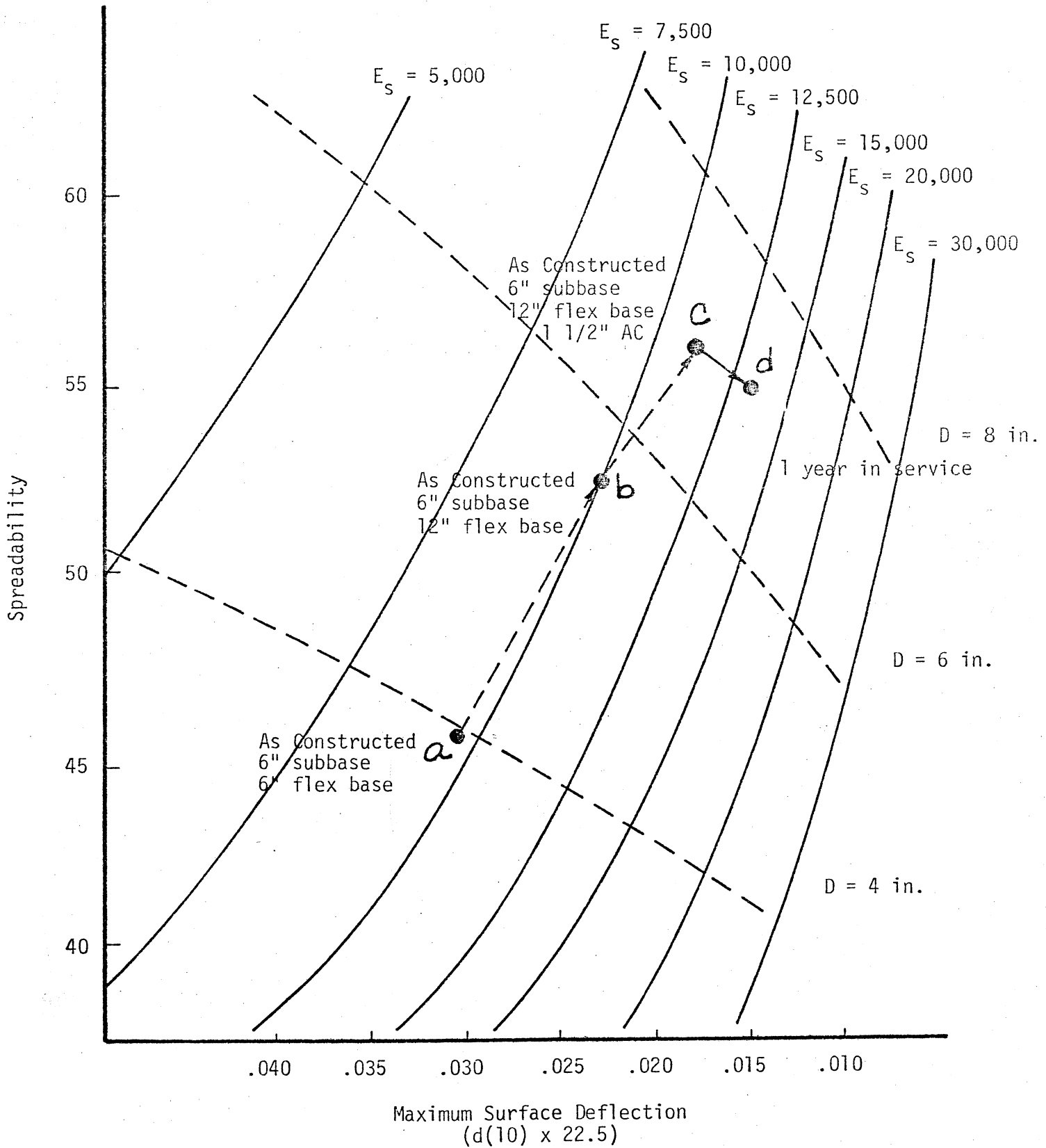


Figure 21. Dual parametric evaluation of Test Site 8-SH335 (3% lime - 0% fly ash).

is added. The change from point b to c represents the change in structural pavement effective thickness or 1.5 inches (38 mm) of asphalt concrete surfacing is applied. Finally the change from point c to d represents the effect of 1 year in service which saw an increase in subgrade stiffness but no change in the structural pavement.

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Appendix A

Analysis charts based on the actual dynaflect lead configuration and maximum deflections of $22.5 \times d(10)$. Thus to use these charts one would plot the locus of $d(10) \times 22.5$ and the spreadsability measured from the dynaflect.

