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Pennsylvania Department of Transportation

Project No. 67-17

Application of AASHO Road Test Findings to the
Design of Flexible Pavement Structures in Pennsylvania

CRITICAL REVIEW OF FLEXIBLE PAVEMENT

PERFORMANCE AND DESIGN EQUATIONS

by

G. E. Hunter

T. J. Hirst

H. Y. Fang

This work was performed in cooperation with the Pennsylvania Department of Transportation and the U. S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads.

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Pennsylvania Department of Transportation or the Bureau of Public Roads.

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ABSTRACT

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Key words: Pavement, flexible, design, performance, AASHO Road Test.

In 1962 the American Association of State Highway Officials presented a method for the design of flexible highway pavements which was based on a large scale field study. The steps in the development of the basic design method and the assumptions necessary for its application are enumerated and critically discussed in this report.

The concept of highway performance was the basis upon which the Road Test was evaluated. The significance and validity of using performance expressions to estimate pavement life and strength are discussed.

The individual design variables, which include structural coefficients, soil support, traffic intensity

and regional factors are presented. Currently available methods for determining each of these variables are examined and evaluated. The importance of selecting appropriate values for the design variables when calculating the pavement life is discussed.

It is concluded that, although it has received widespread acceptance, the AASHO design method has serious limitations. None of the attempts to adopt the procedure to an individual State's requirements have been entirely successful. The need for a clearer definition of material properties, and their relationship to the statistically based AASHO design variables, is indicated.

I. INTRODUCTION

In 1962 the American Association of State Highway Officials, in cooperation with a wide variety of interested states, institutions, industries and agencies, completed a comprehensive, full-scale highway study. The analysis and subsequent evaluation of the observed performance of the test sections at the Road Test led to the development of the AASHO design method. The resulting design equations and charts were intended to provide the entire country with an efficient and practical design method.

The Road Test experiment design was constructed so that relationships between pavement design, number of applications of load and performance could be established. Special studies were focused on finding the in-place behavior of individual types of materials commonly used in highway construction. Attention was also directed towards including the influences of environmental factors and embankment strength on pavement life.

General use of the AASHO design method requires that specific structural coefficients and soil support terms be assigned to the pavement and subgrade materials. These terms reflect a material's strength and suitability

in the highway. In addition, the effects of environmental conditions must be assessed and represented by a regional factor. Finally, the traffic anticipated over the life of the roadway must be estimated and reduced to a number of applications of a standard reference axle load.

This report includes a discussion of the history and development of the Road Test equations, and their extension to performance studies. The background and significance of the required design values, as well as current methods of obtaining them, are also discussed and evaluated. Appendix A, included at the end of this report, contains brief abstracts of articles considered to be of special interest to this study. Appendix B lists all articles reviewed during the preparation of this report.

II. DEVELOPMENT OF THE AASHO DESIGN METHOD

2.1 The AASHO Road Test

The AASHO Road Test was a highway research project sponsored by the American Association of State Highway Officials, in conjunction with many private and public sponsors, for the purpose of examining the behavior of typical highway pavements and structures under full scale conditions.

A carefully planned experiment design was developed in which both flexible and rigid pavements of known layer thicknesses were constructed in six traffic loops in order to examine the interrelations between thicknesses, and magnitude and frequency of loading. A complete description of the road test facilities are given in the Highway Research Board Special Report Nos. 61B and 61C, (1962).

The scope, magnitude and duration of the Road Test greatly exceeded any such previously completed project. The efforts to carefully control the material properties and construction procedures at the site, as well as to fully develop the experiment design and provide thorough and consistent testing procedures have been well documented by many researchers (Shook and Fang, 1961; HRB Special Report 61E, 1962).

First among the list of carefully chosen Road Test objectives stated by the National Advisory Committee was to determine the significant relationships between load and performance for various thicknesses of uniform pavement components constructed on a uniform basement soil. The results were then to be examined in light of variations in climate, soil type, materials, construction practice and traffic type.

To accomplish this objective, the Advisory Committee chose to develop the concept of performance in terms of a highway's capacity to serve the traveling public. The level of quality, or serviceability, was based on a subjective, zero to five rating scale established from rider reaction to a particular roadway. The performance of a road may then be represented by the serviceability history as a function of the loading history. For example, good performance is typified by continued high serviceability under many load applications.

In order to apply the serviceability concept to the actual Road Test pavements, rapid, simple and reproducible test methods were developed to objectively rank a pavement's current riding quality or present serviceability index (PSI or p_t), in a manner which correlated with the subjective rating system.

The physical aspects selected as being indicative of the road surface quality were slope variance, rutting,

patching and cracking. Actual test procedures used at the Road Test are detailed in HRB Special Report 61E (1962).

Test vehicles with known axle configurations and loads were cycled over each pavement structure at known frequencies. Periodically, at biweekly intervals called index days, the PSI of each section was determined. Traffic was continued until the PSI dropped to a value of 1.5, indicative of a very low level of serviceability, or until the Road Test was terminated. Thus, a complete performance history of a wide range of combinations of types and thicknesses of road pavements were obtained.

2.2 Road Test Results

The method whereby performance of flexible pavements is related to roadway design and number of load applications is examined. The main aspects of this are found in Appendix G of HRB Special Report 61E (1962).

Performance curves were obtained for each section by plotting the observed PSI values against the index day or the accumulated number of load applications obtained at each particular index day, as shown in Fig. (1). The shape or trend of the curve represents the performance of the section. In order to eliminate the seasonal effects, the accumulated number of loads was adjusted or weighted prior to developing the curves. The assumed weighting functions tended to overcome the fact that the effect of

the loads was related to the moisture and temperature of the sections.

The objective of the Road Test Committee was to develop a mathematical model which described the performance record curves obtained from all sections. It was assumed that the loss of performance was some power function of axle load application, expressed as

$$p_0 - p_t = K W_t^\beta \quad (1)$$

where p_0 is the initial serviceability index, p_t is the present serviceability index and W_t is the accumulated axle loads (both at time = t), and K and β are terms related to both the load and the section design.

At the conclusion of testing at each section, whether by p_t reaching the terminal value of 1.5 or by termination of the Road Test, the following relationship existed:

$$p_0 - p_1 = K (\rho)^\beta \quad (2)$$

where ρ is the terminal number of axle load applications at a terminal value of PSI equal to p_1 .

Solving Eq. (2) for K and substituting the

resulting value into Eq. (1) yields:

$$p_t = p_o - (p_o - p_1) \left(\frac{W_t}{\rho}\right)^\beta \quad (3)$$

which expresses p_t at any intermediate time in terms of initial and final values of PSI and intermediate and final loads.

Rearranging Eq. (3) and converting to logarithmic form results in,

$$G = \beta (\log W_t - \log \rho) \quad (4)$$

where G is defined as the known quantity:

$$G = \log \left(\frac{p_o - p_t}{p_o - p_1} \right) \quad (5)$$

Values for β and ρ for each section were then obtained from slope and intercept, respectively, of the linear plots resulting from Eq. (4).

β was then assumed to be related to the magnitude of applied loads and the pavement design as:

$$\beta = \beta_o + \frac{B_o (L_1 + L_2)^{B_2}}{(a_1 D_1 + a_2 D_2 + a_3 D_3 + a_4)^{B_1} L_2^{B_3}} \quad (6)$$

and ρ expressed as

$$\rho = \frac{A_o (a_1 D_1 + a_2 D_2 + a_3 D_3 + a_4)^{A_1} L_2^{A_3}}{(L_1 + L_2)^{A_2}} \quad (7)$$

where a_1, a_2, a_3 = structural coefficients related to material strength; a_4 = a coefficient related to the sub-grade strength; D_1, D_2, D_3 = layer thicknesses, in inches, of the surface, base and subbase, respectively; L_1 = nominal axle load in kips; L_2 = an axle code, (1 for single axles, 2 for tandem axles). The remaining terms are mathematical constants used in the analysis.

The exact method of solving Eqs. (6) and (7) is beyond the scope of this discussion. However, statistical analysis of the Road Test data, using linear regression analysis techniques to obtain "best fits" of the observed information, allowed the effectiveness of various pavement components to be ranked in terms of a_1, a_2, a_3 .

The reduction techniques reduced Eq. (6) to

$$\beta = 0.40 + \frac{0.081 (L_1 + L_2)^{3.23}}{(SN + 1)^{5.19} L_2^{3.23}} \quad (8)$$

and Eq. (7) to

$$\rho = \frac{10^{5.93} (SN + 1)^{9.36} L_2^{4.33}}{(L_1 + L_2)^{4.79}} \quad (9)$$

where SN is the structural number as defined by

$$SN = a_1 D_1 + a_2 D_2 + a_3 D_3 \quad (10)$$

A significant result from the AASHO Road Test is the statistical evaluation of the structural coefficients (a_1, a_2, a_3) which reflect the in-place behavior of each pavement layer (D_1, D_2, D_3).

2.3 Design Equations

A main objective of the AASHO Committee was to transform the results of the performance study into a useful design method (Langsner, Huff & Liddle, 1962). The method considers not only pavement design and number of load applications, but also parameters reflecting both subgrade soil support and regional effects.

A relationship between number of axle loads, structural number and performance was obtained by adopting an 18^k single axle load as a standard and solving Eqs. (8) and (9), respectively, for β and ρ . These two quantities were then substituted into Eq. (4) which could then be reduced and rearranged as

$$\log W_{18} = 9.36 \log (SN + 1) - 0.20 + \frac{G}{0.40 + \frac{1,094}{(SN + 1)^{5.19}}} \quad (11)$$

where W_t is now noted as W_{18} .

Equation (11) represents the mathematical development of the Road Test results which predicts the number of 18^k axle load applications, W_{18} , required to reduce the

serviceability from an initial high of p_0 to any intermediate value, p_t , for a pavement having a structural number of SN.

The next step in formulating the design procedure was to expand Eq. (11) to include soil support and regional influences beyond the limited conditions which prevailed at the Road Test site.

The AASHO Committee realized that the behavior of a road is significantly effected by environmental factors such as temperature, rainfall and drainage conditions. In order to relate the test results obtained from the single test site to a wide variety of possible conditions elsewhere in the country, the Design Committee developed the concept of a regional or environmental factor. This term would modify the fundamental design equations for national use.

Although the exact relationship was not established, the AASHO Committee assumed that the destructive effect of accumulated 18 kip axle loads, W'_{18} , on any highway could be related to a comparable level of effectiveness due to the accumulated 18 kip axle loads, W_{18} , at the test site, by a proportionality or regional factor, R , as

$$W'_{18} = \frac{1}{R} W_{18} \quad (12)$$

or in logarithmic form as

$$\log W'_{18} = \log \left(\frac{1}{R}\right) + \log W_{18} \quad (13)$$

It was tentatively estimated that the value of R ranged from 0.2 to 5.0 as the road bed strength decreased due to environmental factors.

In order to expand the design method to encompass soil support conditions beyond the single roadbed constructed at the AASHO Road Test, the Design Committee established a 10 point soil support scale with the intent that soils of different supporting characteristics could be evaluated and correlated with the scale.

A soil support value, (SS = 3), was arbitrarily assigned to the roadbed which underlaid a typical pavement with a structural number of 1.98. The total number of load applications, for typical pavements, was distributed over an assumed 20 year design period, resulting in a figure of 2.5 equivalent 18 kip daily single axle applications.

Special studies of particularly heavy crushed stone bases indicated that an asphaltic layer with a structural number of 1.98 on a roadbed with supporting characteristics of crushed stone would carry 600 and 1000 18^k applications per day to terminal serviceabilities of 2.5 and 2.0, respectively. A soil support value of 10 was assigned to the hypothetical high support roadbed.

Thus, the two conditions of soil support, load applications and structural number allowed a scale to be set up by assuming a linear distribution between the values of 3 and 10.

If the effect of axle loads is assumed to vary with some function of the soil support, $f(SS)$, then

$$W_{18}'' = f(SS) W_{18}' \quad (14)$$

or in logarithmic form

$$\log W_{18}'' = \log f(SS) + \log W_{18}' \quad (15)$$

where W_{18}'' and W_{18}' are two values of accumulated axle loads which have the same ability to deteriorate a given pavement constructed on roadbeds of soil support SS_i and SS_o , respectively.

The soil support function is assumed to be related to the soil support value as,

$$f(SS) = 10^{k'} (SS_i - SS_o) \quad (16)$$

where K' is a proportionality constant. In logarithmic form, Eq. (16) is

$$\log f(SS) = K' (SS_i - SS_o) \quad (17)$$

Again considering the two values of $W'_{18} = 2.5$ and $W_{18}'' = 1000$ for accumulated axle loads corresponding to $SS_0 = 3$ and $SS_i = 10$, the value of $f(SS)$ from Eq. (14) was found to be 400. Applying this value, as well as the scale values of soil support, to Eq. (17) results in a proportionality constant of 0.372.

The general relationship for any soil support value of SS , referenced to the AASHO roadbed, becomes

$$\log f(SS) = 0.372 (SS - 3.0) \quad (18)$$

and the variation in allowable loads may be expressed by Eq. (15) as

$$\log W_{18}'' = 0.372 (SS - 3.0) + \log W_{18}' \quad (19)$$

where W_{18}'' corresponds to a roadbed soil support of SS and W_{18}' corresponds to any roadbed with a soil support of 3.0.

Therefore, to weight or adjust a value of allowable load applications at any location, the term $\log W_{18}$ in Eq. 11 has to first be modified for soil support conditions by Eq. (19) and the resulting value modified for regional conditions according to Eq. (13).

Combining Eqs. (19) and (13) with Eq. (11) results in the final AASHO design formula

$$W_{18}'' = \frac{(SN + 1)^{9.36} \cdot 10^{0.372} (SS - 3.0) \cdot 10 \left[0.40 + \frac{G}{(SN + 1)^{5.19}} \right]}{R \cdot 10^{0.20}} \quad (20)$$

or in logarithmic form,

$$\begin{aligned} \log W_{18}'' &= 9.36 \log (SN + 1) + 0.372 (SS - 3.0) & (21) \\ &+ \log \left(\frac{1}{R} \right) - 0.20 + \frac{G}{0.40 + \frac{1,094}{(SN + 1)^{5.19}}} \end{aligned}$$

The resulting design charts, as shown in Fig. (2), were constructed for specific limiting serviceabilities (Langsner, Huff and Liddle, 1962). It was reasoned that terminal values of PSI (or p_1) for high type and secondary roads of 2.5 and 2.0, respectively, would result in satisfactory service over the design life.

A recent independent study sponsored by HRB verified the AASHO design procedure and charts within the scope of the original assumptions (McCullough and Van Til, 1968).

2.4 Enumeration of Variables

The design chart, Fig. (2), can be readily used to obtain required structural numbers for proposed pavement provided that the basic assumptions and limitations of both the method and input information are understood. For convenience, a 20-year design life was assumed in order to reduce the total allowable axle loads to daily

load applications. However, since the basic design equations are in terms of total accumulated axle loads, any other design life period may be used provided that the total number of load applications is known.

A list of required design variables is as follows:

1. Structural coefficients based on material properties.
2. Layer thicknesses.
3. Daily 18^k equivalent axle load applications.
4. Soil support based on subgrade strength.
5. Regional factor based on environmental conditions.

The success of the resulting pavement in carrying the required traffic through reasonable values of serviceability over the design period will depend upon the accuracy of the variables listed above. Current thinking regarding the variables and existing methods for evaluating them will be examined in subsequent chapters.

III. PERFORMANCE

3.1 Uses for the Performance Concept

The importance attached to the concept of performance by highway researchers was suggested in Chapter II. The fundamental ideas underlying serviceability and the actual development of a practical rating system have been established (Carey and Irick, 1960). A great deal of emphasis has been placed on the relationship between initial pavement design and the deterioration resulting from load applications.

One major area of highway research following the Road Test was the development of mathematical formulations which describe the performance curves obtained from the various test sections. In general, these equations relate values of performance and wheel load applications to various parameters. In turn, attempts have been made to evaluate these parameters in terms of initial values of layer thickness and composition, soil support and climate. The AASHO equations developed in Chapter II are but one of the existing models developed to describe the performance curves.

Three general areas of use have been established for the performance relationships. The first is to estimate pavement life based on a relatively few number of observed serviceability ratings. The second is to relate performance

to structural design. Finally, measures of composite strength have been correlated to serviceability with the hope that these studies will aid in the basic understanding of roadway behavior.

3.2 Estimating Pavement Life

There are numerous advantages to both researchers and maintenance forces if the life expectancy of a road can be approximately determined by a relatively few simple measurements taken years in advance of predetermined terminal conditions. Several mathematical models will be presented and their applicability to the problem will be examined.

The general AASHO equation, as expressed previously, is

$$p_t = p_o - (p_o - p_l) \left(\frac{W_t}{\rho}\right)^\beta \quad (3)$$

A somewhat simpler model was developed by the Asphalt Institute after an independent analysis of the Road Test data (Painter, 1962). It was originally presented as

$$p_t = p_o e^{-\frac{bW_t}{10^6}} \quad (22)$$

where b is a deterioration rate parameter similar to β of Eq. (3).

A model of similar form was advanced by Irick in the preliminary satellite study guidelines (Irick and Hudson, 1964) as

$$p_t = p_o \cdot 10^{-\left(\frac{W_t}{r'}\right)^{b'}} \quad (23)$$

where b' and r' are terms dependent upon the highway design.

Converting Eq. (3) into logarithmic form and rearranging in terms of $\log W_t$, the performance index, the AASHO equation becomes:

$$\log W_t = \frac{1}{\beta} \log \left(\frac{p_o - p_l}{p_o - p_t} \right) + \log \rho \quad (24)$$

similarly, from Eq. 22 for Painter's equation,

$$\log W_t = \log \log_e \left(\frac{p_o}{p_t} \right) - \log b + 6 \quad (25)$$

and from Eq. 23 for Irick's equation,

$$\log W_t = \frac{1}{b'} \log \log \frac{p_o}{p_t} + \log r' \quad (26)$$

The similarity between the formulas can readily be seen and common practice is to develop linear equations of the form,

$$\log W_t = B f(p_o, p_t) + A \quad (27)$$

whereby appropriate plotting yields both the slope, B , and the intercept, A , of the straight line.

The object of prediction studies is to obtain observed values of serviceability corresponding to known values of accumulated axle loads. The manner in which the equations are used, and the resulting accuracy of the answers, depends upon the number of observations and the proper conversion of mixed traffic to equivalent axle loads.

If one observed data point on the performance plot is known, values of p_0 and B need to be established. It may be that the initial serviceability is known, but it is more likely that this value will have to be estimated either by assuming the average value of 4.2 found for flexible pavements at the Road Test or assumed from prior experience. The weaknesses of assuming p_0 have been pointed out by the Virginia Satellite Study Program (Vaswani, 1967). The slope B , for each particular model, may be assumed from the Road Test data. Irick indicates that a suitable approximation for the B term in Eq. (24) based on the AASHO results is 1.0 for flexible pavements. However, actual determinations of B for various pavements in Minnesota indicate a wide range of scatter (Kersten and Skok, 1968).

With these inherent drawbacks in mind, values of p_0 and slope are assumed and the intercept term, A ,

calculated. Then, with both A and B defined, a desired terminal serviceability, generally about 2.5, is used to solve the basic equations for W_t .

The need to estimate B is eliminated if two or more data points are obtained. Irick presented an expression for the performance index for multiple data points based on Eq. (26), as

$$\log W_t = \bar{Y} + B'_1 \left[\log \log \frac{P_0}{2.5} - \bar{X} \right] \quad (28)$$

where \bar{Y} is the average of observed values $Y = \log W_t$ and \bar{X} is the average of the observed values $X = \log \log P_0/p_t$. B'_1 is defined as:

$$B'_1 = \frac{\sum (Y - \bar{Y})(X - \bar{X})}{\sum (X - \bar{X})^2} \quad (28A)$$

Equation (28) presupposes known values of initial serviceability and a terminal serviceability of 2.5.

Vaswani demonstrated a method of establishing p_0 based on a linear form of Painter's equation when several data points are available.

In general, the serviceability of a road must deteriorate at least one full point below the initial value before successful evaluation of the "road life" may be obtained. The Minnesota satellite has begun analyzing observed and estimated serviceabilities. Kersten points

out that within a relatively short period of three years the results have not proved encouraging. However, the final verification of these techniques will require many years of study.

3.3 Performance as Related to Structural Design

The final expressions of the AASHO Road Test analysis, Eqs. (8) to (9), indicate that the variables ρ and β may be successfully predicted by mathematical models which contain basic material type and layer thickness parameters.

Additional analysis of the AASHO Road Test data by HRB resulted in the following performance equation (Irick and Hudson, 1964)

$$P_t = P_o \cdot 10^{-\left[\frac{W_{18}}{R^4 D^8}\right]^{b''/4}} \quad (29)$$

in which the influence of the regional factor, R , and a design term, D , have been added to Eq. (23). The design term is expressed as

$$D = a_1 r_1 D_1 + a_2 r_2 D_2 + a_3 r_3 D_3 + r_4 \quad (30)$$

where r_1 to r_4 are ratios of the relative strength of a particular material from layer 1 to layer 4 as referenced to the test site.

Painter's work also was directed towards breaking down the deterioration rate parameter into design and climate factors (Painter, 1965). The original form of the performance equation

$$\ln \frac{P_o}{P_t} = b W_t \quad (31)$$

was revised to

$$\ln \frac{P_o}{P_t} = b_o W_t^* \quad (32)$$

in which the design related factors were isolated in the quantity b_o as

$$\ln b_o = a'_o + a'_1 D_1 + a'_2 D_2 + a'_3 D_3 + a'_4 L' \quad (33)$$

where a'_1 to a'_3 in the above equation are Painter's derived structural coefficients, D_1 to D_3 are the respective layer thicknesses, a'_4 is the subgrade strength coefficient, L' is dependent upon the axle load and configuration and a'_o is a mathematical term. Climate or regional factors were isolated in the weighed traffic count, W_t^* .

Thus, a great deal of effort has gone into relating structural design to performance. Within the bounds of the AASHO Test data it is possible to develop coefficients and quantities which reflect material strength, layer thickness, soil support and regional effects. These

factors may be tied together into various equations which give reasonable estimates of the number of wheel loads required to reduce a roadway to a given level of serviceability.

However, the methods of analysis used require a large number of sections with carefully selected variations in layer thicknesses and material in order that significant trends develop and can be analyzed. Unfortunately, conditions such as these have only been available at the Road Test. The complete reduction of performance data to yield structural coefficients and allowable axle loads is not practical for satellite study programs. Current research trends are toward finding this type of information from other sources such as in-situ or laboratory strength tests (Seed, Mitry, Monismith and Chan, 1967; Coffman, Ilves and Edwards, 1968).

3.4 Relationship between Performance and Composite Strength

The AASHO Road Tests presented relationships between number of wheel loads and measurements of composite strength throughout the life of the pavements (Irick and Hudson, 1964).

In general form

$$P_t = A'_0 - A'_1 \log S \quad (34)$$

where A'_0 and A'_1 are numerical constants and S is a quantity, such as the Benkelman Beam deflection, which reflects total composite strength. This relationship will be examined more closely in Chapter IV, but is presented to introduce the fact that Benkelman Beam deflections can be related to wheel load applications.

Pavement behavior analysis at the Texas Transportation Institute has related Benkelman Beam deflections to initial pavement design through the use of Painter's basic performance equation (Schrivner and Moore, 1966).

Equation 31 is commonly expressed as

$$\log \frac{P_o}{P_t} = b W_{18} \quad (35)$$

where Painter defined the deterioration parameter, b , as a function of design, type and magnitude of load, soil support and climate. Schrivner assumed b varied only with pavement deflection, d , as

$$b = 10 A''_0 d A''_1 \quad (36)$$

where A''_0 and A''_1 are constants which can be determined from the Road Test deflection data.

A performance expression Q_L was defined as

$$Q_L = \log W_t - \log \log \left(\frac{p_o}{p_t} \right) \quad (37)$$

or more commonly expressed as

$$Q_L = \log \left[\frac{W_t}{\log p_o - \log p_t} \right] \quad (38)$$

Q_L was then found to be related to the Road Test data as

$$Q_L = 9 - 3.2 \log d \quad (39)$$

The basic mathematical statement for relating performance to design and region was assumed as

$$Q = B' * TDI + C_r \quad (40)$$

where Q is the performance reduced to 18 kip equivalent axle loads, B' is a constant, C_r is a regional coefficient and TDI is the Texas Design Index defined as

$$TDI = S_1 D_1 + S_2 D_2 + S_3 D_3 + 1 \quad (41)$$

S_1 to S_3 are strength coefficients determined by test data.

Thus, a method has been established which uses the basic concepts of performance trends and behavior in relating composite strength data to the allowable design.

3.5 Methods of Obtaining the Present Serviceability Index

The serviceability of a roadway section at the Road Test was found to be related to the slope variance, rut depth and amount of cracking and patching. Descriptions of the AASHO longitudinal profilometer for measuring slope variance, the transverse profilometer and gauges used to obtain the rut depth and methods for obtaining cracking and patching have been well documented (Carey, Huckins and Leathers, 1962; HRB Special Report 61E, 1962).

Many recent advanced and alternate methods for determining the above mentioned quantities have been suggested (Yoder and Milhous, 1944; Holbrook, 1969; Phillips and Swift, 1969). The object of such work is to determine the PSI rating of a road as rapidly as possible with accurate, relatively inexpensive equipment. A list of the commonly used devices is given in Table 1.

IV. EVALUATION OF STRENGTH OF PAVEMENT COMPONENTS

4.1 Basis for Structural Coefficients

The evaluation of the structural coefficient terms was one of the most significant results of the Road Test. The analysis of the test data produced definite numerical evaluations of the contributing effects of various types of materials within the roadway. The concept of structural coefficients and their use to determine the structural number of a pavement, as expressed by Eq. (10), has become an integral part of the AASHO design method. The essential idea is that different road building materials possess varying characteristics which, when assigned a numerical coefficient, may be properly related to the overall design. For everyday use of the AASHO design method, the correct coefficient values are of immediate importance.

The origin of the structural coefficients lies within the statistical analysis of the performance data gathered at the Road Test. The individual values, as reproduced in Table 2, are the result of mathematical evaluation rather than direct determination of individual physical properties. There is a strong tendency to consider the structural coefficients as being specific and fundamental material properties which may either be found or assumed for design purposes. However, close

examination of the background of the coefficients indicates that they are inherently tied directly to the Road Test pavements. Ignoring this fact will result in improper use beyond the original intent and meaning of the values.

The structural coefficients are valid only for layered systems arranged as those at the Road Test, or, in other words, the relative positions of the surface, base, subbase and subgrade must be maintained. Further, the values are dependent not only upon material composition but also upon the layer thickness. In addition, the relative proportions of surface, base and subbase must be held to within the limits of the sections examined at the Road Test.

The loading conditions at the Road Test were very well defined in terms of speed, magnitude, direction of travel, axle configuration and wheel contact area. Control of these factors was considered essential to the success of the Road Test. Subsequent research, both on a theoretical and experimental basis, has shown that the material properties also vary with the above conditions (Finn, Coffman, 1967; Ilves and Edwards, 1968).

The values given in Table 2 are based on weighted axle load applications. If the actual number of axle loads,

uncorrected for environmental effects are used, another set of structural coefficients are obtained (HRB Special Report 61E, 1962). Therefore, the coefficients are dependent not only upon environmental factors at a proposed highway location, but also upon how well the factors were initially evaluated and used in the basic analysis.

The structural coefficients assumed for materials used at the test site, and those calculated or assumed for materials used in other locations, must be regarded with care since their correct use ultimately involves many factors beyond individual physical properties.

4.2 Evaluation of the Structural Coefficients

The intent of the Design Committee was to provide structural coefficients for many basic road building materials which would serve the majority of design situations. Furthermore, the individual satellite study programs were to verify or modify the original AASHO values and develop new coefficients for other materials used throughout the country (Irick, 1964; Irick and Hudson, 1964). However, due to their background, the direct evaluation of the structural coefficients for use in the AASHO design method is not practically possible.

4.2.1 Correlation Studies

Perhaps the simplest and most straight-forward method of evaluating the structural coefficients is by

correlation studies. In general, standard laboratory tests measuring readily obtainable properties, such as cohesion, shear strength, stability or bearing strength, are performed on materials similar to the Road Test. The tests are repeated on materials of varying qualities used by the particular state. Ratios, relative scales or graphs are then established.

Many states, such as Illinois, performed tests on the actual components used at the Road Tests. Relative ratings for stabilized base courses were developed by knowing, 1) coefficients and laboratory values for AASHO stabilized materials, and 2) coefficients and laboratory values for similar, but unstabilized, AASHO materials. Graphs for finding the coefficients of other stabilized bases were then constructed based on the two known reference points (Chastain and Smith, 1965).

An extensive survey of current methods for establishing or modifying the coefficients indicates a variety of approaches for analyzing the layer components (McCullough and Van Til, 1968).

The quality of asphaltic surface materials is commonly related to the Marshall Stability test. Coefficients for base materials stabilized with asphaltic or bituminous materials are determined on the basis of Marshall Stability, Texas triaxial, triaxial and cohesionmeter tests. In addition, variables such as composition

and abrasive properties are sometimes included. Cement stabilized bases are commonly evaluated on the basis of 7-day unconfined compressive strength. Untreated granular bases and subbase are related to R-value, CBR and triaxial tests.

4.2.2 Estimation and Judgement

The AASHO Guidelines emphasize the fact that rationalization, judgement and experience must be used in order to successfully apply the Road Test coefficients. Many states, such as Illinois, Pennsylvania and New Jersey, use the assigned values without modification, whereas others prefer to reduce the coefficients in order to compensate for adverse conditions such as lack of high quality material and substandard construction techniques.

New materials are often ranked strictly by judgement. For example, Massachusetts uses a crushed stone base penetrated with asphalt. The resulting bonded mix is stronger than unstabilized crushed stone but not as effective as a well-graded black base. A structural coefficient for the penetrated stone base was selected as being the numerical average of the coefficients previously evaluated by the AASHO Committee for crushed stone and black base (Tons, Chambers and Kamin, 1965).

In view of the fact that the structural coefficients depend on a great deal more than basic material properties,

individual use and modification of the values is and will continue to be based strongly on individual judgement and long term experience with the AASHO design method.

4.3 Direct Evaluation of Material Equivalencies

Due to the lack of readily available, straightforward methods of evaluating pavement structural coefficients, a great deal of research is directed towards determining equivalencies or relative rankings. The purpose of these laboratory and field tests is to isolate some specific property or set of properties which reflect the materials inherent strength. These test values are then used as a basis for evaluating the suitability of the material within a pavement structure. Equivalency tests are used both to rank dissimilar materials with one another, or, more commonly, to rank or rate similar materials. Standard quality control tests would fall into the latter classification.

4.3.1 Laboratory Methods

There are a variety of physical properties which relate to material strength. In addition, there are many factors which directly affect these properties. The chief advantage of laboratory testing is that the test conditions may be closely controlled, allowing individual contributing factors to be isolated and analyzed. Many

of the properties sought, and techniques used, are similar for various types of materials. For this reason, methods rather than specific layer materials will be discussed.

4.3.1 a. Moduli Tests

Moduli of materials are of prime importance for they are directly related to the load, stress, and deformation properties of a material. The objective of these studies is to define a relationship or moduli which realistically relates some loading condition to the resulting strain. These values are then used to directly rank material effectiveness or used to calculate known field load-deflection conditions based on some assumed layer system.

An extensive series of laboratory tests have been carried out by the Asphalt Institute in which a number of moduli were examined (Kailas and Riley, 1967). They recognized the importance of using dynamic or repeated load tests in order to obtain conditions dynamic closely related to actual highway behavior.

The dynamic complex modulus, $|E^*|$, for asphaltic surfaces and stabilized bases is expressed as:

$$|E^*| = \frac{\sigma_o}{\epsilon_o} \quad (42)$$

Where σ_o is the applied vertical stress on a simple,

unconfined sample and ϵ_0 is the resulting vertical strain as recorded by SR-4 strain gages mounted on the specimen.

The dynamic stiffness modulus, E_s , was found by loading small beam samples of stabilized materials under dynamic conditions. The modulus,

$$E_s = \frac{P a (3 l^2 - 4 a^2)}{48 I d'} \quad (43)$$

is a function of the applied load, P the beam dimensions, l and a moment of inertia, I and the observed deflection, d' .

A third repeated load parameter, the modulus of resilient deformation, is a dynamic triaxial test. The modulus is expressed as

$$M_R = \frac{\sigma_d}{\epsilon_r} \quad (44)$$

where σ_d is the repeated deviator stress and ϵ_r is the recoverable axial strain. Kailas and Riley found the following relationship existed for the resilient modulus;

$$M_R = K'' \sigma_3^N \quad (45)$$

where K'' is a proportionality constant, σ_3 is the lateral confining pressure and N is a material constant. Similar studies of a limited series of resilient moduli tests on

surface base and subgrade material produced the same relationship (Seed, Mitry, Monismith and Chan, 1967).

A second expression,

$$M_r = K'' \theta^{N'} \tag{46}$$

was also found by the latter experimenters, where K'' and N' are constants, $\theta = \sigma_1 + \sigma_2 + \sigma_3$, σ_1 is the vertical stress and σ_2 and σ_3 are the lateral stresses.

The laboratory determined moduli are intended to show the stress-strain relationship which exists for a particular material after many repetitions of load. It has been found that the behavior may be considered essentially elastic after many loading cycles, and as many as 10^4 to 10^5 applications are frequently applied to reach conditions which are assumed to exist in highway pavements.

More significantly, the moduli values obtained by any testing procedure are not constant. Factors such as temperature, water content, magnitude, frequency and duration of applied load, lateral pressure (if used), thixotropy or sample age, material type, and degree of compaction are all related to the moduli values. The importance of this is that, if the values are to be used for ranking purposes, or in subsequent analysis, the initial conditions which exist in an actual pavement system must

be carefully and realistically defined. Although parallel trends are observed, the moduli values from the various tests do not agree due to the differences in testing techniques.

An interesting addition to the dynamic complex modulus test is that Poisson's ratio, μ , may be readily obtained by mounting an additional strain gage horizontally on the sample. The ratio was found to be frequency and temperature dependent.

4.3.1 b. Seismic Tests

A relatively new technique of measuring seismic waves provides an alternate method for the laboratory determination of fundamental physical properties. The velocity of a compression wave passing through an elastic material is directly proportional to its elastic properties. The exact nature of seismic measurements is not completely understood, but the resulting measured velocities do serve as a method for ranking the elastic behavior of a variety of materials (Schrivner and Moore, 1966).

4.3.1 c. Additional Laboratory Tests

The standard laboratory tests, such as Marshall Stability, R-value, triaxial and CBR, (See Sec. 4.2), may be used to obtain relative rankings of material strength. However, the fact must be kept in mind that these tests may not reflect the same in-situ strength properties which

exist in a highway. A second serious drawback to the conventional tests is that they are not generally applicable to all road building materials.

Additional tests not mentioned in Sec. 4.2 which may be used to obtain relative strengths of stabilized materials are the Hveem Stability, ultimate tensile and splitting tensile tests. Numerous specialized test methods for asphaltic materials, such as creep, relaxation and viscosity tests, have been reported (Finn, 1967).

4.3.2 Field Test Methods

There are several significant advantages in field testing as contrasted to laboratory testing. The final objective of this form of research work is to evaluate the behavior of highways. In this sense, field tests tend to be more realistic in that they obtain some form of response from an actual pavement system which reflects, in many cases, the total environment of the structure. It is difficult to obtain the same degree of similarity to actual field conditions by laboratory testing. Factors such as layer interaction, temperature changes and confining pressure gradients across the system are very complex. If not completely understood or isolated by a field testing method, their effect is at least included in the results. Field testing, in many instances, also avoids sample size problems or scale factors needed to relate laboratory tests to field conditions. Since some

field testing procedures are applicable to all layers, the discussion of those methods will also include evaluation of the subgrade layer.

4.3.2 a. Vibratory Methods

The principle behind vibratory or seismic testing, as noted in Sec. 4.2.2 b, has been adapted for field use in order to obtain in-situ properties of material layers. The first property which may be examined is the velocity of compression wave transmission. As previously stated, the velocity is related to the elastic properties of the material. The dynamic modulus of elasticity may be computed as,

$$E = K_o \gamma V^2 \quad (47)$$

where V is the wave velocity, γ is the density and K_o is a proportionality constant (Jones, 1958).

An approximate method for correlation between the dynamic modulus of elasticity and field CBR tests on subgrade material has been established (Heukelom and Foster, 1960), where

$$E = 100 \text{ CBR} \quad (48)$$

Similar correlation studies have indicated

good agreement between vibratory techniques and the use of large sized plate-load equipment.

A second pavement property, the dynamic stiffness, has been obtained by vibrational methods and expressed as

$$S' = F/Z \quad (49)$$

where S' is the dynamic stiffness, F is the applied dynamic force and Z is the resulting pavement displacement. The total stiffness of a layered system may be related to 1) the elastic stiffness and 2) the moving mass and damping effects. The elastic stiffness, R' , is independent of frequency and is more closely related to actual highway load-response conditions (Heukelom, 1961).

R' is related to the elastic properties of a roadbed as

$$R' = q a' E \quad (50)$$

where q and a' are factors which depend upon Poisson's ratio and the stress distribution beneath the loaded area, and E is the modulus of elasticity of a soil. The influence of a layered pavement on the dynamic stiffness is expressed as

$$R'_p = \phi R'_s = \phi q a' E'_s \quad (51)$$

where E'_s is the dynamic modulus of the soil, R'_p and R'_s are the elastic terms for the pavement and soil, and ϕ is a function developed by the theoretical analysis of layered systems (Henkelom and Klomp, 1962).

The vibrational responses of pavement structures to complex seismic waves has been applied to predicting actual pavement deflections under moving traffic. Theoretical mechanical models have been formulated containing such parameters as mass, stiffness and damping factors, which represent the pavement behavior (Szendre and Freeme, 1967).

The operation of two currently available vibratory systems, the Lane-Wells Dynaflect and the Shell Vibrator, were reviewed by the Texas Transportation Institute (Schrivner and Moore, 1968).

Use of the Dynaflect in obtaining relative measurements of pavement component strength has been reported (Schrivner and Moore, 1966). Relative rankings were obtained by observing the Dynaflect deflections for a wide variety of carefully constructed mats of varying layer thickness. The surface deflections were then related to the material properties by mathematical models which were based on the theory of elastic deformations

for layered systems. Good agreement was obtained with other ranking methods but Schrivner and Moore concluded that, at that time, information provided by one set of Dynaflect readings was not sufficient to determine the relative stiffness of each layer.

Currently, devices such as the Dynaflect are most commonly used for quality control measurements during highway construction. Relative measurements may be readily obtained which yield ratings or evaluations of uniformity based on layer stiffness (Swift, 1966).

4.3.2 b. Plate-Load Tests

The use of plate-load tests would appear to be the most reliable and direct method of obtaining realistic strength values based on layer properties, since the magnitude of the applied load and extent of influence on the pavement system is similar to the actual vehicle loading conditions. However, numerous theoretical and field studies indicate that plate-load behavior is quite complex and the values obtained are of limited applicability unless consideration is given to understanding the nature of plate bearing behavior. Two layer systems will be considered in the discussion of the plate-load test. Multi-layer development and application will be discussed in Sec. 4.4.

The surface deflection, w , of a rigid plate on a two-layer system has been theoretically established as

$$w = \frac{1.18 \text{ sr}}{E_2} F_w \quad (52)$$

where s is the applied pressure in psi, r is the plate radius in inches, E_2 is the modulus of elasticity of the lower layer and F_w is a dimensionless constant which depends upon the ratio of the moduli of layer 1 and layer 2 as well as the ratio between the depth of layer 1 to the radius of the plate (Burmister, 1943). The above expression is valid for homogeneous, isotropic elastic solids which are continuous across the interface between the two layers. Burmister has published graphical relationships between E_1/E_2 , h/er and F_w where h is the depth of the upper layer.

Various approaches have been used to apply the basic elastic expressions to plate load testing. Perhaps the simplest and most straightforward method is to perform a plate-load test on the subgrade, in which case the load-deflection relationship is

$$w = \frac{1.18 \text{ s r}}{E_2} \quad (53)$$

from either the Boussinesq or Burmister theory. E_2 may

then be evaluated for the subgrade. In normal testing procedures the load, and hence s , is increased until a given deflection of normally 0.2 inches is obtained. Repeating the plate-load test on the surface results in the determination of a value for F_w from which the modulus of the upper layer may be determined (McLeod, 1963).

An alternate approach is to perform several plate-load tests on the pavement surface with varying sized plates. The load required to obtain a 0.2 inch deflection is graphically related to the radius of each plate used. A similar theoretical curve is then found by trial and error. A ratio E_1/E_2 and a value for E_2 are assumed, and with a known h/r ratio, a value of F_w is obtained which will produce a calculated load equal to the observed load. When correct values of E_2 and E_1/E_2 are selected, the theoretical and field curves will coincide (Brown, 1962).

The simple two layer theory has been extended to actual pavement structures by Brown. He assumed that the surface, base and subbase act as a single upper layer overlying the subgrade.

Another approach has been suggested in which two or more lower layers are considered to act

compositely, resulting in a combined or effective modulus (McLeod, 1965). McLeod found that stepwise approximate applications of two layer theory to multi-layer conditions lead to relatively poor results even if all layer moduli are considered equal.

A recognized limitation of the plate-load test is that the plate's supporting power is related to the perimeter/area ratio of the plate itself. As this ratio decreased with increasing plate size the allowable pressure required to reach a specified deflection decreases (Campen and Smith, 1947). In addition, the rate of loading, the magnitude of the deflections obtained, the layer thicknesses and the material type all contribute to variations in moduli calculated by plate-load tests.

A large scale, cooperative field study of the application of plate load testing to pavement behavior was carried out in 1958 at Hybal Valley, Virginia (Benkelman and Williams, 1959). Initial analysis of the data confirmed the existing concept that the unit pressure, s , developed was expressed as

$$s = m \frac{P}{A} + n \quad (54)$$

where m is the perimeter shear in lbs/in, n is the developed pressure in psi, P is the applied load and A' is the cross sectional area of the plate (Ingimarsson,

1961).

An extensive study of the Hybal Valley tests found a total of thirteen independent factors affecting the test results (Kondner and Krizek, 1961; 1966). The results of a dimensional analysis of the test results showed that hyperbolic equations could be used to explain the effects of temperature, repeated loadings plate size, pavement thickness and material strength.

A simple, straightforward approach was used by Oklahoma to evaluate the load supporting capacity of various layers within a pavement. The loads required to obtain various deflections of 0.03, 0.04 and 0.05 inches, were divided by the layer thickness. Each type of material was then ranked relative to a standard stabilized aggregate base course (Helmer, 1965).

A limited number of full size layer systems have been tested under repeated load conditions by plate-load methods (Seed, Mitry, Monismith and Chan, 1967). The cyclic plate-load tests were intended to obtain a more realistic appraisal of pavement behavior. One-, two- and three-layer systems were tested with various sized plates over several thousand applications of load. The resilient deformation of the surface and interfaces was continuously recorded. The method of analysis used to evaluate the data will be discussed in Section 4.4.2.

4.3.2 c. The Benkelman Beam

The Benkelman Beam is a simple, mechanical device used to measure pavement deflections under actual wheel load conditions. It was developed in 1953, and since that time has demonstrated its versatility as a research tool (Carey, 1953; Carneiro, 1966).

The Canadian Good Roads Association has made extensive use of the Benkelman Beam as a measurement of relative pavement strength and as a means of determining fluctuations of annual load carrying capacity (Sebastyan, 1960; Curtis and Shields, 1960). An extensive investigation into procedures, influencing factors and practical applications for the Benkelman Beam have been reported (Wilkins, 1962).

Deflection studies at the AASHO Road Test resulted in the mathematical model

$$d = 10 a_0 + a_1 D_1 + a_2 D_2 + a_3 D_3 + a_4 L_1 \quad (55)$$

which relate the Benkelman Beam deflections, d , to the pavement layer thicknesses, where a_0 to a_4 are strength coefficients for the respective layers and L_1 is the axle load.

The general form of the model was adopted by Virginia as

$$\log d = a_0 + a_1 D_1 + a_2 D_2 + a_3 D_3 + a_s G_s \quad (56)$$

where a_s is a function of the soil strength and G_s is the equivalency grading of the subgrade soil support. With the exception of the subbase layer, the tests produced relative strength coefficients in good agreement with those recommended by the AASHO Committee (Vaswani, 1967).

Benkelman Beam tests have been used by the state of Minnesota in the development of a method for predicting allowable axle loads on existing highways during periods of spring thaw. A linear load-deflection relationship was assumed as

$$L_A = L_D \frac{d_a}{d_s} \quad (57)$$

where L_A is the allowable spring axle load, L_D is the axle load used for the tests, d_s is the predicted deflection based on the Benkelman Beam test and d_a is the allowable spring deflection based on theoretical pavement behavior (Kersten and Skok, 1968; Kruse and Skok, 1968).

An alternate use of the Benkelman Beam was mentioned in Sec. 3.4, where deflection measurements were directly related to performance expressions. The resulting terms were then related to initial pavement design and regional behavior.

Benkelman Beam measurements have been used to determine the modulus of elasticity of individual pavement layers (Walker, Yoder, Spencer and Lowry, 1962). This was accomplished by measuring the deflections at the interface of each pavement layer as well as on the pavement surface.

Correlations have been established between Benkelman Beam and plate-load test results (McLeod, 1965, Sebastyan, 1960). The load on a large rigid plate required to produce a specified deflection was converted to the load required to produce a deflection equal to that obtained from the Benkelman Beam test. Relationships between the composite Benkelman Beam and plate-load moduli were then established.

Recent studies have indicated a reasonable correlation exists between static Benkelman Beam deflections and dynamic deflections produced by the Lane-Wells Dynaflect. This has led to the conclusion that the vibratory system responds to the same physical properties of a flexible pavement structure which govern the behavior observed by the Benkelman Beam tests (Scrivner, Swift and Moore, 1966).

The desirability of measuring in-situ pavement deformations under full-scale loading conditions has led to the development of additional methods for evaluating

deflections (Zube and Forsyth, 1966). Automatic recording optical and mechanical devices provide deflection measurements more rapidly and with greater precision than the conventional Benkelman Beam (Prandi, 1967).

4.4 Uses for Layered Elastic Theory

4.4.1 Background

Highway pavement systems are composed of layers of material constructed on a subgrade to form a structure capable of carrying traffic loads. The theory of elasticity, as applied to multi-layered systems has been extensively examined in an attempt to understand the complex load, stress, deformation relationships which occur in a pavement structure.

The theoretical behavior of one- and two-layer systems has been investigated by Westergaard, Boussinesq and Burmister (Westergaard, 1925; Boussinesq, 1855 and Burmister, 1943). The latter two theories have received the most consideration in the area of flexible pavements for it is felt they more accurately describe the actual behavior. Extensions of Burmister's work resulted in the evaluation of mathematical expressions and coefficients from which stress, strains and deflections could be obtained throughout a two layered system (Fox, 1948; Hank and Schrivner, 1948; Odemark, 1949). Use of the Westergaard theory has been suggested for predicting the stress distribution in asphalt pavements whose bases are rigid

relative to the strength of the subgrade (Hagstrom, Chambers and Tons, 1965).

With the advent of the electronic computer, general expansion of layered theory was feasible (Acum and Fox, 1951; Peattie and Jones, 1962). Theoretical stresses and deflections were predictable within the upper layers and at layer interfaces for several material and continuity conditions.

Recently, multi-layer programs have been developed for general use which will describe the complete state of stress and strain within any part of a multi-layered system (Peutz, Jones and Van Kempen, 1968; Warren and Eieckmann, 1963). A great deal of emphasis is currently being placed on such solutions and how they relate to observed behavior. The determination of structural equivalencies and equivalent wheel loads, based on the elastic layer theory, stem from this research.

4.4.2 Verification of Elastic Behavior

Various investigations have tried to verify the elastic theory on laboratory and field bases. The behavior of circular, loaded plates resting on a uniform sand layer demonstrated that the vertical and radial stresses could not be predicted by the Boussinesq theory. The deflections measured under repeated-load conditions were better predicted by assuming a homogeneous, anisotropic, elastic material (Morgan and Holden, 1967).

Model tests on two-layered systems have been examined (McMahon and Yoder, 1960). In general, the observed stresses were only in fair agreement with those predicted by elastic theory. Field studies of three-layered systems indicate that the distribution of stresses in upper layers of material, such as soil cement or concrete stabilized bases, can best be approximated by the Burmister theory. The material's ability to carry tensile stresses accounts, in part, for this agreement. The Boussinesq stress distribution appears more applicable for untreated granular and asphaltic materials (Vesic, 1962).

The surface deflections observed by repeat-load plate-load tests on several multi-layer systems have been predicted with good agreement by using multi-layer analysis (Seed, Mitry, Monismith and Chan, 1967). An extensive series of laboratory repeated-load triaxial tests were performed to determine how various factors affected the resilient modulus. The large-scale system was then examined, using the Boussinesq theory, to determine the confining pressure at various points throughout each layer. Appropriate laboratory moduli were selected on the basis of the number of load cycles and conditions of confining pressure. The predicted deflections were based on the summation of individual deflections calculated from each incremental division for the entire structure.

4.4.3 Predicting Material Equivalencies

The behavior of three-layer pavement systems, based on assumed models, has been used as a means of developing theoretical design methods (Dorman and Metcalf, 1965). The elastic properties of the three layers, the loading conditions and the number of repetitions were defined. Design criteria were selected as limiting values of vertical compressive strain in the subgrade and tensile strain within the asphalt layer. The individual depth of surface and base required to maintain acceptable limits of strain were plotted graphically against one another. This allowed all alternate designs to be shown graphically. The equivalency ratio between the surface and base for any suitable combinations of either material was also obtained.

A similar three-layer investigation was performed using an assumed pavement model with a specified loading condition. Laboratory determined values of the complex moduli for each layer were used. Allowances were made for the frequency of the load and the temperature distribution and fluctuation within the pavement. Theoretical equivalency ratios were established for the base material by calculating the required amount of base needed to compensate for decreasing the surface thickness one inch while maintaining constant surface deflections (Coffman, Ilves and Edwards, 1968).

4.5 Factors Relating to the Structural Coefficients

The use of structural coefficients greatly enhances the AASHO Design procedure for they allow various combinations of acceptable designs to be readily examined. However, the concept of structural coefficient has several serious shortcomings.

As indicated in Sec. 4.2, the practical evaluation of the coefficient values by standard tests is not possible either for materials used at the AASHO Road Test or for other types of materials used elsewhere. For this reason, equivalent strength ratings are frequently used to measure the effectiveness of road building materials.

The difficulty in establishing these values is twofold. There are serious doubts as to whether the standard material tests accurately describe in-situ behavior. Secondly, complex and extensive testing programs, both on a theoretical and experimental basis, demonstrate that the behavior of pavement material cannot, at present, be adequately described. Young's modulus, E , and Poisson's ratio, μ , govern the behavior of elastic solids. Under actual test conditions, both values have been found to vary with the factors given in Sec. 4.3.1 a.

The behavior of a layered system, and hence the resulting equivalency ratios vary with the basic

boundary and continuity conditions, the criteria established for equivalency and the relative position, strength and thickness of each layer. Thus it appears that, at best, equivalency ratios and structural coefficients are variable. A more accurate picture of the possible range of these coefficients should be established for all adverse conditions which are normally obtained under conventional loading and environmental conditions. In addition, further research is needed to theoretically account for the non-ideality of pavement systems.

A recently completed study has considered the consequences of using incorrect structural numbers when predicting pavement life by the AASHO design method (McCullough and Van Til, 1968). The general AASHO flexible pavement formula was differentiated with respect to the structural number, and percent errors introduced in that term to determine the variation in the calculated number of wheel loads. Overestimating the structural number was found to be far more serious than underestimating it. The amount of error increased with decreasing structural numbers. The effect of relatively small errors, such as 5 percent, may lead to overestimating the design life of a typical section by 100 percent. The significance of such findings justifies current research into the behavior of materials and pavements.

V. SUBGRADE SOIL SUPPORT

5.1 Soil Support in the AASHO Design Method

The concept of a subgrade soil support term was advanced by the AASHO Committee so that the design method developed from the Road Test results could be extended to geographic areas which have soil characteristics different to those at the test site. The assumed relationship between soil support and number of axle loads, and its incorporation into the design method, are given in Chapter II. Hence, a soil support value must be either assumed or determined for a proposed roadbed prior to using the design charts, (see Fig. 2).

The fundamental problems are involved in the soil support concept. First, there is no basic physical relationship between the soil support term and currently used testing methods. Secondly, there are no rational or definite experimental methods for establishing valid correlations between any standard testing procedures and the soil support term.

5.2 Correlation Studies

Despite the fact that no standard, universally accepted correlation methods are available, several such scales have been proposed by the AASHO Design Committee (HRB Special Report 73, 1962). An extensive research

program was carried out at the Road Test in order to determine the subgrade soil properties by the best available methods. In addition, samples of the soil were tested by a large number of agencies throughout the country (Skok and Fang, 1961). The results of the site tests, and that done by other groups, served as a basis for the correlation studies. The AASHO correlation charts were based on

1. R-value (California)
2. R-value (Washington)
3. CBR (Kentucky)
4. CBR (Kentucky, for bituminous bases)
5. Group Index

As shown in Fig. 3, the R-value and Group Index scales are linear and the CBR scales are logarithmic.

Several similar correlation studies have been performed since the Road Test. Laboratory tests performed by the state of Illinois on the AASHO A-6 subgrade soil and crushed aggregate base course resulted in CBR values of 3 and 110 respectively. The soil support values of 3 and 10 were replaced by the Illinois CBR values, and a logarithmic distribution assumed for intermediate values (Chastain and Schwartz, 1965).

Utah conducted a number of laboratory tests in order to determine the repeatability of four test methods: the AASHO 3 Point CBR, Static CBR, Dynamic CBR and R-Value. A logarithmic correlation scale

between soil support and Dynamic CBR was assumed. The other three tests were tied into the soil support scale by equating their results to those from the Dynamic CBR tests (Sorbe, 1967). Graphical relationships between the soil support term and results from each test were established for design purposes.

The state of Massachusetts formulated a similar correlation scale between CBR and soil support (Tons, Chambers and Kamin, 1965). A literature survey of available information covering support values for the compaction methods desired by Massachusetts resulted in selecting bearing values of 5.5 and 100 as representing soil support terms of 3 and 10, respectively. A logarithmic distribution was assumed between the two points.

A correlation scale for Georgia soil was developed after an evaluation of the entire pavement structure. Undisturbed cores obtained from pavement sites, as well as several from the AASHO Road Test, were subjected to undrained triaxial tests with varying conditions of lateral pressure. Simplified expressions for the elastic deformation and ultimate bearing behavior of the roadbed were assumed. Relationships between loadings, pavement design and factor of safety against subgrade bearing failure were established for both AASHO and Georgia conditions. A logarithmic scale was then proposed which related

computed ultimate bearing capacity, based on triaxial tests, and subgrade soil support values (Sowers, 1965).

The use of undrained triaxial tests was also proposed by South Carolina as a means of finding the subgrade support of the roadbed at sixteen sites (Chu, Humphries and Fletcher, 1966). The tests were conducted on disturbed specimens whose density and water content equaled those which were assumed to exist during construction. Samples 4 in. in diameter and 8 in. high were subjected to lateral pressures comparable to those existing under 18^k loading conditions in the field and the modulus of deformation of the soil determined. The results of additional tests on AASHO embankment and granular base material, both by South Carolina and others, served as a basis for a correlation between the soil support term and the logarithm of the modulus of deformation.

A recent theoretical study has developed a correlation scale relating soil support values to resilient moduli (McCullough and Van Til, 1968). An elastic, multi-layer model was chosen to represent the behavioral characteristics of a highway pavement. A literature survey indicated that subgrade moduli on the order of 3000 psi for a clay roadbed and 15,000 to 35,000 psi for a crushed stone base would describe the two predetermined soil

support conditions at the AASHO test site. Various values of thicknesses and elastic moduli of the surface were selected to cover the ranges normally encountered in practice. Standard dual wheel, 18 kip axle loads served as a basis for the assumed model load. Vertical compressive strains in the subgrade and tensile strains in the bottom fibers of the asphalt surface were calculated. These values were related to the weighted number of load applications obtained from the standard AASHO design equation. The evaluation of the trends between number of applications and derived strain resulted in a logarithmic scale between soil support and resilient moduli values.

5.3 Significance of the Soil Support Term

The structural behavior of a subgrade is reflected by the material's in-situ properties. These vary according to the items mentioned in Sec. 4.3.1 and 4.3.2. Elastic layer analysis has indicated that subgrade compressive strains are a critical design criteria for typical pavements (Dorman and Metcalf, 1965). It has been tentatively concluded that as the stress on a layered system increases, the modulus of the base increases while that of the subgrade decreases. The resulting resilient deformations in the subgrade therefore become more critical (Seed, Mitry, Monismith and Chan, 1967). Thus knowledge of the behavior of the subgrade is important and the magnitude and variation of the subgrade's properties contribute to the overall

behavior of the structure.

A significance study indicated that, similar to the structural number, small errors in the assumed values of soil support lead to large errors between the actual and calculated number of load applications as determined by the AASHO design method (McCullough and Van Til, 1968). As with the structural number, underdesign resulting from overestimating the soil support value results in more significant errors than if conservative values were selected.

At present, correlation charts are the only practical means of relating soil properties to the soil support values required by the AASHO design. However, further research is required to adequately demonstrate that these methods actually evaluate in-situ behavior.

VI. TRAFFIC

6.1 Background

The behavior of the AASHO Road Test pavements were evaluated under a definite, controlled loading program. Each series of related sections, or loops, were subjected to axle loads of known magnitude, configuration and frequency in such a manner that the effects of very light to very heavy loads could be observed. The analysis of the performance data, as summarized in Chapter II, was based on the relationships between structural design, change in serviceability and accumulated 18 kip axle loads. The equivalent axle concept allowed various types of loads to be reduced to a common or equivalent number of repetitions in order to simplify the analysis and resulting use of the test data. Thus, based on the resulting Road Test equations, it was possible to predict the total number of applications of load which would reduce a given highway, of known design, roadbed and environment, to a specified level of serviceability.

For convenience, an arbitrary design life of 20 years was selected, and the total applications were reduced to the more conventionally accepted form of daily equivalent applications. Hence, the AASHO design method, as summarized by Fig. 2, requires a value for the equivalent daily 18 kip single axle load applications.

6.2 The Equivalent Applications Concept

The AASHO Road Test loadings were very limited when contrasted to the wide range of vehicle size, type and speed normally encountered under actual situations. The conversion of mixed traffic into forms related to the AASHO conditions can be expressed by either mixed traffic or equivalent applications theory (Scrivner and Duzan, 1962).

The mixed traffic method provides an approach for summing the results of individual weight classes based on representative samples. The relationships between deterioration, serviceability index, application, load and design from the AASHO Road Test data were applied to each weight class in a manner which allowed the summation of all repetitions in each class to be evaluated. However, the resulting mixed traffic theory formulas were in forms impractical for general application.

The equivalent applications theory is based on the concept that if one load is selected as a standard, the effects of both lesser and heavier loads may be referenced to it by ratios which reflect equivalent, long term behavior. The basic AASHO equations provided a means for accomplishing this. Equation 4 may be rewritten as

$$W_a = \rho_a G^{1/\beta_a} \quad (58)$$

where one axle load type was denoted by the subscript "a". An equivalency ratio, or factor, between this weight class and another, denoted as "i", was then established as

$$R_i^! = \frac{W_a}{W_i} = \frac{\rho_a G^{1/\beta_a}}{\rho_i G^{1/\beta_i}} \quad (59)$$

The factor, $R_i^!$, was a function of the structural number, axle configuration and terminal serviceability. Equivalency factors have been based on the 18 kip single axle load and tabulated for design purposes (HRB Special Report 73, Appendix B, 1962).

6.3 Uses of the Equivalent Applications Concept

Many factors enter into the practical conversion of mixed traffic to equivalent axle loads. Foremost among these are establishing methods to count and weigh samples of existing vehicles in order to determine current traffic characteristics. Secondly, methods of projecting traffic information over the expected design life of the roadway are necessary. In many instances simplified projection factors are used, but a complete growth rate analysis is very complex and involves many factors, a discussion of which is beyond the scope of this report.

The basic requirements for a fundamental traffic analysis have been set forth in the Satellite Study Guidelines (Irich and Hudson, 1964). A complete des-

cription of the traffic over a pavement section requires parameters which must be approximated by sampling techniques to obtain a representative traffic history. Several fundamental steps will be given to develop the basic approach used in traffic studies.

All possible types of vehicles are broken down into axle load categories which are normally divided into 2 kip increments. Loadometer or vehicle load studies then weigh vehicles passing a specified section over a predetermined period, such as 24 hours. In general, only trucks and other heavy commercial vehicles are weighed due to the basic similarity of automobile weights. The total number of equivalent axle loads is then the summation of the number of equivalent loads in each weight class, as converted by using the appropriate factor.

Since loadometer studies are costly and time consuming, traffic counts are commonly used to supplement this information. Traffic is divided into broad, readily identifiable classes and the number in each class passing a particular point is counted. The percent within each class is then used to extrapolate the loadometer information. The daily load and count studies are then either developed to establish a traffic history or extended to estimate future volume. Counting and load studies are required often enough to obtain an accurate picture of the trends and fluxuations in a particular area.

A recent study has indicated that nine independent variables commonly affect traffic flow at a specific site (Deacon and Dean, 1969). These include road type and direction, availability of alternate routes, type of service provided, traffic volume, allowable gross weights, geographic area, year and season. Determining methods to encompass and correlate the variables has proven difficult. The significance of these items is twofold. First, the study indicated that traffic data observed at one location may not readily be extended to another without very careful consideration of the factors involved. Secondly, changes or trends in any one of the variables may invalidate traffic predictions established for a given roadway.

6.4 Traffic Data

The reduction and use of traffic data is handled differently by many states due to many differences in the nature of traffic, basic needs, past data collected and availability of funds. The approaches used by several states for satellite studies or design practices will be discussed briefly.

Loadometer data which reflected conditions surroundings a portion of the Road Test sections were available for use in Alabama. This information allowed graphical relationships between average daily traffic, ADT,

and anticipated equivalent axle loads to be developed and used to estimate the traffic history at each site (Karrh and Stephenson, 1967). Visual classification of traffic into several broad categories was carried out at each site not covered by existing data. Approximate equivalent 18^k applications were then obtained from the count and estimated weight survey by the procedures recommended in the AASHO design method.

Count surveys for the type and amount of each vehicle were available during the Virginia study. The conversion of this information to 18 kip equivalent wheel loads was based on values established at loadometer stations with similar traffic conditions. The equivalency factors presented in 1966 by the Bureau of Public Road's Truck Weight Study were used in preference to those originally recommended by the AASHO Design Committee (Vaswani, 1967).

An extensive traffic analysis was associated with the Minnesota satellite study program in order to evaluate the total 18 kip EAL's applied to the test sections. Methods for projecting the traffic data based on satellite trends were formulated. The study concluded that the state should convert from basing design on average daily commercial traffic to the equivalent applications approach. The study also pointed out the significance of seasonal variation in the number of heavy commercial

vehicles and concluded that traffic load studies should be conducted over several periods spaced throughout the year (Kersten and Skok, 1968).

Loadometer data from 19 stations throughout Illinois was used to formulate axle load distributions which were considered applicable to the entire rural primary system in the state (Chastain, 1962). Based on many years of collected traffic data, general projected graphical relationships were formed between 18^k EAL's per 100 commercial vehicles and any specific year. This allowed the total equivalent applications to be determined from truck counts. The effects of passenger cars was determined independently on the basis of a normal 4000 lb. vehicle.

The state of Massachusetts has broken its traffic data into weight classifications other than those established by the AASHO method. This required that revised equivalency factors be calculated in terms of the previously defined weight classes (Tons, Chambers and Kamin, 1965).

A recent study of the AASHO design method summarized several basic traffic analysis methods currently in use (McCullough and Van Til, 1968). Variations between methods are basically due to how many vehicle weight divisions are selected and how the information obtained by traffic counts and loadometer studies is related and projected. Differences in number of traffic classifica-

tions and methods used to project the data, reflect the many different systems for handling traffic. The survey concluded that the loadometer data reduced by the BPR's W4 tables was the best available method.

6.5 Further Research Requirements

The equivalent applications concept, obtained from the Road Test findings, serve as basis for incorporating traffic data into the AASHO design method. Revisions by the BPR in the actual values of the equivalency factors are felt by some to be more accurate than the originally recommended values. Theoretical studies, using elastic layer theory, are currently being considered for finding load equivalencies (Huang, 1969). These are, at present, limited, for only the effects of design, single wheel load and critical strains and deformations are considered.

The limitations of the equivalent wheel load concept should be recognized. It is the result of a statistical study of a relatively restricted highway test. The complete description of actual mixed traffic is very complex due to the effects of variations in speed, axle configuration and load, and the long term relationship between loads and pavement system behavior.

The need for more accurate traffic information has been recognized by many researchers since the

development of the Road Test. Irick pointed out that existing techniques in traffic counting were adequate but loadometer information, in general, was inadequate for the AASHO design method. The same general conclusion has been advanced by McCullough. In addition, it is possible to obtain a wide range of results from the same fundamental data by using various existing traffic projection methods currently available. It is pointed out that this may not be significant within a state which, through its own experience, has probably learned to inherently compensate in other steps in the design method. However, the general use of incomplete or simplified methods is not advised for it can lead to serious errors.

VII. REGIONAL FACTOR

7.1 Philosophy

A regional factor was incorporated into the AASHO design method to account for environmental influences on the behavior of a highway. The assumed relationship between regional effects and pavement life, and its inclusion into the general AASHO design formula, is given in Chapter II, (see Fig. 2).

It was recognized that no rational procedure was available to evaluate the regional factor for the variety of conditions present throughout the country. However, guidelines and suggested values were proposed by the Design Committee (Langsner, Huff and Liddle, 1962).

Following the Road Test, evaluation of regional factors was to be accomplished through satellite study programs. The tentative procedure was to observe the behavior of many similar pavements with similar loading conditions which were located in different environments. The regional factor would then explain differences in test data not covered by the structural and soil support terms. Furthermore, determining the properties of one section with characteristics similar to those at the Road Test would allow correlations to be made with the original regional factor scale. A list of climatic and topographic

variables, such as precipitation, frost, drainage and grade, have been recommended by the Guidelines as being areas of potential interest for individual states (Irick and Hudson, 1964).

7.2 Environment-Evaluation by States

Various states have attempted to experimentally evaluate regional conditions for their own specific locale. These have generally been carried as part of a total assessment and study of the AASHO design method.

A performance study in Alabama suggested that the behavior of a wide variety of sites could be better explained by dividing the state into several geographic regions. However, it was concluded that regional factors required to explain the variations in pavement behavior were excessively large and that the effects of climate and construction techniques, as related to the structural design, could not be explained in terms of the basic AASHO equations (Karrh and Stephenson, 1967).

Minnesota completed an extensive study of year-round pavement behavior to determine a means of evaluating the effects of seasonal variations. It was found that an average variation of 152 percent existed between maximum (or springtime) and fall Benkelman Beam deflections (Kersten and Skok, 1968). This information was used to develop a design procedure for specifying

allowable spring tonnages on Minnesota's highways. No work was directed towards developing an AASHO regional factor but further research into the general area of environmental effects was recommended.

Illinois found that the direct application of the AASHO formulas did not correctly express the deterioration of serviceability for its highways. However, the formulas did follow observed trends if somewhat weaker structural designs were assumed. The use of a time exposure factor was proposed which would alter the Road Test results to fit the observed performance (Chastain, 1962). The factor, T, was defined as

$$T = \frac{D_t}{SN} \quad (60)$$

where D_t = the Illinois structural number in the form of Eq. (10). This factor was to account for the long-term deterioration of pavements due to environmental effects. Subsequent studies indicated a value of $T = 1.10$ could be used for design purposes (Chastain and Schwartz, 1965).

A study of the regional influences on pavement behavior has been carried out in Texas to evaluate the factor, C_r , as given by Eq. (40) (Schrivner and Moore, 1966). A series of Dynaflect tests were taken on 188 flexible sections throughout the state and the results

correlated with those observed at the TTI Pavement Test Facility. Three regions of equivalent pavement behavior and corresponding design values of C_r were proposed. A continuation of this study divided the state into five regions and revised the regional factors (Schrivner and Moore, 1968). Although these values are applicable to the Texas design method, their relationship to the regional factor, R , was not given.

A blanket 15 percent increase in calculated structural requirements for use in Massachusetts highways was proposed due to frost problems, construction techniques, material differences and long term effects (Tons, Chambers and Kamin, 1965). The increase, which is comparable to a regional factor of 3, was based primarily on judgement and experience. Further research into regional problems was proposed.

Studies into general environmental conditions and/or regional factor determinations were proposed by the satellite projects in Georgia, Virginia, South Carolina and Oklahoma.

7.3 The Significance of Regional Factors

A great deal of field and laboratory research has been carried out relating the effects of frost action, moisture content and temperature effects (Haley,

1963; Jumikis, 1967). The significance of environmental conditions on basic material strength was discussed in Chapter IV and V. However, judging by the results of recently completed projects, there has been very little progress in the development of specific regional factors.

A recent study, examining various aspects of the AASHO design method, revealed that misuse of the regional factor can lead to serious over or under design (McCullough and Van Til, 1968). The error between actual and anticipated road life increases rapidly with decreasing values of the regional factor. The study also pointed out that many methods currently used for estimating the required factors are based on the conditions as rainfall, frost depth, elevation, drainage and temperatures. In general, the development of these values relies chiefly on experience and judgement.

The concept of the regional factor is the least advanced and perhaps the most difficult to ultimately establish. Much further study will be necessary before environmental factors can be explained or reduced to the simple terms of the AASHO design scale.

VIII. SUMMARY

The development of the fundamental AASHO design equations express the underlying concepts of structural design, soil support, accumulated axle loads and regional effects. Basic understanding of the framework and inherent limitations of the analysis is required before the method can be applied with any degree of success.

The AASHO performance equations, and those resulting from additional research, emphasize the importance of the performance criteria as a means of evaluating the suitability of a highway. The use of mathematical models describing deterioration have lead to techniques for predicting pavement life, assessing material strength and understanding composite behavior. The need for better serviceability measuring devices is currently receiving much attention.

The evaluation of material strength is of primary importance to researchers and highway engineers. Values of the structural coefficients for various surface, base and subbase materials resulted from the statistical analysis of the data observed at the Road Test. It was the intent of the Design Committee that subsequent work, mainly by state satellite study programs, would develop testing methods to verify the existing values and find

new ones for material used elsewhere. Correlation studies using relatively standard testing techniques have only partially satisfied this demand.

Since currently employed conventional testing methods generally examine only one limited strength parameter and are applicable to one type of material, much emphasis has been placed on developing laboratory and field tests which more closely approximate the in-situ conditions. The purpose of such tests is to determine the equivalent strength of a variety of material types under realistic loading conditions. Equivalencies based on different types of dynamic moduli obtained from repeated-load or seismic tests are under current examination.

The need for a better rational approach to pavement behavior has lead to extensive examination and use of multi-layer, elastic solutions. Although not altogether successful, combined field, laboratory and theoretical studies have greatly increased the understanding of significant interrelationships between the many factors involved in pavement behavior.

The support properties of the roadbed have to be expressed in terms of the AASHO soil support factor. Various standard testing techniques, such as R-value or triaxial tests, have been used to formulate correlation charts. Interestingly enough, no significant developments

have been made in using field testing techniques to evaluate the soil support factor.

The AASHO design method is based on prior knowledge of the loading conditions over the life of the highway. Furthermore, the estimated mixed traffic must be reduced to standard 18 kip equivalent axle loads by traffic equivalency factors. The number and distribution of various types of traffic is found by count and loadometer studies. This information may be reduced and projected over the design life by a number of currently available methods.

Guidelines were suggested by the Design Committee for specifying the regional factor based on general environmental conditions. It was originally intended that this factor could best be defined by individual studies in each state. As a whole, although most states understand their particular environmental problems and compensate for them in design methods, little success has been met in developing a rational method for finding the AASHO regional factor.

IX. CONCLUSION

The AASHO design method, either in part or in total, has received widespread acceptance throughout the country. The rapid acceptance and adoption of the design method pointed out the need for a comprehensive national road test research program whose magnitude exceeded anything which could be accomplished by individual states. The AASHO Road Test has perhaps been the most significant single event in the history of roadbuilding for it offered, in addition to the design method, opportunities to explore new methods of analysis and to develop new equipment and testing techniques. Further, the Road Test has served as the chief stimulus for highway research over the past decade.

However, the AASHO design method does have serious drawbacks and limitations, many of which lie within the fundamental approach, scope and analysis of the results. Pavement behavior was established primarily on a statistical basis. As a consequence, terms such as the structural coefficients have no direct physical or rational basis and cannot be reproduced, or even correlated completely successfully, with existing methods. In addition, the Road Test was conducted in one environment and on one roadbed. The necessary elements of soil

support and regional factor were only indirectly evaluated in terms of arbitrary mathematical models. As with the structural coefficients, the soil support and regional factors do not readily lend themselves to rational analysis and experimental evaluation.

Although important advancements have been made, especially in the area of material strength, no one satellite study program has successfully covered each aspect of the design method. More significantly, several states which are most active in highway research, such as Texas and California, have not adopted the design method.

A recent study of current practice pointed out that many states use the AASHO method without modification, and develop the necessary terms mainly on the basis of experience and judgement (McCullough and Van Til, 1968). The serious ramifications of errors in any one of the required variables have been demonstrated by the study.

Current literature indicates a trend towards more fundamental research in basic material behavior. At present, factors which govern the strength of individual types of materials are not fully understood. Furthermore, theoretical, field and laboratory tests have all clearly established the highly complex nature of the soil-pavement system. Additional problems, such as environmental in-

fluences, long term loading conditions and the effects of mixed traffic, require much further study.

The use of theoretical multiple layer, elastic solutions has shown promise as a means of finding significant trends in behavior. Ultimately, material properties may be defined well enough and the existing theories modified to the extent that actual pavement behavior may be rationally defined.

The satellite study programs and parallel research have contributed greatly to the understanding of highways, but have as yet failed to establish the necessary testing techniques and methods of analysis required for a satisfactory evaluation of the variables required by the AASHO design method.

X. FIGURES

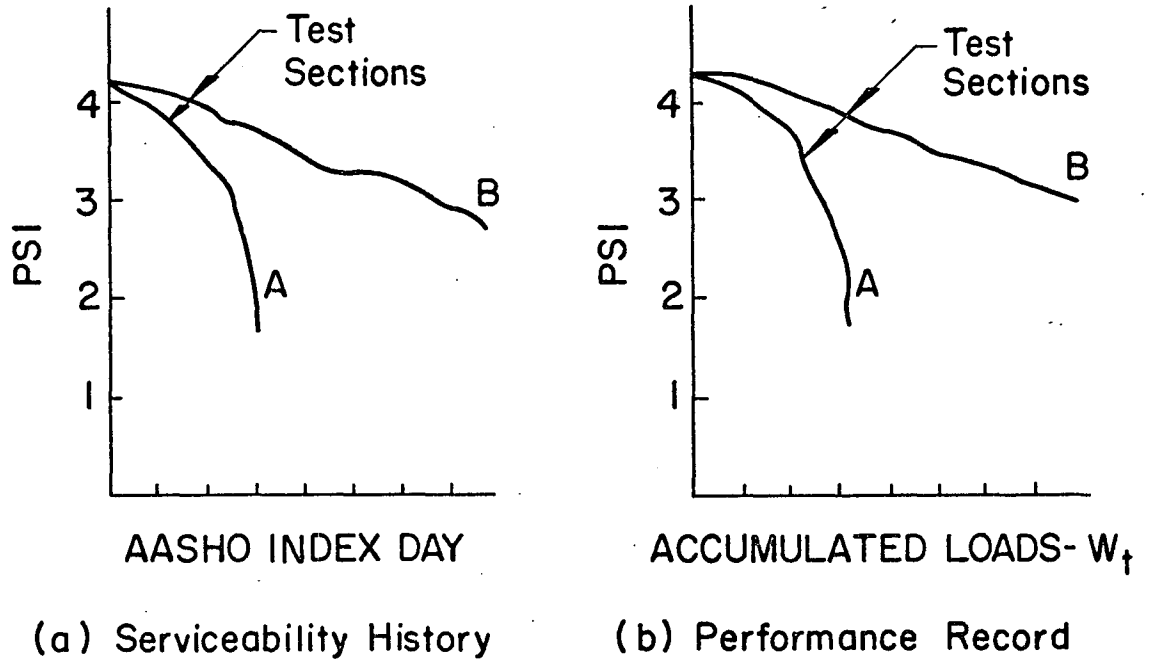


Fig. 1 Graphical Expressions of Performance

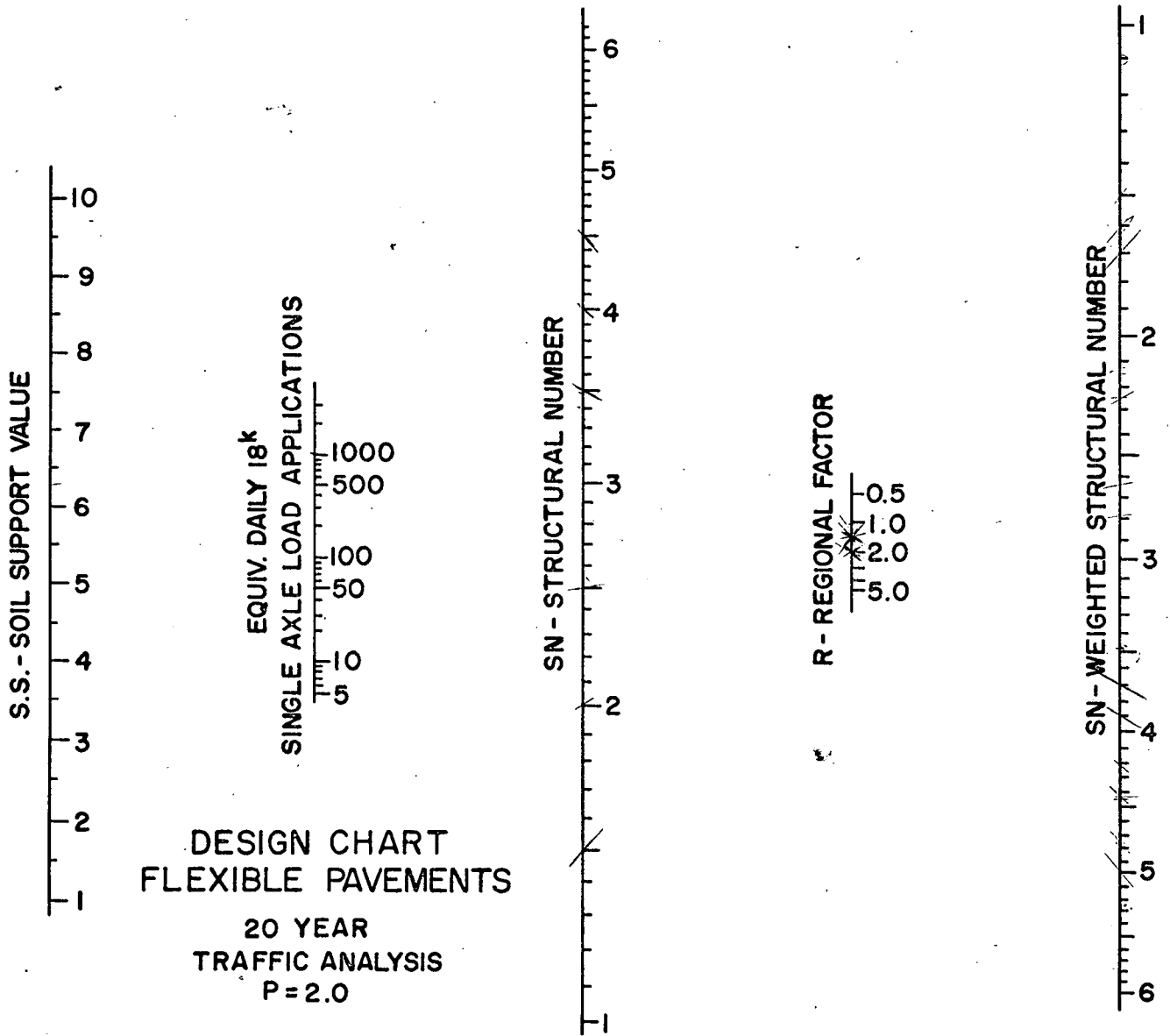


Fig. 2 AASHO Design Chart

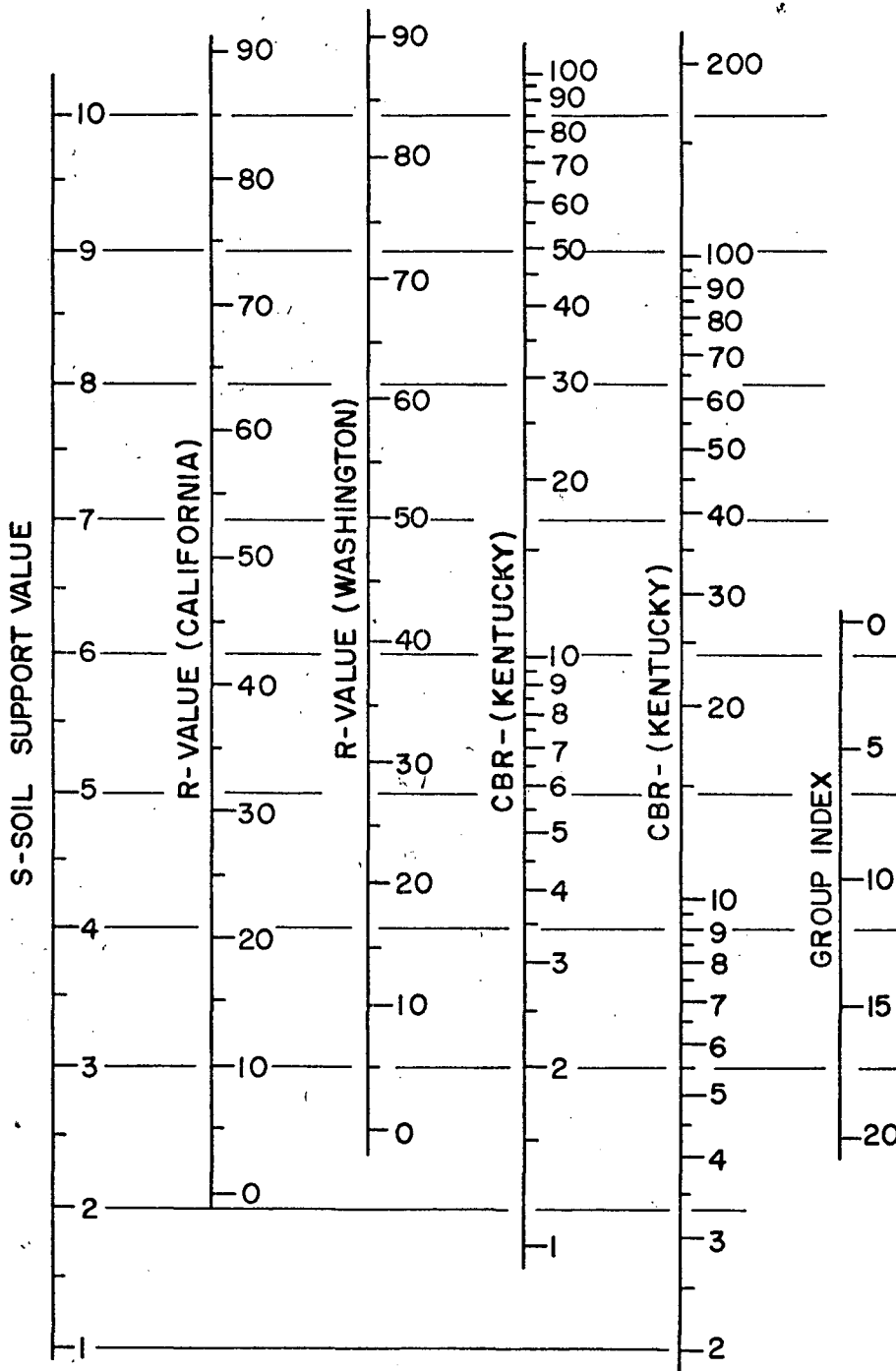


Fig. 3 AASHO Correlation Scale for Soil Support Values

XI. TABLES

DEVICE	REFERENCE
AASHO Slope Profilometer	HRB Special Report 61E, 1962
CHLOE Profilometer	Carey, Huckins and Leathers, 1962
BPR Roughometer	Yoder and Milhous, 1964
Minnesota Roughometer	Kersten and Skok, 1968
PCA Roadmeter	Brokaw, 1967
Kentucky Accelerometer	Rizenbergs, 1961
General Motors Profilometer	Spangler and Kelly, 1965
Univ. of Michigan Profilometer	Housel, 1962
Purdue Tire Pressure Measurement Device	Wilson, 1964
Mays Road Meter	Phillips and Swift, 1969
Texas Texture Meter	Scrivner and Hudson, 1964

Table 1. Devices Related to Performance Determinations

COEFFICIENTS¹ OF PAVEMENT COMPONENTS

Pavement Component	a ₁	a ₂	a ₃
Surface course:			
Roadmix (low stability)	0.20		
Plantmix (high stability)	0.44*		
Sand asphalt	0.40		
Base course:			
Sandy gravel		0.07 ²	
Crushed stone		0.14*	
Cement treated (no-soil-cement):			
650 psi or more ³		0.23 ²	
400 psi to 650 psi		0.20	
400 psi or less		0.15	
Bituminous treated:			
Coarse graded		0.34 ²	
Sand asphalt		0.30	
Lime treated		0.15—0.30	
Subbase:			
Sandy gravel			0.11*
Sand or sandy-clay			0.05—0.10

¹It is expected that each State will study these coefficients and make such changes as their experience indicates necessary.

²This value has been estimated from AASHO Road Test data, but not to the accuracy of those factors marked with an asterisk.

³Compressive strength at 7 days.

TABLE 2. Proposed AASHO Structural Coefficients

XII. NOMENCLATURE

A, A_0'	Intercepts of linear plot
A'	Cross sectional area of plate
A_0, A_1, A_2, A_3	Mathematical constants
A_1	Slope of linear plot
A_0'', A_1''	Mathematical constants
B	Slope of linear plot
B'	Mathematical constant
B_1'	Slope of a performance index equation
B_0, B_1, B_2, B_3	Mathematical constants
C_R	Regional coefficient
D	Structural design term
D_1, D_2, D_3	Layer thickness of surface, base and subbase
D_t	Illinois structural number
E	Dynamic modulus of elasticity
E_s	Dynamic stiffness modulus
E_s'	Dynamic modulus of soil
E_1	Modulus of elasticity of layer 1
E_2	Modulus of elasticity of layer 2
$ E^* $	Complex modulus
F	Applied dynamic force
F_w	Dimensionless constant
G	Logarithmic expression of serviceability terms
G_s	Equivalency grading

I	Moment of inertia
K	AASHO design formula term
K', K'', K''', K_0	Proportionality constants
L_1	Nominal axle load
L_2	Axle code
L'	Axle load and configuration term
L_A	Allowable spring axle load
L_d	Axle load used for test
M_R	Modulus of resilient deformation
N, N'	Material constants
P	Applied load on plate
PSI	Present serviceability index
Q	Performance expression in terms of 18^k EAL
Q_L	Performance expression
R	Regional factor
R'	Elastic stiffness
R_i	Axle load equivalency ratio
S	Measure of composite strength
SS, SS_1, SS_0	Soil support
SN	Structural number
S_1, S_2, S_3	Strength coefficients
S'	Dynamic stiffness expression
T	Time exposure factor
TDI	Texas Design Index
V	Wave velocity
W_t	Accumulated axle loads at time = t
$W_{18}, W'_{18}, W''_{18}$	Accumulated 18^k axle loads at time = t

W_t^*	Accumulated axle load term
X	Observed value of $\log W_t$
\bar{X}	Average of observed values of X
Y	Observed value of $\log \log \frac{P_o}{P_t}$
\bar{Y}	Average of observed values of Y
Z	Pavement displacement
a	Specimen dimension
a'	Elastic property of roadbed
a_1, a_2, a_3	Structural coefficients
a_4	Subgrade strength coefficient
a'_1, a'_2, a'_3	Structural coefficients
a'_4	Subgrade strength coefficient
a'_o	Mathematical term
a_s	Function of subgrade strength
b, b', b'', b_o	Deterioration rate parameters
d	Benkelman Beam deflection
d'	Observed deflection
d_a	Allowable spring Benkelman Beam deflection
d_s	Predicted Benkelman Beam deflection
h	Depth of upper layer
l	Specimen length
m	Plate-load perimeter shear
n	Developed plate-load pressure
P_o	Initial serviceability index
P_t	Present serviceability index
P_l	Terminal serviceability index
q	Elastic property of a roadbed

r	Radius of plate
r_1, r_2, r_3, r_4	Ratios of relative material strength
r'	Mathematical term
s	Applied plate-load pressure
w	Surface deflection from plate-load test
β, β_o	AASHO design formula terms
γ	Density
ϵ_o	Vertical strain
ϵ_r	Recoverable axial strain
θ	Sum of vertical and lateral stresses
μ	Poisson's ratio
ρ	Terminal number of axle load applications
σ_o, σ_1	Applied vertical stresses
σ_2, σ_3	Lateral confining stresses
σ_d	Repeated deviator stress
ϕ	Function relating seismic expressions

XIII. ACKNOWLEDGEMENTS

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The investigation was carried out under sponsorship of the Pennsylvania Department of Transportation. Sincere appreciation is expressed to this organization for their support.

APPENDIX A

Annotated Bibliography

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Stress Repetitions in Pavement Design,
Journal of the Aero-Space Transport Division, ASCE,
Vol. 91, No. AT2, Proceedings Paper 4489, pp. 29-37,
October 1965.

If repetitions of stress or load are now (as of 1965) important in pavement design, they must always have been important in design; they have not suddenly become significant, when they were not formerly so, because of a recent research finding or other technical development. In fact, many designers have long recognized the need to differentiate between heavily and lightly trafficked pavements in regard to design strengths. It is true, however, that recent findings and developments are making inadequate the mere recognition of such categories as "heavily traveled" or "primary". Past methods and knowledge requiring only crude determinations of stress repetition will no longer suffice. Although precise determinations of stress repetitions may not be possible, future progress demands better means of realistically determining quantities and effects of load repetitions. Various problem areas involved in determining quantities and effects of stress repetitions are delineated.

6. Brokaw, M. P.
Development of the PCA Road Meter: A Rapid Method for
Measuring Slope Variance,
Highway Research Record No. 189, pp. 137-145, 1967.

Results of the AASHO Road Test were determined in part by measurements of variations in longitudinal slope of pavement surfaces as made by the AASHO Profilometer. Later, a device known as the CHLOE Profilometer was developed by members of the Road Test staff to afford a less expensive method for measuring slope variance. Both profilometers operate at a speed well below that of traffic. Highway tests can be made only with extreme precautions that are costly to the operating agency and traveling public. Furthermore, the devices require multiple operating personnel, are expensive to acquire or construct, and neither is able to survey large mileages of pavement in a short time.

The PCA Road Meter was developed to afford a rapid method for measuring slope variance. The method uses a simple electromechanical device, installed in a conventional passenger automobile, which measures the number and magnitude of road-car deviations. These are statistically summed and correlated with slope variance measured by the CHLOE Profilometer. The test automobile can be operated at speeds consistent with traffic and without extra personnel.

Brokaw, M. P. (cont.)

The PCA Meter is not difficult to construct, is inexpensive, and has been tested and compared during the period from June 1965 to July 1966 in thousands of miles of highway use. At present, it is being used in extensive studies of pavement performance for the Portland Cement Association.

In this paper, the basic mechanical and electrical features are described, results of correlative tests with the CHLOE Profilometer are presented, and physical limitations are defined and discussed.

7. Broms, B. G.

Effect of Degree of Saturation on Bearing Capacity of Flexible Pavements,
Highway Research Record No. 71, pp. 1-14, 1965.

The bearing capacity of flexible pavements is frequently governed by the bearing capacity of the subgrade soil. The bearing capacity of the subgrade is reduced considerably during the spring breakup period due to reduction in the relative density and increase in the degree of saturation. A method for the evaluation of the bearing capacity of partially saturated soils has been developed. The effects of the apparent shear strength parameters c' and ϕ' , the pore pressure coefficients A and B , the coefficient X , the coefficient of lateral earth pressure at rest K_0 , and the location of the initial groundwater table have been investigated. The method is based on the assumption that the rate of loading of the subgrade soil caused by moving traffic loads is rapid enough that no or very small changes in moisture content of the subgrade soil take place during loading.

14. Carneiro, F. B. L.

Benkelman Beam - Auxiliary Instrument of the Maintenance Engineer,
Highway Research Record No. 129, pp. 28-53, 1966.

The aim of this paper is to demonstrate how deflections measured by a Benkelman beam can assist the maintenance engineer in evaluating the structural condition of pavements in terms of required maintenance.

This paper describes methods of measuring deflection using the Benkelman beam, analyzes the disadvantages of the methods used on the WASHO Road Test, and presents the method used by the Canadian Goods Roads Association, which we propose be standardized and adopted in Brazil.

The author also discusses modern methods currently used to design and plan pavement overlays, and describes the types of data which must be obtained in Brazil.

16. Chastain, W. E., Sr. and Schwartz, D. R.
AASHO Road Test Equations Applied to the Design of Bituminous Pavements in Illinois, Highway Research Record No. 90, pp. 3-25, 1965.

This paper is concerned with the work done in applying the findings of the Road Test flexible pavement research to the structural design of bituminous pavements in Illinois. It presents background information and concepts used in developing the design procedure, describes the development of the procedure, and demonstrates its application.

The procedure provides for establishing the types and thicknesses of materials to be used in the various layers of the pavement structure consistent with the volume and composition of traffic, the length of time the pavement is to serve this traffic, the strength characteristics of the subgrade soils and pavement materials, and the minimum level of service to be provided by the pavement during its lifetime.

The AASHO Road Test flexible pavement performance equation serves as the basis of this design procedure. The equation explains performance of the test sections as related to pavement design, the magnitude and configuration of the axle load, and the number of axle-load applications. This equation necessarily is limited to the physical environment of the project; to the materials used in the test pavements; to the range in pavement thicknesses included in the experiment; to the axle loads, number of axle-load applications, and the specific times and rates of application of the test traffic; to the construction techniques employed; and to the climatic cycles experienced during construction and testing of the experimental facility. To apply the equation in the design of regular highway pavements, it was necessary to make certain assumptions and extrapolations based on experience and engineering judgment. As additional knowledge is gained through further research and experience, the precision of these assumptions and extrapolations should become sharpened. Therefore, the design procedure presented herein is provisional in nature and is subject to modification based on additional experience and research.

17. Chu, T. Y. and Humphries, W. K.
Application of AASHO Road Test Findings to the Design of Flexible Pavement Structures in South Carolina, Highway Research Record No. 131, pp. 87-106.

Field and laboratory investigations conducted in South Carolina for the development of a tentative procedure involve the use of undrained triaxial tests for evaluating the modulus of deformation of subgrade materials. From this modulus, the soil support value of a subgrade is determined, permitting the application of the AASHO Interim Guide general design procedure to the design of flexible structures in South Carolina.

18. Coffman, B. S.

Pavement Deflections from Laboratory Tests and Layer Theory, Proceedings, Second International Conference on the Structural Design of Asphalt Pavements, August 1967.

The primary purpose of this work has been to provide a basic understanding of the behavior of the component materials in flexible pavement systems under loading.

The concept of the frequency of loading as an important factor in considering material response was developed by Papazian. He defined the general stress-strain relationship of linear viscoelastic bodies in the frequency domain through use of the complex modulus. Following this development, laboratory tests were performed on the constituent materials of the AASHO Road Test pavements, and these test results were used to calculate the deflections measured on the test road. This previous work has provided the background for the present study.

The behavior of a flexible pavement system under loading represents a complex problem and is dependent on many variables. For simplicity, loading conditions may be divided into three classes:

- (1) Moving loads under which the pavement response is essentially elastic.
- (2) Stationary loads under which the pavement response is a complex function of time-dependent stresses and strains.
- (3) Acceleration loadings which can impose shear and/or normal forces on a pavement.

19. Coffman, B. S., Ilves, G. and Edwards, W.

Theoretical Asphaltic Concrete Equivalences, Highway Research Record No. 239, pp. 95-119, 1968.

Theoretical asphaltic concrete equivalences were calculated on a continuous hourly or fourth-hourly basis for a 245-day period. For these calculations equivalence was defined as that thickness of base necessary to replace one inch of surfacing for equal deflection. Deflections were calculated using the layer elastic theory and the results of static and dynamic lab tests of the pavement materials in the frequency domain. The materials investigated were two asphaltic concrete surfacings and three asphaltic concrete bases. The effect of testing specimens with H/D ratios of less than two was investigated. The subgrade was that determined from the 1960 trenchings at the AASHO Road Test and the continuous hourly temperature data were those reported by the Asphaltic

Coffman, B. S., Ilves, G. and Edwards, W. (cont.)
Institute. Continuous 19-kip single-axle loadings moving at 50 mph were assumed for the principle calculations. The effects of different loadings were examined as functions of weight, speed, time, and contact area together with the effects of different subgrades and layer thicknesses. It was concluded that there is no unique equivalence and that the inclusion of a failure term is necessary to the theoretical calculation of equivalence for given materials, environment and loadings.

20. Corman, R. and Miller, F.
Modified Rut Depth Gage,
Envirotronics Bulletin No. 2, 1969. (Available at
Envirotronics Corporation, P. O. Box 594, Bethlehem,
Pennsylvania 18015).

The modified rut depth gage is designed and constructed in a manner which enables the leg spread to be variable. The distance between the feet of the gage may be varied from one foot to six feet so that the gage may accommodate any wheel path distance.

21. Culley, R. W.
Evaluation of a Dynamic Deflection Determination System
(Lane-Wells Dynaflect),
Saskatchewan Dept. of Highways, Technical Report No. 4,
44 pp., October 1966.

A Lane-Wells Dynamic Deflection Determination System (Dynaflect) is evaluated as a replacement for Benkelman beam static loading deflection testing and as a research tool for determining dynamic deflections and associated engineering properties of pavement structure components. Correlation studies with the Benkelman beam indicated that a linear function was most significant, and a computer regression analysis provided the following equation as the most significant: Benkelman beam deflection (milli-inches) = 14 x Dynaflect deflection (milli-inches) + 0.002. The coefficient of correlation for this function was 0.735, not a high degree of correlation. Correlation studies with the CBR for newly constructed subgrades did not result in an acceptable degree of correlation. It is concluded that the Dynaflect has very good potential as a research system for determining strength and performance characteristics of pavement structure materials, but requires improvements to minimize downtime and reduce testing time before it can be used for routine deflection testing under Saskatchewan's operating conditions.

23. Deacon, J. A. and Deen, R. C.
Equivalent Axleloads for Pavement Design,
Paper presented at 48th Annual Meeting, Highway Research
Board, January 1969.

One significant means for evaluating the relative destructive effects of repetitive vehicular loading on highway pavements is the equivalent axleload (EAL) concept. To apply this concept to design situations, proper methods must be available for making valid predictions of design EAL's based on data gleaned from traffic volume counts, vehicle classification studies, and loadometer surveys. This paper reports on the development and testing of such a predictive method for rural highways in Kentucky. The problem was treated as three separate but yet interrelated parts: (a) development of proper methodology and identification of pertinent traffic parameters, (b) identification of relevant local conditions which serve as indicators of the composition and weights of the traffic stream, and (c) development of significant relationships between the traffic parameters and the local conditions. Percentages of the various vehicle types and the average EAL's per vehicle were selected as the most significant traffic parameters. They were empirically related by multiple-regression and other techniques to the set of local conditions, which included road type, direction, availability and quality of alternate routes, type of service provided, traffic volume, maximum allowable gross weight, geographical area and season. The resultant methodology was judged to be sufficiently accurate, simple, reasonable, and usable to satisfy the problem requirements. It is recommended for use, however, only when valid, long-term vehicle classification and weight data are unavailable for the route under investigation.

24. De Barros, S. T.
A Critical Review of Present Knowledge of the Problem of
Rational Thickness Design of Flexible Pavements,
Highway Research Record No. 71, pp. 105-128, 1965.

A study of the theoretical knowledge of the structural behavior of flexible pavements is reported. The limitations of present concepts of the elastic layer theory are discussed and means for developing better theoretical relationships are suggested. Several concepts of elastic models including two- and three-layer systems were studied. The hypothesis that flexible pavements are perfectly elastic appears to be valid for limited numbers of safe loads of short duration. However, for slow-moving or static loads large enough to nearly overstress the pavement, a rheologic model is more applicable. It was also determined that pavement layers lacking tensile strength may account for a large part of the difference between calculated and measured deflections and stresses.

De Barros, S. T. (cont.)

Also, there may be merit to an approach using an equivalent modulus of elasticity, E , for the system. In a discussion of Poisson's ratio it is concluded that although this parameter has little effect on calculated stresses, a value of 0.5 seems to be most appropriate for soils and pavements. A discussion of the effect of pavement rigidity on pavement deflections indicated that the deflection factor is most important. The layered system model of flexible pavements should be expanded to include the condition of zero tensile modulus of the component materials.

A well-documented history of the development of theoretical solutions for the design of flexible pavements for the period 1906 through 1962 is presented. At least five different theoretical approaches to the design of flexible pavements have been developed.

25. Dorman, G. M. and Metcalf, C. T.
Design Curves for Flexible Pavements Based on Layered System Theory,
Highway Research Record No. 71, pp. 69-82, 1965.

Use of the recently developed theoretical three-layer elastic theory has aided the development of a method for design of flexible pavements. A series of design curves is presented which show the relationship between the combined thickness of granular base and asphalt surface necessary to support heavy truck loading (18,000-lb axle load). Development of the theoretical curves is based on the use of the three-layer elastic theory. The curves have been created by methods similar to those described in a paper for the International Conference on the Structural Design of Asphalt Pavements. The provisional curves of the previous paper have been modified slightly and also expanded to include a fatigue factor. Principal assumptions of the design method are outlined.

Adequate design according to the present method is based on the prevention of failure at critical locations in the pavement structure. Consideration is given to extent of displacement (strain) in the subgrade, and magnitude of tensile strain at the base of the asphalt surface. The relative severity of these conditions governs the design of pavement. Within calculable limits, surface and base can be replaced by each other. Examples are given which demonstrate the use of these principles in the design of pavements for "weak" (CBR = 2.5) and "strong" (CBR = 20) subgrades.

26. Fang, H. Y.
Influence of Temperature and Other Climatic Factors on the Performance of Soil-Pavement Systems, International Symposium on the Effects of Temperature and Heat on the Engineering Behavior of Soils, Highway Research Record No. 103, pp. 173-185, 1969.

Typical climatic and environmental data obtained during the AASHO Road Tests are summarized. A brief description of the instruments, methods of installation, and measuring techniques are presented. The influence of temperature and climatic factors on the performance of soil-pavement systems are examined. They include the effect of the various cover conditions on the seasonal fluctuation of the ground water level, on the depth of frost penetration, and on the temperature in different parts of the soil-pavement system. In addition, the influence of temperature on the soil-pavement performance as reflected in surface strains and deflections is discussed. Finally, the seasonal fluctuation of strength characteristics of pavement components and of subsurface conditions are evaluated. It is suggested that the data available from the AASHO Road Test can provide a useful basis upon which to develop a more complete understanding of the performance of soil-pavement systems.

27. Fang, H. Y. and Schaub, J. H.
Analysis of the Elastic Behavior of Flexible Pavement, Proceedings, Second International Conference on Structural Design of Asphalt Pavements, August 1967.

Analysis of the elastic behavior of flexible pavement as measured by the rigid plate load test and the Benkelman beam deflection test results is reported. The experimental data for these tests were obtained from the AASHO Road Test, Ottawa, Illinois. The fundamental relations between pavement deflections and environmental variables are discussed. The correlations between pavement deflection and the strength of pavement components and subsurface conditions are presented.

A simple equation based on the elastic theory is developed. The modulus of subgrade reaction, K , can be easily estimated by the use of the equation if the thickness of the pavement components and pavement surface deflection as measured with the Benkelman beam are known.

An equation using nondimensional techniques based on methods of dimensional analysis is developed for analyzing the results of Benkelman beam deflection tests on flexible pavement.

Fang, H. Y. and Schaub, J. H. (cont.)

It is concluded that there is a close agreement, theoretically and experimentally, between the Benkelman beam and conventional test methods. It is suggested that the Benkelman beam could be adopted for general use for the evaluation of pavement performance and structural design of flexible pavements at a savings of considerable time and money.

28. Finn, F. N.

Factors Involved in the Design of Asphaltic Pavement Surfaces, National Cooperative Highway Research Program Report No. 39, National Academy of Sciences - National Research Council, 1967.

The purpose of this report is to present a comprehensive review of information related to factors which influence the design of asphaltic surfaces in terms of loading conditions, strength requirements, and mix properties. The report is mainly concerned with factors which are not as yet included in mix design requirements for asphaltic surfaces. Those factors specifically included are (a) rheological properties, (b) fracture or tensile strength, (c) thermal stresses, (d) fatigue characteristics, and (e) durability or long-term performance. A brief review of such factors as (a) designs for standing loads, (b) designs for braking and acceleration, and (c) designs for orthotropic bridge decks is also included.

30. Grubbs, E. C.

A Review of Literature Pertaining to the Development, Subsequent Evaluations and Current Use of the General AASHO Road Test Equation, Civil Engineering Department, University of Arkansas, Technical Report No. 1, 118 pp., January 1965.

This report constitutes a summary of the literature studied to date which pertains to the development of the actual flexible pavement road test equation, subsequent evaluations of the road test program and current methods used by agencies involved in design of roadways. A continual program of literature study with emphasis on new techniques and applications will be maintained throughout the life of the project. Supplements to this study will be assembled and included in the final reports of the various phases of the research project.

34. Helmer, R. A.

Results of Oklahoma Flexible Paving Research Project, Highway Research Record No. 71, pp. 39-68, 1965.

From 1955 to 1962 the Oklahoma Highway Department carried out an extensive investigation of previously constructed pavements.

Helmer, R. A. (cont.)

Plate bearing tests and Benkelman beam tests were correlated and the safe load-supporting ability of the pavements was determined. The effects of soils, climate, traffic and other factors on pavement depreciation and life were studied. A method to design the required thickness of flexible pavement was developed. A Soils Manual was published giving engineering and pedological soil information and the location of the principal soils in Oklahoma. Recently constructed projects giving unsatisfactory service were investigated and studies were made to determine the causes of poor pavement performance.

43. Huang, Y. H.

Chart for Determining Equivalent Single-Wheel Loads, Journal of the Highway Division, ASCE, Vol. 94, No. HW2, Proc. Paper 6213, pp. 115-128, November 1968.

A new chart based on Burmister's layered theory programmed for a high-speed computer is developed for determining equivalent single-wheel loads for flexible pavements. The equivalent single-wheel load is defined as a single wheel load which results in a maximum deflection in the subgrade equal to that produced by a set of dual wheels. A salient feature of the chart is that it takes the ratio of the moduli of elasticity of the pavement and subgrade into account and presents the results of a very involved problem in a simple manner. The equivalent single-wheel load for any combinations of pavement thickness, modulus ratio, wheel spacing, and contact radius can be obtained from the chart with simple calculation and interpolation. The chart shows that the equivalent single-wheel load increases appreciably with the increase in modulus ratio. Current practice of assuming pavements as homogeneous media always gives an equivalent single-wheel load which is too small and is not in line with the finding of the WASHO road test.

44. Huculak, N. A.

Evaluation of Pavements to Determine Maintenance Requirements, Highway Research Record No. 129, pp. 12-27, 1966.

Contrary to normal practice employed in the design and construction of a modern highway, the maintenance aspects of providing this facility are seldom based on adequate pre-engineering and evaluation data. Sufficient time is seldom available to perform a thorough diagnosis of the maintenance problem through conventional sampling and testing techniques. A method of pavement evaluation based on surface deflections and observed performance of existing routes is described and summarized in the form of charts which permit a ready appraisal of the problem as an aid in the establishment of maintenance warrants and highway planning.

45. Hudson, W. Ronald
High-Speed Road Profile Equipment Evaluation,
Highway Research Record No. 189, pp. 150-160, 1967.

The importance of evaluating the relative smoothness of pavements is well recognized in the highway profession but such evaluation is largely a matter of qualitative judgment. These evaluations are useful in serviceability-performance studies and in studies of mechanistic evaluation of pavements for structural adequacy. Pavement surveys are used by maintenance engineers, design engineers, and highway administrators to help make many decisions with reference to the highway system.

This paper discusses the parameters affecting the measurement of roughness profiles, the evaluation of these parameters by various techniques, and the importance of measuring these profiles at high speeds. Several types of available equipment are discussed and associated data-processing techniques are described.

46. Hutchinson, B. G.
A Conceptual Framework for Pavement Design Decisions,
Highway Research Record No. 121, pp. 1-14, 1966.

The purpose of this paper is to establish the elements necessary for a rational and conceptually complete pavement design system. In particular, a formal approach to the uncertainty of future pavement performance will be developed, as well as objective technique for incorporating the economic characteristics of pavement designs.

1. Current pavement design decisions are heavily biased by the personal experiences of individual designers, and the selection of an optimum solution to a pavement design problem is not always realized. No general framework has been established to date whereby systematic and objective comparisons of various pavement designs can be made.
2. The elements of a rational pavement design procedure have been established wherein both the technical and economic characteristics of designs, as well as the uncertainty of their future performance, are objectively accounted for.
3. The principles of statistical decision theory have been summarized, and the techniques for analyzing decision problems under uncertainty illustrated.

Hutchinson, B. G. (cont.)

4. The pavement design system has been formulated in terms of the framework provided by statistical decision theory, and the steps basic to this formulation have been described. The framework allows an objective and systematic comparison of possible solutions to design problems which is relatively free from the personal biases and immediate experiences of individual designers.

47. Hutchinson, B. G. and Haas, R. C. G.
A Systems Analysis of the Highway Pavement Design Process,
Highway Research Record No. 239, pp. 1-24, 1968.

This paper attempts to recognize in an explicit manner both the technological and economic attributes of pavements that are pertinent to their design. It demonstrates that a true rationalization of the highway pavement design process is best achieved through a comprehensive application of systems engineering principles. The principal objectives of the paper are (a) to provide a systems analysis of the highway pavement design process and to define each of the elements of this process; (b) to suggest methods for organizing existing information on each of these elements, to explore the deficiencies of available information, and to suggest methods for the systematic collection of information, its storage, retrieval, and analysis; and (c) to provide some preliminary discussion relating to a sensitivity analysis of the pavement design process, which will provide an ordering of the probable payoff that is likely to accrue from information generated on the various subproblems.

The paper is essentially divided into two major sections. In the first section, existing design procedures are reviewed and the current philosophy of pavement design and the deficiencies of these methods are discussed. A comprehensive systems analysis of the highway pavement design process is described in the second section, along with some of the requirements pertinent to a sensitivity analysis of the process.

50. Isada, N. M.
Detecting Variations in Load-Carrying Capacity of Flexible Pavements,
National Cooperative Highway Research Program Report No. 21,
National Academy of Sciences - National Research Council, 1966.

Isada, N. M. (cont.)

The study reported herein was made to determine the feasibility of detecting seasonal variations in the load-carrying capacity of flexible pavements by using an impulsive loading technique. The study was implemented in three phases: 1) analytical investigations to establish the applicability of impulsive loading techniques; 2) the design and construction of a towable impulse generator, a portable dynamic displacement transducer, and instrumentation and recording equipment; and 3) a series of field tests. It is concluded that the impulsive loading technique is a feasible method of detecting seasonal variations in the load-carrying capacity of flexible pavements, the first peak deflection indicated by the dynamic displacement transducer being the most promising variable to be measured. The technique appears to be a promising method of distinguishing a poor road from a good one.

51. Jimenez, R. A.

Bending Strength of Asphaltic Concrete,
Texas Transportation Institute, Texas A & M University,
Research Report No. 32-6, 50 pp., August 1966.

Pavements were examined for application of the AASHO findings to Texas conditions. In this program, samples of surfacing were taken for laboratory measurements to assign or determine values of a_1 . Several sections in the study were sampled for evaluation with both static (cohesiometer) and repeated (deflectometer) test procedures. Variability between specimens within a test site and limited information on the paving materials resulted in a lower coefficient of determination, r^2 , between the factors A_0 and I_0 as compared to the laboratory specimens. Additional data secured from pavement samples obtained from the parent project and also from another Texas project are presented to show variations in permeability of new paving surfaces, viscosity of asphalt in pavement, and microductility values for asphalts recovered from old pavements.

55. Karrh, J. B. and Stephenson, H. K.

Application of AASHO Road Test Results to Alabama Conditions,
Alabama Highway Research, HPR Report No. 22, 93 pp., August 1967.

An investigation was made to determine how or whether the results of the AASHO Road Test might be applied to flexible pavement design in Alabama. Some 120 old test sections were located on existing Alabama highways and evaluated according to design and performance. Attempts were made to relate these two parameters in the AASHO model equation.

Karrh, J. B. and Stephenson, H. K. (cont.)

The results were uniformly unsuccessful primarily because of the heterogeneous nature of the base and subbase layers encountered. A layered system model was used, which satisfactorily related performance to design. Three regional performance areas were isolated within the study area. Utilizing the layered system solution as a basis for relating performance to design, it was found that an AASHO Regional Factor varying in value from 0.01 to 10.0 would be necessary to account for the extremes likely to be encountered in Alabama.

56. Kersten, M. S. and Skok, E. L., Jr.
Application of AASHO Road Test Results to Design of Flexible Pavements in Minnesota,
Paper presented at 48th Annual Meeting, Highway Research Board, January 1969.

The method presently used for flexible pavement design in Minnesota uses ADT and HCADT (heavy commercial average daily traffic) along with a designation of 5-, 7-, or 9-ton axle loads to categorize the traffic. The AASHO soil classification system is used to classify the subgrade soil in order to vary the required subbase thickness from sections designated for an A-6 subgrade soil. The relative strengths of the layers in the pavement section are indicated by gravel equivalent factors.

In order to make the results of the AASHO Road Test generally applicable to the design of flexible pavements it is necessary to determine the effect of different climate, subgrade soils and pavement materials. It is also necessary to adapt the language and concepts of the AASHO Road Test to the present method of design. It was decided to do this by establishing in-service test sections on trunk highways throughout the state. The performance, pavement section characteristics, subgrade strengths, and traffic for each of about 50 sections of road have been determined. These factors have been used to evaluate Minnesota flexible pavements and to recommend changes in the present design method.

58. Kondner, R. L. and Krizek, R. J.
Factors Influencing Flexible Pavement Performance,
National Cooperative Highway Research Program Report 22,
Highway Research Board, 1966.

One of the most significant findings presented in this report is the development of a trend between flexible pavement performance and local factors considered, such as pavement structural composition, applied load, and number of load applications. This development makes use of

Kondner, R. L. and Krizek, R. J.

the basic assumption that flexible pavement serviceability may be realistically represented by a present serviceability index (PSI) which has been correlated with a panel serviceability rating. The selected expression used to describe PSI as a function of number of applications, N , assumes that the rate of deterioration (that is, $\Delta\text{PSI}/N$) is constant during both years of the controlled traffic phase of the AASHO Road Test and that the very rapid deterioration associated with spring thaw periods may be represented by jump discontinuities at these times.

In general, both the rate of deterioration during the major part of the year and the abrupt deterioration associated with spring thaws may be expected to be functions of local factors as well as environmental and climatic conditions.

Nondimensional parameters are used in relating applied load, strength characteristics of the pavement components, bearing plate size, and pavement component thickness to surface, base, and subgrade deflections. Hyperbolic equations are used to represent the response. Correlation of actual results with those given by the equations developed are presented in graphic form.

59. Krizek, R. J.

Seasonal Variation in Flexible Pavement Deflections, Journal of the Highway Division, ASCE, Vol. 94, No. HW2, Proc. Paper 6250, pp. 219-228, November 1968.

A mathematical model is formulated to relate flexible pavement deflections to single-axle load, thickness of pavement components, and time (or season of the year). Plotting creep speed deflection versus time for the AASHO Road Test data reveals significantly higher deflections in the spring than in the winter. This behavioral pattern is described reasonably well by a sine wave of constant amplitude oscillating about a displaced horizontal base line. The assumptions of constant amplitude and horizontal base line are substantiated to some degree by data taken over a ten year period from seven highways in Maryland, but they are subject to modification as more data becomes available. The amplitude of the wave and level of the base line are then determined as functions of the thickness index and applied single-axle load, and correlation plots are given to indicate the reliability of the resulting mathematical model in predicting measured deflections.

60. Kruse, C. G. and Skok, E. L., Jr.
Flexible Pavement Evaluation with the Benkelman Beam,
Office of Materials, Minnesota Department of Highways,
Investigation No. 603, Summary Report 1968.

The purpose of this investigation was to determine the relationship between the Minnesota Quickie plate bearing test and the Benkelman beam test for predicting the allowable spring load, and to determine the relationship of the two test methods to load carrying capacity, pavement structure, and performance of county roads and municipal streets in Minnesota.

The study was begun in 1960. The field work consisted of conducting Minnesota Quickie plate bearing tests and Benkelman beam tests simultaneously for comparison. Soil borings were made to determine the thickness of the various pavement layers and the embankment type. Data analysis was performed largely by the Department of Civil Engineering, University of Minnesota, using a computer to perform multiple correlation analyses.

A mathematical correlation was developed between the Minnesota Quickie plate bearing test and the Benkelman beam test. However, the data scatter, or variance, is such that it cannot be recommended for use.

Correlations were also developed between the two test methods and pavement structures but again the data scatter is such that it cannot be recommended for use.

A method for determining allowable spring deflection with the Benkelman beam was developed from a literature survey and from a closely related field study.

It is a general conclusion of this investigation that the Benkelman beam can be a very effective tool for obtaining information which will be a valuable aid in making engineering decisions with respect to the strength of flexible pavements. It is recommended that Minnesota highway engineers strongly consider using a program of deflection measurements as an objective basis for evaluating the strength of their flexible pavements.

62. Lauzanne, J. L. and Tcheng, Y.
First Contribution to the Rational Design of Pavements,
Annales de l'Institut Technique du Bâtiment et Travaux
Publics (Société de Diffusion des Techniques du Bâtiment
et des Travaux Publics, 9 Rue La Pèrouse, Paris 15e),
Vol. 18, No. 209, pp. 669-708, May 1965. (In French).

Lauzanne, J. L. and Tcheng, Y. (cont.)

First, the authors describe original road model and measurement devices they used to determine characteristics of one- (sand) and two-layer (sand-cement, sand) systems and show testing difficulties and improvements. Second, they study the influence of Poisson's ratio on deformations by using computer CAB 500; it is an extension of Burmister's theory, usually used with Poisson's ratio of 0.5.

The principle conclusions are (a) in a one-layer system, sand presents an elastic behavior, and measured and theoretical deformation of the surface agree with a good approximation; and (b) with flexible disks and free finders, the behavior of the studied two-layer systems is also elastic, but measured and theoretical deformation do not agree. In practical cases, how does one make a choice of Poisson's ratio (μ_1 and μ_2)? As the case $\mu_1 = \mu_2 = 0.30$ corresponds approximately to mean values of obtained measurements of elastic module (E_1, E_2), authors will prepare detailed tables for this value 0.30.

63. Lettier, J. A. and Metcalf, C. T.

Application of Design Calculations to "Black Base" Pavements, Proc. Association of Asphalt Paving Technologists, Vol. 33, pp. 221-240, 1964.

A method of flexible pavement design based on principles of the theoretical three-layer elastic system has been proposed by Dormon. An outline of the method including design curves was presented to the International Conference on the Structural Design of Asphalt Pavements. Subsequently, the method was modified to include fatigue factors which permit the method to be used in the design of pavements for different traffic volumes.

Design by this method is based on limiting the magnitudes of strain at critical locations in the pavement to permissible values. Critical strains for design purposes are the compressive strain in the subgrade and the tensile strain at the base of the asphalt layer. Control of these values provides control over the pavement's ability to resist deformation of the subgrade and cracking of the surface. A brief resumé of the principles of the method demonstrates its application to design.

Theoretical design curves of the method show the combinations of thickness of asphalt layers and granular layers at which the strain values in the pavement are within acceptable limits. Because the method involves the relationship between separate layers, it provides a basis for preparation of alternate designs. These offer information by which specified thicknesses of granular material can be replaced by smaller thicknesses of black base.

Lettier, J. A. and Metcalf, C. T. (cont.)

Investigation of alternate designs provides additional information on equivalency ratios between asphalt and granular materials. Curves demonstrate that equivalent ratios do not remain constant but vary according to the thickness of asphalt layers and the strength of the subgrade. Calculations show that black bases have their greatest economic advantage in areas of weak subgrades. In addition, maximum equivalency ratios are developed by complete replacement of granular bases by black bases.

68. Moore, W. M., Scrivner, F. H., Poehl, R. and Phillips, M. B. Detecting Seasonal Changes in Load-Carrying Capabilities of Flexible Pavements, Paper presented at 48th Annual Meeting, Highway Research Board, January 1969.

The main effort of this research was directed toward finding an instrument capable of measuring, with speed, accuracy, and economy, seasonal changes in the strength of flexible pavements, and showing how it could be used in a program to protect pavements from overloading during critical periods. The instrument selected was the Dynaflect, a trailer-mounted device that loads the pavement dynamically and indicates the corresponding deflection at several points on the surface. One-man operated and towed by a passenger car, the Dynaflect appears to meet the requirements for the job. Tests were made with the Dynaflect on pavements at locations ranging from Springfield, Ill., northward to Duluth, Minn. The tests revealed that the annual strength history of pavements in northern climates is divisible into four distinct periods: (a) a period of deep frost and high strength, (b) a period of rapid strength loss, (c) a period of rapid strength recovery, and (d) a period of slow strength recovery. Periods b and c together constitute the critical period for flexible pavements.

A series of correlation studies indicated that Dynaflect measurements could be used, with reasonable accuracy, to predict the results of plate bearing tests and Benkelman beam deflection tests, as well as the curvature of the pavement in the vicinity of a heavy wheel load. Thus, the Dynaflect apparently could be substituted for other instruments being used to detect seasonal changes in strength. In addition, the Dynaflect "though not the most economical to operate", proved to be more sensitive than the other instruments to changes in strength. The research resulted in suggested warrants for deciding when, where, and how long to impose reduced load limits, and what those

Moore, W. M., Scrivner, F. H., Poehl, R. and Phillips, M. B. (cont.)
load limits should be. It appears that if these warrants were used to control the placement and removal of load restrictions, some reduction in the duration of the restricted period might result.

70. Nichols, F. P., Jr.

A Practical Approach to Flexible Pavement Design, Proceedings, Second International Conference on the Structural Design of Asphalt Pavements, August 1967.

The results of the AASHO Road Test are discussed with emphasis on the variability in published equivalency values for the several types of material included in that experiment. In spite of this variability, certain weighed average values have been considered as constants and are used as coefficients of relative strength in pavement design procedures patterned after the 1961 AASHO Interim Guide.

This paper points out the fallacy of constant equivalency ratios and cites the fact that, even on the same project, the relative strength ratio between the same two materials varies with the magnitude of load and, most particularly, with depth below the surface.

A more practical approach to a universal design procedure is proposed. Every design would include provision for: (1) permanently firm, non-resilient support at the subgrade level, to be assured where necessary by means of chemical stabilization, (2) a base course affording stability without brittleness, and (3) a binder-surface combination of high stability with adequate cohesion to resist horizontal shear stresses from acceleration and deceleration. Thicknesses would be essentially standard for standard materials under standard traffic loadings. Although minor thickness adjustments might be made where only non-standard materials are available, all three components should still be present, and overall thickness should be great enough to prevent overstressing the road-bed soil beneath the lowest improved layer.

The appendix contains a brief summary of the latest deflection and performance data from experimental sections on Virginia highways. The design recommendations are largely based upon these data.

71. Nowlen, W. J.

Techniques and Equipment for Field Testing of Pavements, Journal of the PCA, Portland Cement Association, Vol. 6, No. 3, pp. 43-55, September, 1964.

Tests of pavements in service supplement laboratory studies

Nowlen, W. J. (cont.)

of structural behavior and provide data to correlate with field performance. This paper considers some of the factors important in planning a field test program and describes equipment used to obtain strain, deflection, and other pertinent data.

74. Painter, L. J.

Analysis of AASHO Road Test Asphalt Pavement Data by The Asphalt Institute,
Highway Research Record No. 71, pp. 15-38, 1965.

This report is the result of the need, as foreseen by The Asphalt Institute, for independent analyses of the results of the AASHO Road Test. The Asphalt Institute took cognizance of this need in 1960 in setting up its Road Test Board of Study. The Institute reasoned that in an area so new, because of its vastly increased scope, examination of the research results from many different points of view could only help to shed still more light on the problem of adequate highway structural design.

In addition to the independent analysis of the AASHO Road Test presented here, the Road Test Board of Study was charged with developing thickness design relationships to be used in a revised edition of The Asphalt Institute's Thickness Design manual. The resulting thickness design method, distinct from but not unrelated to the work presented in this paper, is based on many sources of data besides the AASHO Road Test and has been reported elsewhere.

79. Quinn, B. E. and Hagen, K.

Problems Encountered in Using Elevation Power Spectra as Criteria of Pavement Condition,
Highway Research Record No. 189, pp. 166-181, 1967.

A power spectrum, calculated from highway elevation measurements, was used as a criterion for pavement condition. The criterion was influenced by the location, accuracy and spacing of the elevation measurements, and by the method used to determine pavement roughness from the variation in measurements. The influence of these factors on the resulting power spectrum was investigated, and the pavement condition criterion obtained from some of these spectra was compared with the corresponding BPR roughometer rating for certain highways.

The need is shown for a standardized procedure for obtaining elevation measurements and for making power spectrum calculations, if comparable criteria of pavement condition are to be obtained.

Quinn, B. E. and Zable, J. L.
Evaluating Highway Elevation Power Spectra From Vehicle Performance,
Highway Research Record No. 121, pp. 15-26, 1966.

A relatively new technique for describing the condition of a highway has been developed which consists of making a power spectral density analysis of elevation measurements obtained from the longitudinal pavement profile.

In calculating the elevation power spectrum it is necessary to make certain assumptions that influence the resulting spectrum. The question thus arises as to the validity of these assumptions.

A procedure is described in this paper that was used to obtain a pavement elevation power spectrum from dynamic tire force measurements. This involved the experimental determination of tire forces which were used as a criterion of vehicle performance.

The power spectrum obtained by this procedure is compared with power calculated from elevation measurements (using different assumptions) to check the validity of the assumptions.

84. Scrivner, F. H. and Moore, W. M.
An Electro-Mechanical System for Measuring the Dynamic Deflection of a Road Surface Caused by an Oscillating Load, Texas Transportation Institute, Texas A & M University, Research Report Number 32-4, 19 pp., December 1964.

This report describes a measurement system developed by the Lane-Wells Division of Dresser Industries, Inc. for the purpose of recording the deflection of a road surface caused by application of an oscillating load. The results of the investigation are included. The relatively high correlation coefficient is taken as good evidence that the system responds to those properties of a flexible pavement structure that govern the deflection of the pavement under heavy wheel loads. The device appears to be rugged, rapid, reliable and more economical to operate than other systems known to the writers, especially in cases where the objective is to determine the shape of the deflection basin.

88. Scrivner, F. H. and Moore, W. M.
Some Recent Findings in Flexible Pavement Research, Texas Transportation Institute, Texas A & M University, Research Report No. 32-9, 46 pp., July 1967.

The report is concerned primarily with two objectives:

Scrivner, F. H. and Moore, W. M. (cont.)

to correlate the average level of pavement performance determined from a two-year controlled traffic test, and to study the effect of weather and so-called regional effect throughout the state: and for flexible pavements, to determine approximate values of coefficients for representing Texas materials to replace the layer coefficients determined at the AASHO Road Test, and to develop relationships between these coefficients and material tests. With a significant regional effect evaluated, the net result of the research was an equation for deflections that contained: (1) "Field Compression Coefficient" for each layer dependent on both laboratory strength and regional effect, and (2) a "Depth Coefficient" for each layer (including the foundation layer) dependent upon the thickness of the layer and its position in the structure, the equation presumably could be used in the design of flexible pavements in Texas, if deflection criteria were made a part of the design procedure, and if the underlying causes of the regional effect were known.

89. Scrivner, F. H. and Moore, W. M.

Some Recent Findings in Flexible Pavement Research, Journal of the Highway Division, ASCE, Vol. 94, No. HW2, Proc. Paper 6252, pp. 229-254, November 1968.

This paper is based on sponsored research done by the Texas Transportation Institute on Texas highways. The results reported include: (1) The development of an empirical equation for estimating load-induced deflections from the thickness and laboratory-determined strength of the materials used in a highway pavement, and (2) the use of the equation, together with deflections observed on 323 highway test sections, to evaluate the regional effect in Texas. With a surprisingly large regional effect determined, the net result of the research was an equation for deflections that contained: (1) a "Field Compression Coefficient" for each layer dependent on both laboratory strength and regional effect, and (2) a "Depth Coefficient" for each layer dependent upon the thickness of the layer and its position in the structure. The equation presumably could be used in the design of flexible pavements in Texas if deflection criteria were made a part of the design procedure, and if the underlying causes of the regional effect were known.

85. Scrivner, F. H., Swift, G. and Moore, W. M.

A New Research Tool for Measuring Pavement Deflection, Highway Research Record No. 129, pp. 1-11, 1966.

This report describes the Lane-Wells measurement system,

Scrivner, F. H., Swift, G. and Moore, W. M. (cont.) gives the results of the preliminary investigation, and presents some data illustrating how the deflection basin is affected by variations in the structural design of the pavement. It also describes an improved model of the system developed in 1965 by Lane-Wells as a result of their experience in this research. The Lane-Well Dynaflect, developed after completion of the 1964 measurements program on Texas highways, consists of a small two-wheel trailer containing a dynamic force generator and equipped with a set of motion sensing devices. Deflections of the roadway, or other material beneath the trailer, caused by a cyclic downward force, are measured while the trailer is halted briefly at each test location. Deflections are read directly on the meter.

92. Seed, H. B., Mitry, F. G., Monismith, C. L. and Chan, C. K. Prediction of Flexible Pavement Deflections from Laboratory Repeated - Load Tests, National Cooperative Highway Research Program Report No. 35, National Academy of Sciences - National Research Council, 1967.

The investigation was initiated to attempt to predict the resilient deflections of pavement structures. The program involved the laboratory measurement of the resilient behavior of representative paving materials, field measurement of deflections of prototype pavements composed of the same materials as those tested in the laboratory, and the relating of the laboratory test results to observed deflections of the prototype pavements through available theory.

94. Skok, E. L., Jr. Use of Texas Dynaflect Apparatus on Minnesota Test Sections, Special Report No. 1 for Minnesota Highway Department Investigation No. 183, Department of Civil Engineering, University of Minnesota, 18 pp., November 1966.

This report will summarize the test procedures for the tests of ten Minnesota highway sections, list the results, and show correlations which have been obtained between the dynaflect readings, Benkelman beam deflections, and plate tests made on the same sections. Comparisons will also be made between Present Serviceability Ratings run during the summer and Present Serviceability Indices calculated with the readings from the CHLOE profilometer, the Texas roughometer, and the Minnesota roughometer. If the dynaflect device is to be used in Minnesota, a great deal of correlation work must be done between it and the plate bearing or Benkelman beam on Minnesota soils for immediate usefulness and some sort of performance study should be

Skok, E. L., Jr. (cont.)

established using the dynaflect for strength measurements for the most intelligent use of data from the device in the future.

95. Skok, E. L., Jr.

The Development of the Traffic Parameter for the Structural Design of Flexible Pavements in Minnesota, Paper presented at 48th Annual Meeting, Highway Research Board, January 1969.

At the present time traffic is evaluated for flexible pavement design in Minnesota using the total ADT and heavy commercial average daily traffic (HCADT). Heavy commercial traffic is defined as all trucks with six tires or more. To relate the performance of a number of sections of highway in Minnesota to the performance of the AASHO Road Test section, it was necessary to convert the mixed traffic sections to equivalent 18,000-lb axle loads. The three purposes of the study are: (a) to determine the total traffic in terms of the summation of equivalent 18,000-lb axle loads on each of the 50 Minnesota test sections since each was built, (b) to estimate a reasonable growth factor based on the data of the last 12 to 15 years, and (c) to correlate various traffic parameters to equivalent 18,000-lb axle loads for design purposes.

A traffic study which included weight and volume distributions at each test section was made three times throughout 1964 and once during the spring load restriction period in 1965. The rate of increase in equivalent loads has been studied over the last 12 years and it is concluded that a rate of increase of 8 percent is reasonable for an overall estimate, but that local conditions can cause a significant range in growth factor. The 1964 traffic study was used to correlate ADT, HCADT, and the daily sum of Types 4 and 5 (4-, and 5-axle trucks) to fairly equivalent axle loads. The errors in equivalent loads from predicting traffic by these three parameters have been related to gravel equivalent thicknesses. It was found that for design purposes the summation of Types 4 and 5 trucks could best predict equivalent axle loads, but that only a slightly poorer correlation resulted using the HCADT. The error in terms of gravel equivalent is about 1.2 in. which represents about 0.6 in. of asphalt surface.

Using the results of the traffic correlations back to 1956, the correlation between HCADT and daily equivalent loads has been studied and it has been found that the equivalent loads predicted from HCADT over the last ten years has had an annual increase between 4 and 26 percent depending on the span of years considered for the increase. Over a 10-year or longer period an increase of 5 to 8 percent is shown to be appropriate. This increase along with an

Skok, E. L., Jr. (cont.)

annual 3 percent increase in HCADT yields the growth factor of 8 to 11 percent. Using the results of this study the summation of equivalent 18,000-lb axle loads over a 20-year period represented by the present Minnesota traffic categories is calculated.

97. Southgate, H. F. and Deen, R. C.
Temperature Distribution Within Asphalt Pavements and its Relationship to Pavement Deflection,
Paper presented at 48th Annual Meeting, Highway Research Board, January 1969.

A method has been developed to estimate the temperatures at depth in an asphaltic-concrete pavement utilizing the measured pavement surface temperature and the 5-day average air temperature history. Temperature prediction nomographs were developed for each hour between 0600 and 1900 hours. This temperature prediction method is independent of calendar month and (or) season of the year. A method for adjusting Benkelman beam deflections for temperature effects has been developed and is presented. This enables the deflections taken at any temperature to be adjusted to a reference temperature, thus enabling direct comparisons of deflections.

An analysis of AASHO Road Test data was made using the Boussinesq and Burmister equations and charts. The results indicate that the temperature-modulus of elasticity relationship is curvilinear, has the same basic shape found by Kallas in the laboratory, and has the same basic shape as the temperature-deflection adjustment-factor curve. There appears to be a linear relationship between deflection factors and modulus of elasticity. Therefore, there seems to be a temperature-deflection-modulus of elasticity correlation between field test data and theory.

98. Sowers, G. F.
Georgia Satellite Flexible Pavement Evaluation and Its Application to Design,
Highway Research Record No. 71, pp. 151-172, 1965.

A study was made of the deterioration or failure of flexible pavements in all the geologic provinces of Georgia. The pavement serviceability was estimated visually and from measured rut depth. Total traffic was estimated from short-term counts and from data of nearby traffic stations. Laboratory tests were made of undisturbed samples of subgrade. The serviceability rating of the pavement

Sowers, G. F. (cont.)

was found to be a function of the computed safety factor of the subgrade against shear failure beneath the pavement and the amount of traffic. A similar analysis of the AASHO Road Test flexible pavement failures found a comparable relationship. The bearing capacity of the AASHO subgrade compared to those of the Georgia subgrades furnished the quantitative tie between the proposed AASHO design charts and Georgia materials and environment, and makes it possible to utilize the AASHO interim design for Georgia pavements. Alternatively, a direct design method can be derived for pavements from the traffic-soil bearing-serviceability relationship.

99. Spangler, E. B. and Kelly, W. J.

GMR Road Profilometer - A Method for Measuring Road Profile, Highway Research Record No. 121, pp. 27-48, 1966.

Accurate road profiles are often required for the analytical study of vehicle ride and vibration phenomena induced by road irregularities. The desire to bring profiles of existing roads into the laboratory has led to the development of a road profilometer for the rapid measurement of such road profiles. The continued interest in this device by persons engaged in highway design, construction and maintenance encouraged the authors to further develop and simplify this instrument and to make it available to these highway groups. This paper discusses the basic operating principle of the GMR profilometer, describes the unit supplied to the Michigan State Highway Department, and presents some typical test results.

102. Tons, E., Chambers, R. E. and Kamin, M. A.

Layered Pavement Design Method for Massachusetts, Highway Research Record No. 71, pp. 193-219, 1965.

A Method for the design of flexible pavements has been developed for Massachusetts. The method is simple, rational and practical, and can be applied immediately on a routine basis in the design office, yet is flexible enough to permit modification as indicated by future research. Data and analyses that evolved from the AASHO Road Test experiments were used as a guide in the development of the design method.

Straightforward conventional procedures have been selected to provide a value for soil support. Preliminary soils data are obtained from geological and soil maps, and borings and samples for test are taken as needed. Laboratory Bearing Ratio and other tests are performed. Test results and boring data are then used as a basis for a Design Bearing Ratio. Traffic factors are computed from anticipated traffic conditions and existing traffic and Loadometer data.

Tons, E., Chambers, R. E. and Kamin, M. A. (cont.)

The 18-K Daily Equivalent Axle Load is used directly as defined in AASHO procedures.

The Regional Factor as recommended by the AASHO guide was not adopted in its present form. This approach was deemed too specifically related to materials, soils and environment of the test site. To account for possible moisture, frost, traffic, time (aging) and other effects, a blanket increase of 15 percent in Structural Number was introduced. This increase probably approximates a reasonable Regional Factor. More study is needed in this area.

There are an infinite variety of layered pavement systems that will satisfy the strength requirements as dictated by a given soil and traffic. AASHO coefficients of relative strength of various materials for surface, base and subbase were adopted where possible. A new coefficient was derived for the penetrated base. The general design chart correlating DBR values with traffic and structural number permits the use of any type and thickness of surface, base, and subbase, provided the strength coefficient for each material is known. The pavement thicknesses obtained by using the derived design chart are reasonable when compared to past experiences in Massachusetts and other states.

103. Turbull, W. J., Ahlvin, R. G. and Brown, D. N.

Evaluation of Applicability of AASHO Road Test Results to Corps of Engineers Flexible Pavement Design Criteria, Proceedings, Second International Conference on the Structural Design of Asphalt Pavements, August 1967.

Various approaches were investigated in an effort to use the results of the AASHO Road Test completed in 1961 to validate or modify present Corps of Engineers (CE) flexible pavement design criteria. The AASHO Road Test results are not directly applicable for use in improving existing CE design criteria because sufficient data were not obtained during application of test traffic to determine material strength conditions, especially at failure.

The present serviceability index method of evaluating pavement performance, developed by the AASHO Road Test staff, appears to have considerable merit in quantitatively assessing pavement condition. However, the specific variables for which objective measurements are taken for use in this method of evaluation are not those normally considered in pavement design.

Turbull, W. J., Ahlvin, R. G. and Brown, D. N. (cont.)
The various approaches followed in attempting to relate the pattern of behavior represented by the AASHO Road Test results to the pattern inherent in the CE design procedures are explained and comparisons are shown. Mathematical patterns seem to be strongly parallel, but the specific field measurements needed to draw a direct comparison are lacking.

104. University of Minnesota
Use of Benkelman Beam Deflections to Determine Allowable Spring Tonnages,
Special Report No. 2 for Minnesota Highway Department Investigation No. 183, Department of Civil Engineering, University of Minnesota, 60 pp., 1967.

The purpose of this special report is to present a method of establishing allowable tonnages for Minnesota highways using data obtained from the three years of spring recovery testing on the test-highway sections. It is felt that if the beam deflection test could be established as a good tool for setting tonnages then a greater mileage of roads could be tested each year and a better amount of variation along a road could be obtained.

105. University of Minnesota
Traffic Analyses,
Special Report No. 3 for Minnesota Highway Department Investigation 183, Department of Civil Engineering, University of Minnesota, 60 pp., March 13, 1967.

The first part of this report is a presentation of the traffic study made on the test sections and analysis of data. The statewide weight distribution and volume distribution data for the year can be put into the computer program to bring the traffic for each test section up to date. In the second part of this report correlations have been made between equivalent axle loads, and (1) Average Daily Traffic, (2) Heavy Commercial Average Daily Traffic, and (3) Summation of types 4 plus 5 trucks. It is shown that the equivalent loads can be predicted with increasing accuracy using parameters (1), (2), and (3) in order as listed. The errors in these predictions are related to design thickness.

106. Vaswani, N. K.

AASHO Road Test Findings applied to Flexible Pavements in Virginia, Virginia Highway Research Council, University of Virginia, 1967.

The main purpose of this investigation was to conduct a pilot study for evaluating the strength coefficients of the different materials in the pavement system and correlate the strength coefficients with the pavement performance along with other variables such as soil support, traffic and age. Since the study was within a limited geographic area, the climatic and regional factors were considered constant, and hence the unweighted traffic - i.e., actual traffic not corrected for climatic conditions - was considered in the analysis.

Twenty projects with varying pavement structures, all in the Piedmont region of Virginia, were chosen for this study. All these projects are on primary or interstate roads. One is an experimental section on Route 360 with four different structural designs; another was an experimental project on Route 58 with four different structures of design. This project was resurfaced in 1962 and only the data collected on it prior to 1962 have been evaluated. Thus a detailed study of 27 different sections - without any resurfacing or heavy maintenance - was undertaken.

107. Vedros, P. J. and Brown, D. N.

Evaluation of the Applicability of AASHO Road Test Results to Corps of Engineers Flexible Pavement Criteria, U. S. Army Engineer Waterways Experiment Station, CE Technical Report No. 3-721, 42pp., November 1966.

Various approaches were investigated in an effort to use the results of the AASHO Road Test completed in 1961 to validate or modify present Corps of Engineers (CE) flexible pavement design criteria. The AASHO Road Test results are not directly applicable for use in improving existing CE design criteria because sufficient data were not obtained during application of test traffic to determine material strength conditions, especially at failure. The present serviceability index method of evaluating pavement performance, developed by the AASHO Road Test staff appears to have considerable merit in quantitatively assessing pavement condition. However, the specific variables for which objective measurements are taken for use in this method of evaluation are not those normally considered in pavement design. The various approaches followed in attempting to relate the pattern of behavior represented by the AASHO Road Test results to the pattern inherent in the CE design procedures are explained and comparisons

Vedros, P. J. and Brown, D. N. (cont.)

are shown. Mathematical patterns seem to be strongly parallel, but the specific field measurements needed to draw a direct comparison are lacking.

111. Washington Highways

WSU's Pavement Tester Takes to the "Road",
Vol. 12, No. 4, p. 15, May 1965.

A sprawling, three-legged giant on wheels that goes nowhere but will travel millions of miles during the next few years took its maiden drive recently. The purpose of the newly developed facility at Washington State University is to test full strength and full thickness experimental highway pavement sections built in a circular tract by applying total truck weight wheel loads on conventional wheels and tires. When one set of experimental pavement is tested to destruction, it will be removed and replaced with another.

A 15-ton structural steel frame and water tank revolving over an 83-ft diameter ring of pavements applied a 10,000-lb load to each of three sets of dual wheels. Water can be added to the tank to bring the total load of each set of wheels to 20,000 lb. The facility cost about \$100,000, not including the cost of land, engineering, development, and operation. The tester is designed to turn in either direction at from 15 to 55 mph, with a normal operating speed of 35 mph. At this speed approximately 3,200 wheel load repetitions per hour are applied to the pavement. A million passes of a legal-limit truck load should indicate what the pavement will do.

A 6-ft wide reinforced observation gallery is located on a quarter circle arc just inside the inner edge of the pavement and under the level of the pavement surface.

115. Yang, N. C.

Systems of Pavement Design and Analysis,
Highway Research Record No. 239, pp. 25-47, 1968.

An analytical system is advanced for the design of new pavement based on the introduction of vehicle response as an important design parameter; the integration of design theories governing "rigid" and "flexible" pavements; and the tolerance of surface deformation and stress intensity in the pavements as well as in the subgrade. The system completely defies traditional design practice, but represents the collective work of theoreticians, practical engineers, material specialists, construction inspectors and maintenance crews. An even more important factor is the contribution of the pavement user who accepts the level of vehicle response and the one who pays the cost of construction.

117. Yoder, E. J. and Walker, R. D.
Evaluation of the AASHO Profilometer for Measuring
Airfield Pavement Profiles,
U. S. Army Cold Regions Research and Engineering Laboratory,
Special Report 96, 22 pp., April 1966.

The purpose of this study was to determine the capability of the AASHO profilometer to measure airfield pavement profiles. To accomplish this, a number of test tracks were established on pavements at Chanute AFB, Rantoul, Illinois, and profiles obtained with the AASHO instrument were compared with those obtained using standard precise level procedures.

It is apparent that the accuracy of the profilometer is to a large extent dependent on the accuracy of the horizontal reference system. Results of the tests indicate that the differences between level and profilometer data are the result of accumulated errors in the horizontal reference system; however, the reason for the errors did not become apparent during the course of this study. There appears little doubt that the use of a precise gypsometer would eliminate most of the accumulated errors introduced by the present reference system.

118. Zube, E. and Forsythe, R.
An Investigation of the Destructive Effect of Flotation
Tires on Flexible Pavement,
Highway Research Record No. 71, pp. 129-150, 1965.

As a result of the increased usage of flotation or "wide base" tires in lieu of the normal dual-wheel configuration during the last three years, an investigation has been completed to compare the relative destructive effect or to determine the single-axle loading which would produce the same destructive effect as that resulting from the dual-wheel single-axle legal loading of 18,000 lb. The two criteria of destructive effect selected for this investigation were pavement deflection and strain. Deflection measurements were made using linear variable differential transformer gage installations and the Benkelman beam. Pavement strain measurements were made using SR-4 strain gages attached to the top and bottom of the AC surfacing. Test sites with widely varying structural sections were selected for this study. Analysis of strain and deflection data indicates that the destructive effect of a flotation tire with a single-axle loading of 12,000 lb equals or exceeds that of the dual-wheel configuration at an axle loading of 18,000 lb. Relationships between tire pressure, pavement temperature, axle loading, pavement deflection, surface tensile strain, and type of wheel loading are presented.

119. Zube, E. and Forsythe, R.
Flexible Pavement Maintenance Requirements as Determined
by Deflection Measurement,
Highway Research Record No. 129, pp. 60-78, 1966.

The prime purpose of these investigations was the recommendation of the appropriate corrective treatment. As a result of this intensive program, a large volume of data on the deflection attenuation properties of various roadway materials has been accumulated and is presented in this report, along with the results of individual deflection studies. The test procedure, method of evaluation of deflection data, and design criteria which have evolved are examined in detail. In addition, economical and practical factors involved in making a specific recommendation are discussed. A separate section of the report is devoted to a review of current deflection research including work we are now carrying out on the establishment of maximum deflection criteria which may be adjusted for variations in traffic volume. A brief analysis of radius of curvature data obtained with the Dehlen "curvature meter" is also included.

APPENDIX B

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