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Development of a Rationally Based AASHO Road Test Algorithm

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A new design algorithm for flexible pavements that uses performance data from the AASHO Road Test and layered-elastic theory is described. The algorithm, developed by correlating road test data with subgrade vertical strain calculated by the layered-elastic program ELSYM5, allows the characterization of seasonal variation in pavement strength and traffic volume and is implemented in a pavement design and management system. A comparison between the original design equation and the subgrade strain algorithm indicates that the latter is about 5.6 percent more accurate in correlating with road test performance data. However, the major advantage of the subgrade strain algorithm is that the pavement is characterized by using the modulus of elasticity of each layer, which allows consideration of seasonal variation and is a more rational basis for the extrapolation of results. When implemented in a pavement management system, the algorithm considers different axle loads separately by using the concept of cumulative damage; thus there is no need to convert mixed traffic to equivalent axle loads. It was also found that equivalent axle loads can vary significantly with different pavement structures.

Today in the United States many flexible pavements are designed or evaluated by using the procedure developed from the AASHO Road Test, i.e., the American Association of State Highway and Transportation Officials (AASHTO) Pavement Design Guides (1). This method and many other design methods are fundamentally empirical and therefore restrict the conditions under which the methods may validly be used. Some of the most difficult restrictions that engineers have had to overcome are conversion of mixed traffic into a single unit, such as 80-kN (18-kip) equivalent single-axle loads; consideration of seasonal variation in pavement strength; adjustment for different regional climatic conditions; and characterization of the relative strengths of different pavement materials.

In an effort to eliminate some of these restrictions, the Transportation Group at the University of Texas at Austin has developed a new design algorithm for flexible pavements. The algorithm is based on the relationship between compressive strain at the top of the subgrade and number of repetitions to a terminal level of serviceability derived from the AASHO Road Test data. This development, sponsored through a cooperative agreement with the U.S. Forest Service, was carried out as part of a project to improve an existing pavement design and management system (PDMS) also developed at the University of Texas (2). The design problems mentioned above are critical to U.S. Forest Service engineers, who design and manage a road network of more than 320 000 km (200 000 miles). Of particular importance to these engineers is the consideration of seasonal variation in pavement strength and in traffic volume. Forest roads, and even many state and county roads in northern climates, often have axle-load restrictions during spring thaw periods because of the weakened condition of the pavement. The improved pavement management system will make it easier for engineers and planners to evaluate the economic trade-offs involved in these spring restrictions.

This paper explains how the new design algorithm was developed and compares results with the AASHTO design method. Applications are discussed, particularly those that consider seasonal variation. Conclusions and an outline for further research are summarized at the end of the paper.

AASHTO DESIGN METHOD

The AASHTO pavement design method was developed by using the results from the AASHO Road Test conducted October 1958 through November 1959 near Ottawa, Illinois. This carefully engineered experiment included six loops and 468 test sections of asphalt pavement that were subject to traffic loads ranging from 9-kN (2-kip) single axles to 214-kN (48-kip) tandem axles. These test sections were monitored to determine how different pavement thicknesses and traffic loads affected pavement performance. Performance was subjectively measured by a panel of raters by using a Present Serviceability Rating that ranges from 0 for very poor to 5 for excellent. Correlation of the panel ratings of performance with measurements of cracking, rut depth, and roughness gave a more quantitative Present Serviceability Index (PSI), so that the condition of the pavement could be accurately determined by measurement, rather than by assembling a panel of raters.

The analysis of road-test data resulted in a design method that determines the strength required of a pavement structure to withstand a given number of load applications before the performance of the pavement reaches a given minimum (or terminal) PSI. The required strength of a pavement is given in terms of the structural number (SN), which is the thickness of each pavement layer, multiplied by a strength coefficient for each layer, summed over all the layers of the pavement, as in Equation 1:

$$SN = a_1 d_1 + a_2 d_2 + \ldots a_n d_n \tag{1}$$

where

a_n = strength coefficient for layer n,
d_n = thickness of layer n (in), and
n = number of layers above subgrade.

The AASHTO strength coefficients (a_i) for each layer of material at the road test were determined empirically (3) by using the different layer thicknesses as independent variables to predict the SN. The coefficients from the regression equation were then related as the material strength coefficients for the road test. A problem developed when different material strength coefficients were determined for different pavement thicknesses (see Table 1). The final values determined for materials at the road test were taken as the average of the coefficients from each loop.

For a given pavement SN and given minimum PSI, the AASHTO design equation computes the number of allowable applications of a certain load, as in Equation 2 (1):

$$\log W_{t_x} = 5.93 + 9.36 \log (SN + 1) - 4.79 \log (L_x + L_2) + 4.33 \log L_2 + G_t/\beta_x \tag{2}$$

where

W_{tx} = number of applications of axle load x,
L_x = magnitude of axle load (kips),
L_2 = axle type (1 for single and 2 for tandem),
G_t = $\log [(4.2 - p_t)/(4.2 - 1.5)]$,
β_x = $0.40 + [0.081(L_x + L_2)^{3.23}/(SN + 1)^{5.19} L_2^{3.23}]$, and
P_t = terminal value of PSI (value of PSI used to indicate failure).

Equation 2 only serves to predict pavement life for the same conditions found at the AASHO Road Test and does not consider regional differences of climate or subgrade soil types. In addition, to design for mixed traffic it is necessary to convert various axle loads to single-equivalent axle loads.

These factors are considered in the AASHTO design equation most familiar to pavement engineers, shown here as Equation 3:

$$\log W_{t_{18}} = 9.36 \log (SN + 1) - 0.20 + \left(G_t/\left\{0.40 + [1094/(SN + 1)^{5.19}]\right\}\right) + \log (1/R) + 0.372 (S_i - 3.0) \tag{3}$$

where

W_{t18} = number of 80-kN (18-kip) axle applications,
R = regional factor (ranging from about 0.5 to 5.0, where the higher number represents a more severe climate), and
S_i = soil support, which normally ranges from 1.0 to 10.0 and is correlated with different soil strength tests, such as California bearing ratio (CBR).

The R and S_i terms are qualitative and were inserted to permit the regional factor and subgrade soil type to be reflected in design, as would be rationally expected. The S_i term has no rational basis and was selected as a compromise between the many potential test methods in use by various agencies in the United States at the time of the road test analysis. The S_i values from the AASHO Road Test were arbitrarily set at 3.0 and 10.0 for the subgrade soil and the crushed-stone base, respectively. Thus, by using these two control points each agency was permitted to develop a correlation between the S_i scale and the agency's test methods.

The R term is used for climatic variation and was inserted to permit adjustments for conditions other than those at the road test. It also has no rational basis, and each agency is left to determine the proper adjustment factor(s) for its area(s). In essence, the term is simply a divisor for the load repetitions from the AASHO equation. A pavement structure lasting x applications at the road-test site would only last x/3 applications for an R of 3.0.

Except for a few states, the AASHTO design method is used by most highway departments in the United States to design or evaluate designs of flexible pavements (4). To determine how accurately the AASHTO design equation models the performance observed at the AASHO Road Test, actual values of SN, axle load, and terminal PSI at the road test were used as inputs to Equation 2. The calculated number of applications from the AASHTO equation was then plotted against the actual observed number of weighted applications for a given test section at the road test. [The weighted applications are the same data used to develop the AASHTO equation and represent original observations corrected for seasonal variations (3)]. This involved plotting 523 observations, which included all the results from the main block of road-test experiments (3). Figure 1 contains this plot, and indicates graphically how accurately the AASHTO equation predicts the AASHO data. Statistically, the coefficient of determination (R^2) is 0.738, indicating that 73.8 percent of the variation in the AASHO data is described by the AASHTO equation, and the standard error of estimate (S_e) is 0.300. Examination of Figure 1 reveals that the widest range of scatter about the line of equality corresponds to an AASHO data value of about log 6.0. This results from the fact that at the end of the road test, after a total of 1 114 000 applications, some pavements remained that had not reached the lower performance level of the terminal PSI. These pavements that have higher PSI values are not predicted as well as when a lower terminal PSI level is used.

Background information just given on the AASHTO design method indicates some of the problems encountered with the method, particularly in extrapolating beyond the conditions at the road test. Variables such as R, S_i, and material strength coefficient are used to design for different climatic and material conditions, but the basis for their use is very qualitative and subject to speculation. It was felt that some other algorithms that would have a more rational basis could be developed from the AASHO Road Test data; these algorithms could then be more realistically extrapolated to other conditions.

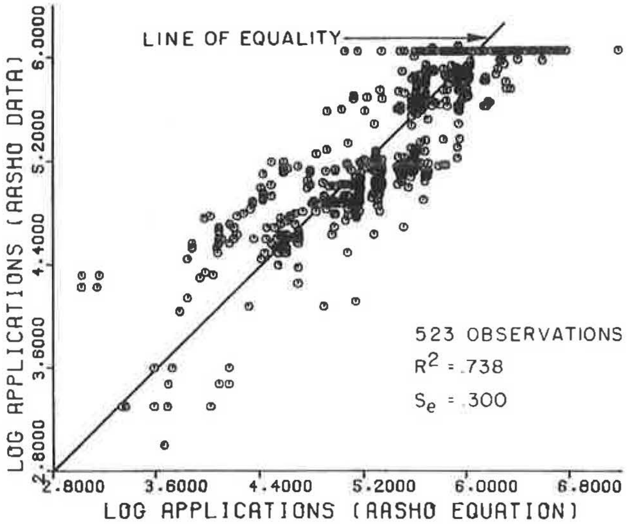
DEVELOPMENT OF THE NEW DESIGN ALGORITHM

The concept in developing the new design algorithm was that some stress-strain parameter of the pave-

Table 1. AASHO Road Test material strength coefficients.

Material	Loop 2	Loop 3	Loop 4	Loop 5	Loop 6	Weighted Average
Asphalt (a_1)	0.83	0.44	0.44	0.47	0.33	0.44
Base layer (a_2)	0.25	0.16	0.14	0.14	0.11	0.14
Subbase layer (a_3)	0.09	0.11	0.11	0.11	0.11	0.11

Figure 1. AASHTO equation as predictor of AASHO data.



ment could be incorporated into a design equation similar to the form of the AASHTO design method. In this way, the procedure would have a more mechanistic orientation and therefore be more adaptable to conditions outside the range of the road-test data. To determine the validity of this concept, stress-strain characteristics of different pavements under various loads were calculated by using the layered-elastic theory program ELSYM5. This program is a modification of the Chevron layered-elastic program developed at the University of California at Berkeley (5).

Input data required for the program include the thickness, Poisson's ratio, and modulus of elasticity of each layer in the pavement; the tire pressure; and the magnitude of the applied wheel loads. The ELSYM5 program was used to analyze the same pavements and axle loads used at the road test in order to allow a comparative analysis with the AASHO Road Test performance data. The moduli of elasticity used were those determined from laboratory tests on the materials used at the road test and are listed below (4). Values of Poisson's ratios, found to have a very small effect on the ELSYM5 program, were estimated (1 MPa = 145 psi):

Material Property	Value
Modulus of asphalt concrete (MPa)	3103
Modulus of base layer (MPa)	207
Modulus of subbase layer (MPa)	103
Modulus of subgrade (MPa)	20
Poisson's ratio of asphalt concrete	0.30
Poisson's ratio of base layer	0.40
Poisson's ratio of subbase layer	0.40
Poisson's ratio of subgrade	0.45
Tire pressure (kPa)	520

The material properties shown above are normalized values that reflect a range in conditions at the AASHO Road Test. For example, the modulus for asphalt concrete would vary daily as well as seasonally. The moduli for the base, subbase, and subgrade layers would vary seasonally, depending on the moisture content and density in the layers.

ANALYSIS PROCEDURE

At the beginning of the analysis, a small group of observations was made to see whether parameters such as tensile strain at the bottom of the asphalt, stress in the subgrade, and compressive strain at the top of the subgrade would correlate with results from the AASHTO design equation. It was quickly apparent that the most promising parameter was the compressive strain at the top of the subgrade and that a further analysis should be completed. Others, after analyzing some selected data from the road test (6), have used the compressive subgrade strain as a prediction of performance or distress, particularly for rut depth. There was, however, no evidence to indicate that compressive subgrade strain had been examined as an indicator of performance for all test sections at the road test. Computations of subgrade strain by using ELSYM5 were made on all combinations of road-test pavements and axle loads. A regression analysis that used the stepwise program STEP01 was then made to see how well the subgrade strain parameter as an independent variable could predict the AASHO Road Test performance data. However, because of the wide scatter found with the AASHTO equation for observations where there were high values of PSI, it was decided to transform the road-test data in the following way: log W_{tx} was transformed to $\log\{W_{tx} \div \sqrt{[(4.2 - p_t)/(4.2 - 1.5)]}\}$, where all terms are as defined in Equation 2. In this way, the observations that have a high value of p_t are transformed to the number of applications required to reach a p_t of 1.5. The square-root function allows for a nonlinear PSI curve from construction to failure, with the deterioration of the pavement accelerating more as its condition becomes worse.

The regression equation computed from the STEP01 program was the following:

$$\log\left\{W_{tx}/[(4.2 - p_t)/(4.2 - 1.5)]^{1/2}\right\} = 2.151\,22 - 597.662\,\epsilon_{SG} - 1.329\,67\,(\log \epsilon_{SG}) \quad (4)$$

where ϵ_{SG} = compressive vertical strain at top of subgrade as calculated from ELSYM5. Statistically, this equation has an R^2 of 0.810 and an S_e of 0.240. This is significantly better than the prediction of the AASHTO equation, as is illustrated in Figure 2.

Equation 4 predicts the anticipated number of applications to reach a p_t of 1.5. However, for designs requiring a different terminal PSI, the equation should be put in the same form as the AASHTO equation, as shown in Equation 5:

$$\log W_{tx} = 2.151\,22 - 597.662\,(\epsilon_{SG}) - 1.329\,67\,(\log \epsilon_{SG}) + \log\left\{[(4.2 - p_t)/(4.2 - 1.5)]^{1/2}\right\} \quad (5)$$

Figure 3 shows how well Equation 5 predicts the same 523 road-test observations predicted by the AASHTO equation in Figure 1. A comparison of Figures 1 and 3 reveals that the strain equation has less scatter about the line of equality, particularly for the observations at the end of the road test. Statistically, Equation 5 has an R^2 of 0.794, meaning that it predicted the variation of road-test data approximately 5.6 percent better than did the AASHTO equation. The S_e of Equation 5 is

0.266, an improvement over the value of 0.300 for the AASHTO equation.

Equation 5 represents the best-fit equation for the average material properties presented in the text table above. An improved statistical fit might be obtained by inputting the material properties to represent the seasonal variation during the road test. It is beyond the scope of this paper to consider these seasonal variations in road-test material properties, but future developments described below will consider these variations.

It is also recognized that Equation 5 is, in essence, a performance equation for one subgrade soil type. The coefficients may quite possibly vary with different soil types, but only extensive investigations could ascertain this. The equation considers different soil types by changing the modulus of elasticity of the subgrade.

The real benefit of the subgrade strain design equation (Equation 5) is not the fact that it is more accurate than the AASHTO equation but that it represents a more rational and mechanistic characterization of the pavement parameters. The subgrade strain is computed by using the modulus of elasticity of the pavement layers and subgrade, rather than empirical material strength coefficients and S_i. The modulus of elasticity is a far more universal and understandable parameter and is measurable in the laboratory through resilient-modulus testing techniques. With the strain design equation, there is no need for a term like R because the modulus of elasticity can be used to characterize the environmental effects of climate on materials, as is discussed in the implementation section of this paper.

Figure 2. Strain equation as predictor of transformed AASHO data.

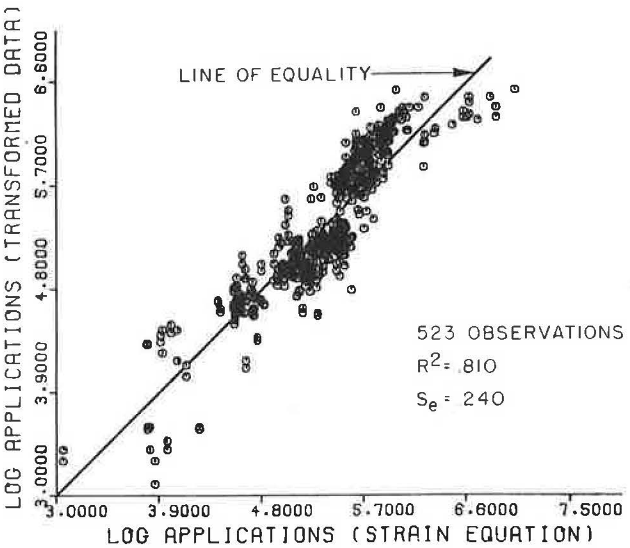
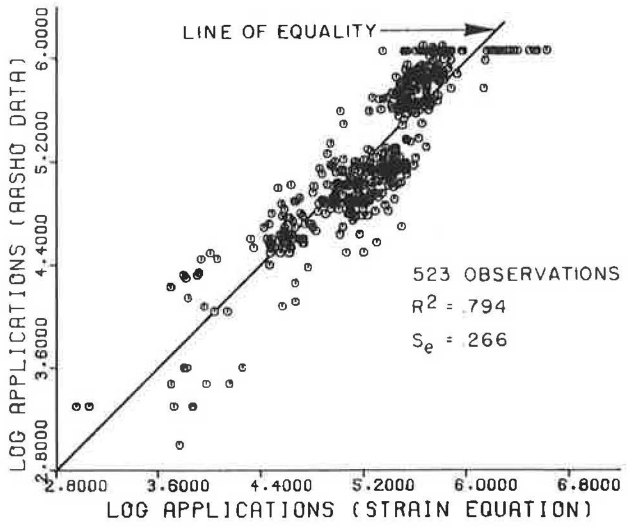


Figure 3. Strain equation as predictor of AASHO data.

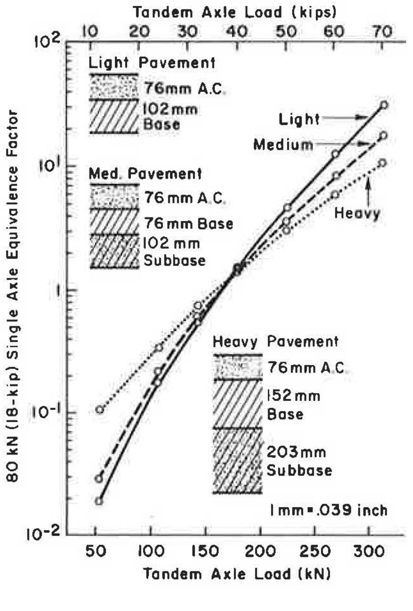


LOAD EQUIVALENCY FACTORS

Use of the strain equation eliminates the need to convert mixed traffic into equivalent 80-kN (18-kip) axle loads. The effect of various axle loadings can be analyzed separately, and this is discussed later in the paper. In an exercise to again compare results of the AASHTO design method with those of the subgrade strain equation, 80-kN axle equivalencies for a number of cases were calculated by using the strain equation and were then compared with the AASHTO equivalencies. It was found that the 80-kN equivalencies from the strain equation will vary substantially with the pavement structure, whereas AASHTO equivalencies vary only slightly with a change in SN. This is illustrated in Figure 4, where 80-kN equivalencies for the strain equation are plotted versus tandem-axle load for three different pavement structures. Figure 5 then shows the same equivalencies from Figure 4 for the light and heavy pavement structures compared with the AASHTO equivalencies. There is only one line for the AASHTO equivalencies in Figure 5 because with the logarithmic scale virtually no difference exists between the AASHTO equivalency lines for different pavement structures.

The suggested hypothesis for the difference in equivalency factors with the strain equation comes from the consideration of the stress sensitivity of the pavement materials. It has been found that with a larger confining pressure, or a smaller deviator stress, the resilient modulus of a fine-grained material will increase (7). This factor is not reflected in a layered-elastic program such as ELSYM5,

Figure 4. Plot of 80-kN single-axle equivalencies computed from strain equation.



which does not modify the moduli of the materials as a function of confining pressure or deviator stress. On the other hand, because the AASHO Road Test performance data were subject to the stress sensitivities of the materials at the road test and the strain equation is a regression of that data, the equation should relate those same stress-strain characteristics. This hypothesis can be further evaluated by observing the equivalency relationships in Figure 4. Remembering that the axle equivalencies are computed by $e_x = W_{t18}/W_{tx}$ = 80-kN (18-kip) equivalence factor, the difference between equivalencies for high loads can be noted for the three pavements. As the load increases, the value of W_{tx} decreases, causing the value of the 80-kN equivalence to increase. For a heavy pavement, the confining pressure is more than that for a light pavement and the deviator stress is less, thereby resulting in a higher modulus of the pavement materials. This causes a larger value for W_{tx} and W_{t18}, but the effect on W_{tx} is greater because it is related to a heavier load. For this reason the ratio of W_{t18}/W_{tx} is larger for light pavement structures than for heavy ones, as is shown in Figure 4. The same concept is used when the loads become lighter and W_{tx} increases. From a light to heavy pavement, W_{tx} and W_{t18} both increase, but this time W_{t18} is related to the heavier load and increases more on a relative basis. This causes W_{t18}/W_{tx} to be smaller for the light-pavement structure than for the heavy one.

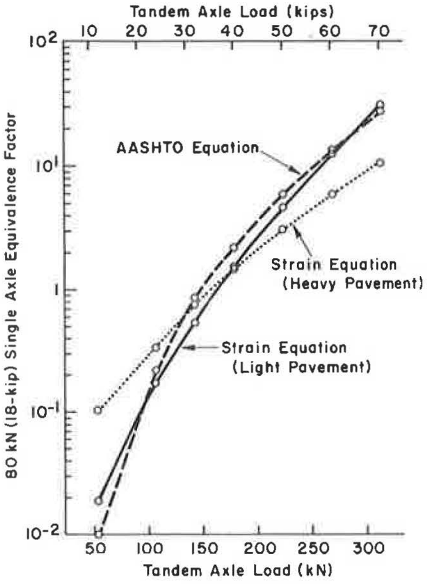
In general, the relationship shows that difference in load magnitude has more of an effect on weak pavements than on strong ones. It is encouraging to find that the strain equation is influenced by stress sensitivity, since it is not practical at this time to compute the strain by using a costly iterative process that would take this stress sensitivity into consideration. It will, however, be investigated in future development work, as discussed below.

We recognize that most agencies have developed traffic projections by using the load equivalencies determined from the AASHO Road Test. The new algorithm does not in any way limit the application of these projected equivalent 80-kN (18-kip) loads for a given facility. Basically, the new algorithm could be solved for an equivalent 80-kN single-axle load for a given pavement structure and all solutions could be made in terms of the standardized real load. The new algorithm can therefore be inserted as a design equation without interrupting the normal traffic projection procedures if any agency so desires.

IMPLEMENTATION OF SUBGRADE STRAIN EQUATION IN A PAVEMENT MANAGEMENT SYSTEM

As previously stated, the University of Texas developed PDMS for the U.S. Forest Service as an instrument for designing and maintaining flexible pavements, and it is for this system that the new design procedure was developed. By using the AASHTO design method alone, engineers were unable to characterize seasonal variation in pavement strength. R was a very crude means of considering seasonal variation, but there was no way to also consider any seasonal variation in traffic. The U.S. Forest Service, like many transportation authorities in northern climates, often restricts axle loads on roads during the spring thaw periods when most pavements are in a very tender condition. Design engineers needed some way to evaluate the economic difference between building a pavement strong enough to withstand the spring traffic and building a weaker pavement where loads are restricted during the worst times of the year. An example of such use of the new design procedure in PDMS is summarized here.

Figure 5. Comparison of equivalence factors computed from AASHTO and strain equations.



The conceptual approach of the subgrade strain design procedure is illustrated in Figure 6. For a single-axle load of 80 kN (18 kips) on a given pavement structure, there are W_{t18} applications of that load before failure, as computed by Equation 5. If the load is a 214-kN (48-kip) tandem axle for the same pavement, there are W_{t48} applications of that load before failure. When mixed traffic of both loads is applied to the pavement, then both contribute to pavement distress. If W_{t18} is equal to 800 000 applications and there are 200 000 80-kN applications (n_{18} = 200 000) at a time t, then at time t the cumulative damage is n_{18}/W_{t18} or one-fourth the damage at failure. If W_{t48} is equal to 300 000 applications and in the same time t there have been 225 000 214-kN applications (n_{48} = 225 000), then the total damage is as follows: $(n_{18}/W_{t18}) + (n_{48}/W_{t48}) = (1/4)+(3/4) = 1$. As soon as the cumulative damage sums to a value of 1, then the pavement is predicted to have failed. In this way each element of a mixed traffic load can be considered separately, and there is no need for axle-load equivalencies.

The same concept is used to consider seasonal variation in pavement strength, as shown in Figure 7. At a given time of the year for a certain pavement structure, the modulus of elasticity of each layer can be used to characterize the strength of the pavement materials. The moduli of pavement layers could change as a result of heavy rainfall, poor drainage, frozen conditions, dry weather, or almost any environmental effect. During the summer a certain load may produce a calculated strain ε_{sum} that corresponds to the number of load applications to failure of W_{t-sum}. During a spring thaw condition, the modulus of the subgrade may be very low, leading to a high strain ε_{spr} and low number of applications to failure W_{t-spr}. By considering the amount of traffic in the summer n_{sum} and spring n_{spr}, the cumulative sum of n/W_t can again be used to predict when the pavement will fail. Table 2 gives an example of combining seasonal variation of pavement strength and traffic $[\Sigma(n/W_t) = 0.200]$.

Figure 6. Strain algorithm results for 80-kN single-axle and 214-kN tandem-axle loads.

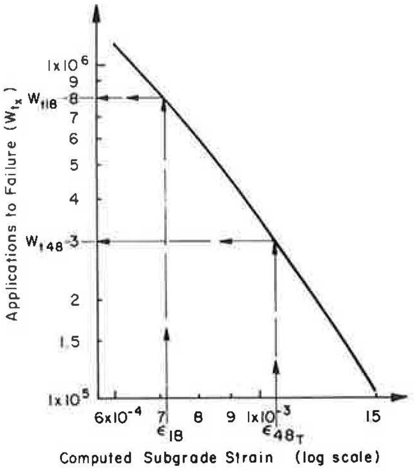


Figure 7. Strain algorithm results for seasonal variation.

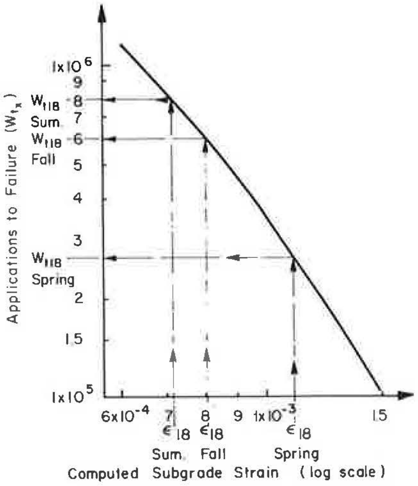


Table 2. Example of 80-kN single-axle and 214-kN tandem-axle loads during one year.

Season	$W_{t_{18}}$	$W_{t_{48}}$	n_{18}	n_{18}	n/W_t
Summer	800 000	300 000	10 000	12 000	0.053
Fall	600 000	225 000	7 000	8 000	0.047
Spring	250 000	100 000	5 000	8 000	0.100

The results from Table 2 would indicate that the pavement in question would be predicted to fail after approximately 5 years of the same traffic. By using PDMS, the user specifies the minimum number of years of service required before pavement rehabilitation is allowed. In the example given, if 10 years had been specified as the minimum time before rehabilitation and the pavement was estimated to last only 5 years, then the program would automatically increase the thickness of the pavement structure until the pavement lasted at least 10 years before failing [$\Sigma(n/W_t) = 1$].

This new design procedure, therefore, eliminates the need for considering S_i or R, and instead the pavement is characterized by using the modulus of elasticity for each layer. Because the design method is used in a computer program, the number of axle weights or number of periods in the year may be divided into as many units as desired. It is very easy for the program to sum all the possible n/W_t values.

In this entire analysis, the values of subgrade strain were calculated by using the program ELSYM5. Because the PDMS program sometimes considers hundreds of candidate design strategies, it would be too costly to have ELSYM5 calculate the subgrade strain for each design. For this reason, a regression analysis of a statistically designed factorial of ELSYM5 solutions was made to see whether an equation could be derived that, given the same inputs, would predict accurately the results from ELSYM5. In a trial analysis of this type with two-layer pavements, it was found that the regression equation explained 99 percent of the variation in the ELSYM5 calculations and would therefore be acceptable to use in the PDMS program to calculate subgrade strain. More ELSYM5 regression analyses of this type will be made in the future to include more pavement layers and a wider range of input values.

CONCLUSIONS

Based on this study, the following specific conclusions may be derived.

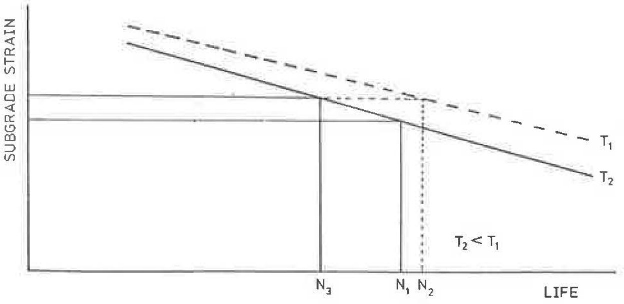
1. Equation 5 presented herein predicts the number of applications to reach a desired terminal serviceability based on a predicted subgrade strain value. The equation improved the statistical correlation of the AASHO data, improving the R^2 from 0.738 to 0.794 and the S_e from 0.300 to 0.266.
2. By using Equation 5, the designer may consider any regional or seasonal variation of material properties to whatever level of sophistication desired, i.e., from one set of conditions to any number of conditions desired.
3. Equation 5 is, in essence, a performance equation based on one subgrade soil type, but it may more reliably be extrapolated to other soil types since the extrapolation is on a rational basis.
4. The material properties of the surface, base, and subbase layers are more rationally characterized by using modulus of elasticity than by using empirical material strength coefficients. Thus, design values may be established by testing new materials rather than by relying on engineering judgment.
5. The computations may be made for each axle weight, thereby eliminating the need for determining equivalent axle loads.
6. The analysis shows that if axle equivalencies are evaluated they will vary significantly for different pavement structures, whereas AASHTO equivalencies show a small variation.
7. The algorithm presented in Equation 5 may be substituted for the AASHTO design equation used by many agencies with a minimal effect on the normal design techniques.

OUTLINE OF FUTURE DEVELOPMENT

Future development work on the algorithm presented in this paper will concentrate in three areas.

1. Stress sensitivity: A capability will be developed in the PDMS program to characterize the modulus of elasticity of granular or fine-grained materials as a function of the calculated in situ stress condition. This will increase the mechanistic viability of the algorithm and allow for more reliable extrapolation of results.
2. Seasonal variation of AASHO Road Test data:

Figure 8. Subgrade strain: life relationships at two temperatures.



The material used at the road test will be characterized seasonally, including the consideration of stress sensitivity mentioned above. This will eliminate the need to use normalized values of material properties and will more accurately model the seasonal variation in pavement performance.

3. Remaining life of pavement structure: Because pavements do not deteriorate linearly with time or traffic, a capability will be developed to express the rate of deterioration as a function of the present condition of the pavement structure.

The Forest Service of the U.S. Department of Agriculture is also initiating a new data base system that will collect and store information concerning typical pavement characteristics at different times of the year. This development will expand the data from which inputs for the PDMS program are selected and from which performance equations are derived.

The new design procedure presented in this paper is considered to be an excellent framework for the future that can be modified and improved as more information becomes available.

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Discussion

A.F. Stock

In their paper, Luhr and McCullough use the subgrade strain criterion for a cumulative damage analysis of pavement systems on the basis of a linear summation of cycle ratios (Miner's hypothesis). Since the subgrade strain criterion was developed from back analysis of pavements for average conditions, it is incorrect to use it in this way; therefore, conclusions based on this type of analysis are highly suspect.

Consider, first of all, the derivation of the subgrade strain criterion. Analysis carried out by following the AASHO Road Test indicated that the development of permanent deformation in the flexible pavement test sections could be related to the strain on the subgrade calculated by an elastic analysis. This analysis was carried out for average conditions, particularly with regard to temperature, and provides a relationship of the type shown by the solid line in Figure 8.

Asphalt stiffness decreases as temperature increases. If a pavement is analyzed for several temperature conditions, under constant loading conditions the strain on the top of the subgrade will increase with the temperature. If the unique subgrade strain criterion is used, such an analysis predicts that pavement life will decrease (from N_1 to N_3) as the temperature increases, which is quite logical. However, if a relationship between performance and subgrade strain for the same pavement is derived at a higher temperature, the line so derived will be as shown by the dotted line in Figure 8, i.e., above the original line. Use of this second line, which is relevant to the higher temperature condition, indicates that for this condition the pavement may have an increased life (N_2). This is not logical and indicates clearly the major limitation of the subgrade strain criterion, i.e., that, since it was derived for a given set of conditions, it cannot logically be applied to any others.

A similar argument follows for different axle loads.

It is not the purpose of this discussion to suggest that the subgrade strain criterion is of no value in estimating the life of a pavement structure. It is a simple indicator of performance and, provided that this is borne in mind, it is a useful tool. However, its simplicity and the background of its derivation make it inappropriate to use in a sophisticated cumulative-damage calculation.

Authors' Closure

Stock's discussion makes a valid point concerning the use of only one modulus of elasticity to characterize the asphalt-concrete layer; however, the discussion includes some misconceptions about the algorithm that we would like to clarify.

As was stated in the paper, the stiffness of asphalt concrete in a pavement structure can vary seasonally as well as hourly. The concept of using one normalized modulus of elasticity to characterize an asphalt concrete with varying stiffness has been described by Shahin and McCullough (8). We feel that the use of a normalized asphalt-concrete stiffness does not seriously detract from the usefulness of the algorithm.

It is not always true that pavement life decreases with increased temperature, as is stated in the discussion. There is a probability that increased rutting will occur at the lower stiffness of asphalt concrete associated with higher temperatures, but the reduced stiffness will also reduce the amount of temperature and fatigue cracking. In addition, the stiffness of base, and especially subgrade, materials commonly increases during seasons associated with higher temperatures. This additional stiffness would act to decrease, rather than increase, the subgrade strain. It is imperative to remember that the subgrade strain algorithm is a predictor of PSI, which is primarily associated with roughness and not singularly a predictor of rutting or cracking.

We feel that the effect of temperature and, therefore, the effect of asphalt-concrete stiffness on subgrade strain as indicated in Figure 8 is somewhat exaggerated. If relationships were derived for different temperatures, they would lie much closer to the solid line than to the dashed line associated with T_1. Actually, this is one of the benefits associated with an algorithm based on subgrade strain. The algorithm is not dominated by asphalt stiffness but, rather, is affected by the combination of thickness and material properties of all the layers in the pavement structure.

Stock states in the discussion that an argument similar to that proposed concerning the asphalt modulis is also applicable for different axle loads. This is not the case, since 10 different axle loads ranging from 9-kN (2-kip) single-axle to 214-kN (48-kip) tandem-axle loads were included in the subgrade strain analysis.

We appreciate Stock's comments. As we stated in the paper, development work is continuing in order to consider a more complex seasonal characterization of road-test data.

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Interactive Pavement Behavior Modeling: A Clue to the Distress-Performance Problem

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A framework and suggested methodology for identifying objective relationships between pavement distress and performance is presented. The nature of the problem and the suitability of two widely used models of pavement performance are reviewed. The status of pavement behavior modeling is assessed, and a more comprehensive theory is advanced based on the hypothesis that (a) the levels of different types of pavement distress behavior are interdependent through time and (b) pavement behavior elements are recursive in that they depend on their own historical values. The viability of the theory is investigated through postulating a deterioration mechanism for flexible AASHO Road Test sections. A preliminary interactive model involving three behavior subsystems (rutting, cracking, and roughness) is described.

In recent years, pavement engineers have become increasingly aware of the need to make more efficient use of pavements in service. The very noticeable shift in pavement expenditures from capital construction to the maintenance and repair of existing pavements bears testimony to this need.

The efficient use of existing pavements involves the programming of expenditures over large pavement networks so as to maximize the total benefits. These benefits are directly related to pavement performance, mainly from the user's perspective.

However, because pavement performance is affected by distress, because it is distress that is treated in maintenance, and because such maintenance varies with the type and degree of distress, it would be desirable to take the appropriate improvement action at the best time(s) in order to have the maximum impact on performance. To achieve this it is first necessary to know the relationships between distress and performance, as schematically illustrated in Figure 1.

The need for relating pavement distress to performance was identified as the primary research need in a workshop of top-ranking pavement experts in 1970 (1). It was subsequently considered for several years by a Transportation Research Board (TRB) task force and discussed in various forums, including a two-day workshop at the 1977 TRB conference. This task force also conducted a survey of American state and Canadian provincial highway agencies to review the current practices in this area (2). It was found that, although some agencies have attempted to relate distress to performance, all such investigations are in very preliminary stages.

This paper considers the nature of relationships between pavement distress and performance in the context of an interactive approach to modeling pavement behavior. Specifically, the objectives are to

1. Present an interactive approach to modeling pavement behavior,
2. Present and discuss a preliminary investigation of the workability of this modeling approach to the development of pavement distress-performance relationships by using AASHO Road Test data, and
3. Identify and discuss areas of refinement and deficiency that are requisite to the development of