# Rut Depth Prediction

C. L. Saraf, W. S. Smith, and F. N. Finn, Woodward-Clyde Consultants, San Francisco

**This paper describes a method for the prediction of rut depth in asphalt pavements that is based on a combined mechanistic-empirical approach. Three methods, viscoelastic, elastoplastic and linear-elastic, were originally evaluated. The viscoelastic methods are under study by the Federal Highway Administration. The elastoplastic procedures offer the best long-range solution, but cannot yet be implemented for a multilayered structure such as an asphalt pavement. Therefore, this paper concentrates on linear-elastic procedures to relate the various mechanistic responses, stress, strain, and deformation to the rate of rutting observed on 32 sections at the AASHO Road Test. The rate of rutting was influenced by the season of the year and the number of years for which traffic is applied. Correlations with the surface deflection, the vertical compressive stress in the asphalt concrete, the vertical strain in the subgrade, and the traffic previously applied to the section were obtained. Correlations could be obtained by converting heavy axle loads to equivalent 80-kN (18 000-lbf) single-axle loads using AASHO load equivalency values. The prediction model includes calculations for estimating rut depth in terms of reliability.**

The development of a methodology for the prediction of rut depth has lagged behind that for fatigue cracking. The only procedure currently in use is that of Dorman and Metcalf (1), who have developed limiting criteria for the vertical strain in the subgrade that would adequately minimize the amount of rutting in the pavement. The results of this methodology are summarized by Figure 1, which illustrates the general relationships reported by various investigators (1, 5, 12). The differences in criteria are attributed to the amount of rutting allowed and to the selection of the elastic modulus assigned to the asphalt concrete layer. This modulus is assumed to be representative of those time periods in which rutting is most apt to occur, namely, during periods of higher temperatures.

Three methods (viscoelastic, elastoplastic, and linear elastic) are considered to have some potential for rut depth prediction. The viscoelastic procedure is under study by the Federal Highway Administration. The elastoplastic and linear elastic methods have been studied in project 1-10 B of the National Cooperative Highway Research Program. The former of these was proposed by Romain and investigated by Barksdale (3, 4) and Monismith and others (5) but discarded in this project as not being capable of implementation within the resources available.

The working hypothesis used to develop the rut prediction model discussed in this paper was based on the approach of Dorman and Metcalf, i.e., to find some combination of elastic stress, strain, or deformation that can be correlated with the amount of rutting that will occur. In this approach it is assumed that mixed traffic can be combined into equivalent 80-kN (18 000-lbf) single-axle loads. This assumption is then built into the development of the model through the regression technique. Rut depth data from loops 4 and 6 for the AASHO Road Test were used as a data base for the regression equations. The traffic from loop 6 was converted to 80-kN (18 000-lbf) single-axle loads by using the AASHO load equivalency factors (6).

Plots of load repetitions versus rut depth for both loops showed that the rate at which rutting occurs is dependent on the seasons of the year, being highest during the spring and negligible during the frozen part of the winter. Figure 2 illustrates a typical relation between rut depth, load cycles, and season. These plots showed that, for the second year of traffic on the road, there is a reduction in the rate of rutting per load application.

A regression model of the following form was used to obtain a correlation between the seasonal rate of rutting and the primary responses calculated for an 80-kN (18 000-lbf) single-axle load [40-kN (9000-lbf) wheel load].

$$RR = f(\sigma, \epsilon, \Delta \text{ and } N_{18}) \qquad (1)$$

where

- RR = seasonal rate of rutting or permanent deformation per equivalent load application,
- $\sigma$ = stress in component layers,
- $\epsilon$ = strain in component layers,
- $\Delta$ = surface deflection, and
- $N_{18}$ = total equivalent number of 80-kN (18 000-lbf) single-axle loads up to and including the season for which the rate of rutting is to be calculated.

Publication of this paper sponsored by Committee on Strength and Deformation Characteristics of Pavement Sections.

The rut depth prediction model was developed from information obtained from reports on the AASHO Road Test. The stepwise procedure was as follows:

1. Determine the material properties for each layer and for the subgrade,
2. Determine the rate of rutting from observed data,
3. Relate the rate of rutting to various primary response factors, and
4. Select mechanistic models for conventional construction.

**Figure 1. Rut depth prediction from vertical compressive strain on subgrade and equivalent 80-kN single-axle loads.**

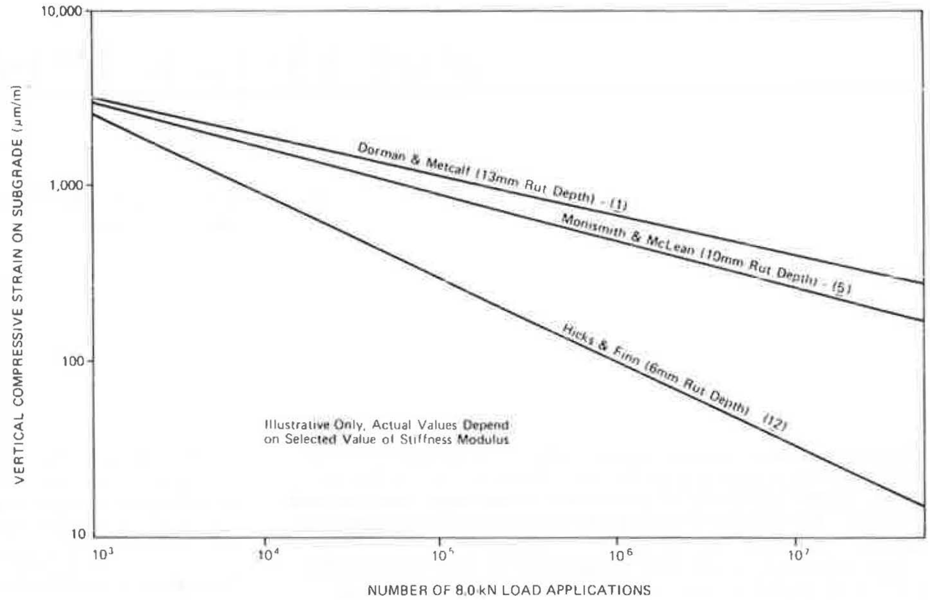


**Figure 2. Typical pattern of rutting on AASHO Road Test.**

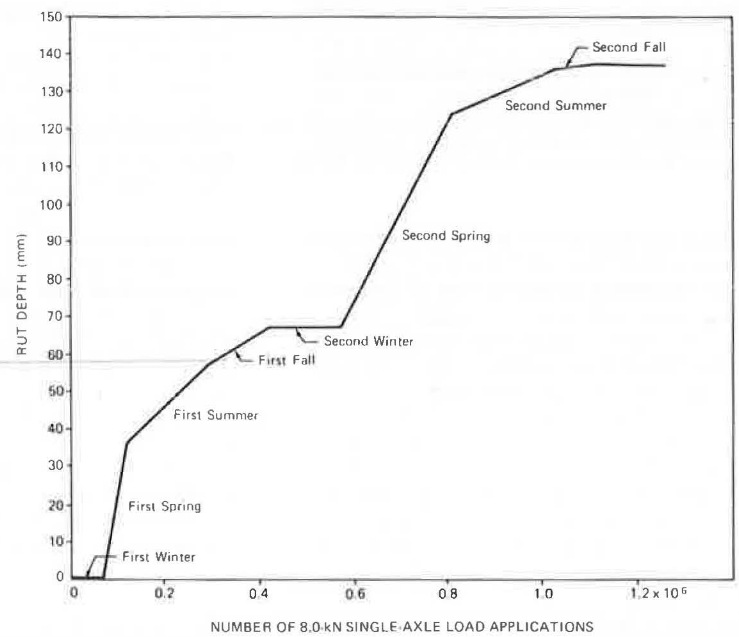


**Table 1. Strength characteristics of AASHO Road Test materials.**

| Season | Complex Modulus of Asphalt Concrete (MPa) | Base | | Subbase | | Subgrade | |
|---|---|---|---|---|---|---|---|
| | | Resilient Modulus (MPa) | Bulk Stress[a] | Resilient Modulus (MPa) | Bulk Stress[a] | Resilient Modulus (MPa) | Deviator Stress[b] |
| November-February | 11 730.0 | 3450.0 | | 3450.0 | | 3450.0 | |
| March-April | 4 900.0 | 6.9 | 0.6 | 10.0 | 0.6 | 428.0 | -1.06 |
| May-July | 1 590.0 | 7.8 | 0.6 | 10.8 | 0.6 | 962.0 | -1.06 |
| August-October | 3 110.0 | 8.7 | 0.6 | 11.7 | 0.6 | 144.0 | -1.06 |

Note: 1 MPa = 145 lb/ft².

[a] $\sigma_1 + 2\sigma_3$. [b] $\sigma_1 - \sigma_3$.

MATERIAL PROPERTIES

The properties of the asphalt concrete, aggregate base, and subbase and the clay-silt subgrade were measured at the Asphalt Institute (7) and are described by the relationships given in Table 1.

RATE OF RUTTING

Thirty-two sections from lane 1 of loops 4 and 6 were used to obtain the seasonal rate of rutting. [Since the traffic on the loop 6 sections had been applied with a 134-kN (30 000-lbf) single-axle load, the number of load applications used to determine the rate of rutting on this loop was converted into 134-kN (30 000-lbf) single-axle loads by multiplying by 7.94, the AASHO load equivalency factor.]

Table 2 illustrates typical values of the rate of rutting obtained from measurements at the AASHO Road Test. The observed inconsistencies in the rate of rutting may be due to field measurements, data analysis, or the use of load equivalency on loop 6, or may be true variations that must be expected in this type of data. Whatever the causes, such inconsistencies will influence the reliability of the prediction model.

INFLUENCE OF PRIMARY RESPONSE ON RATE OF RUTTING

A major requirement for the prediction model is the ability to relate the rate of rutting to the primary response (mechanistic) factors.

In order to reduce the number of sections required for the structural analysis with a layered program, a regression model with which to predict various primary response factors in terms of layer thickness, elastic moduli, and single-axle load was developed.

Primary responses for various sections from loops 4 and 6 were obtained from a selection of the 32 sections used in this part of the investigation by the use of a computer program that is capable of accommodating a five-layer system for analysis. Since the properties of the base, the subbase, and the subgrade are stress-sensitive, a regression model must first be developed for estimating moduli as a function of layer thickness, dynamic modulus of the asphalt concrete, and wheel load.

Four models were fitted to the data, and a linear-linear model that produced a multiple correlation value (r-value) of 0.96 to 0.99 depending on the season of the year was selected for use. The ability to predict the elastic moduli allowed a simple regression estimate for approximately 200 cases in lieu of a structural analysis.

A stepwise regression analysis procedure was used to correlate the rate of rutting with various combinations of primary response factors. The following independent variables were selected for this purpose:

1. Vertical surface deflection between dual tires,
2. Vertical subgrade strain under the centerline of one wheel,
3. Vertical compressive stress at the bottom of the asphalt concrete layer under one wheel,
4. Horizontal tensile stress at the bottom of asphalt concrete under one wheel,
5. Ratio of vertical and horizontal stresses from items 3 and 4 above, and
6. Cumulative traffic expressed as equivalent 80-kN (18 000-lbf) single-axle loads.

The analysis indicated that the most significant correlations were those with the vertical deflection at the surface of the pavement, followed by those with the vertical compressive stress in the asphalt concrete, the cumulative traffic, and the vertical strain in the subgrade. The stress ratio factor was not sufficiently significant to be included in the final prediction model. Since the vertical strain in the subgrade was highly correlated with the surface deflection and was the least significant to the correlation, it also was not included in the final models.

Two prediction equations were obtained. For pavements with 152 mm (6 in) or less of asphalt concrete,

$$\log RR = -5.617 + 4.343 \log d - 0.167 \log(N_{18}) - 1.118 \log \sigma_c \quad (\text{r-value} = 0.980; SE = 0.316) \qquad (2)$$

For pavements with more than 152 mm (6 in) of asphalt concrete,

$$\log RR = -1.173 + 0.717 \log d - 0.658 \log(N_{18}) + 0.666 \log \sigma_c \quad (\text{r-value} = 0.957; SE = 0.174) \qquad (3)$$

where

RR = rate of rutting = 25.4 nm ($1 \times 10^{-6}$ in)/repetition,
d = surface deflection = 25.4 μm ($1 \times 10^{-3}$ in), and
$\sigma_c$ = vertical compressive stress in asphalt concrete = 6.9 kPa (1 lb/ft$^2$).

OPERATING PROCEDURE

Figure 3 shows a flow diagram for the rut depth prediction model. (In the following sections of this report the operations will be described in the numerical sequence shown in the figure.) The rut depth predictions are divided into incremental groupings as follows:

1. Within the year—the rutting that occurs month by month or seasonally within the year, and accumulated for the year, and
2. Across the years—the rutting that can be accumulated for a group of years without recalculating the primary response factors (assuming no change in the rate of traffic growth or material properties).

Designed Structural Section

The prediction model has been developed to work with conventional asphalt pavements that include unbound aggregates. It does not predict rut depth in cement-treated constructions or full-depth asphalt concrete pavements.

The designed structural section can be obtained by any conventional design procedure that includes asphalt concrete and aggregate.

Climatological Information

The major climatological information required for the rut depth model is the temperature and rainfall. This information is used in selecting analysis periods, establishing conditions for sample preparation to obtain representative physical states, and operating the temperature prediction model.

Traffic Information

The program input requires traffic loads for the first year and growth factors for each subsequent year. The growth factors can be changed from year to year depending on the available estimates.

Selection of Annual Distress Analysis Periods

The rate of rutting is a function of the surface deflection, the vertical compressive stress in asphalt concrete, and previous traffic. The cumulative rutting is obtained by multiplying the rate of rutting by the number of equivalent 80-kN (18 000-lbf) loads during a specified time period. The year must be divided into distress analysis periods that recognize changes in both the primary response values and traffic. For most situations, the year can be divided into a maximum of four analysis periods somewhat comparable to the seasons of the year. The general criteria for such within-year subdivisions are

1. Changes in temperature—the initial selection of analysis periods can be based on differences in temperature, e.g., summer versus winter;
2. Changes in material properties—the effects produced by primarily rainy periods, frozen periods, thaw periods, or hot-dry periods; and
3. Changes in traffic during the year, e.g., heavy traffic in summer, light traffic in the winter.

After the annual analysis periods are selected, it is necessary to decide how many years to assign to this group, i.e., the years having similar temperatures, material properties, and traffic. Information that shows changes that will occur with time (e.g., asphalt aging, poor durability in untreated aggregates, or systematic changes in subgrade properties) can be treated in a second or third grouping of years that are designated for the purpose.

**Table 2. Seasonal rate of rutting for selected sections on the AASHO Road Test.**

| | | Rate of Rutting (mm/million repetitions) | | | | | |
|---|---|---|---|---|---|---|---|
| | | March-May | | May-August | | August-October | |
| Loop No. | Thickness[a] (mm) | 1st Year | 2nd Year | 1st Year | 2nd Year | 1st Year | 2nd Year |
| 4 | 76-152-305 | 86 | 23 | 15 | 10 | 16 | 6 |
| | 102-152-203 | 112 | 14 | 21 | 10 | 8 | 6 |
| | 127-152-203 | 86 | 11 | 16 | 2 | 5 | 8 |
| | 127-152-305 | 76 | 11 | 19 | 2 | 8 | 0.02 |
| 6 | 102-229-406 | 18 | 1 | 3 | 1 | – | – |
| | 127-229-305 | 36 | 6 | 4 | – | 1 | – |
| | 152-229-305 | 22 | 5 | 5 | NC[b] | 1 | NC[b] |
| | 152-229-406 | 18 | 2 | 4 | 0.5 | 1 | NC[b] |

Note: 1 m = 39.4 in.
[a]Asphalt concrete-granular base-granular subbase. [b]NC = no measurable change.

## Material Characterization

Materials are characterized by procedures that are applicable to the study of linear elasticity and designed to account for the temperature and the time and stress susceptibility of asphalt concrete and unbound granular materials. Each of the materials in the structural section and the subgrade must be tested to develop descriptive input appropriate to the distress analysis periods. Efforts must be made to duplicate the field conditions as they are affected by climate or aging or both. For example, subgrade material properties vary from winter to spring to summer to fall in areas that experience subgrade freezing. The spring moduli of subgrade materials may be only 40 to 50 percent of the optimum (summer and fall) values.

To develop the probabilities into the prediction model, the material properties are input as average or expected values together with their coefficients of variation, which should be based on the variations expected in the field and not the laboratory. Hence, a rather large coefficient of variation can be expected: Fifty percent is not unrealistic.

Asphalt concrete or asphalt emulsion mixtures are characterized by procedures that are applicable to the study of the dynamic modulus as described by the Asphalt Institute (8). The testing should be performed at 10 Hz over a range of 37.8 to 4.4°C (100 to 40°F). Diametral testing is appropriate, although damage criteria have also been developed by the use of the dynamic modulus from triaxial testing.

Untreated aggregates are tested in triaxial configuration (9). The stress-sensitive expression to be used to describe the elastic constant is

$$M_R = K_1 \theta^{K_2} \quad (4)$$

where

$M_R$ = resilient modulus in kPa,
$\theta$ = first stress invariant $(\sigma_1 + 2\sigma_3)$, and
$K_1, K_2$ = fitting coefficients with $K_1$ generally between 2000 and 7000 and $K_2$ equal to approximately 0.6.

Subgrade materials are tested by procedures similar to untreated granular materials and described by an equation of the same form. The sign of $K_2$ may be plus or

**Figure 3. Flow diagram for the rut depth prediction model.**

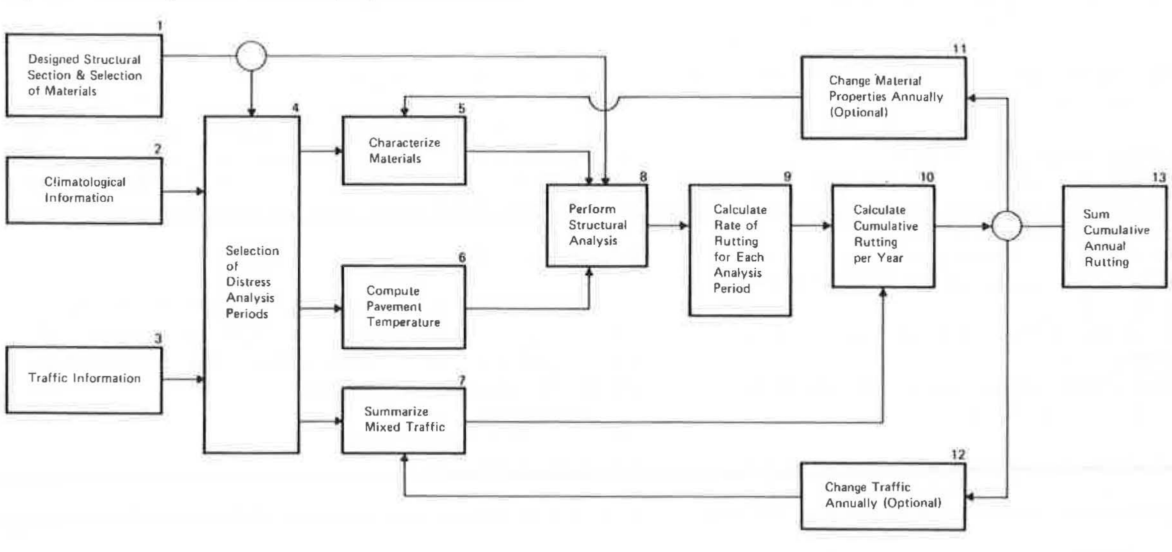

Table 3. Summary of rut depth data and estimates.

| Section No. | July 1967 | Oct. 1967 | April 1968 | May 1968 | Aug. 1968 | Nov. 1968 | April 1969 | May 1970 | May 1971 | Aug. 1971 | June 1972 | June 1973 | Estimated Rut Depth (mm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | AASHO Model | Adjusted Model |
| 9 | 6.1 | 6.6 | 7.9 | 7.4 | 6.9 | 8.4 | 9.1 | 11.7 | 13.7 | 14.2 | | | 17.5 | 11.8 |
| 10 | 5.3 | 5.3 | 5.8 | 5.8 | 6.1 | 6.6 | 7.1 | 9.4 | 6.6 | 7.4 | 8.9 | | 19.1 | 12.2 |
| 22 | 5.8 | 6.1 | 6.6 | 6.9 | 6.9 | 7.4 | 8.4 | 10.9 | 9.9 | | | | 17.0 | 11.4 |
| 16 | 4.8 | 5.1 | 5.6 | 5.8 | 5.6 | 5.8 | 6.6 | 8.9 | 10.2 | 11.2 | 11.9 | 10.9 | 10.2 | 7.5 |
| 18 | 5.8 | 6.1 | 6.6 | 6.9 | 7.1 | 7.9 | 7.4 | 9.4 | 7.4 | 8.6 | 9.7 | | 12.4 | 9.1 |
| 12 | 5.6 | 6.1 | 7.1 | 8.1 | 7.9 | 8.4 | 12.7 | | | | | | 12.2 | 8.9 |
| 19 | 6.1 | 6.1 | 6.1 | 7.1 | 7.9 | 8.1 | 7.1 | 13.0 | | | | | 16.8 | 11.4 |
| 20 | 6.4 | 6.1 | 7.4 | 7.6 | 7.6 | 8.1 | 11.2 | 9.7 | | | | | 17.0 | 11.7 |
| Equivalent loads | 121 | 137 | 142 | 150 | 182 | 193 | 228 | 291 | 357 | 370 | 424 | 487 | 487 | 487 |

Note: 1 m = 39.4 in.

minus depending on whether the materials are granular (+) or fine grained (-).

Computed Pavement Temperature

The relations developed by Barber (10) are used to calculate the temperature in the asphalt layers. The program is designed to calculate these temperatures for a typical day in each analysis period. The specific temperature used to obtain a dynamic modulus for the asphalt concrete is the average temperature for the typical day. The program will automatically interpolate the dynamic modulus to temperature relation based on input data from the material information.

Seasonal Traffic

To accommodate the possible variations in traffic during the year, the program accepts traffic according to analysis periods. The average traffic for each first-year analysis period, based on the traffic information previously summarized into equivalent 80-kN (18 000-lbf) single-axle loads, is input, and the program automatically expands according to any growth rate specified for a designated group of years. A seasonal grouping, by years, can also be incorporated into the program.

Structural Analysis

The primary response factors are obtained for each structural section through the use of elastic layered solutions to a boundary value problem (11). The program used is capable of including five layers of different materials and provides for superposition for dual tires and the stress sensitivity of unbound materials. Probabilistic subroutines have been added to the basic structural analysis programs to provide rut depth predictions at various levels of reliability. The main program is designed to calculate primary response factors for each analysis period.

Calculate Rate of Rutting

The basic distress model is designed to predict the rate of rutting [the rutting per application of 80-kN (18 000-lbf) single-axle loads]. This part of the prediction model computes the expected rate of rutting as a function of the appropriate primary response factors from the structural analysis.

Calculate Cumulative Amount of Rutting

The cumulative rutting is calculated by multiplying the rate of rutting for each analysis period by the number of equivalent load applications during that period.

## APPLICATION OF MODEL TO OTHER CONDITIONS

Although this model was developed for the AASHO road tests, it could be used for other conditions either as is or after the introduction of appropriate changes in the fitting coefficients. In an application to the Brampton Test Road, eight sections were selected from the available data to estimate rut depths. The structure of these sections is shown below, and a summary of the analysis is shown in Table 3.

| Section No. | Section Thickness (mm): Asphalt Concrete Surface | Granular Base | Granular Subbase |
|---|---|---|---|
| 9 | 89 | 152 | 152 |
| 10 | 89 | 152 | 152 |
| 22 | 89 | 152 | 152 |
| 16 | 140 | 51 | 457 |
| 18 | 140 | 51 | 152 |
| 12 | 89 | 102 | 152 |
| 19 | 89 | 102 | 152 |
| 20 | 89 | 102 | 152 |

The estimated values of rut depth were about two times higher than the observed values. Therefore, the model was adjusted so that the average estimates of the rut depth were similar to the observed values. These estimates are shown in the last two columns of Table 3.

## SUMMARY

The rate of rut depth model presented in this paper was derived from the AASHO Road Test data, but was found capable of predicting rut depths in Brampton Test Road sections within reasonable limits. Therefore, it can be assumed that the model is capable of predicting rut depths in conditions that may be different from those at the AASHO Road Test site. Slight adjustments may be necessary to accommodate local conditions.

## ACKNOWLEDGMENTS

This work was sponsored by the American Association of State Highway and Transportation Officials, in cooperation with the Federal Highway Administration, and was conducted in the National Cooperative Highway Research Program, which is administered by the Transportation Research Board of the National Research Council.

## REFERENCES

1. G. M. Dorman and C. T. Metcalf. Design Curves

for Flexible Pavements Based on a Layered System Theory. HRB, Highway Research Record 71, 1965, pp. 69-84.
2. J. E. Romain. Rut Depth Prediction in Asphalt Pavements. Centre de Recherches Routieres, Bruxelles, Research Rept. 150/JEK/1969, Dec. 1969.
3. R. D. Barksdale. Laboratory Evaluation of Rutting in Base Course Materials. Proc., 3rd International Conference on the Structural Design of Asphalt Pavements, 1972, pp. 161-174.
4. R. D. Barksdale. Rutting of Pavement Materials. School of Civil Engineering, Georgia Institute of Technology, Atlanta, 1973.
5. C. L. Monismith, D. B. McLean, and N. Ogawa. Design Considerations for Asphalt Pavements. Department of Civil Engineering, Univ. of California, Berkeley, Rept. 73-5, 1973.
6. Interim Guide for Design of Pavement Structures. AASHO, Washington, D.C., 1972.
7. B. A. Vallerga and R. G. Lee. Modern Pavement Evaluation Techniques. Proc., ASCE, Air Transport Division Specialty Conference, 1973.
8. M. Witczak. Full-Depth Asphalt Pavement Design for Air Carrier Airports. Asphalt Institute, MS-11, 1971.
9. C. L. Monismith and D. B. McLean. Design Considerations for Asphalt Pavements. Department of Civil Engineering, Univ. of California, Berkeley, Rept. 71-8, 1971.
10. E. S. Barber. Calculation of Maximum Pavement Temperatures From Weather Reports. HRB, Bulletin 168, 1957, pp. 1-8.
11. D. A. Kasianchuk. Fatigue Considerations in the Design of Asphalt Concrete Pavements. Univ. of California, Berkeley, PhD dissertation, 1968.
12. R. G. Hicks and F. N. Finn. Prediction of Pavement Performance From Calculated Stresses and Strains at the San Diego Test Road. Proc., AAPT, 1974, pp. 1-40.
13. R. C. G. Haas, N. I. Kamel, and J. Morris. Brampton Test Road: An Application of Layer Analysis to Pavement Design. Ontario Ministry of Transportation and Communications, Rept. RR 182, Nov. 1972.