Pavement Response and Equivalences for Various Truck Axle and Tire Configurations

Ronald L. Terrel and Sveng Rimsritong, Department of Civil Engineering, University of Washington

Many changes in allowable loading and operating procedure for trucks are under consideration in Washington and other states. For example, dual tires and single "flotation" tires for heavy truck loads may have varying damaging effects on pavements. Furthermore, at least for asphalt pavements, time of year and vehicle speed may also influence the analysis for special heavy load permits. This paper is a brief attempt to consider some of these variables on a relative basis. This paper is intended to be a limited approach to answer several pertinent questions from a theoretical study based on hypothetical pavements and loads and also on reasonable material characteristics and pavement behavior from previous research. The computer program was used to compute structural behavior. Maximum allowable numbers of load applications were determined by use of known fatigue and failure design curves. The results are a series of relationships based on pavement life that can be used to determine any number of equivalences. These equivalences can be used to compare the relative destructive effects of various sizes of single and dual tires, axle loads, pavement thicknesses, speeds, and temperatures. The general nature of these relationships provides a wide range of conditions for comparison. Within reason, interpolation is valid. One must keep firmly in mind, however, that these relationships are for assumed conditions (although reasonable) and do not represent actual pavements.

Indications are that many trucks now have front axle loads approaching the maximum allowable for single axles [8.16 Mg (18 kips) in the state of Washington]. That these loads are on single tires increases the potential for pavement damage. In addition, many changes in allowable loading are under consideration in other states. For example, substituting single "flotation" tires for dual tires on heavy truck loads may have varying damaging effects on the pavements. Furthermore, at least for asphalt pavements, time of year and vehicle speed may also influence analysis for special heavy load permits. This paper is a brief attempt to point out the relative effects of some of these variables.

Most of the past studies deal only with relationships between dual-tired single axles and dual-tired tandem axles. Therefore, this study examines relative destructive effect of the single tire versus dual tires and especially the effect of the wide single tire (super single or flotation tire) versus conventional dual tires.

Although this paper is not intended to be a state-of-the-art approach, it is a summary of a larger study (1) based on hypothetical pavements (with reasonable material characteristics and pavement behavior determined from previous research) and loads to answer several pertinent questions by means of current technology. The results are a series of behavior-response relationships based on pavement life. One can use them to determine any number of equivalences of relating variables based on a certain set of conditions.

Basic variables considered in this study include

1. Wheel load,
2. Tire contact pressure and width,
3. Thickness and nature of pavement layers,
4. Speed of vehicle, and
5. Pavement temperature.

A three-layer pavement structure with an asphalt concrete (AC) surface, untreated aggregate base (UTB), and natural soil subgrade was selected for this study. Multilayered elastic theory is used to compute structural response.

The deflections, stresses, and strains are computed by using the Chevron n-layer computer program. The horizontal tensile strain at the bottom of the asphalt-treated layer and the vertical compressive strain at the top of the subgrade are examined in determining the maximum number of load applications to failure (Figure 1). Maximum strains, especially in the thin pavement layers, can occur directly under one of the dual wheels rather than midway between them.

The maximum number of load applications N is determined (a) from criteria developed from laboratory fatigue tests on asphalt to minimize pavement cracking from repeated loading and (b) from criteria developed by Shell Oil Company to minimize surface rutting caused by overstressing the subgrade.

Fatigue and rutting equivalences are established based on the maximum number of standard axle load applications. These equivalences can be used to compare the destructive effects of various sizes of single and dual

Publication of this paper sponsored by Committee on Flexible Pavement Design.

tires and various axle loads.

The effects of changes in the level of temperature and variation in vehicle speeds on fatigue in terms of the maximum number of load applications are also examined.

BACKGROUND INFORMATION

As noted by a number of researchers, the assumption that pavement responds as a layered elastic system appears reasonable at this time. Several computer solutions are available; CHEV 5L was selected for this project to facilitate determination of the stresses. When using such solutions for material response characteristics that depend on stress, one must use an iterative type of solution for pavement sections containing a granular material.

Material Characteristics

In general, asphalt materials are viscoelastic; therefore, their stress-strain characteristics are dependent on both time of loading and temperature. A number of experimental methods have been developed to describe the relationship between stress and strain for asphalt mixes (2). For this study, the resilient modulus for typical Washington mixtures was used and was confirmed by the stiffness concepts of Van der Poel (3) and Heukelom and Klomp (4).

For untreated granular materials and untreated materials such as the subgrade, a measure of stiffness termed the resilient modulus can be determined from

1. The resilient modulus test by using repeated load triaxial apparatus (5),
2. The California bearing ratio test (6), and
3. The repeated plate load test (7).

In this study, data from the Washington State University test track studies (8) and other tests of typical Washington materials (9) were used for the subgrade and base layers. Other materials and localities would require appropriate adjustments.

Distress Criteria

Fatigue has been defined as the phenomenon of fracture under repeated or fluctuating stress and has a maximum value generally less than the tensile strength of the material. Stiffness plays a predominant role in determining the fatigue behavior of asphalt mixes, and maximum principal strain is a major determinant of fatigue crack initiation.

In practice, pavements are subjected to a range of loadings. In accordance with that, a cumulative damage hypothesis is required because fatigue data are usually determined from the results of simple loading tests. One of the simplest of such hypotheses is the linear summation of cycle ratios. Fatigue life prediction under compound loading becomes a determination of the time at which this sum reaches unity.

Numerous studies have been conducted to evaluate the fatigue behavior of AC, and data are available for materials similar to those used in Washington (10). These data were used as the basis for cumulative fatigue damage due to truck traffic.

The other mode of failure considered in this study is permanent deformation, more commonly called rutting. Structural failure due to rutting can occur in one or more pavement layers. Recent research has shown that rutting in the asphalt layers can be predicted reasonably well. This failure mode may be particularly important for thick asphalt sections in hot climates.

A somewhat broader approach to rutting failure is used in the Shell design method (11) as well as in this study. A critical subgrade stress-strain level beyond which the rutting is extended into the subgrade soil appears to exist. For example, if the vertical subgrade strain does not exceed the critical level, ruts due to subgrade failure are not formed. From experience in Washington, rutting failure is not a significant factor, but it was used here to illustrate the different failure modes that the highway engineer must guard against.

Other Factors

Pavement temperatures can be computed from weather data by solving the heat conduction equation by numerical technique, such as finite-difference procedure or finite-element procedure, or by closed form techniques as presented by Barber (12). As an alternative, a representative temperature can be estimated by one of several methods. As indicated, fatigue life is dependent on the asphalt stiffness, and temperature changes throughout the year will affect the analysis of pavement life accordingly. For the limited example in this paper, reasonable pavement temperatures were assigned and computations of pavement life were made to show this relative effect.

In addition to temperature, speed of the moving vehicle has often been considered to affect stresses induced in the pavement and ultimately the pavement life. To illustrate this factor, we considered only the change in stiffness of asphalt as caused by variable rates of loading. For the sake of simplicity, the other pavement layers were assumed to be unaffected.

COMPUTATIONS

Various wheel loads and tire widths to be considered as input variables in the computer analysis were suggested by the Washington Department of Highways. Although the tire-pavement pressure interface is generally known to be somewhat complex and affected by tire design, simplifying assumptions were made to accommodate the CHEV 5L program. These include a circular contact area with tire pressures equal to the contact pressure. Various tire pressure were calculated by dividing the wheel load by a reasonable contact area.

Several thicknesses of pavement structure have been selected: 7.62, 15.24, and 24.13 cm (3, 6, and 9.5 in) of asphalt concrete surface on 20.32 cm (8 in) of untreated base. The subgrade layer is assumed to be semiinfinite.

The types of material in each layer of the pavement structure were selected for this study based on the availability of the laboratory and field test data in combination with whether they were common in Washington. Those chosen are class B wearing course, untreated aggregate base, and the natural undisturbed clay subgrade soil.

The CHEV 5L computer program (13) was used to calculate the stresses, strains, and deflections. The effect of the dual load on any point is then determined by linear superposition of the effects of each of the loads at the point in question. The application of superposition implies linear response; thus use of this principle is an approximation of the dual wheel load.

The computational procedure includes several iterative steps. The summary for a particular computation is made up of seven steps.

1. Select thickness of each layer.
2. Estimate modulus and Poisson's ratio for each layer.

3. Select wheel load and contact area (radius of circular area of contact with pavement).

4. Select points for calculation of stresses, strains, and displacements. These will usually include depths ranging from the surface downward at least into the subgrade. Points are selected radially from the center of load sufficiently far away to include the adjacent dual tire if any. Preliminary calculations indicated that tires at the opposite end of the axle from those under consideration do not contribute significantly.

5. Following computer calculation, select appropriate values from the printout and compare them to the material behavior data. If the required moduli are not within the given range, they are adjusted and the computation repeated until reasonable agreement is attained. When dual tires are used, the additive values are used for this comparison so that maximum values are always considered.

6. When agreement is attained, use the final iteration as representative of that combination of load and pavement response.

7. Repeat steps 1 through 6 for each combination of load, tire width, pavement thickness, and the like.

EQUIVALENCE DETERMINATION

Surface deflection is often a good indicator of pavement behavior changes, but cannot of itself be readily related to performance over a wide range of conditions. Therefore, the main concern here will be with radial tensile strain on the bottom of asphalt concrete layers as it relates to fatigue cracking or failure. In addition, vertical compressive strain on the subgrade is examined with respect to its relationships to limiting rutting in the pavement structure.

By using the computed data, we evolved a series of steps to reduce these data to a form directly applicable to pavement life. This was a relatively straightforward but time-consuming procedure to eventually arrive at the primary relationships shown in Figures 2 and 3.

Fatigue

A complete and reasonably convenient summary of all the data is shown in Figure 2. In this figure, the relative number of applications of a particular load or combination of loads can be determined. As a basis for comparison in establishing Figure 2, a "standard" condition was defined as an 8.16-Mg (18-kip) axle load with 25.4-cm-wide (10-in-wide) dual tires on a pavement with 15.24 cm (6 in) of asphalt concrete. Thus this point on Figure 2 has an equivalence equal to unity. With the data normalized in this manner, any two points can be compared (divided) directly by using the relative equivalences on the vertical scale.

Rutting

In a manner similar to that used for fatigue, Figure 3 has been prepared as a summary of all the combined data for rutting behavior. Use of these data is similar to the use of those for Figure 2. Any two points can be compared in terms of their relative life to failure by their ratio or equivalence.

Climate (Temperature)

For the average case, 20.3°C (68.5°F) was assumed to be the temperature for AC at all depths. However, a range of temperatures is known to be encountered (for example, during the summer and winter months). A profile of temperature within the AC for these pavements was estimated from weather data.

Because of the excessive computations and analysis required, the effect of temperature on pavement behavior is limited to the case for 25.4-cm-wide (10-in-wide) dual tires, 8.16-Mg (18-kip) axle loads, and the usual range in asphalt concrete thickness appropriately adjusted for stiffness by sublayers. By using the same fatigue criteria as before, we determined and plotted the number of load applications to failure in the format shown in Figure 4. These data are for 8.16-Mg (18-kip) axle loads only, but they can be extrapolated to include other axle loads by using the linear nature of curves in Figure 2.

Vehicle Speed

Speed analysis has also been limited to the standard 8.16-Mg (18-kip) axle load with 25.4-cm-wide (10-in-wide) dual tires. Using the 25.4-cm-diameter (10-in-diameter) contact area between tire and pavement as the contributing loaded area, we assumed the wheel to be rolling at a range of speeds. These speeds were converted to load duration. These loading times were used to determine stiffness of the AC based on the principles of Van der Poel (3) and calculated for a particular mix as was done by Monismith, Alexander, and Secor (14) and from data on Washington mixtures (15).

By use of fatigue data, the relative effect of speed on the number of applications of load to failure is shown in Figure 5. Although the basic equivalence relationships shown earlier in Figures 2 and 3 did not indicate a speed, most of the stiffness data were developed for testing load duration of about 0.5 s [about 16 km/h (10 mph)]. The user of these data should be cautioned, however, that only relative values should be compared and not actual load applications to failure, for example.

SUGGESTED USE AND APPLICATIONS

Appropriate use and recognition of the limiting factors in this study are very important. The user must realize that comparisons among the variables considered are only relative and should not be used for actual pavement life predictions, for example. This approach is predicated on the fact that computed data are based on hypothetical pavements, although they are reasonable approximations of typical pavements constructed in Washington.

By means of the key relationships developed herein, one can use Figures 2 through 5 to determine a wide range of equivalences as illustrated in the form of examples or typical situations.

Example 1

Problem

Compare the relative pavement fatigue life expectance of a 7.62-cm (3-in) asphalt pavement when subjected to an 8.16-Mg (18-kip) axle load with 25.4-cm (10-in) dual tires and with 47-cm (18.5-in) single flotation tires.

Solution

From Figure 2, the relative lives for the dual and single cases are 250×10^{-3} and 180×10^{-3} respectively. Therefore, the equivalence of these two is $(250 \times 10^{-3})/(180 \times 10^{-3}) = 1.38$. That is, the single tire would be 38 percent more damaging in terms of fatigue.

One should note that these equivalences are compared for conditions that are constant except for those being compared.

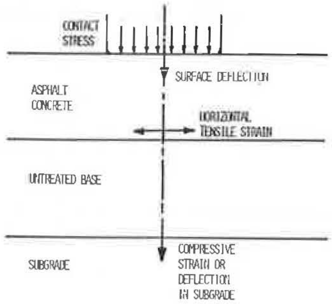


Figure 1. Location of critical strains in pavement.

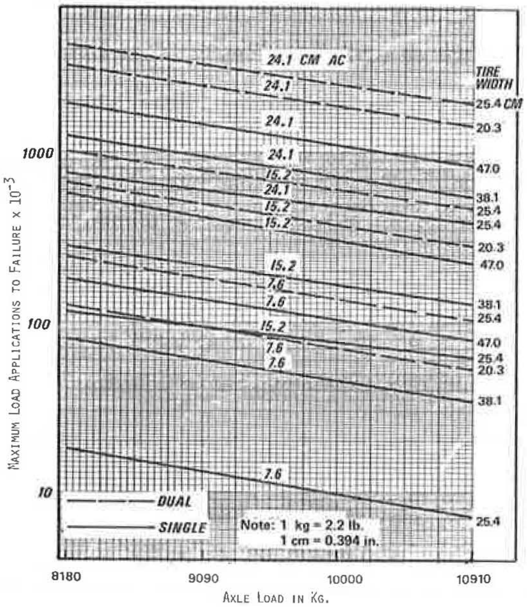


Figure 2. Relative pavement life to failure for a range of loads and pavements based on fatigue of AC layer.

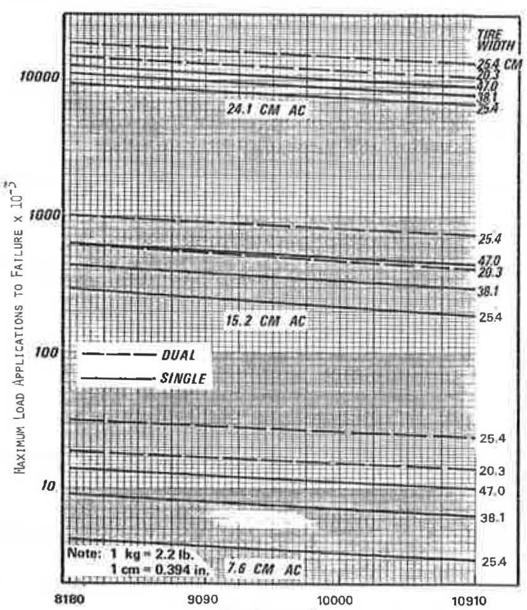


Figure 3. Relative pavement life to failure for a range of loads and pavements based on rutting of subgrade.

Example 2

Problem

Determine the equivalence for the same loads as in example 1 but in terms of rutting distress.

Solution

From Figure 3, for 7.62-cm (3-in) AC, $N = 32 \times 10^{-3}$ for dual tires and $N = 14 \times 10^{-3}$ for single tires. The equivalence would then be $(32 \times 10^{-3})/(14 \times 10^{-3}) = 2.3$ for rutting damage, which means that the pavement will last 2.3 times longer under dual tires.

Assuming that the pavement was originally designed to preclude failure over a reasonable design life, one can compare the two examples. By changing the 8.16-Mg (18-kip) axle load from dual to single tires as illustrated, the pavement life will be shortened when one considers both fatigue and rutting. From this analysis, one would expect fatigue to be more critical.

Figure 4. Relative pavement life of AC for summer and winter conditions when vehicles have 8.16-Mg (18-kip) axles and 25.4-cm-wide (10-in-wide) dual tires.

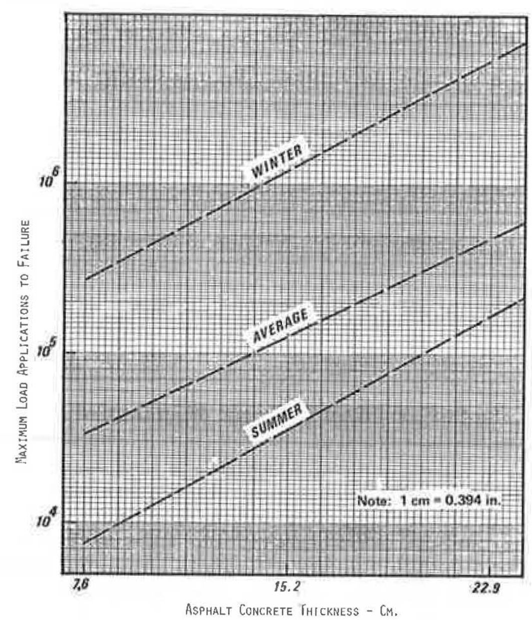
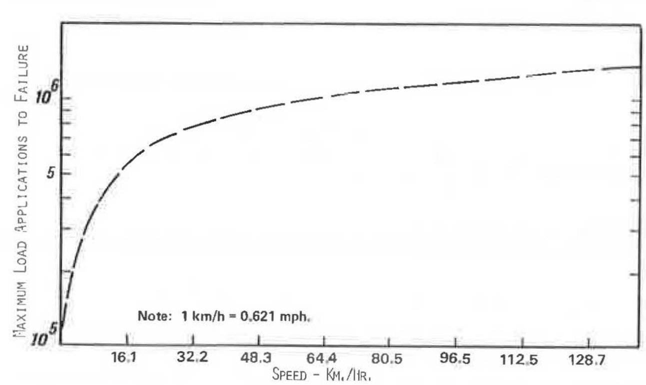


Figure 5. Relative pavement life of AC for range of vehicle speeds when vehicles have 8.16-Mg (18-kip) axles and 25.4-cm-wide (10-in-wide) dual tires.



Example 3

Problem

What is the difference for summer and winter conditions as determined by using the results from example 1?

Solution

From example 1, the equivalence was equal to 1.38 and this can be considered the "average" condition in Figure 4. The actual equivalence between 25.4-cm (10-in) dual tires and 47-cm (18.5-in) single tires would remain about the same, but actual life to failure (for a particular case) would need to be adjusted. From Figure 4, summer, average, and winter applications for 7.62-cm (3-in) AC would be 7.4×10^3, 3.3×10^4, and 2.7×10^5 respectively. Therefore, pavement life could be expected to be increased by $(2.7 \times 10^5)/(3.3 \times 10^4) = 8.2$ times in winter and decreased by $(3.3 \times 10^4)/(7.4 \times 10^3) = 4.5$ times in summer.

One must realize, however, that the actual range of winter to summer temperatures are distributed throughout the year, month by month, and a weighted average would be more realistic. The data in Figure 4 are primarily for illustrative purposes and show that because of higher stiffness of AC in winter, it is more resistant to fatigue cracking.

Example 4

Problem

What is the effect of reducing average truck speed from 112.6 to 88.5 km/h (70 to 55 mph) as determined by using the results from example 1?

Solution

The curve in Figure 5, although developed for the "standard" load, can be used for general speed comparisons. At 112.6 km/h (70 mph), load application to fatigue cracking is 1.25×10^6. At 88.5 km/h (55 mph), this value is 1.15×10^6. Therefore, pavement life is reduced by a factor of $(1.15 \times 10^6)/(1.25 \times 10^6) = 0.92$, or 8 percent.

Example 5

Problem

A special highway user requested permission to use a 4.8-km (3-mile) segment of highway for trucks having average single axle loads of 10.89 Mg (24 kips) and 47-cm (18.5-in) single flotation tires. The existing pavement is 7.62 cm (3 in) of AC, and other conditions are similar to those developed in this report. What change in pavement would be required to provide equivalent pavement life compared to the standard 25.4-cm (10-in) dual tire and 8.16-Mg (18-kip) axle load case?

Solution

Provide an AC overlay. Locate the given conditions on Figure 2 [10.89-Mg (24-kip) axle load, 47-cm (18.5-in) single tire, and 7.62 cm (3 in) of AC pavement]. This point is approximately 82×10^{-3} on the vertical equivalence scale. Next, locate the "standard" condition [8.16-Mg (18-kip) axle load, 25.4-cm (10-in) dual tire, and 7.62 cm (3 in) of AC]. This point is approximately 250×10^{-3}. That is, pavement thickness must be increased sufficiently to increase the 82×10^{-3} to 250×10^{-3}.

By examining the family of AC thickness curves [7.62 cm (3 in), 15.24 cm (6 in), and 24.13 cm (9.5 in)], one can interpolate any point in between. Therefore, by moving vertically along the 10.89-Mg (24-kip) axle load line from 82×10^{-3} to 250×10^{-3}, one can interpolate the AC thickness as being approximately midway between the 7.62-cm (3-in) and 24.13-cm (9.5-in) curves or 15.75 cm (6.2 in). This indicates that 15.75 cm (6.2 in) is required and 7.62 cm (3 in) is existing (assuming it is new); therefore, an 8.13-cm (3.2-in) overlay of this 4.8-km (3-mile) section would be required to make it equivalent to the adjoining highway that will receive "standard" traffic.

Additional solutions may be more appropriate depending on the conditions.

1. Add axles to reduce average axle weight.
2. Change to dual tires. [Figure 2 does not include large enough dual tires—27.94 cm (11 in) or 30.48 cm (12 in) would be required by extrapolation but may not be practicable.]
3. Combine solutions 1 and 2.

For larger special loading, the speed may be reduced considerably and this should be considered in the equivalence evaluation. Furthermore, the time of year may be a factor—special hauling may be seasonal and compensation for temperature correction may increase or decrease the equivalency.

SUMMARY AND CONCLUSIONS

This study was initiated in an attempt to examine relative destructive effects of wide single and conventional dual tires on pavements. Basic variables are wheel load, tire width, and AC thickness. Based on available laboratory and field data, three pavement layers consisting of AC surface, untreated aggregate base, and clay subgrade were selected as the materials for this study. The CHEV 5L program was used to compute deflections and critical strains. Prior to determining the fatigue and rutting equivalences, we compared maximum computed deflections and critical strains with other sources. These experimental data seem to agree reasonably well. By using known fatigue and failure design curves, we determined maximum allowable numbers of various axle load applications. Fatigue and rutting equivalence relationships for various axle loads are established by dividing the maximum number of axle load applications by the maximum applications of 8.16-Mg (18-kip) axle loads on an AC thickness of 15.24 cm (6 in) when dual 12.7-cm (5-in) tires are used. These equivalences, shown in Figures 2 and 3, can be used to compare the relative pavement life when subjected to various sizes of single and dual tires and axle loads.

The effects of variation in temperature between summer and winter were also examined. It can be said that, as temperature decreases, pavement structure rigidity increases, thus causing a decrease of vertical stress and thereby permitting a greater number of load applications. As shown in Figure 4, the destructive effect of a vehicle on the pavement during the summer is much greater than in winter, exclusive of spring frost break-up conditions and other soil-moisture variations.

The effect of variation in vehicle speed on the pavements was also briefly considered. In general, slower speed tends to cause longer load duration, resulting in an increase in vertical stress and thereby permitting fewer load applications to failure as shown in Figure 5. This figure can be used to compare the relative pavement life at various speeds as illustrated by the solution to the problem in example 4.

The general nature of Figures 2 through 5 provides a wide range of conditions for comparison on a relative basis. Within reason, interpolation is valid. One must keep firmly in mind, however, the fact that these relationships are for assumed conditions (although reasonable) and do not represent actual pavements. Comparison must be made on a relative basis and not according to actual pavement life as shown in load applications to failure.

On the basis of this study, several conclusions appear warranted.

1. Single wide flotation tires are generally more destructive than dual tires with equivalent contact area.
2. Wide flotation tires require a thicker asphalt pavement than dual tires do.
3. Pavement requirements for both wide single and dual tires increase at about the same rate as total axle load increases.
4. Pavement life in terms of fatigue is at least an order of magnitude greater in winter than in summer for the conditions of this study.
5. Pavement life is increased directly with speed of the vehicle if all other factors are equal.

ACKNOWLEDGMENT

We wish to thank the Washington Department of Highways and the Federal Highway Administration for their support of this study.

REFERENCES

1. R. L. Terrel and S. Rimsritong. Pavement Response and Equivalencies for Various Truck Axle-Tire Configurations. Washington Department of Highways, Olympia, Research Rept. 17.1, Nov. 1974, 106 pp.
2. R. L. Terrel and I. S. Awad. Symposium on Technology of Thick Lift Construction—Laboratory Considerations. Proc., AAPT, Cleveland, Feb. 1972.
3. C. Van der Poel. A General System Describing the Viscoelastic Properties of Bitumins and Its Relation to Routine Test Data. Journal of Applied Chemistry, May 1954.
4. W. Heukelom and A. J. G. Klomp. Road Design and Dynamic Loading. Proc., AAPT, Dallas, Feb. 1964.
5. Full-Depth Asphalt Pavements for Air Carrier Airports. Asphalt Institute, College Park, Md., Manual Series 11, Jan. 1973.
6. W. Heukelom and C. R. Foster. Dynamic Testing of Pavements. Trans., ASCE, Vol. 127, Part 1, 1962, pp. 425-427.
7. Soils Manual for Design of Asphalt Pavement Structures. Asphalt Institute, College Park, Md., Manual Series 10, May 1964.
8. R. L. Terrel. Analysis of Ring No. 2, WSU Test Track. Asphalt Institute, College Park, Md., Dec. 1968.
9. D. A. Voss and R. L. Terrel. Structural Evaluation of Pavements for Overlay Design. HRB, Special Rept. 116, 1971, pp. 199-211.
10. J. A. Epps and C. L. Monismith. Influence of Mixture Variables on the Flexural Fatigue Properties of Asphalt Concrete. Feb. 10, 1969.
11. J. O. Izatt, J. A. Letter, and C. A. Taylor. The Shell Group Methods for Thickness Design of Asphalt Pavements. Shell Oil Co., Jan. 1-3, 1967.
12. E. S. Barber. Calculation of Maximum Pavement Temperatures from Weather Reports. Bureau of Public Roads.
13. J. Lysmer and J. M. Duncan. Stress and Deflections in Foundations and Pavement. 4th Ed., Univ. of California, Berkeley, 1969.
14. C. L. Monismith, R. L. Alexander, and K. E. Secor. Rheologic Behavior of Asphalt Concrete. Proc., AAPT, Minneapolis, Vol. 35, Feb. 1966.
15. R. L. Terrel and I. S. Awad. Resilient Behavior of Asphalt Treated Base Course Materials. Washington Department of Highways, Research Rept. 6.1, Aug. 1972.