Seasonal Load Limits Based on Rut Depth

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ABSTRACT

In hot climates, the prevention of excessive rutting failures in flexible pavements often requires limits on the allowable axle loads on such pavements during periods of high temperature and moisture. A rational approach for selecting this load limit to ensure a uniform rate of rutting failure throughout a typical year is discussed. The approach selected is based on the use of mechanical methods for determining the effects of seasonal changes in temperature and moisture on the pavement's response to load. The rate of rutting failure with traffic is regarded as the performance variable with traffic. The concept of pavement performance relates the rate of change of rutting damage units with traffic divided into straight-line segments for each season. The performance variable is predicted for each season, allowing for consideration of seasonal pavement behavior and traffic conditions. The validity of the method has been verified by determining the seasonal load limit for a typical road pavement under a particular set of seasonal environmental conditions, pavement materials, and axle load distributions in Kuwait. If a seasonal load limit based on the rutting damage criterion were adopted, pavement service life would be significantly extended.

Highway managers recognize that the load carrying capability and the rate of decrease of useful service life of asphalt pavement vary during the year. Under uniform traffic, these variations reflect seasonal changes such as temperature and moisture content in the physical characteristics of various layers of pavement materials. The application of normally acceptable heavy axle loads during critical periods when the pavement materials are in their weakened condition leads to an accelerated deterioration rate and premature failure.

In cold regions seasonal temperature changes cause poor spring-thaw performance as a result of differences in the response of materials to freezing and moisture changes. In nonfrost regions, however, environmental factors, such as temperature of the asphalt layers and moisture within granular layers and subgrade, have an overriding influence on the performance behavior of the pavement structure. The seasonal variations in temperature and moisture conditions are sometimes more important than the stress states because most of the permanent shear deformation observed occurs when the pavement material is subjected to high temperatures or moisture (1,2).

The surface curvature index (SCI) measured on asphalt pavements 150 to 300 mm thick during the high-temperature summer period in Kuwait was found to exceed two to three times the normal SCI values (3,4). This explains the relatively high reduction in the load carrying capacity of the asphalt layers during the high-temperature summer season.

In current practice decisions concerning the magnitude of seasonal load limits, the dates of their imposition, and the duration of the restricted period are usually made on the basis of local experience based on seasonal observations of pavement surface deflections. The method described in NCHRP Synthesis 26 (5) and Report 76 (6) is typical of these approaches. It directly accounts for seasonal changes in pavement performance by measuring SCI and deflections at both normal and peak periods of a year.

Recently, other methods of pavement response analysis and materials testing have been used in a more rational mechanical approach and applied to the problem of selecting the spring-thaw load limit. The fatigue-based criterion (7) and the uniform failure rate criterion (8), which predicts pavement distress in terms of fatigue cracking, rutting, and roughness, are among the recent criteria developed for this purpose.

The objective of this study is to develop a rational seasonal load limit procedure based on the rutting damage potential of the pavement layers. Because shear strength of a layer material is a function of the state of stress and its level in the pavement structure, resulting changes in rutting damage depend mainly on seasonal axle loads and environmental conditions. The method is demonstrated with an application to an in-service asphalt pavement road in Kuwait.

RUTTING DAMAGE CRITERION

Justification of the use of the rutting damage-based criterion as a basis for selecting the critical season load limit follows.

Asphalt pavement failures in hot climatic regions are mainly due to excessive permanent deformations or rutting of asphalt-bound and granular layers as well as of subgrade soil. Rutting damage occurs in these layers in the form of cumulative permanent deformation or inadequate stability. Both distress modes are related to the shear strength of the layer material.

The allowable shear stress (q_f) can be calculated from the single-load shear strength as $q_f = (\sigma_1 - \sigma_3)/2$, where $(\sigma_1 - \sigma_3)$ is the failure deviator stress obtained from a triaxial test at a confining pressure value (σ_3) equal to that computed in the pavement layer under a standard dual wheel load system during a given period.

Shear failure in any layer of a pavement subjected to the standard dual wheel load system is assumed to occur when the maximum shear stress attains the shear strength of the material under triaxial loading condition. The factor $F = q_i/q_f$ indicates the relative probability of failure for the ith pavement layer, where q_i denotes the maximum shear stress developed within the ith layer.

The computer algorithm relevant to the layered elastic theory coupled with the seasonal values of the elastic response parameters of the pavement are used for calculating stresses and strains at three specific points: (a) directly under the centerline of one wheel, (b) at the edge of one wheel, and (c) at the centerline of the dual wheels. All these points are located at the middepth of each pavement layer and at the surface of subgrade as shown in Figure 1.

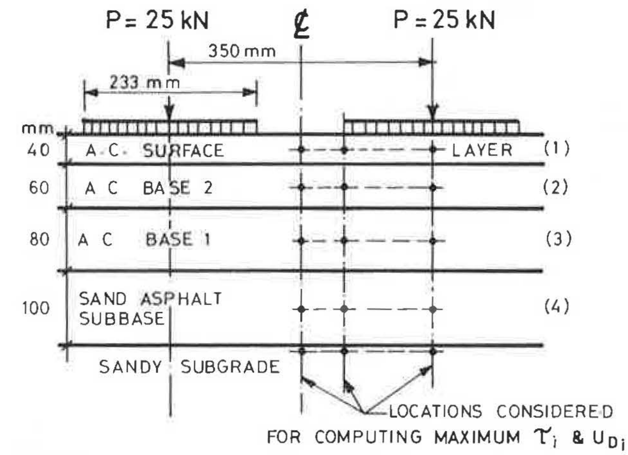

FIGURE 1 Asphalt pavement structure analyzed for a standard dual wheel load system.

The rutting damage potential (RD) of each pavement layer is assessed from the permanent deformation curves, relating the magnitude of permanent strain (ε_p) to the number of deviator stress repetitions (N). A typical curve presented in a double-logarithmic scale, as shown in Figure 2, can be developed for each layer material under specific environmental conditions. Changes in the deviator stress (q) would produce results that would follow parallel lines. These linear relationships are the result of extensive laboratory tests carried out on different asphaltic and granular paving materials (9-11). On the other hand, changes in mix characteristics, environmental conditions (such as temperature or moisture), and experimental conditions (such as degree of confinement or frequency of loading)

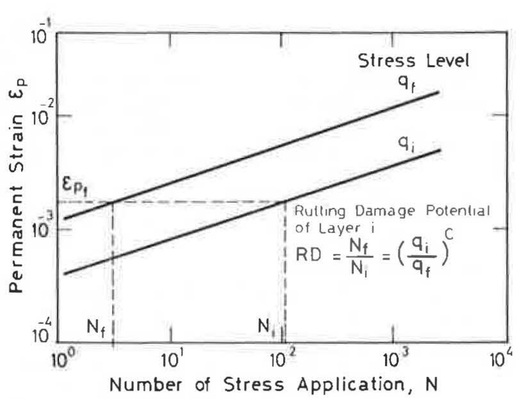

FIGURE 2 Equivalent rutting damage in asphalt pavement layer at different stress levels.

would change the slope of these linear relationships. Consequently, for a certain permanent strain value, the rutting damage potential of the ith layer material during a given period j is defined as follows:

$$RD_{ij} = (N_f/N_i)_j = (q_i/q_f)_j^c \tag{1}$$

where

- q_f = half the failure deviator stress, which is taken as a limit for the range of linearity. Above this stress level, the rate of permanent strain is greatly accelerated and eventually leads to failure (Figure 3).
- N_f = number of applications of the deviator stress level (q_f), assumed to be equal to 1 in the criterion proposed here (i.e., one single application of half the failure deviator stress would produce the maximum permissible permanent strain).
- q_i = an applied deviator stress level equaling the maximum shear stress computed in the ith pavement layer.
- N_i = number of applications of the deviator stress level (q_i), which produces the maximum permissible permanent strain.
- c = a coefficient that characterizes the susceptibility of the layer material to rutting damage. Its value depends on the properties and mix composition of the material and environmental and experimental conditions.

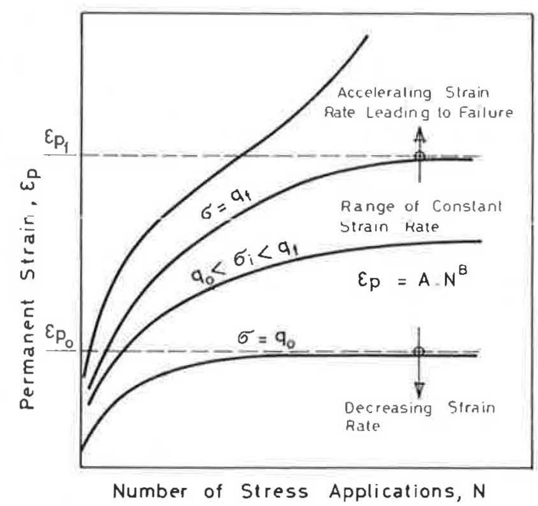

FIGURE 3 Relationship between permanent strain and applied stresses.

For asphalt paving mixtures, the c-value was found to range from 5 to 8 (11,12), so that higher values are more appropriate to finer gradation mixtures with high bitumen content tested at relatively high temperatures. For unbound granular materials and sandy subgrade soils, c-values range from 8 to 14 depending on grain size distribution and moisture content (10).

The permanent deformation within a pavement layer is assumed to be a function of the elastic volume change calculated in the same layer (13). Accordingly, the rutting damage potential for the whole pavement structure during period j is determined by averaging the weighted rutting damage for each pavement layer with respect to the value of strain energy of distortion (U_{D_i}) absorbed by each layer as follows:

$$RD_j = \Sigma_i (RD_i \times U_{D_i})/\Sigma_i U_{D_i} \quad (2)$$

The daylight hours in each season are divided into environmental periods to allow prediction of changes in rutting damage due to variable temperature gradients in the pavement structure. This is especially important in seasons with a mean air temperature higher than 20°C and where a nonuniform distribution of traffic loading possibly exists during daylight hours. The accumulated rutting damage potential for a pavement structure during the daylight hours of season S is then determined as follows:

$$RD_s = \Sigma_j RD_j \times W_j \quad (3)$$

where RD_S is the accumulated rutting damage potential for season S and W_j is the percentage of load applications while the pavement is in the jth period.

The maximum axle load permitted during the critical season should be restricted to one which produces a rate of rutting damage with traffic ($\Delta RD/\Delta T$) not exceeding 1.5 times the average value produced for the whole year by the maximum legal axle load. The objective of such a criterion is to maintain a uniform rate of pavement distress throughout the year and consequently extend the service life of the pavement.

APPLICATION OF THE LOAD LIMIT PROCEDURE

To evaluate the load limit approach, the following experimental analysis and statistical study of the necessary input parameters were carried out on a section of a highway in Kuwait that is subjected to heavy traffic loading throughout a typical year. The pavement structure consists of 18-cm-thick asphalt concrete layers and a 10-cm-thick sand-asphalt base layer constructed on a sandy subgrade desert soil.

Experimental Investigations and Assessment of Existing Pavement

Field surveys and sampling programs were carried out to evaluate the pavement section and its condition during three different temperature seasons of the year. The following parameters were collected:

- Visual aspect of the bituminous pavement including rut depth measurements using a 1.20-m straightedge;
- Dynamic deflection measurements using Dynaflect;
- The type and thickness of the asphalt pavement layers, properties of subgrade soil, and its water content;
- Information about past service period and maintenance provided; and
- Laboratory testing program to determine resilient moduli of the pavement and subgrade materials and the failure deviator stress at different confining pressures within the range of seasonal temperatures.

The response of the pavement to the maximum legal axle load applied locally was determined using the BISAR layered elastic computer program (14). The stresses and strains in the pavement structure and subgrade due to a dual wheel load of 50 kN spaced at 350 mm between centers were calculated. The maximum shear stress and the strain energy of distortion in each pavement layer and on the top of the subgrade were calculated for each season at four different temperature gradients corresponding to 6:00 a.m., 10:00 a.m., 2:00 p.m., and 6:00 p.m., respectively.

The laboratory testing and the computer analysis necessary to complete the procedure are well established and described elsewhere (9,11,15-17). The general information concerning the road section tested and the principal assessment data are given in Table 1.

Pavement Temperature Distribution

Temperature distribution in the bituminous pavements has been recorded in a real scale model and the re-

TABLE 1 Pavement Material Properties and Assessment Data Used in Seasonal Rutting Damage Analysis[a]

Depth of Pavement Layer (mm)	Season of the Year	E-Modulus (N/mm^2)	Poisson's Ratio	Maximum Shear Stress, q_i (N/mm^2)	Strain Energy of Distortion ($U_D \times 10^{-4}$)	Failure Stress, q_f (N/mm^2)	Deviator $(\sigma_1 - \sigma_2)/2$ at σ_3 (N/mm^2)	Exponential c, 1/log slope of ϵ_p – N curve
Asphalt	1	2120	0.40	0.162	0.024	1.80	0.40	5
Concrete	2	180	0.45	0.152	1.089	0.75	0.30	6
Surface	3	28	0.45	0.148	9.897	0.50	0.30	7
0-40								
Asphalt	1	2810	0.40	0.083	0.039	2.30	0.30	5
Concrete	2	520	0.40	0.098	0.165	1.05	0.20	6
Base 1	3	60	0.45	0.100	1.119	0.62	0.20	7
40-100								
Asphalt	1	3120	0.40	0.089	0.037	2.80	0.10	5
Concrete	2	1300	0.40	0.067	0.044	1.40	0.10	6
Base 2	3	280	0.45	0.059	0.166	0.85	0.10	7
100-180								
Sand	1	3400	0.40	0.162	0.124	1.40	0.00	5
Asphalt	2	1800	0.40	0.138	0.167	0.80	0.00	7
Subbase	3	520	0.45	0.103	0.323	0.40	0.00	7
180-280								
Silt	1	110	0.45	0.046	0.361	0.43	0.40	6
Sand	2	110	0.45	0.068	0.556	0.32	0.30	7
Subgrade	3	130	0.45	0.093	0.870	0.21	0.20	10

[a]For the period 12:00 p.m. to 16:00 p.m.

sults of this investigation have been published (18). On the basis of this experimental work the following approximate temperature frequency function has been established:

$$f(T°C) = 1/[(2\pi)^{1/2}]\ (10)\ \exp[-0.005\ (T - 35)^2] \quad (4)$$

where T°C is the temperature of the pavement surface.

The probability that the temperature of the pavement is lower than T_1 is given by

$$P(T < T_1) = 1/[(2\pi)^{1/2}]\ (10) \int_{-\infty}^{T_1} \exp[-0.005\ (T - 35)^2]\ dT \quad (5)$$

The cumulative histogram of the pavement surface temperature is shown in Figure 4. This histogram indicates three seasonal conditions for the pavement surface temperatures in Kuwait as follows:

Season 1: 8 < T°C < 25 for 25 percent of the year,

Season 2: 25 < T°C < 45 for 50 percent of the year, and

Season 3: 45 < T°C < 67 for 25 percent of the year.

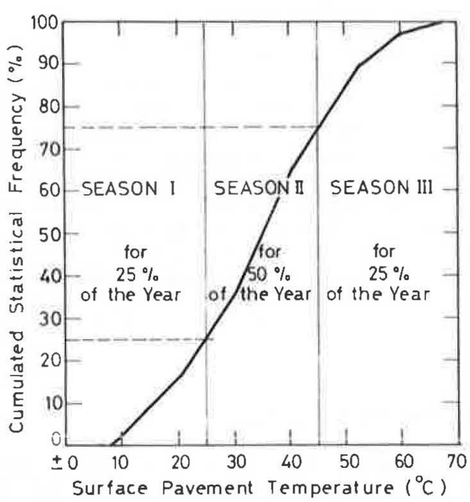

FIGURE 4 Cumulative histogram of pavement temperatures.

Traffic Load Distribution

Previous statistical investigations (15,19), carried out in the development of the local asphalt pavement design method, have permitted characterization of the daily traffic pattern of commercial vehicles on the main roads in Kuwait and the associated axle load distribution. These are shown in Figure 5.

To assess the impact of the axle load limits on pavement failure, an axle load distribution model with a gamma density function is developed to estimate the axle frequency response to variable axle load limits as suggested by Saccomanno and Abdel Halim (20):

$$f(x) = \beta(x - \theta)\ \exp[-\psi(X - \theta)] \quad (6)$$

where

f(x) = proportion of axle loads with a load value of x kN;

θ = smallest axle load observed in the truck fleet = 20 kN; and

β,ψ = calibration parameters, which vary with limiting legislation and other jurisdictional factors.

The cumulative number of axles up to an axle load limit of X_m can be expressed as

$$F(x) = \int_{\theta}^{X_m} \beta(x - \theta)\ \exp[-\psi(x - \theta)]\ dx \quad (7)$$

and the total payload (L) carried by the pavement can be expressed as

$$L(x) = \int_{\theta}^{X_m} \beta(x - \mu)\ (x - \theta)\ \exp[-\psi(x - \theta)] \quad (8)$$

where μ is the average weight per axle of an empty truck = 20 kN.

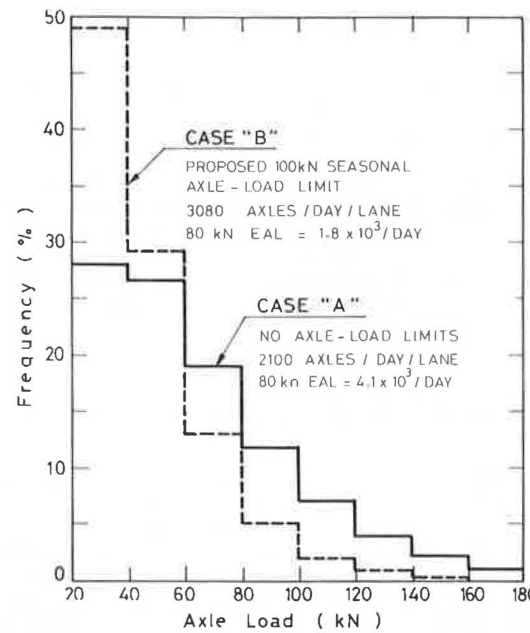

FIGURE 5 Axle load distribution for a constant payload (11,330 ton/day).

In Kuwait as well as in many other developing countries, the usual lack of enforcement and a low response rate to legislation suggest that it would be more appropriate to use the upper limit (i.e., $X_m = \infty$) in the preceding definitions. In the case of the road section analyzed in this study, the observed number of axle passes (greater than 20 kN) was 2,110 per day per lane. The adjusted parameter values of β and ψ for the axle load distribution shown in Figure 5 were taken to be 300 and -0.370, respectively.

The total payload (L) carried by the observed number of axle passes was calculated with Equation 8 to be 11,330 tons per day. On the basis of this, the number of axle passes would increase if an axle load limit were enforced. In Figure 5 a new axle load distribution is shown for the same payload and with the assumption that legislation is enforced. This distribution reduces the axle load limit from $X_m = \infty$ to $X_m = 100$ kN. This axle load restriction would result in an increase in the number of axle passes from 2,110 to 3,080, if it were to be enforced during the critical season. Converting the axle load applications of x kN to an equivalent standard axle load (EAL) of 80 kN, using the fourth power damage function, a reduction in the 80-kN EAL from 4.1 x 10^3 to 1.8 x 10^3 per day is obtained as a result of the axle load distribution under the new axle load limit.

Seasonal Rutting Damage Rate

The implications of a critical seasonal load limit are analyzed in terms of its effect on rutting damage to the pavement studied. The effects of both temperature and moisture variations on the strength of layer materials and consequently on the rutting damage potential have been considered for the three seasons of the year. Due to the slight seasonal changes in moisture content of the sandy subgrade under the pavement section (2 to 4 percent), the effect of temperature variations on the rutting damage rate was dominant. For each season, the 16 daylight hours are divided into four equal periods from 4:00 a.m. to 8:00 p.m. to account for the effect of variation in both temperature gradient and traffic load distribution.

An example of the effect of temperature gradient on the unit rutting damage corresponding to the three seasons is shown in Figure 6. The distribution of the rutting damage rate within the pavement layers during the period from 12:00 p.m. to 4:00 p.m. is calculated according to the mechanical approach introduced in this paper. As seen in Figure 6, the 40-mm-thick surface asphalt concrete layer has the highest rutting damage potential because its temperature during this period of the day compared to the underlying base layers is highest. However, due to the relatively low shear strength value of the sand-asphalt subbase at zero confining pressure, the rutting damage potential of this layer is almost of the same order as that for the surface asphalt concrete layer.

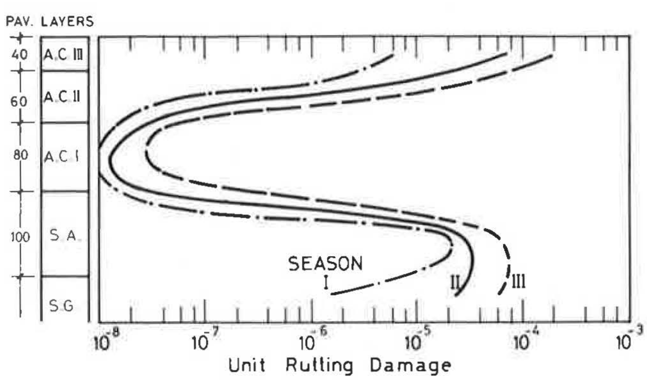

FIGURE 6 Distribution of rutting damage rate within pavement layers during the period 12:00 noon to 4:00 p.m.

The pronounced effect of the variable moisture content on the failure deviator stress of the sandy subgrade soil and consequently on the rutting damage potential is shown in Figure 6. There is no significant effect on the temperature gradient in the pavement on the rutting damage potential of the subgrade soil. However, the effect of seasonal temperatures was found to be extremely high. During Season 3 with the highest summer temperature, the rutting damage potential in the subgrade is 30 times greater than that for the winter temperature (Season 1) between 12:00 p.m. and 4:00 p.m.

The weighted average rutting damage rate for the whole pavement structure has been calculated for the different 4-hr periods considering the distribution of the traffic axle loads. The results are shown for the three different seasons in Figure 7. During Season 3 with the highest temperature, the predicted rutting damage rate for the pavement under study was found to be five times greater than that for Season 2 with the medium temperature range. This result in-

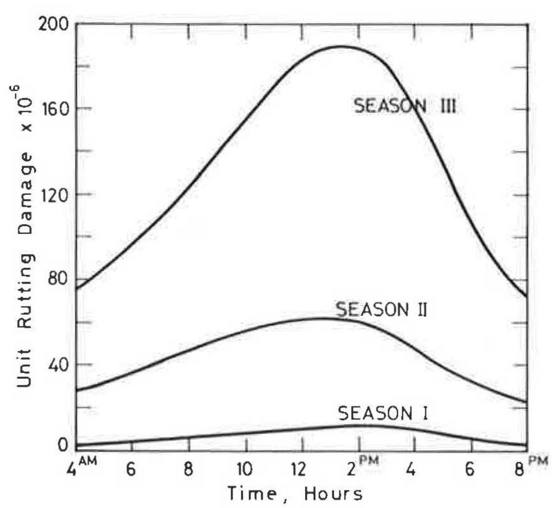

FIGURE 7 Unit rutting damage development during 1 day at different seasonal temperatures.

dicates that if a uniform rutting damage rate criterion is used, a seasonal axle load limit should be imposed. Table 2 gives a summary of the resulting weighted average rutting damage rates for the three seasonal conditions. A maximum allowable axle load limit of 100 kN is proposed for the study pavement during the critical Season 3.

The change in the rutting damage resulting from the axle load limit was calculated under the assumption that the total payload remains constant. Figure 8 shows that $\Delta RD/\Delta T$ during the critical season decreases from 39.20 x 10^{-6} for the case of no axle load limit to 17.22 x 10^{-6} for the case of a 100-kN axle load limit. Accordingly, the annual rutting damage rate is decreased by 40 percent as the data in Table 2 indicate. Furthermore, the objective of the proposed criterion, to maintain a uniform rate of pavement distress throughout the year, is also met.

Alternative seasonal load limit policies could be analyzed in terms of their effects on the rate of rutting damage using the proposed procedure. However, an essential step in the economic analysis of alternative load limit policies is the determination of cumulative damage to the pavement or its remaining service life up to a certain maximum rutting value under each of the possible alternatives considered.

The annual rate of increase of rutting measured on the road pavement studied during the past 6 years was found to vary from one location to another depending on the frequency of the lateral distribution of wheelpaths as well as on the average traffic speed (1). Excluding the permanent deformations developed during the first 2 years after construction, the measured rate of increase of rutting varied between 2.5 and 5.0 mm annually. Accordingly, the equivalency of the calculated damage unit to a rut-

TABLE 2 Seasonal Rutting Damage Rate ΔRD/ΔT

Season	Ratio[b]	4:00 a.m.-8:00 a.m. .20 T[a]	8:00 a.m.-12:00 a.m. .35 T	12:00 p.m.-4:00 p.m. .30T	4:00 p.m.-8:00 p.m. .15 T	Seasonal ΔRD/ΔT x 10^{-6}
1	.25 Y	0.7	1.3	1.4	0.4	3.8 x .25 = 0.95
2	.50 Y	5.4	11.2	12.0	3.6	32.2 x .50 = 16.10
3	.25 Y					
No axle load limit		29.4	56.0	56.4	15.0	156.8 x .25 = 39.20
Maximum axle load 100 kN		12.9	24.6	24.8	6.6	68.9 x .25 = 17.22

Note: Annual rutting damage rate: no seasonal axle load limit = 0.95 + 16.10 + 39.20 = 56.25 x 10^{-6}, with seasonal axle load limit of 100 kN = 0.95 + 16.10 + 17.22 = 34.27 x 10^{-6}, and percentage decrease in rutting damage rate = 40.
[a]Ratio to total daily traffic.
[b]Ratio to whole year.

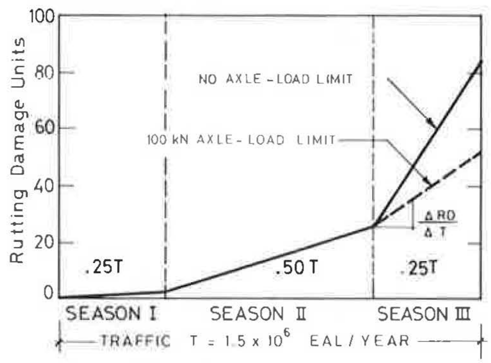

FIGURE 8 Effect of seasonal load limit on annual decrease in rutting damage units.

ting value of the pavement structure for each location could be estimated. Using these equivalency values, the implications of the alternative load limits are analyzed in terms of their effects on the remaining rutting life of the study pavement.

CONCLUSIONS

Previous studies have documented that rutting damage in pavements in the form of shear deformations in flexible pavement layers is experienced in hot climatic areas. Seasonal environmental effects, such as changes in temperature or moisture, or both, on the load-associated distress are considered in order to select a seasonal load limit that will provide a uniform rate of rutting damage. The results of the research described in this paper suggest the following conclusions:

1. The mechanical approach employed provides a rutting performance model. This model is based on the rutting damage potential of each pavement layer for any desired physical condition of the pavement provided that appropriate response parameters are used.
2. The performance variable is used to predict the rate of rutting damage with equivalent number of axle loads, thereby allowing the evaluation of seasonal variations in pavement conditions and axle load distributions.
3. The increased costs for pavement maintenance justify the use of the proposed mechanical procedure. Imposing a seasonal load limit will modify maintenance and rehabilitation costs by changing the time over which these expenditures are required.
4. Seasonal load limits will reduce rut depth and increase time before maintenance.

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Abridgment

Predicting Resilient Modulus: A Study to Determine the Mechanical Properties of Subgrade Soils

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ABSTRACT

Extensive literature review, detailed regression studies, and limited laboratory testing were used to develop models for predicting subgrade resilient modulus. General models are proposed for cohesive soils and nonplastic or granular-type soils. These two models are provided in the new Forest Service Surfacing Handbook (FSH 7709.56a) to provide the practicing engineer with guidance in the absence of test results. More than 250 different soils, representing more than 3,300 modulus test points, were placed in a computerized data base for regression studies. Although these data come from a literature search and testing variations definitely existed, the final models provide a useful first estimate. However, it was strongly recommended that resilient modulus laboratory tests be obtained whenever feasible. The effect of an error in subgrade modulus estimation on the thickness obtained from the design procedure was also studied. Some laboratory tests were made for use in model verification.

Since 1972 the U.S.D.A. Forest Service has been developing a program to provide systematic pavement management for the design of Forest Service roads. As initially developed, this project-level design system uses the AASHO Interim Design Guides as the basic structural and performance model (1-3) for paved roads and a rut depth model developed by the U.S. Army Corps of Engineers for the design of aggregate-surfaced roads.

Recently the structural models in the Surfacing Design and Management System (SDMS) were modified to use the mechanistic approach for determining the thickness of the structural roadway section components (4). This work was basically a revision of Chapter 50 of the Forest Service Transportation Engineering Handbook (5). At this time, the Forest Service has decided to place the information in Chapter 50 in a separate handbook. The Surfacing Handbook, Forest Service publication FSH 7709.56a, will be the new equivalent to the existing Chapter