Allowable Load on Multiple-Axle Trucks

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A methodology is proposed by which, for flexible pavements, the equivalency of various loading configurations with respect to cumulative pavement damage can be computed by using the criterion of maximum shear stress at the top of the subgrade. Computations can be performed with sufficient accuracy by replacing the real pavement with a two-layer elastic model. The results of this approach are found to be in good agreement with equivalencies established by the AASHO Road Test for dual and dual-tandem truck loadings. Good agreement is also found with the results of tests performed by the U.S. Army Corps of Engineers on airfield flexible pavements. Finally, an industry-oriented approach to the analysis of equivalent loads, based on a tonnage criterion and the serviceability index of the road, is presented. It is concluded that the methodology can be used with confidence by highway agencies to determine allowable loads for multiple-axle trucks.

The cost of truck transportation has always been and remains of prime importance in every national economy. Available truck and highway-pavement technologies and their aircraft and runway-pavement counterparts allow for a wide range of alternative policies. In recent years, increases in freight rates and in the cost of road construction and maintenance have led to a search for a means of reducing costs, the criteria being increased load capacity on the one hand and reduced (or at least stabilized) wear and damage to roads on the other. Among the factors involved is the fact that truck manufacturers have been marketing trailers that have multiple axles instead of the dual-axle vehicles used in the past. The profitability of multiple-axle trucks depends on the allowable axle load.

It should be noted that pavement technology is still largely based on full-scale experimentation, and theoretical extrapolation is likewise subject to experimental verification. Fortunately, since wheel-assembly configurations on airfields are more numerous and diverse than those on roads, they can be put to use in tackling the problem.

This paper deals with the concept of equivalent single-wheel load (ESWL) for different wheel-assembly configurations on flexible pavements. The model used is calibrated on the basis of data from the AASHO Road Test (1) and from the U.S. Army Corps of Engineers multiple-wheel heavy-gear-load pavement tests (2, p. 198; 3, p. 43). The paper concludes with an industry-oriented approach based on a tonnage criterion. The proposed model can therefore be used in determining allowable loadings for multiple-axle trucks.

EQUIVALENT WHEEL LOAD

Each pavement is designed for a certain volume of traffic and/or cargo tonnage. This volume is reflected in design formulas in the form of two major factors: (a) the design load per wheel or per axle and (b) the number of repetitions or coverages of this load. In design methods based on single-wheel load, any other configuration is translated to its equivalent single-wheel load, which is defined as causing an equal magnitude of a preselected parameter stress, strain, or deflection as the configuration in question. In design methods based on single-axle load, any other situation in terms of configuration and/or load repetitions is translated to design single-axle-load repetitions by means of traffic equivalency factors, which are generally derived from observations of pavement performance.

Although this measurement is uniformly adopted in many states, there is no unified approach among the design methods in the selection of a procedure for computing equivalent single-wheel load [see Yoder and Witczak (4) for a survey of design methods for flexible pavements]. Gerrard and Harrison (5) have shown that the equivalent wheel load depends largely on the stressing criterion and on the structural stiffness of the pavement.

DESCRIPTION OF PROPOSED MODEL

The model discussed here is based on the original thickness design formula of the Corps of Engineers (since the formulas are calibrated in U.S. customary units of measurement, no SI equivalents are given):

$$z = (0.144 + 0.231 \log N)\sqrt{(1/8.1\ \mathrm{CBR}) - (1/\pi p)} \cdot \sqrt{Q} \qquad (1)$$

where

z = thickness of pavement (in),
N = number of load coverages,
CBR = design California bearing ratio (here, <12),
p = contact pressure of wheel (lbf/in^2), and
Q = single-wheel load (lb), or ESWL.

Table 1. Ratio of ESWL to load on a single truck-assembly wheel for 4.5-in radius of contact area and $E_1/E_2 = 5$.

Configuration	Assembly	13.5-in Depth	22.5-in Depth	31.5-in Depth	45.0-in Depth
2A	Dual	1.384	1.700	1.831	1.912
4A	Dual-tandem	1.360	1.673	1.954	2.321
6A	Dual-triple	1.354	1.703	2.085	2.610
2B	Dual	1.482	1.755	1.863	1.929
4B	Dual-tandem	1.424	1.772	2.083	2.488
6B	Dual-triple	1.422	1.843	2.274	2.868
2C	Dual	1.583	1.807	1.893	1.945
4C	Dual-tandem	1.504	1.908	2.257	2.700
6C	Dual-triple	1.497	1.969	2.403	3.025

Table 2. Ratio of ESWL to load on a single truck-assembly wheel for 22.5-in pavement thickness and 4.5-in radius of contact area.

Configuration	Assembly	$E_1/E_2 = 1.0$	$E_1/E_2 = 2.5$	$E_1/E_2 = 5.0$	$E_1/E_2 = 10.0$
2A	Dual	1.639	1.672	1.700	1.728
4A	Dual-tandem	1.563	1.584	1.673	1.821
6A	Dual-triple	1.548	1.601	1.703	1.871
2B	Dual	1.705	1.732	1.755	1.777
4B	Dual-tandem	1.623	1.688	1.772	1.929
6B	Dual-triple	1.645	1.732	1.843	2.027
2C	Dual	1.768	1.789	1.807	1.825
4C	Dual-tandem	1.741	1.819	1.908	2.070
6C	Dual-triple	1.759	1.852	1.969	2.138

Wiseman and Zeitlen (6), Ahlvin and others (2), and other authors have shown that this formula, although based on full-scale testing, can be derived from considerations of shear failure of the subgrade or, in other words, that the design criterion is the maximum shear stress in the subgrade (this criterion and its analogs, such as maximum shear strain or the vertical strain in the subgrade, are compatible with strength theories). In this context it should be noted that determination of maximum shear stress according to a multilayer structure is feasible in specific cases in which the thicknesses and moduli of the layers are known; an approximate solution is obtainable by replacing the multilayer structure with a two-layer one in which the upper layer represents the pavement (7).

The procedure presented here for calculating ESWL is based on equal shear stress and consists of the following steps: (a) determination of the stress tensor for each point of a grid covering the space between the wheels, (b) determination of the principal stresses at each such point, (c) comparison of the maximal shear stresses for the assembly and for a single wheel with the same contact radius, and (d) correction of the ESWL for number of repetitions. The results are formulated as the ratio of the ESWL to one wheel load of the gear.

Tables 1 and 2 give the results of calculations for the road wheel assemblies shown in Figure 1 [partly reproduced from the work of Gerrard and Harrison (5)], and Tables 3 and 4 give results for aircraft gears. It can be seen that the ESWL increases with decreasing wheel spacing, increasing number of wheels, increasing depth, and increasing stiffness of the top layer. For roads, a variation of the pavement/subgrade modular ratio (E_1/E_2) from 3 to 5 or from 5 to 7 [the 3-7 interval is commonly accepted for conventional

Figure 1. Wheel-assembly configurations.

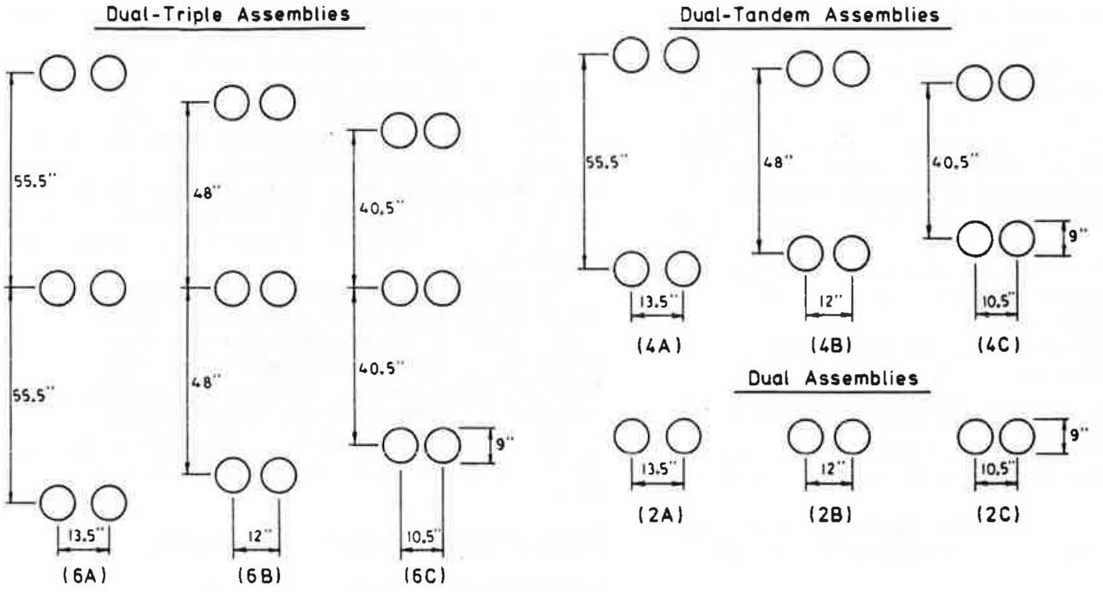


Table 3. Ratio of ESWL to load on a single aircraft-assembly wheel for $E_1/E_2 = 5$.

No. of Wheels	Aircraft	Radius of Contact Area (in)	Contact Pressure (lbf/in²)	Ratio by Depth in Contact Radii			
				3	5	7	10
2	B-727-100	8.587	166.0	1.210	1.521	1.719	1.851
	B-737-220	7.442	148.0	1.286	1.614	1.778	1.884
	DC-9-32	7.265	152.0	1.290	1.619	1.781	1.885
4	B-707-120B	7.514	170.0	1.317	1.719	2.154	2.729
	DC-8-63F	8.359	196.0	1.362	1.865	2.376	2.965
	DC-10-10	9.395	175.0	1.248	1.619	2.062	2.669
	Cv-880	6.800	150.0	1.473	1.989	2.461	3.045
	Concorde	8.928	184.0	1.456	1.924	2.364	2.934
6	L-1011-8	8.768	196.0	1.327	1.853	2.561	3.542
8	B-747F	8.843	185.0	1.300	1.781	2.353	3.244

Table 4. Ratio of ESWL to load on a single aircraft-assembly wheel for 22.5-in pavement thickness and 4.5-in radius of contact area.

No. of Wheels	Aircraft	Depth (in)	$E_1/E_2 = 1$	$E_1/E_2 = 2.5$	$E_1/E_2 = 5$	$E_1/E_2 = 10$
2	B-727-100	60.11	1.663	1.693	1.719	1.745
	B-737-200	52.10	1.733	1.758	1.778	1.799
	DC-9-32	50.86	1.737	1.761	1.781	1.801
4	B-707-1208	52.60	1.728	1.907	2.154	2.490
	DC-8-63F	58.51	2.015	2.168	2.376	2.647
	DC-10-10	65.77	1.542	1.792	2.062	2.401
	Cv-880	47.60	2.157	2.300	2.461	2.780
	Concorde	62.50	2.080	2.214	2.364	2.664
6	L-1011-8	61.38	2.064	2.320	2.561	2.950
8	B-747F	61.90	1.719	1.987	2.353	2.938

pavements, the vertical strain in the subgrade being used as the criterion (7)] changes the wheel-load ratio by about 5 percent and the ratio for airfield runways by about 10 percent. Accordingly, the ESWL determined for a modular ratio of 5 covers a wide range of conventional pavements with sufficient accuracy.

CALIBRATION OF THE MODEL

AASHO Road Test

The configurations used on the AASHO Road Test sections fall in the "wide" and "average" categories. The ESWL was determined from the performance data, as follows:

$$\log(4.2 - p)/2.7 = \beta(\log W - \log \rho) \qquad (2)$$

where

$$\rho = 10^{5.93}(D + 1)^{9.36} L_2^{4.33}/(L_1 + L_2)^{4.70} \qquad (2a)$$

$$\beta = 0.4 + 0.081(L_1 + L_2)^{3.23}/(D + 1)^{5.19} L_2^{3.23} \qquad (2b)$$

$$D = a_1 D_1 + a_2 D_2 + a_3 D_3 \qquad (2c)$$

and

p = final serviceability index of pavement,
W = number of repetitions,
D = thickness index or structural number,
L_1 = assembly load, and
L_2 = coefficient = 1 for a single assembly and 2 for a tandem assembly.

The results of load on a tandem, equivalent to that on a single assembly (at the same W), for p = 1.5-2.5 and D = 2-6 are given below:

Load on Single Axle (lb)	Load on Tandem Assembly (lb)
24 000	44 000-44 800
22 000	40 400-41 000
20 000	36 600-37 300
18 000	33 000-33 600
16 000	29 300-29 800

As the table indicates, the load ratio ranges from 1.83 to 1.87.

At the same time, Table 1 gives, for the same pair of assemblies, a ratio range of 1.55-2.08 (for loads that have the same ESWL) that decreases with increasing depth (2.04-2.08 for 13.5 in, 1.90-2.01 for 22.5 in, 1.79-1.87 for 31.5 in, and 1.55-1.65 for 45.0 in). (The maximum pavement thickness in the AASHO test was 31 in.) This range stems from the lengthwise distribution pattern of τ_{max}; Figures 2-4 show that for the smaller depth (13.5 in) one pass of the tandem assembly is equivalent to two repetitions, since the maximum occurs twice in a conspicuous manner; by contrast, for the larger depths (>31.5 in), the distribution is flat and each pass is in practice one repetition. According to Equation 1, for small depths and in the $N = 10^4$-10^6 interval, the load ratio corrected for the difference in number of repetitions drops to 1.83-1.90. In summary, for depths corresponding to D = 2-6 (up to 31.5 in in thickness), the ratio equals 1.80-1.90 and decreases with increasing thickness (or D) beyond the results of the AASHO Road Test.

It can therefore be concluded that there is good agreement between ratios of tandem to single load calculated by using the proposed model, taking into account the influence of depth on the number of stress repetitions and load ratios determined from the AASHO Road Test. It should, however, be noted that extrapolation of the AASHO results for pavements with D > 5 may lead to overestimation of the equivalent loads and to underdesign of the pavement. Hence, the model is acceptable or, at worst, slightly on the conservative side.

For the triple-dual assemblies of the A and B classes, the ratio (after correction for shear stress repetitions) is 2.5 for thicknesses less than 31.5 in, and, for 45 in, 2.2 and 2.0 in A and B, respectively. Accordingly, in the first case, under a single-axle load of 12 tons, the equivalent load on a tandem assembly is 21.5 tons and, on a triple assembly, 30 tons; for larger thicknesses, the equivalent load is smaller, as explained above.

Corps of Engineers Test

The U.S. Army Corps of Engineers design method consists of determining the equivalent wheel load according to the criterion of maximum settlement of the subgrade by using Boussinesq's theory and disregarding the stiffness of the pavement—an unrealistic approach, both in terms of the failure mechanism of the subgrade and the properties of the pavement materials. With the advent of B-747, C5A, DC-10, and L-1011 aircraft, the Corps of Engineers undertook one-to-one scale experiments and found that the actual performance of flexible-pavement test sections under the twin-tandem and 12-wheel gear was substantially better than had been predicted under the flexible-pavement design methodology that existed prior to the multiple-wheel heavy-gear-load tests (3). This resulted in modification of Equation 1 by means of the so-called load repetition factor α [see Figure 5(8)], which replaced the expression (0.144 + 0.231 log N) and is a function of the number of wheels in the assembly or gear and of the number of cycles. It should be noted that, even for a single wheel, the factor is no longer linear with log N as its predecessor was. The proposed model is therefore based on the modified design thickness formula, as follows:

$$z_w = \alpha_w \sqrt{(1/8.1\,CBR) - (1/\pi p_{ew})} \quad \sqrt{Q_w} \qquad (3)$$

Here, the subscript w refers to the criterion (subgrade deflection and Boussinesq theory) by which the equivalent wheel load Q was determined, and p_e is the pressure of the equivalent single wheel on a contact area equal to that of one of the wheels.

In the case of ESWL computed according to maximum shear stress, the corresponding equation is

$$z_\tau = \alpha_\tau \sqrt{(1/8.1\,CBR) - (1/\pi p_{e\tau})} \cdot \sqrt{Q_\tau} \qquad (3a)$$

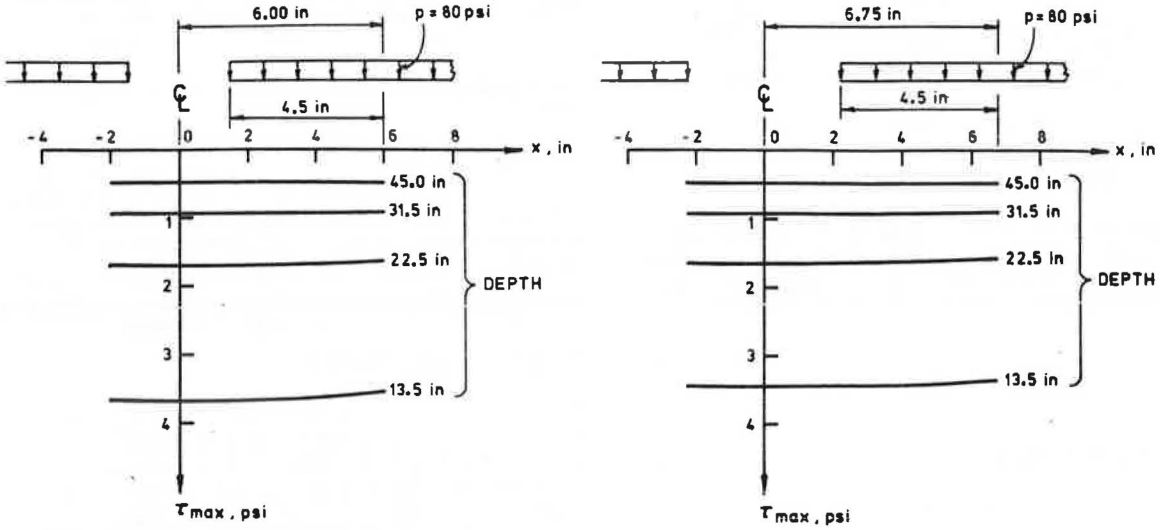
where α_τ is the fatigue factor for one wheel. Equating the two expressions, we find

$$\alpha_w/\alpha_\tau = \sqrt{Q_\tau/Q_w} \qquad (3b)$$

Figure 6 shows values of Q_τ/Q_w for different aircraft (based on Q_τ data from Table 3). In the thickness range of 20-40 in, the following values are obtained for α_w/α_τ: Two wheels = 0.91-0.95, four wheels = 0.85, and six and eight wheels = 0.76.

Figure 5 yields the thickness reduction factor (depending on the number of wheels) obtained under the modified approach. The results given below for N = 1000, 10 000, and 100 000 are seen to be close to those obtained

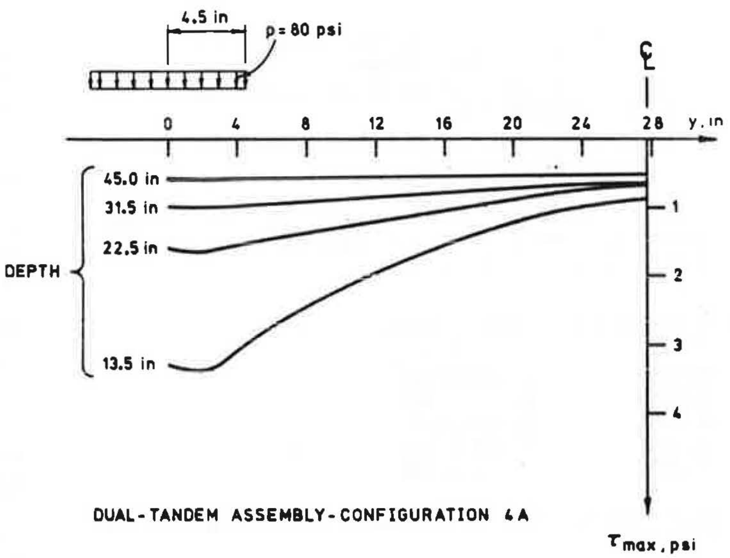
Figure 2. Pattern of distribution of maximal shear stress for single-axle dual assembly.



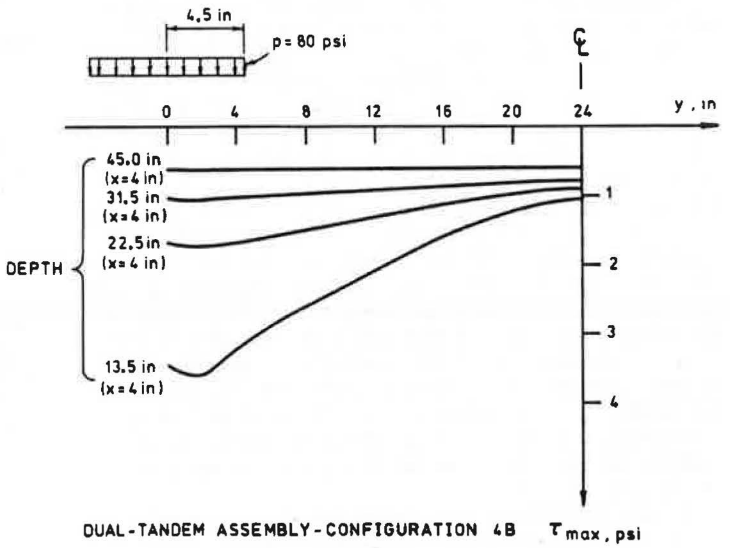
DUAL ASSEMBLY - CONFIGURATION 2B

DUAL ASSEMBLY - CONFIGURATION 2A

Figure 3. Pattern of distribution of maximal shear stress for dual-tandem assembly.

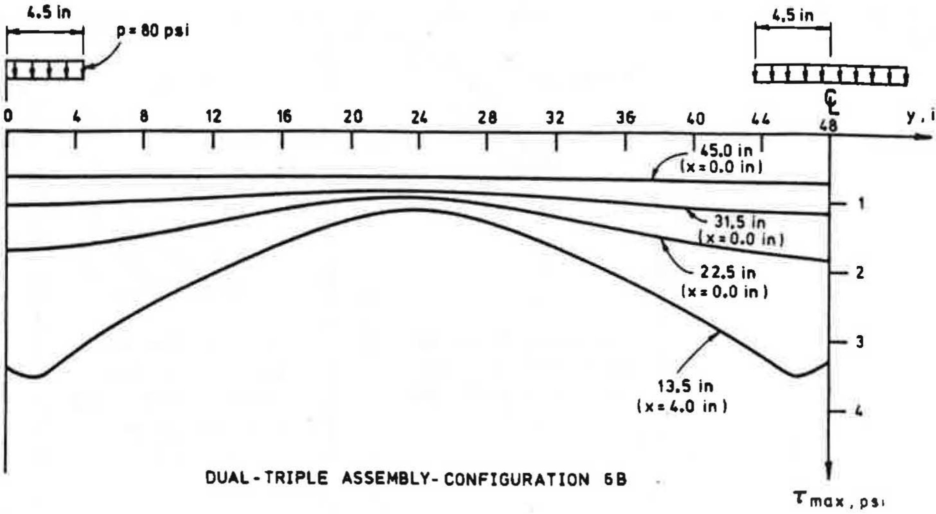


DUAL - TANDEM ASSEMBLY - CONFIGURATION 4A

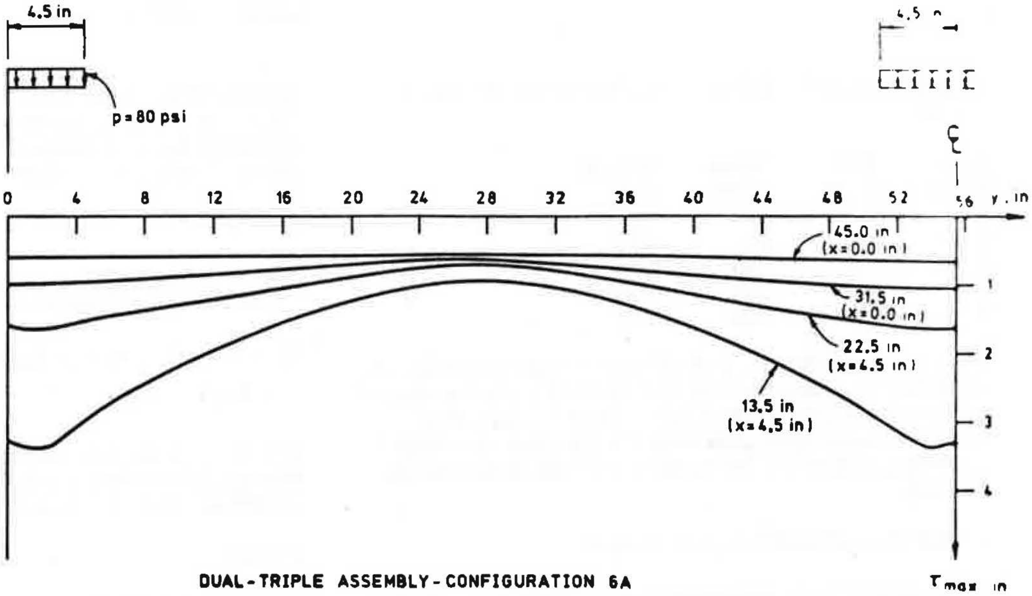


DUAL - TANDEM ASSEMBLY - CONFIGURATION 4B

Figure 4. Pattern of distribution of maximal shear stress for dual-triple assembly.



DUAL-TRIPLE ASSEMBLY-CONFIGURATION 6B



DUAL-TRIPLE ASSEMBLY-CONFIGURATION 6A

Figure 5. Load repetition factor α versus aircraft traffic volume factors.

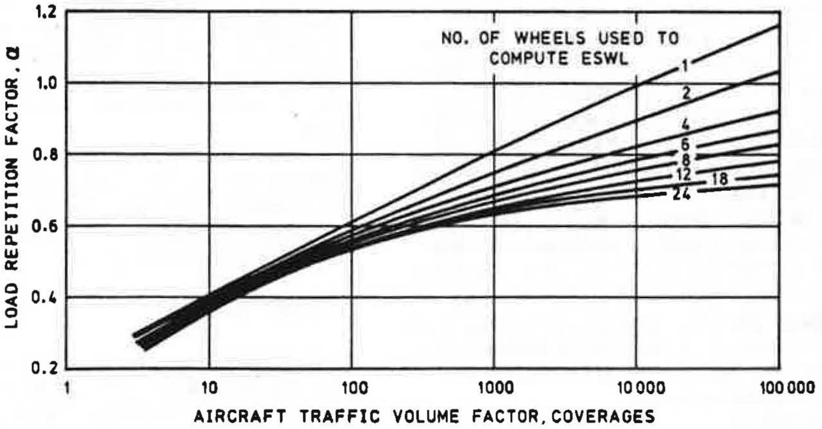
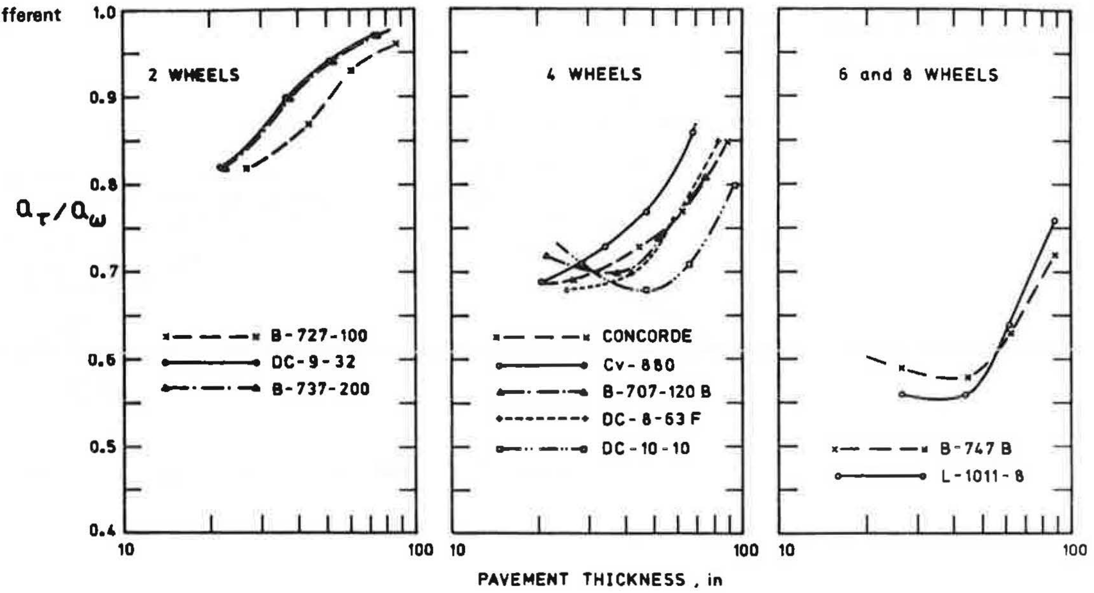


Figure 6. Q_r/Q_w for different aircraft.



in determining the ESWL according to the proposed model:

No. of Wheels	1000 Cycles	10 000 Cycles	100 000 Cycles
1	1.00	1.00	1.00
2	0.92	0.90	0.89
4	0.87	0.83	0.79
6	0.84	0.79	0.75
8	0.82	0.76	0.71

Thus, $\alpha_r \simeq 1$; that is, if the Corps of Engineers design formula for a single wheel (corrected for the number of cycles) is adopted in conjunction with the proposed model, the resulting pavement thicknesses are close to those obtained under the modified Corps of Engineers method.

INDUSTRY-ORIENTED APPROACH

In the conventional approach used in the preceding sections, the ESWL was determined for a given wheel-assembly configuration at a constant number of load cycles (the equivalent load obtained with the model calibrated according to the AASHO Road Test was reduced to preserve this constancy). However, economic considerations make it preferable to use an approach based on the tonnage carried by the road, i.e., on the equivalent load that corresponds to transportation of a given tonnage, subject to the same reduction in the serviceability index of the road. (Although it is the net tonnage that counts in the economic analysis, the present calculation is based on the gross; it is known that the net increases with the number of axles.) For example, if we compare simple dual axles and tandems, then, since for equal damage and one pass the allowable load on the tandem axle is larger, a smaller N suffices for the given tonnage and the load on the tandem can be further increased for equal damage.

Tonnage T is defined as

$$T = \sum_i W_i P_i \tag{4}$$

where W_i is the number of repetitions of configuration i under load P_i.

In comparing the equivalent loads for a single-axle assembly and a tandem according to the AASHO Road Test, we refer to tables given in the AASHO Interim Guide (9) for the necessary values of the traffic equivalence factor, defined as

$$F_j = W_{18}/W_j \tag{4a}$$

where j represents a given traffic class with a uniform configuration. Combining the above two equations yields

$$T = W_jP_j = (W_{18}/F_j)P_j = W_{18}P_{18}(P_j/P_{18}) \cdot (1/F_j)$$
$$= (T/P_{18}) \cdot (P_j/F_j) \tag{4b}$$

where P_j is the load (in thousands of pounds) for the configuration alternative to a single axle under P_{18} = 18 000 lb (18 kip). Hence,

$$P_j = 18F_j \tag{4c}$$

The tables given in the AASHO Interim Guide (9) show that the equivalent load on a tandem is 39 000 lb for a structural number of 1-6. In other words, a given tonnage can be carried on a single-axle assembly under 18 000 lb, or a tandem under 39 000 lb, and the numbers of repetitions corresponding to these would result in the same reduction in the serviceability index of the road.

For other configurations (triple assemblies and still larger ones), the same model used before can be used in similar analyses. Equation 4c applies for economic analyses that include truckage, construction, and maintenance strategies.

CONCLUSIONS

The theoretical model proposed here for determining the equivalent loads for different wheel-assembly configurations is based on a simple and realistic representation of the pavement (a two-layer structure) and on a criterion that is compatible with the failure mechanism of flexible pavements (the maximal shear stress at the top of the subgrade). By this means, minimal deviation is assumed from the expected behavior of the pavement. The model was first calibrated on the basis of AASHO Road Test results by comparing the equivalent loads for a single-axle and a tandem-axle assembly, and the results were in good agreement. Calibration was then carried out on the basis of U.S. Army Corps of Engineers testing, which covers a wider variety of configurations, and, again, the results provided justification for the model.

Finally, an industry-oriented approach is presented for the analysis of equivalent loads, the criterion being transportation of a given tonnage and similar reduction of the serviceability index of the road. According to this approach, the equivalent allowable load on tandem- and triple-axle assemblies in relation to design single-axle load can be determined.

The model is a useful tool for determining allowable loads for different wheel-assembly configurations and for slightly unconventional conditions, such as excessive pavement thickness. Further improvement, as well as adaptation to specific local conditions, can be achieved through field performance studies.

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Publication of this paper sponsored by Committee on Fle[illegible] Design.

Evaluation of Full-Depth Asphalt Pavements

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A research investigation begun in 1971 by the Minnesota Department of Transportation to learn more about the behavior of full-depth asphalt pavements is reported. The project has 26 test sections, each 365.8 m (1200 ft) long, of a variety of thicknesses, and on a variety of soils. The major portion of the research consisted of Benkelman beam measurements at 15.2-m (50-ft) intervals, taken weekly during the spring, biweekly in the summer, and monthly in the fall. The temperature of the upper 3.8 cm (1.5 in) of the mat was measured each time the Benkelman beam deflections were measured. These data were then used to determine the effect of temperature and season on deflections and to create a set of correction factors to apply to the measured deflections so as to adjust them to a 26.7°C (80°F) peak season deflection. This peak season deflection was then taken to be the standard deflection for each test section. These standard deflections were compared with the deflections of aggregate-base pavements, and a relation was developed between the full-depth thickness and the granular equivalency of an aggregate-base pavement with an equal deflection. That relation was used to develop a design chart for full-depth bituminous pavement, which is the deflection equivalent of the flexible-pavement design chart currently used by the Minnesota Department of Transportation.

The purpose of pavement design is to provide a structure of adequate thickness and strength to carry expected traffic loads. Various designs that are considered to be adequate are then examined for construction and maintenance costs so that the engineer can choose the most economical pavement design.

Before 1969, the Minnesota Department of Highways had to choose between rigid pavement or flexible pavement with an aggregate base. In June 1969, "full-depth" asphalt was approved and included as a design alternative, adding a third choice for pavement selection. The alternate allowed 2.5 cm (1 in) of bituminous base to replace 5.1 cm (2 in) of aggregate base. But, although full-depth pavement was approved, very little was known about its structural response to axle loads or its performance under traffic.

The Physical Research Unit of the Minnesota Department of Highways began evaluation of full-depth pavements in 1971 with the prime objective of determining a unit granular equivalent (GE) value for hot-plant-mix bituminous base. The Minnesota project consists of 26 test sections that cover a range of soil types and full-depth thicknesses (see Table 1). To include new test sections on new construction projects, four test sections were designed and constructed: one flexible pavement section with an aggregate base that represents the typical section from the project plans, one full-depth section with an equal GE, and two additional full-depth test sections, one of which had a 5.1-cm (2-in) reduction in full-depth thickness and the other a 10.2-cm (4-in) reduction in full-depth thickness. The reduced sections were included to reduce the time required to make performance