LEF Estimation from Canroad Pavement Load-Deflection Data

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Load equivalency factors (LEFs) versus axle-load regression equations are reported for single-, tandem-, and tridem-axle groups. These functions have been developed from truck loading test data collected at nine sites across Canada in 1985 by the Canroad Transportation Research Corporation. While the load on the axle groups dominated the regression equations, pavement temperature, axle spacing, and vehicle velocity were found to be statistically significant for the tandem-axle groups at a number of the sites. Regression analysis of the pooled tandem data showed that load and axle spacing were significant. Analysis of the pooled tridem-axle group data showed that load, axle spacing, structural number, and vehicle speed were significant. The load equivalency functions are compared with the AASHTO functions and the differences highlighted.

A comprehensive set of field measurements of pavement surface deflections and surface course interfacial strains were obtained at fourteen test sites across Canada in 1985. These measurements have been reported by Christison (*1*) and were part of a major study of vehicle weights and dimensions conducted by the Canroad Transportation Research Corporation. Christison (*2*) analyzed these data and developed a set of response-type load equivalency factors (LEFs) for single-, tandem-, and tridem-axle groups, and these LEFs form the basis of a set of draft regulatory principles for interprovincial trucking in Canada (*3*).

Hutchinson et al. (*4*) have reanalyzed the pavement deflection data collected in this study using the ASTM Standard Practice for Counting Damage Cycles (*5*), instead of the method used by Christison (*2*), to extract the pavement damage cycles. This alternative method of analysis produced LEFs that were, on the average, 8 percent higher than those calculated by Christison (*2*) for the tandem-axle groups and 16 percent higher for the tridem-axle groups.

Neither of the analyses cited above conducted an exhaustive statistical analysis of this very rich data base. Variations in LEFs with vehicle speed, intra-axle spacing, pavement temperature, and pavement structural characteristics were not comprehensively analyzed. This paper describes the results of a comprehensive regression analysis of the influence of these factors on the LEFs, using the surface deflection data. The surface course-base course interfacial strain data have not been analyzed because they are not readily available to outside users at this time.

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DATA BASE

Surface deflections and interfacial (surface-base) strains were observed at fourteen test sites for a variety of test conditions. The Canroad Transportation Research Corporation developed a test vehicle that allowed a variety of tandem- and tridem-axle configurations to be developed and tested under a range of axle-group loads. Tests were also conducted at speeds of 6, 13, and 50 km/h. Each test run consisted of pairs of pavement response measurements under a standard Benkleman Beam truck with an 8,160 kg single-axle load on dual tires and under the candidate axle group. Three test runs were conducted at each velocity, and the published deflection data consist of the average, minimum, and maximum deflections under each axle of an axle group as well as the inter-axle residual deflections for multiple-axle groups. Christison (*1*) provides a detailed description of the data base in terms of the test program and pavement properties.

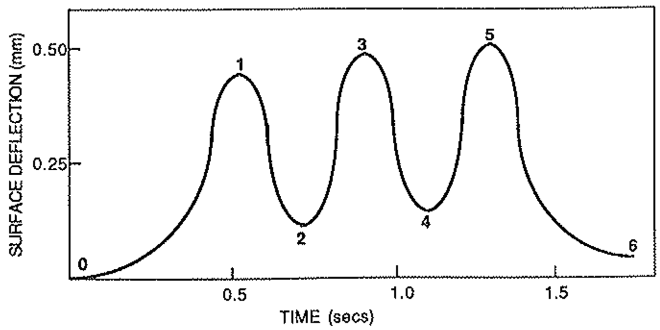
Figure 1(a) shows a typical deflection profile under the passage of a tridem-axle group. The load on the axle group was 26,036 kg, the axle spacing 3.7 m, the truck speed 12.9 km/h, and the pavement temperature 23.6°C. The diagram shows that the measured surface deflection increased from 0.442 mm through 0.498 mm to 0.503 mm under the passage of this tridem. The inter-axle residual deflection increased from 0.119 mm to 0.130 mm between the second and third axles. The deflection under the Benkleman beam truck was 0.422 mm. The maximum deflection tended to occur under the last axle of both the tandem and tridem groups at most test sites.

ESTABLISHING LOAD EQUIVALENCY FACTOR FUNCTIONS

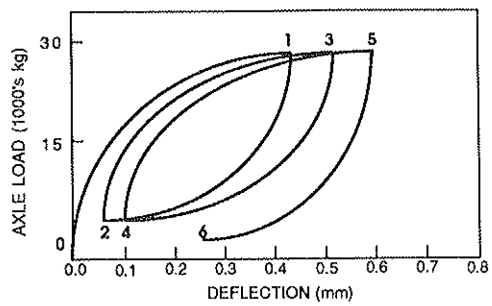
The LEF for a particular load on a candidate axle group is usually defined as the ratio of the number of passes of a standard axle load to the number of passes of a candidate axle load to create the same amount of pavement damage. There are three broad approaches to establishing the LEF functions for different axle groups, and these are frequently referred to as the empirical approach, the theoretical approach, and the mechanistic approach.

EMPIRICAL APPROACH

The principal source of information for empirically determined LEF functions is the AASHO Road Test, where the



(a) SURFACE DEFLECTION PROFILE UNDER 26 036 KG TRIDEM



(b) LOAD - DEFLECTION HISTORY UNDER TRIDEM PASS

$$\mathrm{LEF} = \left(\frac{0.503}{0.422}\right)^{3.8} + \left(\frac{0.498-0.130}{0.422}\right)^{3.8} + \left(\frac{0.422-0.119}{0.422}\right)^{3.8}$$

(c) LEF CALCULATION FOR TRIDEM PASS

FIGURE 1 Calculation of LEF for tridem axle pass.

deterioration of pavement sections of various thicknesses under homogeneous truck loads on single axles and on tandem axles were measured. It is well known that LEFs calculated for different loads on single- and tandem-axle groups vary with the PSI chosen to define failure and with the structural characteristics of a pavement. The AASHO Road Test analyses suggested that the LEF of a candidate axle group could be approximated by the fourth power of the ratio of a candidate axle load to the standard axle load. The results obtained from the AASHO Road Test are difficult to apply directly to current legal axle group loads and to axle groups other than singles and tandems, since this involves extrapolation of the results outside the range for which they were developed. For instance, the AASHTO LEF functions for tridems assumes that a tridem-axle group pass is equivalent to a single plus a tandem pass (*6*). This assumption is not supported by theoretical considerations or field observations.

THEORETICAL APPROACH

The theoretical approach to LEF function estimation proceeds by calculating the deformations or stresses in a pavement structure in combination with a fatigue damage law to establish the relative damage created by different axle groups and configurations.

Deacon (*7*) used maximum principal tensile strain as the fatigue damage parameter and compared his theoretical LEF magnitudes with those established at the AASHO Road Test. The recommended AASHO tandem equivalences were 80 percent of the theoretical values for pavements with structural numbers greater than 3, while the equivalences for single axles were approximately equal. Deacon suggested that for pavements with structural numbers of less than 3 the primary failure mechanism was not fatigue, and his approach might not be appropriate.

Ramsamooj et al. (*8*) used theoretical fracture mechanics to derive load equivalency factors from longitudinal stress intensity factors. They defined the LEF for single axles as the ratio of the maximum rise in the influence line for the stress intensity factor *K* for the candidate axle load to the maximum rise in *K* for the standard load, raised to the fourth power. For tandem axles the ratio of the peak-to-trough value of the stress intensity factor to that of the standard axle raised to the fourth power was also calculated. The accumulation of the damage cycles caused by each axle in the tandem was accomplished by adding these two calculations. This method of damage accumulation is adopted in this paper.

Treybig (6) developed fundamental relationships between damage related factors and performance based equivalency factors through the analysis of AASHO pavements. Subgrade compressive strain was found to have the best relationship with observed pavement performance as compared with surface tensile strain at the surface course-base course interface and surface deflection. This is rational since most of the Road Test pavements failed in rutting. Elastic layer theory was used for computing strains, and these were used for calculating LEFs for axle configurations other than single and tandem over a wide range of loads. These were then used to extend the equivalency factor concept to new size and weight configurations.

MECHANISTIC APPROACH

The mechanistic approach is similar to the theoretical approach, with the primary difference being that the distress indicators are measured in situ and not calculated. Christison (2) applied the cycle damage-pavement distress procedures adopted by Deacon and used measured surface deflection and interfacial tensile strain to predict LEF. For single axle loads the defection-based LEF was calculated using equation 1:

$$LEF_i = \left(\frac{d_i}{d_b}\right)^C \tag{1}$$

where d_i and d_b are the surface deflections under various single-axle loads and under the 80 kN (18 kip) single-axle, dual-tire loads, respectively.

The exponent C is the slope of the deflection-anticipated traffic loading relationship and was set equal to 3.8 following the recommendation by the Pavement Advisory Committee of the Canroad study.

Tandem-axle LEFs were calculated using equation 2:

$$F_i = \left(\frac{d_i}{d_b}\right)^C + \left(\frac{e_i}{d_b}\right)^C \tag{2}$$

where d_i equals the maximum surface deflection under each leading axle, and e_i equals the difference between maximum deflection under the second axle and the intermediate deflection between axles.

It is assumed that a linear summation of cycle ratios will govern the behavior of the pavement. This method has been used by a variety of authors to develop LEF functions based on fatigue analysis principles. For the most part, these functions have been fairly close to the AASHO relationships even though the latter are based on a PSI index, which attempts to combine cracking, shear deformation, and longitudinal profile into a single term. These theoretical methods do allow for the development of LEFs for conditions that were not studied in the AASHO Road Test, and they allow for the analysis of various influential variables that may affect pavement performance. In reviewing the LEF functions developed in this paper is must be remembered that they are based on these assumptions.

ISOLATION OF DAMAGE CYCLES

The calculation of the pavement damage implied by passages of particular axle groups consisted of two steps; these are (1) the isolation of the load-deformation cycles under each axle group and (2) the accumulation of the damage created by each cycle, which was estimated by dividing the maximum deflection observed in a load-deformation cycle by the deflection observed under the standard Benkleman beam truck, raising this ratio to 3.8, and summing the result across all load-deformation cycles induced by an axle group. This procedure is illustrated in figure 1 for the surface deflections observed under a tridem-axle group pass.

Figure 1(b) shows the load-deformation history of the surface course induced by the passage of the tridem. The ASTM Standard Practice for Cycle Counting in Fatigue Analysis (5) has been used to isolate the following load-deformation cycles:

Cycle	*Load-Deformation Path*	*Deflection (mm)*
Largest	0-5-6	0.503
Second largest	3-4-3	0.368
Third largest	1-2-1	0.323

Figure 1(c) shows that this results in an LEF of 2.97. The method used by Christison (2) results in an LEF of 2.5. This method of analysis is described in more detail by Hutchinson et al. (4) and compared with the method of damage accumulation used by Christison (2).

SITE-SPECIFIC LEF FUNCTIONS FOR TANDEM-AXLE GROUPS

The LEFs calculated for nine sites have been subjected to a comprehensive regression analysis in an attempt to isolate the influences of pavement temperature, vehicle speed, and axle spacing on LEF with equations of the following form being estimated:

$$LEF = CONSTANT * LOAD^l * TEMP^t * SPEED^s * AXLE\text{-}SPACING^a \tag{3}$$

where:

LOAD = load on tandem-axle group (1000 kg),
TEMP = average pavement temperature recorded during test run (°C),
SPEED = velocity of test vehicle (km/h), and
AXLE-SPACING = front-to-rear axle spacing in tandems and tridems (m).

The parameters of equation 3 have been estimated using multiple linear regression analysis of a natural logarithmic transformation of the data. Table 1 summarizes the results for the nine test sites analyzed. Sites 2 and 12 were not included, as preliminary results seemed to indicate that the deflection measurements contained excessive residuals. Similarly, site 3B was excluded, as the site was damaged during testing, and site 8 was excluded because the subbase consists of an old road. The number in brackets under each test site number is the structural number of the pavement at that site. The t-magnitudes are shown in brackets below the parameter magnitudes, and the parameters are significant at the 1 percent level except for those identified with an asterisk, which are significant at the 5 percent level. The second equation listed for each site is a simple regression equation relating LEF to load on the tandem-axle group.

TABLE 1 REGRESSION EQUATIONS FOR TANDEM-AXLE GROUPS

SITE	CONSTANT	l	s	t	a	R^2	n
1 (6.3)	.01174885	2.266 (29.8)	0.259 (8.8)	-0.574* (2.6)		.94	69
	.00367574	2.300 (21.0)				.87	
3 (6.1)	.00252883	2.380 (28.1)	0.072* (2.2)			.92	60
	.00308872	2.380 (27.3)				.92	
4 (3.6)	.00048663	3.127 (28.3)			-0.762* (-2.4)	.93	60
	.00034950	3.158 (27.2)				.93	
5 (4.2)	.00039922	2.876 (30.2)	-0.263 (-7.7)	0.497* (2.2)	-0.956 (-3.4)	.95	60
	.00066349	2.902 (20.9)				.88	
6 (4.3)	.00012768	2.774 (43.6)	-0.136 (-5.4)	0.676 (5.7)		.97	69
	.00082758	2.804 (32.8)				.94	
7 (5.1)	.00003884	2.974 (26.9)		0.707* (2.4)		.95	42
	.00043420	2.977 (25.5)				.94	
9 (3.6)	.00116971	2.74 (32.4)	0.207 (6.1)		-1.34 (-4.8)	.94	71
	.00115345	2.755 (24.2)				.89	
10 (3.4)	.00034395	2.869 (42.7)		0.300 (2.7)	-0.460* (-2.1)	.97	71
	.00095672	2.829 (41.3)				.96	
11 (6.6)	.00066150	2.844 (34.8)				.97	44
13 (6.9)	.00257733	2.394 (23.6)				.93	42

n = number of observations

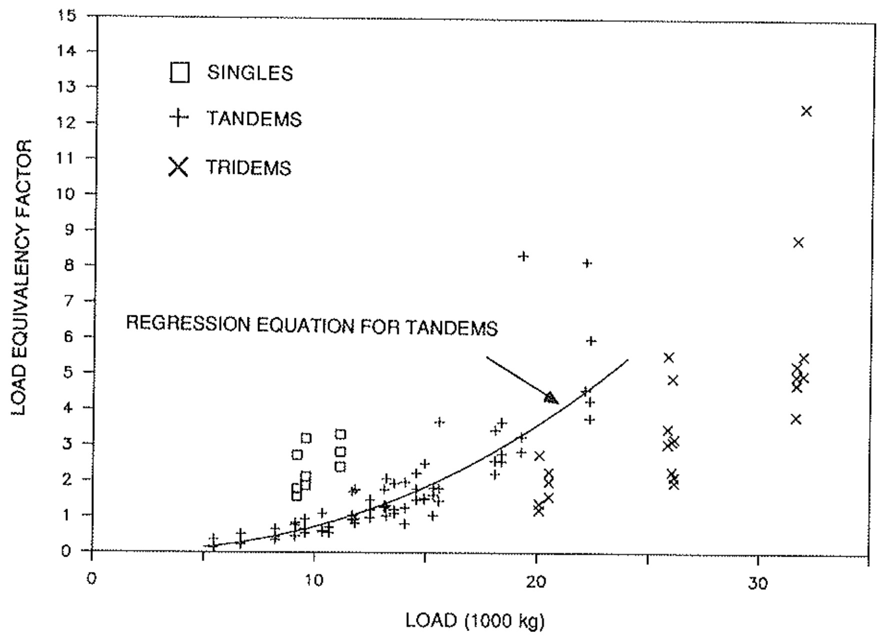


FIGURE 2 LEF vs. load on axle group for site 1.

Figure 2 shows the relationship between calculated LEF and load on axle group for site 1 for the three axle groups. The regression equation estimated for the tandems is also plotted on the diagram. Insufficient data are available to allow meaningful regression equations to be estimated for the single- and tridem-axle groups.

In interpreting these regression equations it should be remembered that the LEFs have been calculated from the ratios of deflections observed under the test vehicle to those observations under the Benkleman beam vehicle. That is, speeds, temperature, and structural number are effectively constant for each pair of test runs.

Inspection of the exponent of the load term shows that it varies only marginally between the two equations for each site and that there are some differences in the magnitudes of the exponent between sites. For example, site 1 has an exponent of 2.266, while site 4 has a magnitude of 3.127. A comparison of the coefficients of determination of the two models developed for each site show that the load term dominates the explanation of the variation in LEF.

Further inspection of the entries in table 1 shows that speed has a significant effect at five of the sites but that the sign of speed is not consistent. Flexible pavement deflection decreases as vehicle speed increases, and the results from the AASHO Road Test indicate that the percentage reduction in deflection is less for heavier vehicles than for lighter ones. Given that the LEF calculation is based on a ratio, one might hypothesize that increasing vehicle speed would result in an increase of the LEF, all things being equal. This would result in a positive coefficient for single-axle calculations.

This question is a little more complex for the tandem axles as there are two elements to the LEF calculation. The dominant factor is the maximum deflection term, and this is always lower for the higher speeds. However, given that the loading sequence is faster at higher speeds, the pavement does not have as much time to recover before the second axle loading occurs. It could be argued that this increase in the maximum deflection relative to the Benkleman beam deflection would result in a higher LEF. The second term could lower or raise the LEF when comparing LEFs across speeds, but since this value is usually less than unity, and it is raised to the 3.8th power, its effect is minimal. For those sites that exhibited positive coefficients for the speed variable, the ratios of maximum deflection over the Benkleman beam deflection increased with speed, while the opposite was true for those with negative coefficients.

Temperature was found to be significant at five sites and the exponents of temperature varied from 0.300 to 0.707 and were all positive, except for site 1. The range of average pavement temperatures at which the majority of tests were conducted at the sites that did not experience a significant temperature effect was about 10°C. The only exception to this was site 9, where the range was approximately 16°C to 30°C. The other sites experienced pavement temperature ranges of about 15°C, except for site 1, where the majority of the temperatures were between 18°C and 28°C. The testing process was not designed to isolate the effects of temperature; and, therefore, at those sites where pavement temperature was relatively constant, it would be expected that temperature would not have a significant influence.

Deflection tends to increase with increasing pavement temperature. A positive coefficient for a single-axle load would indicate that this increase in deflection is not the same percentage for all loads. More specifically, as temperature increases the deflections caused by larger loads increase faster than those for smaller loads. For tandem axles it may be hypothesized that the maximum deflection will increase with increasing pavement temperatures at a greater rate than for the lower load of the Benkleman beam truck. This would explain the positive signs of the pavement temperature variable.

It should also be noted that when the temperature effect was not significant (sites 3a and 9), the speed coefficient was positive. When the exponent of temperature was significant the exponent of speed had the opposite sign. Sites 5 and 6 have negative temperature exponents, while site 1 has a positive temperature exponent.

This change in the sign of the speed variables might indicate a temperature × speed interaction in terms of load equivalency factors. For relatively constant temperatures the load equivalency factor increases with increasing speed. However, when temperature is not constant there seems to be a decrease in LEF with increasing speed. This interaction is accounted for implicitly in the multiplicative forms of the model used in this analysis and would account for the differences found.

Perhaps more interesting are the results from the axle spacing variable. The coefficients were found to be significant only at four sites (4, 5, 9, and 10) and they ranged from −0.46 to −1.34. This means that as axle spacing increases the calculated load equivalency factor decreases. It should be noted that the sites that had the lowest calculated structural number were the ones where axle spacing was significant. This makes sense in that for the larger spacings, the pavement would have time to recover from the deformation caused by the first wheel load before the arrival of the second. Due to the nature of the load equivalency factor calculations the maximum deflection used would not be as high for the larger axle spacings. Conversely, the intermediate deflection used would be higher for the larger axle spacings. However, the maximum deflection term dominates, and this difference tends to yield lower LEF factors and hence the negative exponent of axle spacing.

POOLED LEF FUNCTIONS FOR TANDEMS

The data for the tandems were pooled for all of the test sites, the structural number was added as the fifth independent variable in equation 3, and the following equation resulted:

$$LEF = 0.0013563 \cdot \underset{(73)}{LOAD^{2.698}} \times \underset{(-3.4)}{(AXLE\ SPACING)^{-0.396}} \qquad (4)$$

$R^2 = 0.90$
No. observations = 597

$$LEF = 0.0011420 \cdot \underset{(72)}{LOAD^{2.704}} \qquad (5)$$

$R = 0.90$

Figure 3 shows the LEF versus load on axle group for the 1.5-m tandems, while figure 4 shows the results for 1.2-m and 1.8-m tandems. In addition, the regression lines for each axle spacing are also shown. Equation 4 indicates that axle spacing is the only significant independent variable in addition to load on the tandem-axle group. The exponent of axle spacing means that the LEF decreases with increasing axle spacing. It should be recalled that the maximum deflection normally occurs under the second axle and that this maximum decreases with increasing axle spacing, since the pavement has more time to recover from the deflection induced by the lead axle. For a 16,000-kg tandem-axle load, equation [4] implies that the LEF would decrease from 2.2 at an axle spacing of 1.2 meters to 1.9 at a spacing of 1.8 meters, a reduction of about 14 percent. Sufficient data existed for the tests involving tandems with 1.5-m axle spacing to explore further the impacts of each of the variables and the following equation was estimated:

$$LEF = 0.0008665 \cdot \underset{(53)}{LOAD^{2.692}} \cdot \underset{(3.2)}{SN^{0.191}} \qquad (6)$$

$R^2 = 0.87$
No. observations = 433

Equation 6 indicates that LEF increases with increasing structural number. From the previous discussion it might be expected that as pavement strength increased, there would be a relative decrease in maximum deflection resulting in a lower LEF. Inspection of equation 6 shows that the exponent of structural number is positive, although the magnitude is small and has little absolute impact on the LEF.

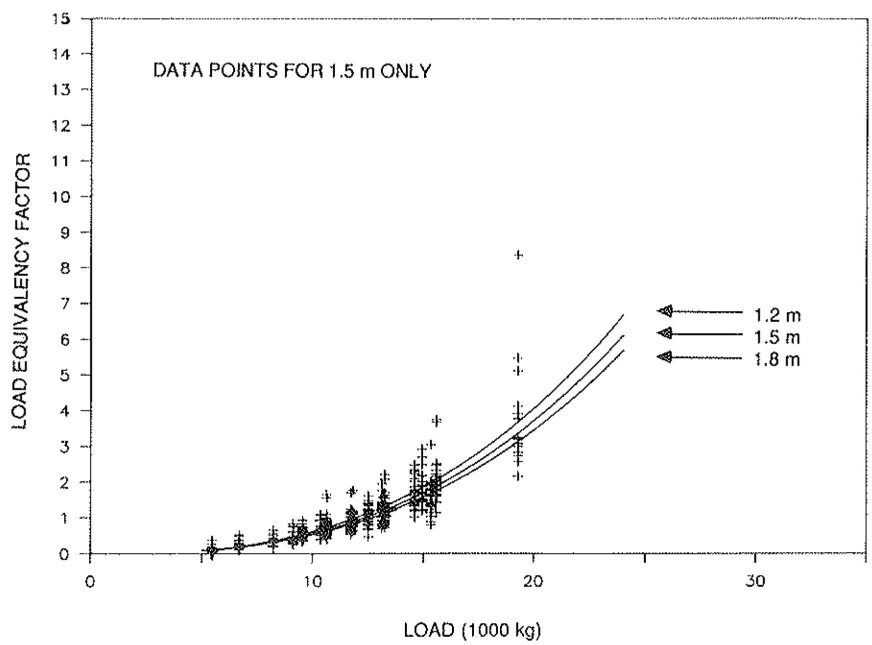


FIGURE 3 LEF vs. load on axle group for 1.5-m tandem.

POOLED LEF FUNCTIONS FOR SINGLE AXLES

Data were pooled for the single axles, as there were insufficient data to establish site-specific LEF functions. The following regression equation was estimated:

$$LEF = 0.0153598 \cdot \text{LOAD}^{2.159} \qquad (7)$$

$R^2 = 0.43$ (75)
No. observations = 75

Equation 7 shows that only load is significant for single axles. Figure 5 shows the LEFs plotted against load on the single axle, along with equation 7. The coefficient of determination of the model is rather low, and this reflects the narrow load range for the single axles, which were only tested at three loads, all of which were very close to the standard axle load. This tends to reduce the influence of the loading variable and helps to explain why the load coefficient value is not closer to the theoretical value of 3.8.

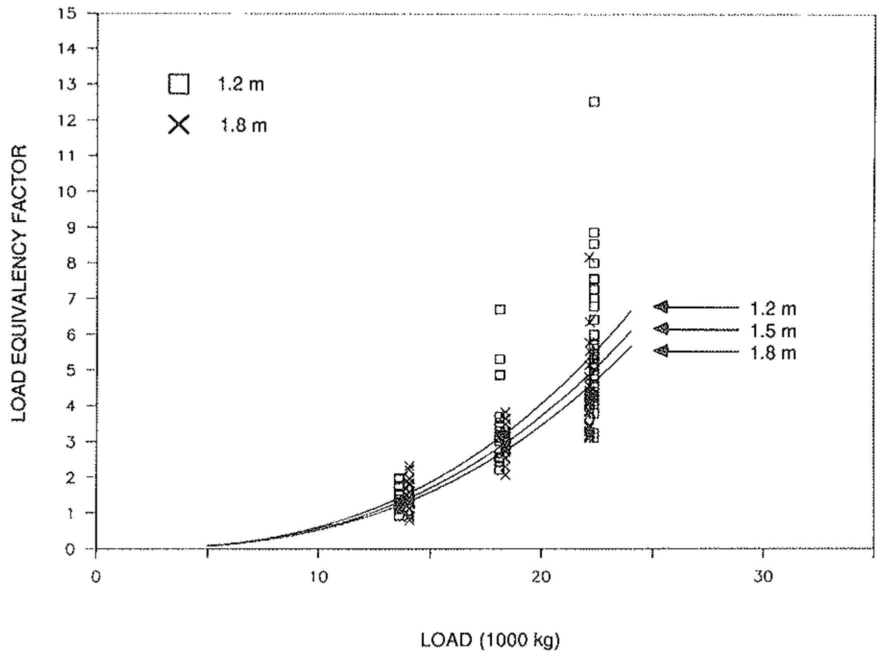


FIGURE 4 LEF vs. load on axle group for 1.2-m and 1.8-m tandems.

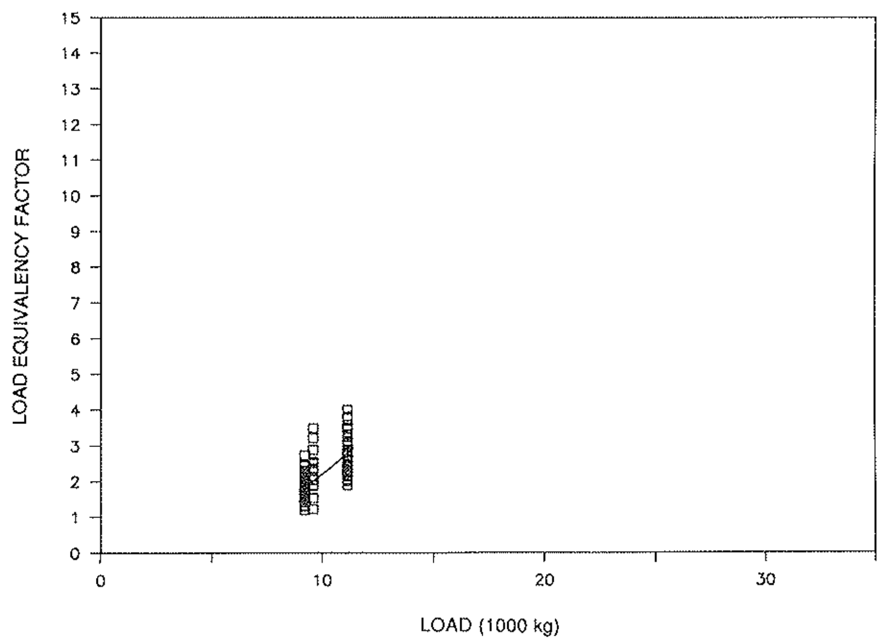


FIGURE 5 LEF vs. load for single axles.

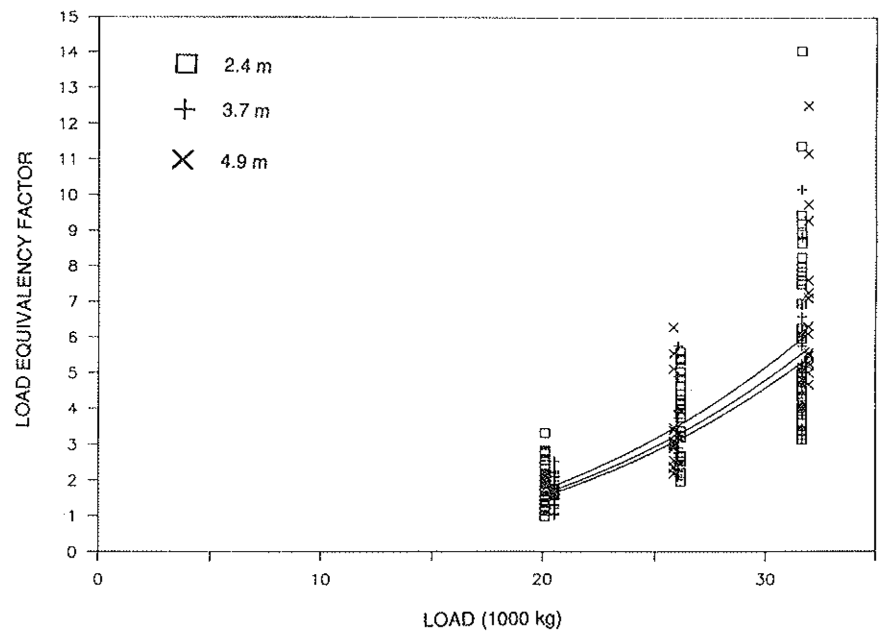


FIGURE 6 LEF vs. load on axle group for tridems.

POOLED LEF FUNCTIONS FOR TRIDEMS

The data available for the tridems were pooled, and the following regression equations were estimated:

$$LEF = 0.0008276 \cdot LOAD^{2.669} \cdot AXLE\text{-}SPACING^{-0.168} \quad (2.9)$$

$$\times\ SN^{-0.251} \cdot SPEED^{.074} \qquad (8)$$

$$(22) \qquad (2.9)$$

$$(-2.9)$$

$R^2 = 0.74$
No. observations = 190

$$LEF = .0006205 \cdot LOAD^{2.639} \qquad (9)$$

$$(21)$$

$R^2 = 0.71$

The LEFs are plotted against the load on the axle group for tridems in figure 6, along with equation 8 for axle spacings of 2.4, 3.7, and 4.9 meters. Equation 8 shows that axle spacing, structural number, and vehicle speed are significant. The exponent of axle spacing is negative, indicating that as axle spacing increases the calculated LEF decreases. This is the same trend found for the tandem axles. The structural number exponent is also negative, which is opposite to the sign found for the tandem analysis. The LEFs reported for singles and tandems in the AASHTO interim guide show that they change in different ways with load, structural number, and terminal PSI. The vehicle speed coefficient is positive, but it is of such a low value that its impact on LEF is minimal.

COMPARISON WITH AASHTO LEF FUNCTIONS

Figure 7 compares some of the LEF functions reported in this paper with the AASHTO load equivalency functions. The tandem-axle function is for an axle spacing of 1.5 meters and an SN of 5. The tridem function is for a spacing of 3.7 meters, an SN of 5, and a velocity of 50 km/h. Inspection of the single-axle LEF function shows that it diverges significantly from the AASHTO function either side of an axle load of 10,000 kg. This divergence reflects the lower exponent of load shown in equation 7. It must be remembered that the range of single-axle loads tested was quite narrow. A comparison of the LEF functions for tandem axles shows that the LEFs calculated in this paper are significantly higher than the AASHTO functions for the range of axle groups between 10,000 and 20,000 kg. The relative positions of the two tandem LEF functions will change with changing assumptions about axle spacing and structural number. The LEF functions for the tridems have similar slopes, but the LEF function reported in this paper produces significantly higher LEFs than the AASHTO function. At a 25,000 kg axle group load the AASHTO LEF is about 1.6 compared with about 3.

CONCLUDING REMARKS

The LEF functions described in this paper are based on the the very strong assumption that load-associated pavement damage is governed by the load-deformation cycles observed under different axle groups. Load-deformation cycles have been extracted using ASTM standard practice. The LEF functions described in this paper may be described as response type functions in contrast to those that might be developed from field trials. The site-specific LEF functions for tandem-axle groups are dominated by the load term, but speed, temperature, and axle spacing also had significant impacts at many of the sites. Inconsistencies in the signs of the exponents for speed and temperature between sites suggest that a speed × temperature interaction effect exists. It is difficult to isolate this effect because the test pavement temperatures were not

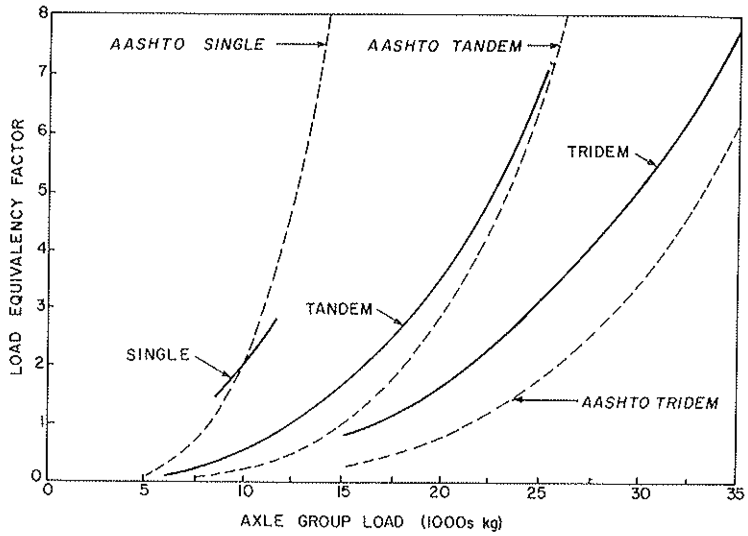


FIGURE 7 Comparison of LEF functions with AASHTO functions.

consistent between sites. Increasing axle spacing on the tandems produced statistically significant reductions in the LEFs at four sites, and these sites had the smallest structural numbers. A regression analysis of the pooled data for all tandems resulted in significant exponents for load and axle spacing but with load dominating the regression equation. Analysis of the pooled data for the 1.5-m tandems resulted in significant exponents for load and structural number, although the exponent of the structural number is small. The LEF function for the single axles had a rather low explanatory power, but this reflects the narrow range of loads tested.

Analyses of the pooled data for the tridems resulted in statistically significant exponents for load, axle spacing, structural number, and speed. The signs of axle spacing and structural number are negative while that of speed is positive, although small. Comparisons of the LEF functions developed in this paper with those of AASHTO showed some important differences. The tandem LEF function produces significantly higher LEF magnitudes than AASHTO and the single and tridem LEF functions had smaller slopes but produced similar magnitudes around LEFs of two.

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