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VARIATIONS OF FATIGUE DUE TO UNEVENLY LOADED AXLES WITHIN TRIDEM GROUPS

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16. Abstract

The effect of unevenly distributed loads on the axles within a tridem has been shown to be very significant. Equations are presented that enable the equivalent load effect for equal load distribution to be adjusted for uneven loading. Considering the relative increase and the relatively small volume of trucks currently using tridems, the equation for all tridems without regard to locations on the vehicle is recommended at this time. Consideration should be given to using equations for individual load patterns as the volume of trucks using tridems increases and more weight data become available.

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INTRODUCTION

The Chevron N-layer computer program was used to analyze the effects on highway pavement performance of tire and axle configurations where all tires in a configuration were equally loaded. At the AASHO Road Test, there were 100 possible combinations of layer thicknesses, of which 67 were constructed. The load for each individual tire in each axle configuration was varied from 2 kips (8.9 kN) to 8 kips (35.6 kN) on 0.5-kip (2.2-kN) increments. All 100 possible combinations of layer thicknesses were used in the computer analyses to obtain fatigue relationships between damage factor and total loads on various axle configurations. Thicknesses of asphaltic concrete ranged from 2 inches (51 mm) to 6 inches (152 mm) on 1-inch (25-mm) increments. Base thicknesses ranged from 0 to 9 inches (229 mm) on 3-inch (76-mm) increments, and subbase thicknesses ranged from 0 to 16 inches (406 mm) on 4-inch (102-mm) increments. An 18-kip (80-kN) four-tired single axleload was applied to each of the 100 structures as the reference condition. Tensile strain at the bottom of the asphaltic concrete may be equated to "work strain" by

$$\log(e_a) = 1.1483 \log(e_\omega) - 0.1638 \qquad 1$$

in which e_a = tensile strain at the bottom of the asphaltic concrete,
e_ω = work strain at the bottom of the asphaltic concrete = $(2W/E)^{0.5}$,
W = strain energy density (or energy of deformation per unit volume), and
E = Young's modulus of elasticity.

The relationship of tensile strain at the bottom of the asphaltic concrete with repetitions (1) was converted to work strain (2) at the bottom of the asphaltic concrete layer by the following relationships:

$$\log(N) = (\log(e_\omega) - (-2.6777807)) / -0.15471249 \qquad 2$$

in which N = repetitions.

The damage factor is defined by

$$DF = N18 / NL \qquad 3$$

in which DF = damage factor,
N18 = repetitions calculated by Equation 2 in which the work strain is that due to an 18-kip (80-kN) four-tired single axleload and
NL = repetitions calculated by Equation 2 in which the work strain is that due to the total load on the axle or group of axles.

Figure 1 shows the relationships between damage factor and total load on axle groups. Equation 4 very closely describes the shape of the curves shown in Figure 1:

$$\log(DF) = a + b(\log(Load)) + c(\log(Load))^2 \qquad 4$$

in which DF = damage factor of total load on axle configuration relative to an 18-kip (80-kN) four-tired single axleload,

Load = axleload in kips, and

a, b, c, = regression coefficients.

Values for the constant and coefficients were obtained by regression analyses and are summarized in Table 1 (2).

LOADS ON TANDEMS

The effects of uneven load distributions on the axles of a 36-kip (160-kN) tandem group was investigated using those structures shown in Table 2. Analyses revealed that the damage factor for the load distributed evenly on the 36-kip (160-kN) tandem should be adjusted by a multiplicative factor defined by Equation 5 and illustrated in Figure 2 (2):

$$\log(MF) = 0.0018635439 + 0.0242188935(percent) - 0.0000906996(percent)^2 \qquad 5$$

in which MF = factor to multiply the damage factor given in Equation 4 to adjust the fatigue for an uneven load distribution and

percent = |(Axleload No.1 - Axleload No.2)| x 100/ (Axleload No. 1 + Axleload No. 2).

An analysis of the first 670 tandem axleload distributions given in the 1980 W-4 Tables for Kentucky indicated a 40 percent increase in the calculated fatigue when the uneven load distribution was considered as compared to the total of the two axles evenly distributed.

LOADS ON TRIDEMS

The increased use of tridem axle groups on current trucks necessitated an investigation of actual load distributions. Inspection of the W-4 Table revealed that the majority of tridems had uneven load distributions. This study was initiated to develop adjustment factors to account for those uneven load distributions and the various patterns of uneven loadings.

INPUT

Structures given in Table 2 were used in this analysis. The total load was kept constant at 54 kips (240 kN). Table 3 summarizes the combinations of individual axleloads used to equal the constant total load. Five basic patterns of load distributions were used. Considering patterns that are mirror images of one of the five and that two of the axles might be equal, there are 13 combinations. The following definitions were used:

M = the heaviest axleload of the three axles,
L = the least axleload of the three axles,
I = the intermediate axleload between the maximum and minimum axleloads, and
E = the axleload is equal to an axleload on at least one other axle.

ANALYSIS

Equations 2 and 3 are the basis for calculating damage factors. The number of repetitions associated with an 18-kip (80-kN) single axleload is obtained from Equation 2 and varies according to the pavement structure. The Chevron N-layer computer program was used to calculate work strain. The location producing the severest damage factor occurs at the edge of the inside tire closest to the outside tire of the dual. This is the same location used to calculate damage factor relationships and equations shown in Table 1 and Figure 1. Each load pattern in Table 3 was subjected to analyses by the Chevron N-layer computer program and the allowable repetitions obtained from Equation 2. The multiplying factor is the ratio of the repetitions associated with 54 kips (240 kN) distributed on the tridem according to the specific load pattern and the repetitions associated with 54 kips (240 kN) uniformily distributed on the tridem.

REGRESSION ANALYSIS

Since Table 1 contains the equation for an evenly distributed load on the tridem, only four basic patterns remained to be analyzed, and results are shown in Figures 3 through 6. Figure 7 shows the results of the regression on all data without regard to load pattern. Table 4 contains the constants, coefficients, and regression statistics for Figures 3 through 7. The influence of structure upon the scatter of data as the result of uneven loading within the tridem was very significant, but structure was not nearly so influential for an uneven load distribution within a tandem. For 670 tandems (2), the accumulated adjusted EAL was 1.4 times that of an evenly distributed load. For 1,951 tridems, the accumulated adjusted EAL was 2.3 times that of an evenly distributed load.

COMPARISON OF TRAFFIC STREAM WEIGH DATA

Tridem axleload distributions (3) were subjected to the equations shown in Table 4. The first part of the listing contained 1,055 tridems located on single-frame trucks that probably were either dump trucks or tractors of semi-trailer trucks. The second part of the listing contained 896 tridems on the semi-trailers. The actual pattern of load was associated with its respective equation and also the equation fitted to all load patterns. Tables 5 and 6 contain the results for the different locations of the tridems on the truck. Table 7 is a summary of all tridems.

In Table 5, the accumulated adjusted EAL by the respective load pattern was 2.9 times larger than if the same total loads had been uniformily distributed within the tridem. This compares with 1.9 for the tridems in Table 6 and 2.5 without regard to location on the truck of the tridem (Table 7). From Table 5, the accumulated adjusted EAL without regard to load pattern was 2.6 times larger than if the same total loads had been evenly distributed. This compares with 1.9 for the tridems in Table 6 and 2.3 without regard to location of the tridem (Table 7). Included in Tables 5 through 7 are the number of tridems in each of the thirteen load patterns. Table 7 shows that approximately 10 percent of the tridems were actually equal. The were only 66 tridems in which one or more axles differed within 0.1 kip (0.44 kN). Thus, for 13.7 percent of the tridems, the load could be considered to be uniformily distributed. It appeared the tridems on the trailer were more likely to be closer to being evenly loaded than those on the tractor. For the tractor, the loads were either equal, within 0.2 kips (0.89 kN) of being equal, or else significantly different from being equal. Table 8 summarizes the percent of tridems by the relative load on the middle axle in the load pattern. The surprise is that nearly 18 percent of the middle axles carried the least load within the tridem.

Tables 5 through 7 also contain the number of tridems for which the load distribution was so extremely uneven that the two lightest axleloads were added together and the group analyzed as an unevenly loaded tandem. Table 7 shows that 19 tridems (approximately 1 percent) analyzed as tandems caused approximately 3 times the fatigue as 1,937 tridems for which the load was more evenly distributed.

SUMMARY

The effect of unevenly distributed loads on the axles within a tridem has been shown to be very significant. Equations are presented that enable the equivalent load effect for uniform load distribution to be adjusted for uneven loading. Considering the relative increase and the relatively small volume of trucks currently using tridems, the equation for all tridems without regard to location on the vehicle is recommended at this time. Consideration should be given to using the equations for individual load patterns as the volume of trucks using tridems increases and more weigh data become available. While this research shows a significant increase in fatigue due to uneven loading within the tridem, it remains to be seen just how significant the relationship is to the total volume of trucks on a given highway.

IMPLEMENTATION

Damage factor relationships shown in Figure 1 and adjustment factors for uneven loading on the axles of a tandem and/or tridem arrangement have been used to calculate fatigue histories of pavements involved in research efforts and investigations of rehabilitation strategies for specific projects. Damage factor relationships shown in Figure 1 have been incorporated into the thickness design method for asphaltic concrete pavements that has been approved by the Federal Highway Administration Washington, D.C., office for use by the Kentucky Transportation Cabinet.

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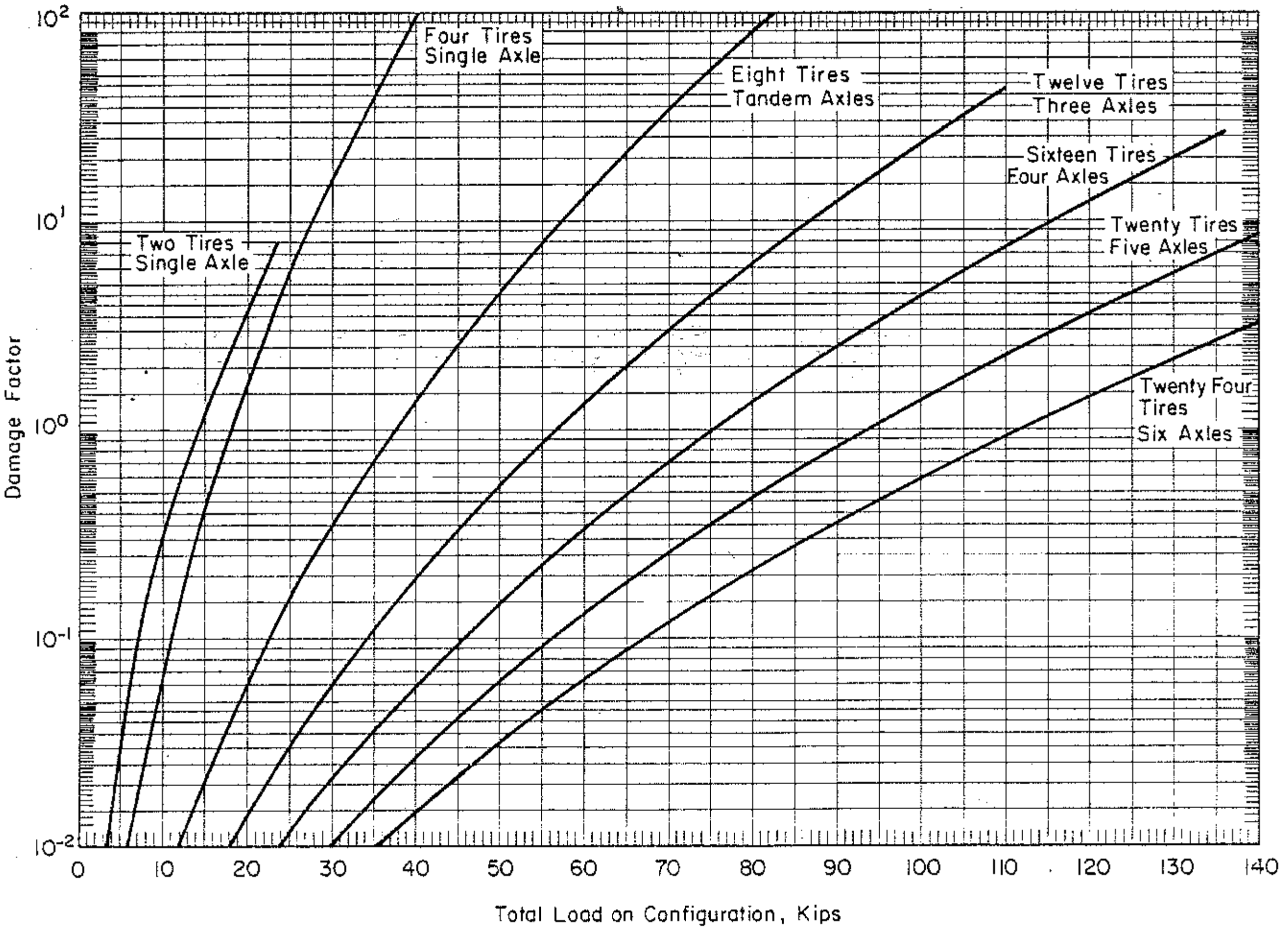

Figure 1. Relationship Between Load Equivalency and Total Load on the Axle Group and Evenly Distributed on All Axles.

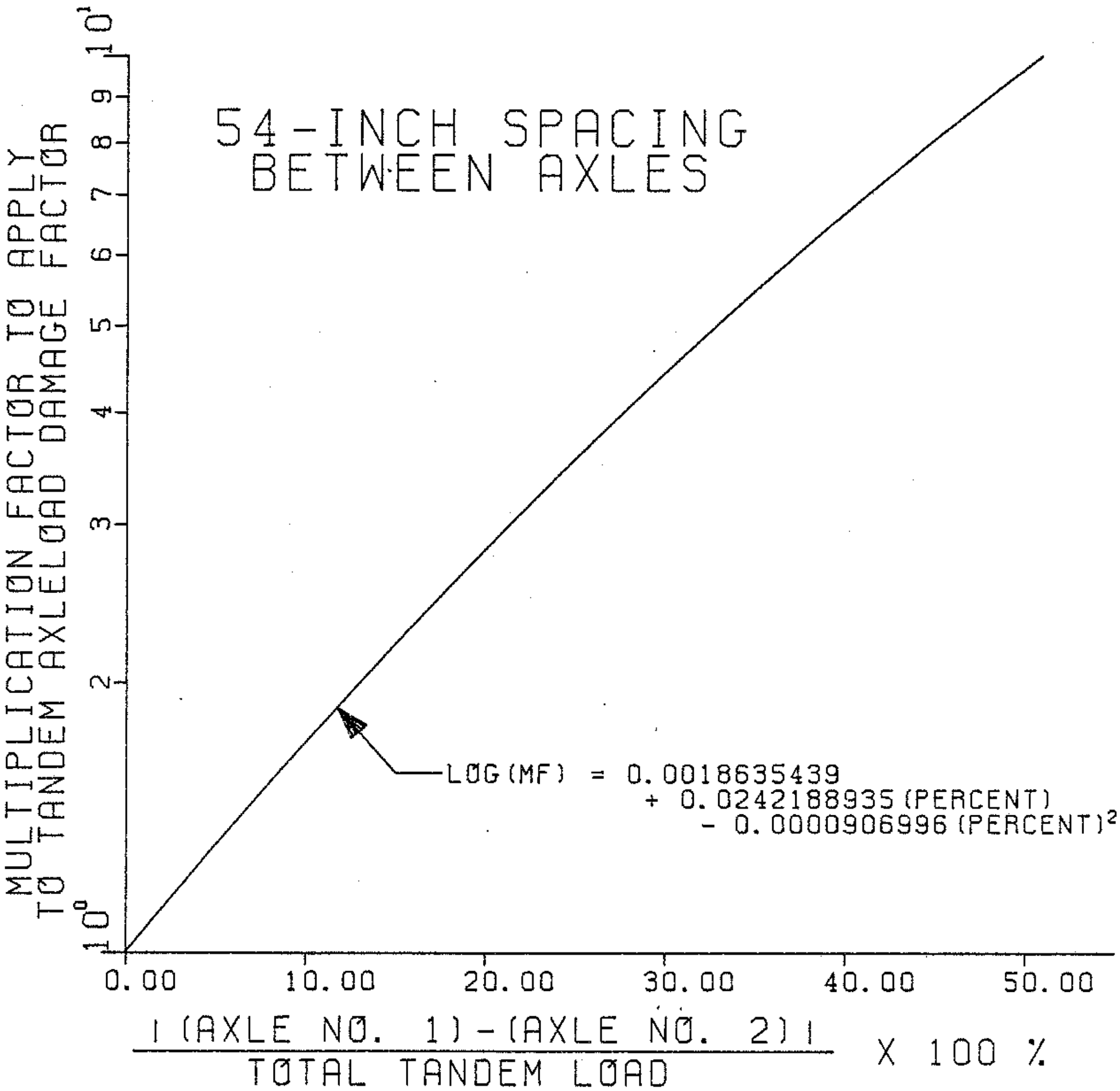

Figure 2. Multiplication Factor to Account for Uneven Load Distribution on the Two Axles of a Tandem

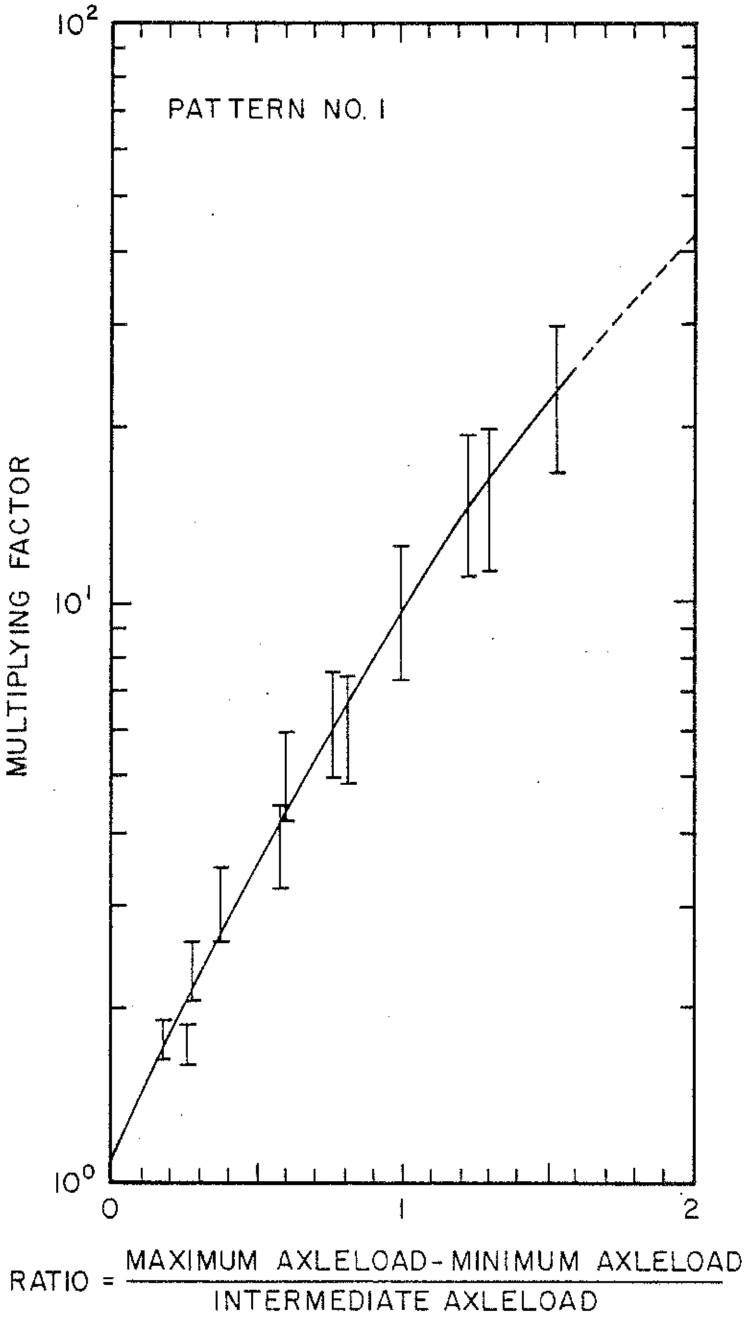

Figure 3. Multiplying Factor for Uneven Load Distribution on the Axles Within the Tridem for Which the Outside Axle Supports the Least Axleload.

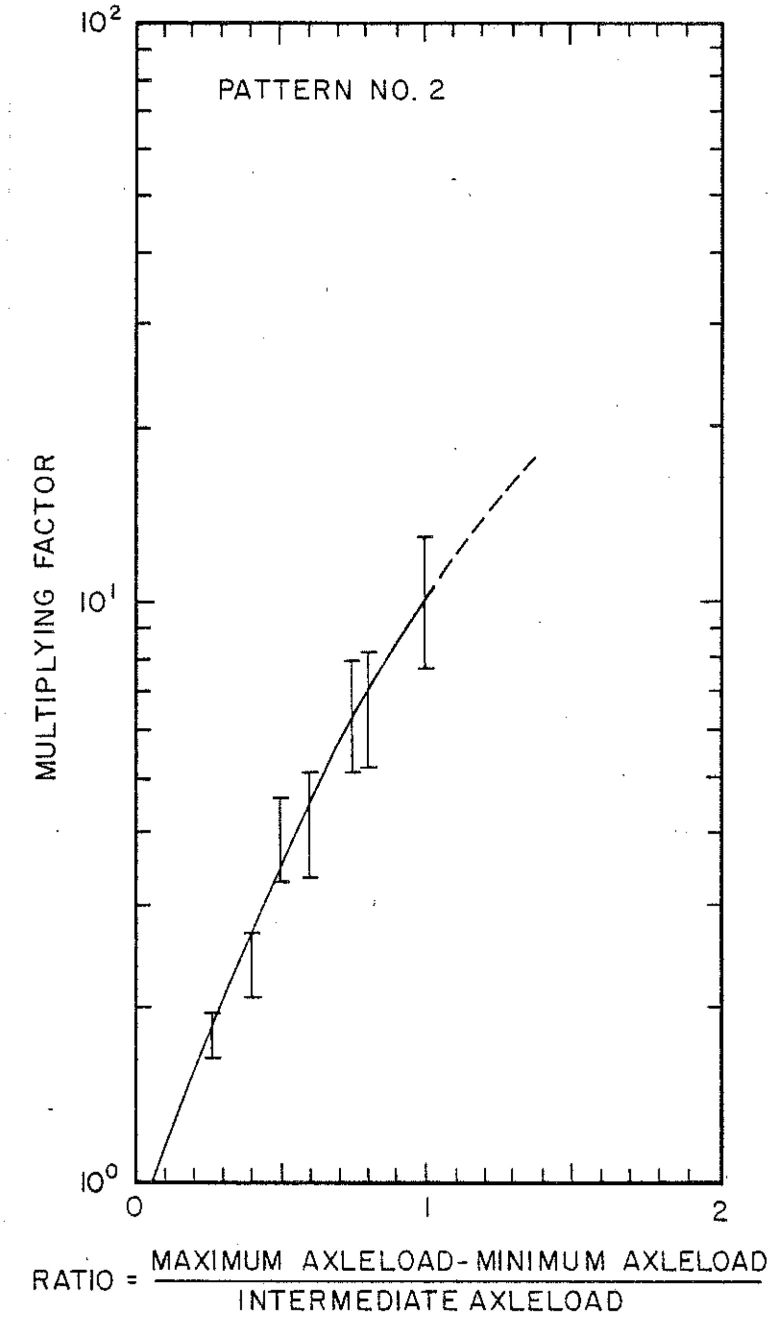

Figure 4. Multiplying Factor for Uneven Load Distribution on the Axles Within the Tridem for Which the Middle Axle Supports the Least Axleload.

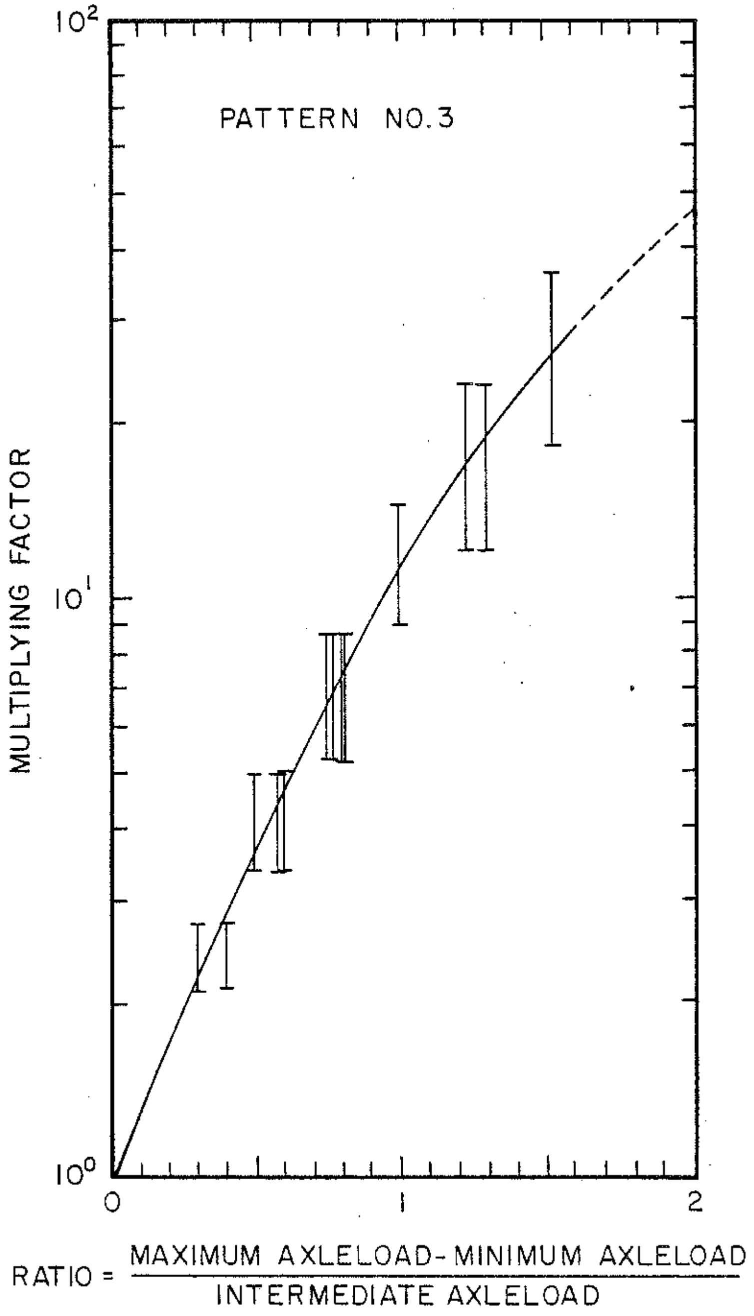

Figure 5. Multiplying Factor for Uneven Load Distribution on the Axles Within the Tridem for Which the Middle Axle Supports the Maximum Axleload.

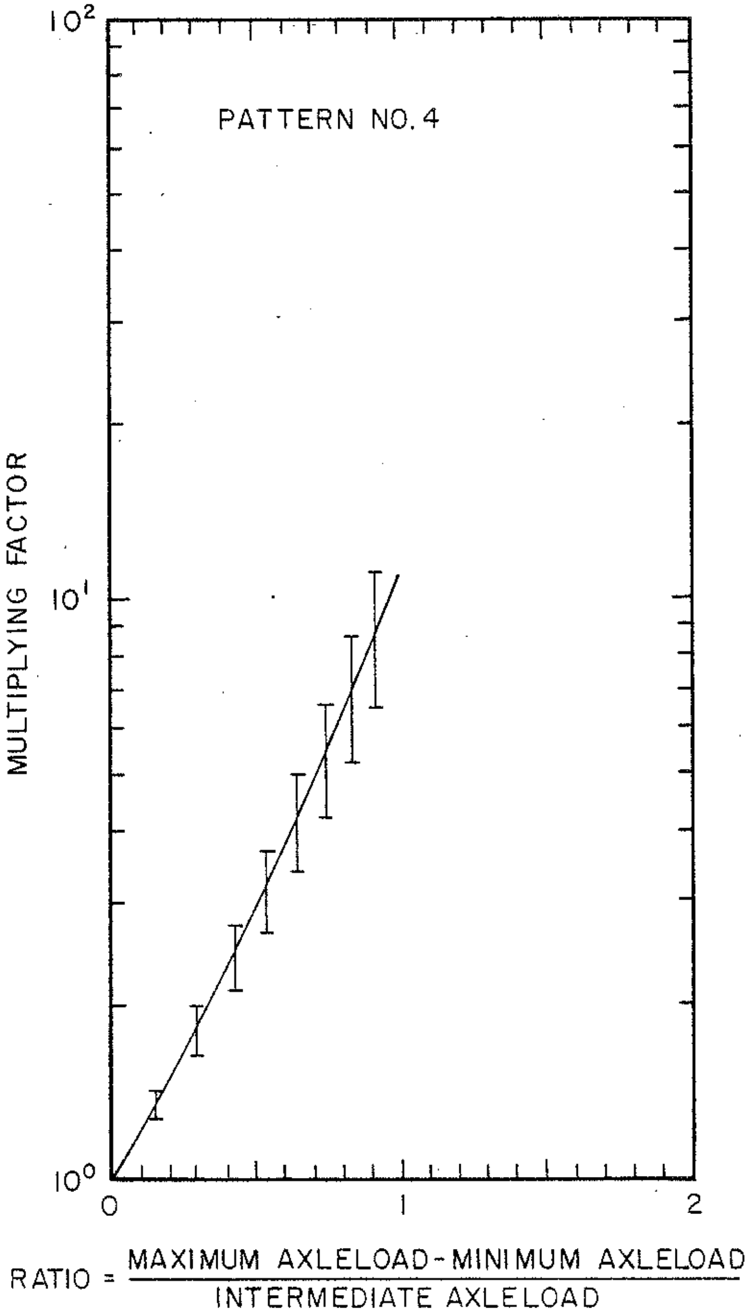

Figure 6. Multiplying Factor for A Load Distribution on a Tridem Having Equal Axleloads on Two Consecutive Axles and a Different Axleload on the Third Axle.

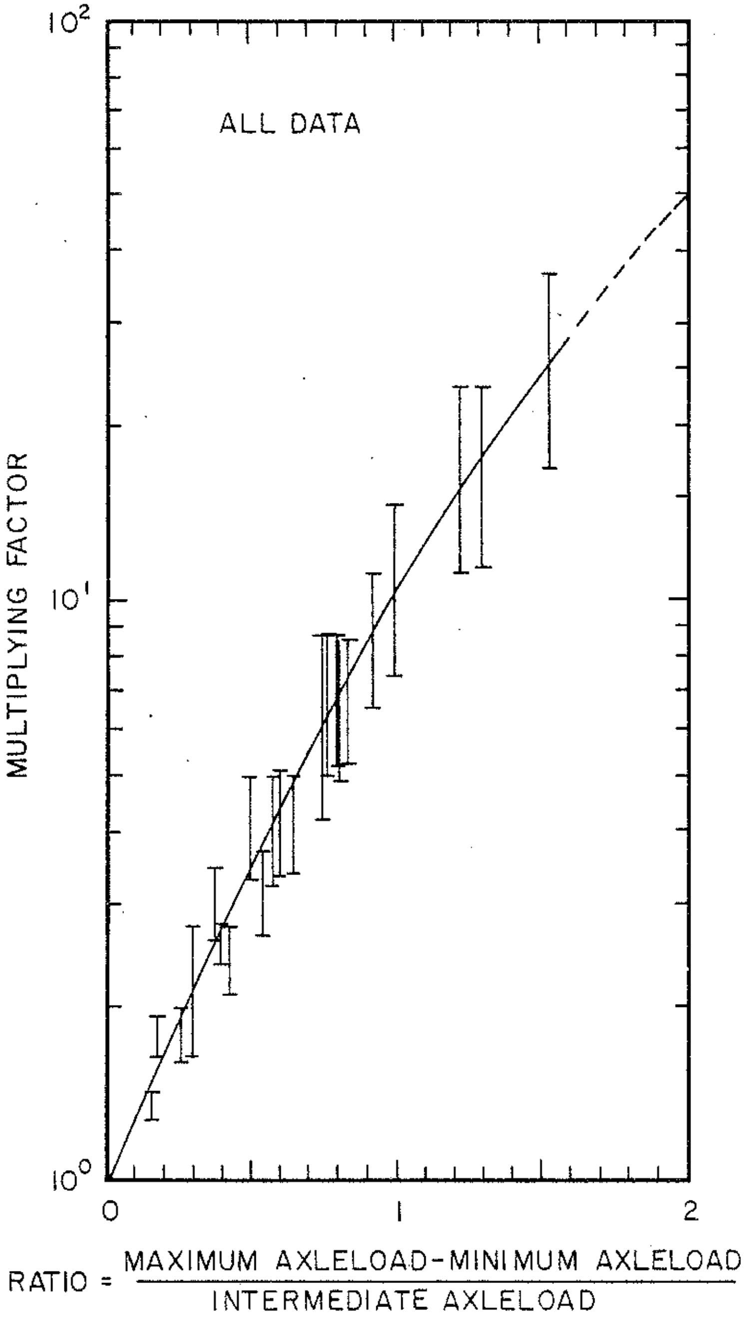

Figure 7. Multiplying Factor for Uneven Load Distribution on the Axles Within the Tridem Without Regard to Location of Maximum or Minimum Axleloads.

TABLE 1. REGRESSION COEFFICIENTS TO CALCULATE DAMAGE FACTORS FOR VARIOUS AXLE CONFIGURATIONS

$\text{Log(Damage Factor)} = a + b(\text{Log(Load)}) + c(\text{Log(load)})^2$

AXLE CONFIGURATION	COEFFICIENTS		
	a	b	c
Two-Tired Single Front Axle	-3.540112	2.728860	0.289133
Four-Tired Single Rear Axle	-3.439501	0.423747	1.846657
Eight-Tired Tandem Axle	-2.979479	-1.265144	2.007989
Twelve-Tired Tridem Axle	-2.740987	-1.873428	1.964442
Sixteen-Tired Quad Axle	-2.589482	-2.224981	1.923512
Twenty-Tired Quint Axle	-2.264324	-2.666882	1.937472
Twenty-four Tired Sextet Axle	-2.084883	-2.900445	1.913994

TABLE 2. PAVEMENT STRUCTURES FROM AASHO ROAD TEST USED IN ANALYSIS

LAYER THICKNESS, inches			
ASPHALTIC CONCRETE	CRUSHED STONE BASE	IMPROVED SUBGRADE	AASHTO STRUCTURAL NUMBER
3	3	8	2.62
4	3	8	3.06
5	3	8	3.50
6	3	8	3.94
3	6	8	3.04
4	6	8	3.48
5	6	8	3.92
6	6	8	4.36

TABLE 3. AXLELOAD DISTRIBUTIONS USED IN INVESTIGATION

	AXLELOAD, kips					
AXLE NUMBER	1	2	3	1	2	3
	HEAVIEST AXLELOAD ON					
DESCRIPTION	OUTSIDE AXLE			MIDDLE AXLE		
Beginning Axleload	8	15	31	8	31	15
Incremental Axleload	0	+2	-2	0	-2	+2
Final Axleload	8	21	25	8	25	21
Beginning Axleload	12	13	29	12	29	13
Incremental Axleload	0	+2	-2	0	-2	+2
Final Axleload	12	19	23	12	23	19
Beginning Axleload	16	11	27	16	27	11
Incremental Axleload	0	+2	-2	0	-2	+2
Final Axleload	16	17	21	16	21	17
Beginning Axleload	20	9	25	20	25	9
Incremental Axleload	0	+2	-2	0	-2	+2
Final Axleload	20	15	19	20	19	15
	Equal Tandem					
Beginning Axleload	2	26	26			
Incremental Axleload	+2	-1	-1			
Final Axleload	24	15	15			

TABLE 4. COEFFICIENTS FROM REGRESSION ANALYSES OF UNEQUAL LOAD DISTRIBUTION ON INDIVIDUAL AXLES OF TRIDEM AXLE GROUP

$$\log(\text{Multiplying Factor}) = a + b(\text{Ratio}) + c(\text{Ratio})^2$$

in which Ratio = $(M - L) / I$
M = Maximum Axleload, kips,
I = Intermediate Axleload, kips,
L = Least Axleload, kips, and
a, b, c = coefficients

Load Pattern: 1. L,I,M 2. M,I,L 3. M,E,E 4. E,E,M	
Constant a	0.468782731
Coefficient b	1.093207072
Coefficient c	-0.1503124207
Standard Error of Estimate	0.073149
Correlation Coefficient, R	0.96024
F Ratio	1183.4

Load Pattern: 1. I,L,M 2. M,L,I 3. E,L,E	
Constant a	-0.1161216122
Coefficient b	1.507954095
Coefficient c	0.377814882
Standard Error of Estimate	0.069341
Correlation Coefficient, R	0.92765
F Ratio	326.9

Load Pattern: 1. L,M,I 2. I,M,L 3. E,M,E	
Constant a	-0.0235937584
Coefficient b	1.283412872
Coefficient c	-0.2187655038
Standard Error of Estimate	0.088165
Correlation Coefficient, R	0.92395
F Ratio	710.7

Load Pattern: 1. L,E,E 2. E,E,L	
Constant a	0.0004399421
Coefficient b	0.8053052125
Coefficient c	0.2363591702
Standard Error of Estimate	0.05634
Correlation Coefficient, R	0.96827
F Ratio	1037.4

Load Pattern: All Patterns Above	
Constant a	-0.198429071
Coefficient b	1.20191282
Coefficient c	-0.1746353238
Standard Error of Estimate	0.09792
Correlation Coefficient, R	0.9240
F Ratio	2085.4

TABLE 5. FATIGUE ANALYSES OF WEIGHT DATA ON TRIDEMS OF SINGLE-FRAME VEHICLES OR TRACTOR OF SEMI-TRAILER VEHICLE, AXLES 2, 3, AND 4

	SUM OF EAL	$\frac{\text{UNEVEN}}{\text{EVEN}}$
Fatigue for Evenly Loaded Tridem	287.65	
Adjusted Fatigue by Load Pattern	839.31	2.9178
Adjusted Fatigue without Regard to Load Pattern	757.24	2.6325
Total Number of Tridems Analyzed	1,055	
Fatigue for Evenly Loaded Tandem	2.53	
Adjusted Fatigue for Unevenly Loaded Tandem	82.66	32.67
Total Number of Tridems Analyzed as Tandems	11	

E = All Axles Evenly Loaded
M = Heaviest Axleload of Tridem
L = Least Axleload of Tridem
I = Intermediate Axleload of Tridem

LOAD PATTERN ON TRIDEM	NUMBER ANALYZED	PERCENT
E,E,E	77	7.3
M,E,E	24	2.3
E,M,E	4	0.4
E,E,M	38	3.6
L,E,E	120	11.4
E,L,E	4	0.4
E,E,L	71	6.7
L,I,M	227	21.5
L,M,I	309	29.3
I,L,M	16	1.5
I,M,L	42	4.0
M,L,I	21	2.0
M,I,L	102	9.6
TOTAL	1,055	100.0

TABLE 6. FATIGUE ANALYSES OF WEIGHT DATA ON TRIDEMS OF SINGLE-FRAME VEHICLES OR TRACTOR OF SEMI-TRAILER VEHICLE, AXLES 4, 5, AND 6

	SUM OF EAL	UNEVEN / EVEN
Fatigue for Evenly Loaded Tridem	216.05	
Adjusted Fatigue by Load Pattern	417.44	1.93
Adjusted Fatigue without Regard to Load Pattern	413.62	1.91
Total Number of Tridems Analyzed	896	
Fatigue for Evenly Loaded Tandem	102.23	
Adjusted Fatigue for Unevenly Loaded Tandem	3336.84	32.64
Total Number of Tridems Analyzed as Tandems	8	

E = All Axles Evenly Loaded
M = Heaviest Axleload of Tridem
L = Least Axleload of Tridem
I = Intermediate Axleload of Tridem

LOAD PATTERN ON TRIDEM	NUMBER ANALYZED	PERCENT
E,E,E	123	13.7
M,E,E	47	5.3
E,M,E	9	1.0
E,E,M	36	4.0
L,E,E	50	5.6
E,L,E	27	3.0
E,E,L	41	4.6
L,I,M	72	8.0
L,M,I	46	5.1
I,L,M	103	11.5
I,M,L	68	7.6
M,L,I	171	19.2
M,I,L	102	11.4
TOTAL	896	100.0

TABLE 7. FATIGUE ANALYSES OF WEIGHT DATA ON TRIDEMS OF SINGLE-FRAME VEHICLES OR TRACTOR OF SEMI-TRAILER VEHICLE, ALL AXLES

	SUM OF EAL	UNEVEN ------ EVEN
Fatigue for Evenly Loaded Tridem	503.70	
Adjusted Fatigue by Load Pattern	1256.75	2.4950
Adjusted Fatigue without Regard to Load Pattern	1170.86	2.3245
Total Number of Tridems Analyzed	1,951	
Fatigue for Evenly Loaded Tandem	104.76	
Adjusted Fatigue for Unevenly Loaded Tandem	3419.50	32.64
Total Number of Tridems Analyzed as Tandems	19	

E = All Axles Evenly Loaded
M = Heaviest Axleload of Tridem
L = Least Axleload of Tridem
I = Intermediate Axleload of Tridem

LOAD PATTERN ON TRIDEM	NUMBER ANALYZED	PERCENT
E,E,E	200	10.3
M,E,E	71	3.6
E,M,E	13	0.7
E,E,M	74	3.8
L,E,E	170	8.7
E,L,E	31	1.6
E,E,L	112	5.7
L,I,M	299	15.3
L,M,I	355	18.2
I,L,M	119	6.1
I,M,L	110	5.6
M,L,I	193	9.9
M,I,L	204	10.5
TOTAL	1,951	100.0

TABLE 8. PERCENT OF TRIDEMS WITH MIDDLE AXLE AS PART OF GIVEN LOAD PATTERN

LOAD PATTERN	PERCENT
x, M, x	24.5
x, L, x	17.6
x, I, x	25.8
x, E, x	32.1
TOTAL	100.0