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EFFECT OF AXLE CONFIGURATIONS ON FATIGUE AND FAULTING OF CONCRETE PAVEMENTS



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Abstract
The new mechanistic-empirical pavement design method in the US does away with the ESAL concept and employs instead the concept of axle load spectra. The state of Michigan allows several heavy truck configurations with up to 11 axles and large axle groups with as many as 8 axles within one axle group. However, very little research has been done on the effect of different axle configurations on pavement damage. In this paper, the fatigue life of concrete beams was determined in the laboratory for different axle configurations. The results indicate that the normalized fatigue damage per axle for larger axle groups is less than the single axle under identical stress ratios. The damage is much lower when considering the reduction of stress under multiple axles. In addition, a mechanistic analysis was performed for faulting and fatigue with and without curling. The results showed that class 13 trucks with multiple axles are less damaging in fatigue than class 9 trucks, while the most damaging truck is that of class 11 with only single axles. The results from faulting analysis showed that class 13 trucks are more damaging than class 9 truck, while the least damaging truck is that of class 11.

Keywords: Concrete, Pavement, Fatigue, Faulting, Axle factor, Truck factor

Résumé
La nouvelle méthode mécanico-empirique de modélisation des chaussées aux États-Unis utilise la notion de spectres de charge à l'essieu au lieu du concept d'ESAL. L'état du Michigan utilise plusieurs configurations de camions lourds comportant jusqu'à 11 essieux et de grands groupes d'essieux (jusqu'à 8 au sein d'un seul groupe). Toutefois, très peu de recherche a été faite sur l'effet des différentes configurations d'essieux vis à vis du dommage aux chaussées. Dans cet article, la durée de vie en fatigue de spécimens de béton a été déterminée en laboratoire pour différentes configurations d'essieux. Les résultats expérimentaux indiquent que le dommage en fatigue normalisé par essieu pour les plus grands groupes est moindre que pour l'essieu simple avec le même rapport de contraintes. Le dommage est encore plus faible en considérant la réduction des contraintes sous les essieux multiples. En plus, une analyse mécanique a été faite sur les fissures et la fatigue avec/sans curling. Les résultats ont montré que la classe 13 des camions à essieux multiples est moins agressive en fatigue que la classe 9, tandis que le camion le plus nuisible est celui de la classe 11 avec des essieux simples seulement. Les résultats de l'analyse des fissures ont montré que les camions de classe 13 sont plus agressifs que ceux de la classe 9, tandis que le camion le moins nuisible est celui de la classe 11.

Mots-clés: Béton, chaussée, fatigue, fissures, facteur d'essieu, facteur du camion.

1. Introduction

The most current concrete pavement thickness design is based on mechanistic-empirical procedures (NCHRP 1-37A, 2004). Mechanistic methods are used to compute the primary slab responses such as stress, strain and deflection due to the load induced by the passage of an axle group or a truck. Empirical transfer functions are then used for relating pavement response to the number of allowable load repetitions to failure. With the adoption of the new mechanistic-empirical pavement design method and the employment of axle load spectra, the question of evaluating the pavement damage resulting from different axle and truck configurations has become more relevant. In particular, the state of Michigan is unique in permitting several heavy truck axle configurations that are composed of up to 11 axles, sometimes with as many as 8 axles within one axle group. Thus, there is a need to identify the relative pavement fatigue damage resulting from these multiple axle trucks.

2. Background

Most researchers studying the effect of concrete fatigue have used primarily constant amplitude pulses in their testing. Many flexural fatigue tests conducted in the laboratory were based on using a sinusoidal or a constant amplitude haversine pulse to simulate a moving wheel load (Hilsdorf and Kesler (1966), Roesler (1988)). However, under multiple axle loading, the pulse shapes do not have uniform amplitudes. Thus, in order to accurately assess the damage induced onto the pavement due to these multiple axles, a more thorough investigation of these non-uniform amplitudes is required. Oh (1991) investigated the fatigue behavior of concrete under varying amplitudes of cyclic loading. He found that concrete fatigue failure was greatly affected by the magnitude and sequence of the applied variable load cycles, and Miner’s linear theory lead to some errors in fatigue failure prediction of concrete materials.

Previous research on the effect of truck configurations on pavement damage using mechanistic analysis is surprisingly somewhat limited. The latest comprehensive study on the subject was done by Gillespie et al. (1993). Efforts by the authors to investigate these effects using laboratory, field as well as mechanistic analysis have been thus far focused on asphalt pavements (Chatti and El Mohtar (2004), Salama et al. (2006)).

3. Flexural Beam Fatigue Testing

One hundred and fifty beams (0.1 × 0.1 × 0.6 m) were subjected to cyclic loading in uniaxial (flexural) four point bending in the lab. The series of cyclic fatigue tests was conducted using different multiple load pulses corresponding to single, tandem, tridem, quad, six and eight axles. The longitudinal stress pulses were determined by the DYNASLAB computer program (Chatti, 1992) and are shown in Figure 1. Note that the stress reversal (compression) was not included in the beam load pulse because of difficulty in running cyclic loading with stress-reversal. Modulus of rupture (MOR) tests were conducted at 7, 28 and 90 days. Two additional MOR tests were conducted one day prior to the actual fatigue testing and one day after end of the fatigue testing. This allowed the variation of strength over time to be monitored in order to adjust the stress ratios, SR (ratio of stress to MOR) accordingly. The stress ratios, were calculated at periodic times throughout the experiment as the ratios of the largest peak within a given pulse over the flexural strength (MOR) at the time of testing. Table 1 shows the experimental test matrix and figure 2 shows the test results for all axle configurations.

Table 1 – Fatigue test matrix (with number of replicates)

	Axle Type						
Stress Ratio	**Single**	**Tandem**	**Tridem**	**Quad**	**Six**	**Eight**	**Total**
0.9	5	X	X	X	X	X	5
0.85	X	5	5	5	6	6	27
0.8	5	7	X	X	X	X	12
0.75	X	X	6	4	6	5	21
0.67	4	4	4	4	4	4	24
0.59	X	5	5	X	X	X	10
0.52	4	X	5	6	4	4	23
0.46	X	X	X	X	X	4	4
Sum	18	21	25	19	20	23	126

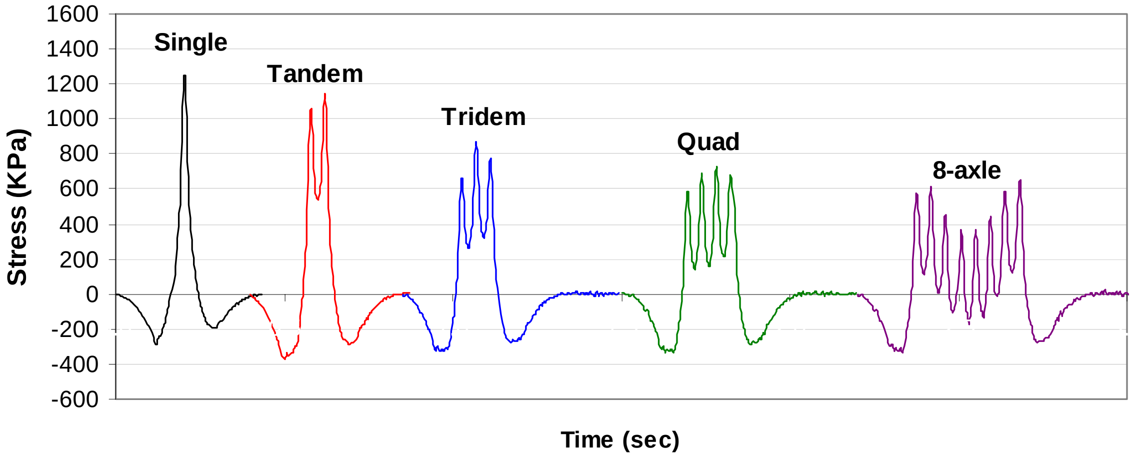


Figure 1 – Longitudinal stress pulses from different axle groups

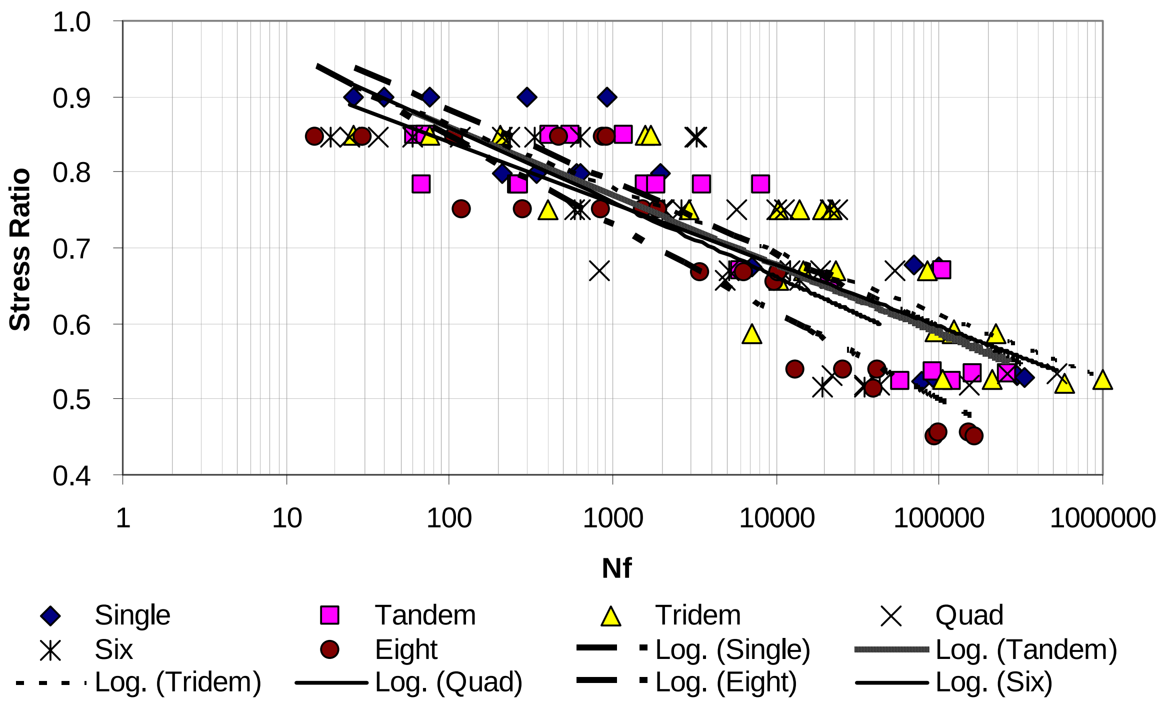


Figure 2 – Fatigue test results

3.1 Multiple linear regression

Because of the large scatter in the data, it was deemed more useful to conduct a multiple linear regression analysis to interpret the relationship between stress ratio, axle type and fatigue life. One of the advantages of using a multiple linear regression equation is that all of the data from the experiments can be used at once, which increases the degrees of freedom in the model, and ultimately decreases the margin of error. Since axle type is not a continuous variable, a new variable was introduced for the regression analysis: A normalized stress impulse, SI. SI is defined as the ratio of the area under the pulse and the peak stress corresponding to the largest stress within a given pulse. SI is constant for a given axle type, regardless of the applied stress, making it a good indicator of axle type. Also, the initial elastic modulus, E_o, for each beam was added as a variable to account for specimen-to-specimen material variability. Table 2 shows the results from the multiple linear regression analysis. The analysis shows that SR, SI and E_o are all statistically significant variables ($p < 0.05$), with fatigue life increasing with decreasing stress ratio, increasing modulus and decreasing stress impulse (i.e., decreasing axle number).

Table 2 – Results from multiple linear regression analysis*

Predictor	Coefficient	SE	t	p
Constant	21.222	1.112	19.08	0.000
SR	-20.838	1.355	-15.38	0.000
SI	-6.970	1.722	-4.05	0.000
E_o	1.84E-06	9.20E-07	2.01	0.047

* $R^2 = 0.772$ Adjusted $R^2 = 0.766$

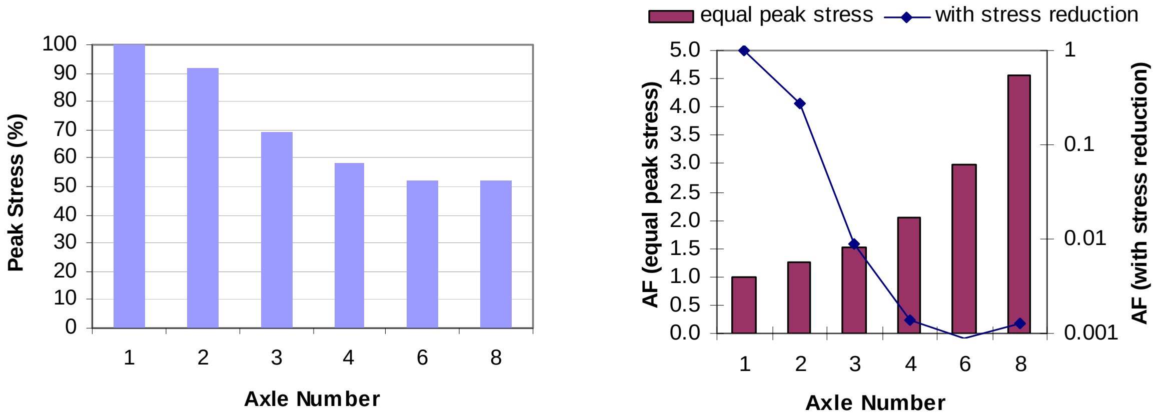
4.2 Axle factors

Axle factors (AF) were defined as the ratio of damage ($1/N_f$) due to the axle group to that due to a single axle, with N_f being the fatigue life obtained from the results of the multiple regression analysis for a constant SR and E_o (table 2). This was done first by using the same peak stress value for all axle groups (laboratory condition). Then, recognizing that the peak longitudinal stress decreases with increasing number of axles because of the interaction between individual axles within an axle group (figure 3(a)) the AFs were recalculated after accounting for this stress reduction. Figure 3(b) shows the AFs for the various axle configurations for the same peak stress value and accounting for the stress reduction.

When the peak stress value is the same for all axle groups, the axle factors increase sharply as the number of axles increases. If one takes into account the reduction in longitudinal stress caused by stress interaction under multiple axles, the damage from multiple axles and the corresponding axle factors become much smaller. Next we compare the AF value for tandem and tridem axles with stress reduction from figure 4 to those obtained from the PCA design manual (PCA, 1984). From the design example provided in the manual for a 0.24 m slab on an untreated base, the allowable number of repetitions for a 232 kN tandem axle is 1.1×10^6, while that for a 116 kN single axle is 230,000. This leads to an axle factor for the tandem axle of 0.21 compared to 0.28 from figure 4, suggesting that they are reasonably close. For the tridem axle, the example in Appendix C of the PCA manual shows an unlimited number of allowable repetitions of a 240 kN tridem for the same design. This agrees well with the AF value of about 0.01 from figure 3(b).

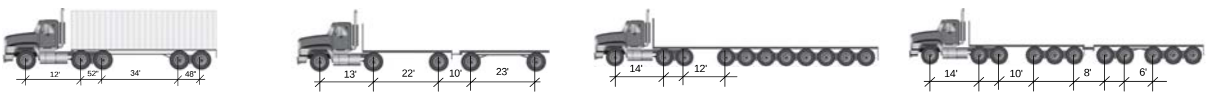
4. Mechanistic Analysis

In parallel with the lab experiments an analysis was performed using the computer program DYNASLAB (Chatti, 1992) to determine the relative damage to pavements caused by trucks with different axle configurations. Separate analyses were done for fatigue near the edge at mid-slab and faulting at the joint. Four trucks were considered in the analysis (figure 4). The slab was 4.9 m (16 ft) long and 3.6 m (12 ft) wide with a thickness of 250 mm (10 in). No gap under the slab was allowed in the preliminary analysis. Loading per axle was according to the legal load limits in Michigan: (1) steering axle at 68.5 kN (15,400 lbs); (2) single axle at 80 kN (18,000 lbs); (3) tandem axle at 71 kN (16,000 lbs); and (4) tridem and higher axles at 58 kN (13,000 lbs).



(a) Reduction in peak longitudinal stress (b) Axle Factors

Figure 3 –Axle factors taking into account stress reduction



Class 9 Class 11 Class 13 Class 13-2

Figure 4 – Trucks used in the mechanistic analysis

4.1 Fatigue cracking

Fatigue life is generally related to the longitudinal stress at the mid-slab in the wheel path under the moving load. However, because of environmental effects the slab may also be undergoing curling. The corresponding stress should be superimposed onto the stress caused by the moving load. Curling stress varies with gradual changes in temperature throughout the day. However, for the sake of simplicity in the preliminary analysis, a constant curling stress of 1234 kN/m^2 was assumed. This corresponds to the maximum daytime thermal stress for such a slab with a temperature difference of 17.2 ^{o}C.

Stresses estimated using DYNASLAB and the empirical fatigue model adopted by the mechanistic-empirical pavement design guide, M-E PDG (NCHRP, 2004) were used for estimating fatigue life:

$$N_f = 10^{\left\{2\left(\frac{MR}{\sigma}\right)^{1.22} + 0.4371\right\}} \quad (1)$$

Fatigue life (N_f) was then used to determine the damage to the pavement by taking its inverse ($1/N_f$). The damage values were then normalized using a standard 80 kN (18 kip) single axle as the reference axle. Table 3 presents the axle factors thus calculated along with the resulting truck factors, assuming 100% load transfer efficiency (LTE) across the joint.

Table 3 - Relative axle and truck factors

	Relative Axle Factor											Truck Factor
Truck Type	Axle 1	Axle 2	Axle 3	Axle 4	Axle 5	Axle 6	Axle 7	Axle 8	Axle 9	Axle 10	Axle 11	
Class 9	0.62	0.22	0.27	0.43	0.28							1.82
Class 11	0.69	0.86	0.31	0.31	1.00							3.18
Class 13	0.17	0.42	0.21	0.01	0.02	0.00	0.00	0.00	0.00	0.01	0.01	0.86
Class 13-2	0.90	0.35	0.11	0.01	0.07	0.00	0.00	0.00	0.00	0.04	0.02	1.51

Since different classes of trucks have varying axle and gross vehicle loads, each truck factor was divided by its gross vehicle weight (GVW). Also, to be able to compare the trucks relative to each other, the truck factor per unit GVW was normalized using the class 9 truck as the reference truck, since it accounts for the majority of trucks in the U.S. (see table 4). The results shown in Table 4 indicate that class 13 trucks are less damaging than class 9 trucks. The truck with the 8-axle group is the least damaging in fatigue. On the other hand, the most damaging truck is that of class 11, which is comprised of only single axles.

Table 4 - Truck factors normalized to gross vehicle weight

Truck Type	Gross wt. (kg)	Truck Factor	TF/GVW	Normalized TF/GVW
Class 9	36048	1.82	5.06E-05	1.00
Class11	39680	3.18	8.01E-05	1.58
Class 13	68736	0.86	1.24E-05	0.25
Class 13-2	68736	1.51	2.20E-05	0.43

4.2 Faulting

The model adopted by M-E PDG for faulting requires several steps (NCHRP, 2004). For the sake of brevity the details of the model are not presented here. However, faulting can be taken to be roughly proportional to the square of the corner deflection. Using this relationship, axle factors for each axle in the four truck configurations were calculated. The rearmost 80 kN (18 kip) single axle in the truck representing class 11 was used as the reference axle. Summation of the axle factors for each truck gives the truck factor. In line with the fatigue analysis, normalized truck factors per unit GVW were calculated assuming 100% load transfer efficiency (LTE) across the joint (table 5).

Table 5 - Truck factors (faulting) normalized for the gross vehicle weight (100% LTE)

Truck Type	Gross wt. (kg)	Truck Factor	TF/GVW	Normalized TF/GVW
Class 9	36048	5.87	1.63E-04	1.00
Class11	39680	4.38	1.10E-04	0.68
Class 13	68736	12.64	1.84E-04	1.13
Class 13-2	68736	10.74	1.56E-04	0.96

Similar analyses were then performed for medium and low values of LTE. Tables 6 and 7 show truck factors corresponding to these two cases. The above results show that at 100 percent LTE, class 13 trucks are more damaging than class 9 trucks. Class 13-2 trucks are only slightly less damaging that Class-9 trucks. The least damaging truck is that of class 11, which is comprised of only single axles. Next we compare truck factors for each class at the different LTE values (table 8). The results show that damage caused by multiple axle groups (classes 9 and 13) decreased with decreasing LTE, with the largest decrease corresponding to the truck with the larger 8-axle group. The reverse trend is observed for single axles (class 11). This could be explained by the fact that multiple axles can bridge between the leave and approach slabs, while single axles cannot.

Table 6 - Truck factors (faulting) corresponding to medium aggregate interlock

Truck Type	Gross wt. (kg)	Truck Factor	TF/GVW	Normalized TF/GVW
Class 9	79400	5.59	7.04E-05	1.00
Class11	87400	4.54	5.20E-05	0.74
Class 13	151400	11.30	7.46E-05	1.06
Class 13-2	151400	10.07	6.65E-05	0.94

Table 7 - Truck factors (faulting) corresponding to low aggregate interlock

Truck Type	Gross wt. (kg)	Truck Factor	TF/GVW	Normalized TF/GVW
Class 9	79400	5.15	6.48E-05	1.00
Class11	87400	4.69	5.36E-05	0.76
Class 13	151400	9.35	6.18E-05	0.88
Class 13-2	151400	9.01	5.95E-05	0.84

Table 8 – Effect of load transfer efficiency on truck factors for faulting

Truck Type	100% LTE	Med LTE	Low LTE
Class 9	0%	-5%	-12%
Class11	0%	4%	7%
Class 13	0%	-11%	-26%
Class 13-2	0%	-6%	-16%

4.3 Effect of slab curling and axle spacing on fatigue cracking

The effect of slab curling on stresses in plain concrete pavements can be significant (Hansen et al., 2002). This section focuses on the potential for transverse cracking that would be caused by particular combinations of spacing between axle groups and joint spacing. In this part of the analysis curling of the slab was allowed, and the possibility of gaps under the curled slab was included; for this reason, the KENSLABS program (Huang, 2004) was used, since it allows for curled slabs and gaps underneath the slab system. The same pavement conditions were used; i.e., 4.88 m (16 ft) long, 3.66 m (12 ft) wide and 250 mm (10 in) thick slabs. The axles (single and tandem axle combinations) were placed at both ends of the slab. The results in terms of longitudinal and transverse stresses and deflections were compared for cases when there is (i) no curling, (ii) upward curling and (iii) downward curling.

In the case of no curling and upward curling the axle groups analyzed were: (a) a single steering axle with single wheels and a single drive axle with dual wheels, (b) a single axle with single wheels and a tandem axle simulating the front drive axle, and (c) two tandem axles simulating the drive and rear axles. The spacing between the axle groups was adjusted so that the two groups would exactly fit on one slab of 4.88 m (16 ft) length. This represents the most critical location of the axles when negative (upward) curling occurs, and such axle spacing would be similar to those found in certain truck configurations. Note that this combination of axle group spacing and negative slab curling of the slab would lead to maximum compressive stresses at the bottom of the mid-slab i.e., maximum tensile stresses at the top, which may lead to top-down cracking. It is clear from the results presented in table 9 that curling with inclusion of gaps causes the stresses to increase significantly.

Table 9 – Maximum longitudinal stresses for top-down cracking

Loading	Max Long. Stress (kN/m^2)	Location (m)		Min Long. Stress (kN/m^2)	Location (m)	
		X	Y		X	Y
Curling Only	911	2.44	1.83	0	0	Joint
Single + Single Load Only	865	1.22	0.91	0	0	Joint
Single + Single & Curling	1980	2.44	1.83	0	0, 4.88	Joint
Single + Tandem & Curling	1963	2.74	1.83	0	0, 4.88	Joint
Tandem + Tandem & Curling	1942	2.44	1.22	0	0, 4.88	Joint

In the case of positive (downward) curling the load was placed at mid-slab. Such load position would cause maximum tensile stresses at the bottom of the mid-slab leading to the possibility of bottom-up cracking. Table 10 shows the longitudinal stresses due to different axle groups with and without curling. When the slab is flat, i.e. without curling, the stresses decrease as the number of axles within a group increases from one to four. This decrease is because of the bridging effect from additional axles leading to lesser flexure in the longitudinal direction. When the slab is curled downward (positive curling), longitudinal stresses increase by two to almost five folds. A component of this stress is the curling stress. In this case a temperature difference of 17.2 ^{o}C (31 ^{o}F) was assumed with the top surface being warmer than the bottom. In addition, the upward curvature of the slab produces higher bending moment leading to higher load-related stresses as well. Interestingly the percent increase in longitudinal stress increases significantly as the number of axles increases from one to four. However the absolute maximum value of longitudinal stress at the bottom of mid-slab goes down with increasing number of axles.

Table 10 - Stresses due to different axle groups for bottom-up cracking

Loading Axle	Maximum Longitudinal Stress (kN/m^2)		% Increase in Max Stress
	No Curling	With Curling	
Single	915.6	2715.1	197
Tandem	786.0	2395.4	205
Tridem	505.4	2304.7	356
Quad	333.7	1928.9	478

5. Statistical Analysis of Long Term Performance Data from In-service Pavements

The Michigan Department of Transportation (MDOT) has very comprehensive pavement surface distress data from in-service pavements. Data from a total of fifty pavement sections together with their corresponding weigh-in-motion (WIM) data from the FHWA Vehicle Travel Information System (VTRIS, 1984) were used to investigate the relative effect of different truck axle configurations on concrete pavement distresses and to verify the mechanistic and laboratory findings. Care was taken in selecting sections with different pavement type, age, cross–sectional design, and traffic loading. The performance measures used in the analysis are the Distress Index (DI) and the Ride Quality Index (RQI). Truck traffic was categorized according to the FHWA classification system, which includes 13 classes according to the number of axles and number/type of vehicle units. In this analysis, only vehicle classes 5 through 13 (trucks) were considered. Some truck classes were excluded because of their low volume (Classes 7 and 12) or light weight (class 5).

Multiple linear regression was used in this analysis. The regression parameter (β), coefficient of determination (R^2), and test statistic (*p-values*) were used to interpret the effects. The analysis included checking the normality assumption and constant variance of the residual. The value of the slopes (βs) in multiple linear regression depends on the unit of measurement (number of truck repetitions). This slope represents the change in DI or RQI (dependent variable) due to a unit increase in the number of axle or truck repetitions (independent variables). Truck configurations with fewer repetitions will have a larger slope value. Moreover, the intercept for each independent variable will be different from each other, which may not help in comparing the relative effects. The standardized slope has been documented as a measure to compare the relative importance of different independent variables (Dillon, W. and M. Goldstein, 1984). Standardized slope values are determined by converting all variables (dependent and independent) into Z-scores. Having the variables in Z-score form will convert the distribution mean to zero and standard deviation to one, such that all variables will have a common measurement scale and one can determine which independent variable is relatively more important. For the above reasons, the standardized slope was used to compare the relative effect of the truck configurations.

Also, because truck traffic distributions do not always vary greatly from section to section, several "independent" variables in the regression model may in fact be correlated and will affect the values of the regression coefficients, and in some cases cause the signs to switch to counter-intuitive values. To solve this multicollinearity problem similar truck configurations were combined together. Therefore, trucks were categorized into two groups: (1) single-tandem trucks, and (2) multiple axle trucks. Trucks with single and tandem axles can be found in classes 6, 8, 9, 10, and 11, while trucks with multiple axles are only in class 13.

Table 11 - Effect of different truck configurations on rigid pavement distress—DI and RQI

Truck classes	**DI**			**RQI**		
	β	***p-value***	**R^2**	**β**	***p-value***	**R^2**
6, 8, 9, 10, and 11	0.668	0.000	0.569	-0.007	0.961	0.424
13	0.129	0.294		0.655	0.000	

The results from the analyses are summarized in Table 11. The results show that single – tandem-axle trucks are significant for distress index (cracking) (β= 0.668 and *p*-value = 0.000) compared to multiple axle trucks (β= 0.129 and *p*-value 0.294). These results fairly agree with the laboratory investigation which showed that multiple axles are less damaging (per load carried) for fatigue cracking (Figure 3). Conversely, multiple-axle trucks are significant for ride quality index (pavement roughness) and show higher β values and lower *p*-value than tucks with single-tandem axles, which are not significant. These conclusions that are based only on the analysis of in-service pavement data, while general, tend to confirm the results obtained from the laboratory and mechanistic investigations.

6. Conclusion

The laboratory investigation showed that the normalized fatigue damage per axle for larger axle groups is less than the single axle under identical stress ratios. The damage is even lower when considering the reduction of stress under multiple axles. In addition, results from the mechanistic analysis showed that class 13 trucks with multiple axles are less damaging in fatigue than class 9 trucks with tandem axles, while the most damaging truck is that of class 11 with only single axles. The results from faulting analysis showed that class 13 trucks are more damaging than class 9 trucks, while the least damaging truck is that of class 11. The above trends were confirmed by the stepwise regression analysis using in-service distress and traffic data.

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