EFFECT OF HEAVY TRUCKS WITH LARGE AXLE GROUPS ON ASPHALT PAVEMENT DAMAGE

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ABSTRACT

The pavement deterioration over time is caused by a combination of factors; however, traffic loads play a key role in consumption of pavement life. The main objective of this paper is to investigate the relative damage (fatigue and rutting) of asphalt pavements using laboratory and field data by considering various axle and truck configurations. The indirect tensile cyclic load test was used in the laboratory to simulate various axle and truck configurations. Data from the General Pavement Study (GPS-1) in the Long Term Pavement Performance Program (LTTP) were used to investigate the relationship between truck repetitions and the deterioration rate of fatigue cracking and rutting. Damage caused by trucks was determined per tonnage carried to identify the most economical axle and truck configurations. Laboratory results showed that trucks with tridem and multiple axles caused less fatigue damage per tonnage carried as compared to trucks with single and tandem axles. The same could not be said for rutting. Field results were inconclusive for both fatigue and rutting.

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The pavement deterioration over time is caused by a combination of factors; however, traffic loads play a key role in consumption of pavement life. The main objective of this paper is to investigate the relative damage (fatigue and rutting) of asphalt pavements using laboratory and field data by considering various axle and truck configurations. The indirect tensile cyclic load test was used in the laboratory to simulate various axle and truck configurations. Data from the General Pavement Study (GPS-1) in the Long Term Pavement Performance Program (LTTP) were used to investigate the relationship between truck repetitions and the deterioration rate of fatigue cracking and rutting. Damage caused by trucks was determined per tonnage carried to identify the most economical axle and truck configurations. Laboratory results showed that trucks with tridem and multiple axles caused less fatigue damage per tonnage carried as compared to trucks with single and tandem axles. The same could not be said for rutting. Field results were inconclusive for both fatigue and rutting.

1. BACKGROUND

Several factors such as traffic, environment, material and design considerations affect the pavement damage over time. Traffic loads play a key role in pavement deterioration. Trucks are the major consumers of the pavement network as they apply the heaviest loads to the pavement surface. Truck loads are transferred to the pavements through various combinations of axle configurations depending on the truck type. The current AASHTO pavement design guide converts different axle load configurations to a standard axle load (18 kips) using Load Equivalency Factors (LEFs). These LEFs are based on loss of Pavement Serviceability Index (PSI), and were developed for a limited number of pavement and axle types, load magnitudes, load applications, age and environment. The PSI is widely based on the functional performance of the road surface (rideability), and accounts to a low degree for other key performance measures such as fatigue and rutting for flexible, and faulting for rigid pavements. Also, increased demands due to economic growth have led to changes in the designs of heavy vehicles and in their weights. Therefore, there is a need to examine damage caused by newer axle and truck configurations using laboratory as well as field data from in-service pavements.

Graus et al (1990) and Mathews et al (1993) have adopted different tests in an attempt to predict the fatigue life of asphalt concrete mixes. Tests such as the flexural beam test (center and third point loadings), the two point trapezoidal beam test, the rotational cantilever test, the direct axial load test, the triaxial test, the wheel tracking test, and the indirect tensile test have been used to assess the fatigue resistance of asphalt mixtures and different failure criteria were developed for each test. These tests can be divided into two major categories depending on the loading mode: stress-controlled and strain-controlled. Strain controlled tests are used to represent thin pavements, while stress-controlled tests represent material behavior in thick pavements. For the same mix type, stress-controlled tests result in a shorter life than strain-controlled tests. Most fatigue tests on asphalt-based mixes have been conducted under single pulse loads or continuous sinusoidal wave pulse. However, the pavement response to different axle configurations, load durations and spacing is different.

Hajek and Agarwal (1990) highlighted the factors to be considered in calculating the load equivalency factors for various axle configurations and developed those factors using the strain criteria. It was concluded that pavement response parameters such as deflections and strains have considerable influence on LEFs. Moreover, axle weight and their spacing also attribute to the pavement damage significantly. Chatti and Lee (2003) studied the effects of various trucks and axle configurations on flexible pavement fatigue using different summation methods (based on strain and dissipated energy) to calculate the damage. Gillespie and Karamihas (1994) analyzed the effect of various axle and truck configurations on pavement damage using different performance measures (fatigue, rutting and roughness). All these studies were based on analytical (static and dynamic) analyses. It is essential to confirm analytical findings from laboratory as well as from actual field data (traffic and pavement performance). Ilves and Majidzadeh (1991) Saraf, Ilves et al. (1995) studied the effect of heavy trucks on pavement damage by using in-service traffic and performance data from a limited number of roads linking the states of Ohio and Michigan. It was found that cracking and faulting, for rigid pavements, and rutting, for flexible pavements, were the most critical distress measurements affected by heavy trucks.

In this study, fatigue damage caused by multiple axle loads and trucks with large axle groups was determined in the laboratory using the Indirect Tensile Cyclic Load Test (ITCLT) with different (multiple) pulse loads. Actual field data form the Long Term Pavement Performance Program (LTTP) General Pavement Study (GPS-1), in the form of traffic and various performance measures, were also analyzed to study the relative effects of various axle and truck configurations on alligator cracking and rutting.

2. LABORATORY FATIGUE TESTING

The asphalt mix used in this study was a 4E3 Superpave mixture with a top aggregate size of ½ inch and target asphalt content of 5.9%. The mix was obtained from an actual batch that was produced in a mixing plant and used by the Michigan DOT on a project in the summer of 2002. The volumetric properties of the mix are shown in Table 1.

Table 1. Volumetric properties of the asphalt mix

Property	G_{mm}	G_{mb}	G_{se}	G_{sb}	VMA	VFA	G_b
Value	2.487	2.388	2.731	2.661	15.6%	74.4%	1.026

A total of 57 samples (4 inches in diameter) were compacted in the laboratory using the gyratory compactor. The average air void content was 3.9% and the standard deviation was 0.2%. Specimens with high or low air voids were not tested. All testing was done at room temperature, with the average temperature recorded being about 70^o F. Three samples were tested under the indirect tensile test to determine the indirect tensile strength and the stored energy density until cracking. The average tensile strength was 171 psi with the lowest and highest values being 168 and 174 psi, respectively. The average stored energy density until failure was 1.556 psi with the lowest and highest values being 1.547 and 1.568 psi. Two samples were tested under the Indirect Tensile

Cyclic Load Test to determine the resilient modulus of the mix. The average resilient modulus was 252,575 psi and the standard deviation was 18,706 psi.

Thirty-one samples were tested for fatigue at room temperature. Specimens were tested under different load pulses representing different axle configurations. Five axle configurations were used: Single, tandem, tridem, 4-axles and 8 axles, with each individual axle carrying a nominal load of 13 kips, and the spacing between the axles being 3.5 feet. Table 2 shows the fatigue-testing matrix. In addition, two specimens were tested under continuous pulse loading (i.e., with no rest period) and two others were tested under a full truck with an eleven-axle configuration (one single axle, two tandem axles and two tridem axles).

Table 2. Fatigue Testing Matrix

Stress Level	Axle no. / Interaction	1	2	3	4	8
Low	Low (25%)	x x		x x		x x
	Medium (50%)					
	High (75%)					
Medium	Low (25%)	x x x		x x x	x x x	x x x
	Medium (50%)		x x x			
	High (75%)					x x
High	Low (25%)	x x	x x	x x		x x
	Medium (50%)					
	High (75%)					

No. of 'x's represents the number of samples tested.

Three tensile stress levels were used: 4.375, 8.75 and 17.5 psi. The shape of the load pulse was obtained by matching the tensile strain time histories at the bottom of the AC layer as predicted by the SAPSI-M computer program [Chatti and Yun.,1996]. Figure 1 shows a comparison between the response at the bottom of the AC layer from SAPSI-M and the response at the center of the specimen under the load pulse obtained from the procedure mentioned above. A constant ratio of 1 to 4 was used for loading and rest periods. For single axles, the loading/unloading duration was found to be 0.1 second using the response calculated from SAPSI-M due to a moving load at 40 mph; therefore a rest period of 0.4 seconds was used. For multiple axle configurations and trucks, the loading time was taken as the time from the beginning of response due to the first axle until the time when the response of the axle dies, as calculated by SAPSI-M. Three interaction levels were used for multiple axle groups: High, medium and low. The interaction level is defined as the peak to valley stress ratio, and represents different AC layer thicknesses (the thicker the AC, the higher the interaction level).

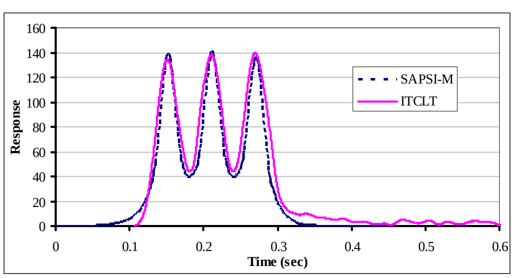


Figure 1. Typical Response Pulses from SAPMSI-M and ITCLT Test Results

Figure 2 shows the dissipated energy based fatigue curve. It can be seen that this curve is unique representing different axle configurations with different interaction levels. Thus, using this fatigue curve would allow for determining the number of repetitions until failure for any axle configuration in one step without the need to build up an axle group from its components. The fatigue model obtained is:

$$N_f = 2.12 \ \ Wo^{-0.955} \qquad (2)$$

where *Wo* is the initial dissipated energy density (in psi) of an axle group.

Two samples were tested under a continuous (i.e., without rest period) haversine load at medium stress level. Another two samples were tested under a load pulse simulating a whole truck. The whole truck was treated as one load cycle, and the dissipated energy density was calculated for the passage of the whole truck. The rest period was determined based on the same ratio used for the axle groups (1 loading to 4 rest period). The loading duration was taken from the point when the influence of the steering axle starts until the response due to the final axle dies. The results from continuous single pulse loading and truck loading were superimposed on the same graph with the dissipated energy fatigue curve and are shown in Figure 3. The points lie on top of the master dissipated energy fatigue curve, thus confirming the uniqueness of the dissipated energy fatigue curve. Therefore, no further fatigue testing was performed for other trucks or axle groups since the dissipated energy fatigue curve was found to be unique regardless of the load pulse.

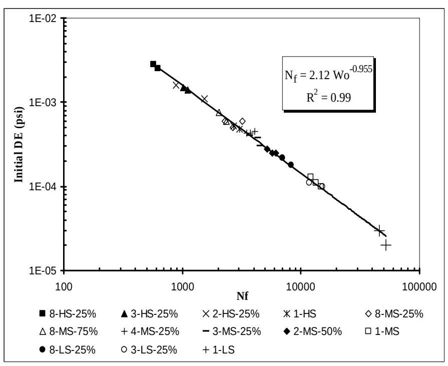


Figure 2 Fatigue Curve based on Dissipated Energy Density

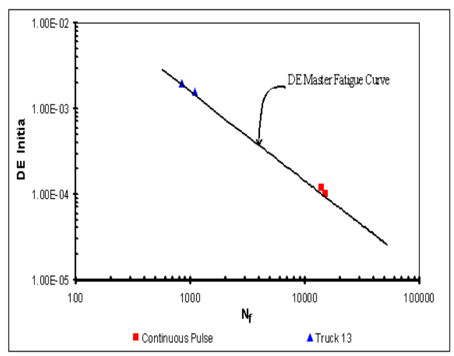


Figure 3 Fatigue Response from Continuous Load Pulse and Truck No. 13

3. FIELD DATA EXTRACTION AND AVAILABILITY

Data from General Pavement Study (GPS-1) in the Long Term Pavement Performance Program (LTTP) were used to investigate the relationship between truck repetitions and the deterioration rate of alligator cracking and rutting. Tables 3 and 4summarie the descriptive statistics from available sections for each climatic zone and pavement thickness for alligator cracking and rutting, respectively.

Weigh-in-Motion (WIM) data provided in the LTPP database contains both axle spectra and repetitions of different truck types according to the Federal Highway Administration (FHWA) classification. Hence, two forms of traffic data were used: 1) Cumulative truck repetitions, and 2) cumulative axle repetitions. The FHWA classifies traffic into thirteen classes, with Classes 5 through 13 representing the truck traffic. The data are reported in the form of the Average Annual Truck Traffic (AATT) count per class type in the LTPP Database. Table 5 shows the class definition, axle groups (number of axles within an axle group), and truck configurations for classes 5 through 13. The AATT for the latest year were extracted from Datapave 3.0 for each truck type. The cumulative truck traffic was calculated based on the age of each section. Constant truck traffic per year was assumed throughout the age of the pavement (i.e. no growth factor was taken into consideration) to simplify the analysis. Hence, the cumulative truck traffic represents the total truck count, which has passed over each section until the time of the latest distress measurement.

Table 3. Descriptive statistics for alligator cracking data

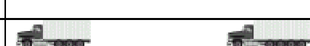
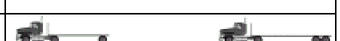
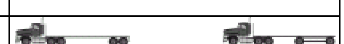
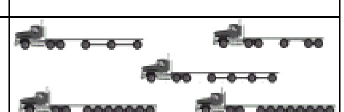
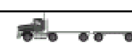
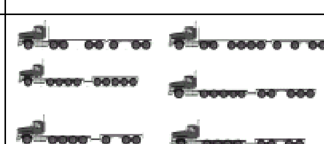
Climatic Zone	Pavement Thickness	Number of sections	Alligator cracking, m^2				Age			
			Min.	Max.	Avg.	Std.	Min.	Max.	Avg.	Std.
DF	<6	5	25.0	247.7	103.5	121.9	13.6	25.1	19.8	5.7
DF	>6	8	2.1	269.7	56.2	90.3	10.0	27.7	18.1	6.0
DNF	<6	5	23.3	309.0	147.0	126.0	15.5	27.8	22.0	5.1
DNF	>6	3	1.1	132.3	46.7	74.2	9.2	17.4	14.0	4.3
WF	<6	14	3.2	337.0	67.3	97.8	3.2	23.7	14.2	5.6
WF	>6	18	1.6	314.9	90.3	102.4	8.5	27.3	17.9	5.5
WNF	<6	35	1.3	468.9	111.5	125.9	6.4	30.0	16.7	5.7
WNF	>6	12	0.2	152.0	47.1	57.3	9.7	26.8	16.0	5.6

Table 4. Descriptive statistics for rutting data

Climatic Zone	Pavement Thickness	Number of Sections	Rutting, mm				Age			
			Min.	Max.	Avg.	Std.	Min.	Max.	Avg.	Std.
DF	<6	12	7.0	33.0	13.6	6.7	4.9	25.7	16.0	6.8
DF	>6	9	4.0	24.0	13.4	6.7	10.0	27.7	17.9	5.4
DNF	<6	11	5.0	18.0	10.4	3.6	5.6	28.3	16.9	8.8
DNF	>6	7	6.0	25.0	15.1	6.8	9.2	21.6	14.0	4.4
WF	<6	23	6.0	33.0	16.4	7.9	4.1	28.5	14.6	6.0
WF	>6	33	3.0	28.0	12.7	6.2	6.1	29.6	16.4	6.2
WNF	<6	55	4.0	35.0	16.0	7.9	4.0	35.0	16.0	7.9
WNF	>6	23	3.0	30.0	12.3	6.9	0.5	26.8	14.0	7.0

The average daily counts for single, tandem, and tridem axles were extracted from the axle load spectrum data. Quad or higher axle groups were not available in the LTPP data.

Table 5. Vehicle class definition, axle groups, and truck configurations

FHWA Class Type	Class Definition	Axle Groups	Truck configuration
5	Two-axle, six-tire, single-unit trucks	1	
6	Three-axle single-unit trucks	1 and 2	
7	**Four or more axle single-unit trucks***	**1, 3 and 4**	
8	Four or fewer axle single-trailer trucks	1and 2	
9	Five-axle single-trailer trucks	1and 2	
10	**Six or more axle single-trailer trucks***	**1, 2, 7 and 8**	
11	Five or fewer axle multi-trailer trucks	1	
12	Six-axle multi-trailer trucks	1 and 2	
13	**Seven or more axle multi-trailer trucks***	**1, 2, 3, 4, and 5**	

*****Classes 7, 10, and 13 have three or more axle groups (multi-axle groups)

4. ANALYSIS

4.1 Fatigue cracking

4.1.1 Laboratory Data

In the laboratory, three different interaction levels were used to simulate different asphalt concrete thicknesses in the field. The interaction level is defined as the ratio of the peak stress to that of the valley (also known as midway) and is shown in Figure 4. The higher interaction level represents a thicker asphalt concrete layer (around 10 inches) while the lower interaction level represents a thinner pavement (around 6 inches). Figures 5 (a) and 5 (b) show the damage and normalized damage relative to the load carried for different axle configurations and for three interaction levels. The results indicate that while fatigue damage increases with increasing number of axles within an axle group, the normalized damage (i.e., relative to the load a given axle carries) decreases with increasing number of axles for multiple axle groups, making these larger axle groups less damaging when considering their economic impact. The figures also indicate that there is no significant effect of the interaction level; hence the laboratory results can be compared with the field results regardless of the pavement thickness. Figures 5 (c) and 5 (d) show the damage and normalized damage per load carried for different FHWA classes. The figures confirm that truck classes that carry heavier axle loads cause more fatigue damage; however, when normalizing the damage by the load carried, they are shown to be less damaging. Note that classes 10 and 13, which include trucks with larger (multiple) axle groups, are the least damaging per load carried. Finally, Truck classes that have single and tandem axles (classes 5, 6, 8, 9, 11, and 12 as shown in table 5) were lumped together as S&T category and those with multiple axles (classes 7, 10 and 13 as shown in table 5) were lumped together as M category. Figure 5 (e) and 5 (f) show the damage and normalized damage per load carried for both categories. The figures clearly shows that while trucks with large multiple axles cause more fatigue damage per passage, they are less damaging when considering the load they carry. In summary, normalizing the damage caused by different axle and truck configurations by the load carried allows for a better understanding of the relative damage caused by different axle configurations and truck categories. The relative damage of axle and truck configurations will facilitate not only determining the most efficient axle configurations and truck categories but will also allow for rational truck regulation based on the actual damage per load carried.

4.1.2 Field Performance Data

For the analysis of performance data from in-service pavements, a simple linear regression was used to compute the slope. The value of the slope depends on the unit of measurement (number of repetitions). This slope represents the change in the distress (dependent variable) due to a unit increase in the axle or truck repetitions (independent variables). An axle/truck type with small effect on pavement performance will have a small slope value, while those axle/truck types with a larger effect will have a large 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. Standardized slope values are computed by converting all variables (dependent and independent) into Z-scores. Having the variables in Z-score will switch 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.

Figure 6 show the standardized slope and normalized slope for different axle/truck configurations in different climatic zones and for different asphalt thicknesses. The results show that only the data from wet freeze zone can be used (positive slopes). This data shows that all axles produce similar standardized slope values [figure 6 (a)]. However, normalizing the standardized slope to the weight carried shows that the single axle tends to be more damaging than tandem and tridem axles [figure 6 (b)]. In the truck categories, there is no clear trend except for WF<6" where the damage from S&T trucks is slightly less than M trucks and slightly higher when it is normalized per kips. Overall, the results from filed data are inconclusive. Comparing Figure 6 to Figure 5, it can be clearly seen that the laboratory results are much more conclusive, with the same consistent trend shown by axle type, FHWA truck class, and truck categories.

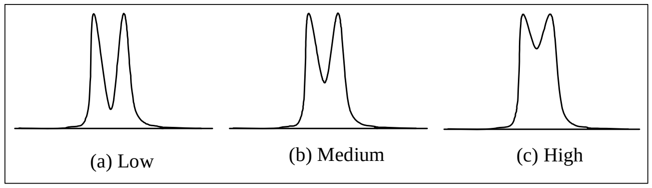
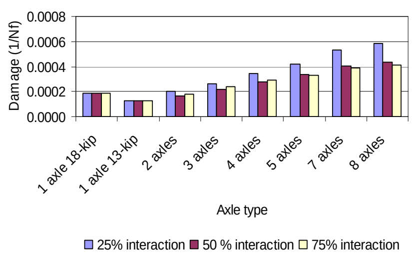
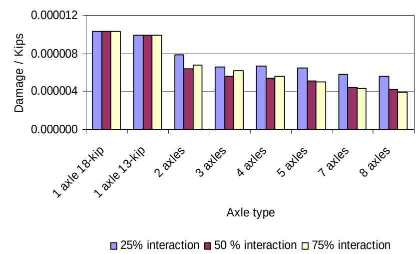


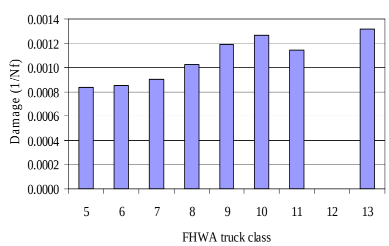
Figure 4 Different Interaction Levels



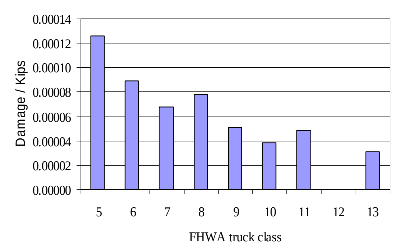
(a) Damage vs. axle configurations



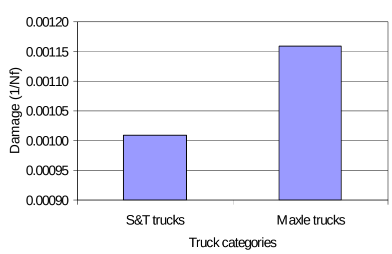
(b) Normalized damage vs. axle configurations



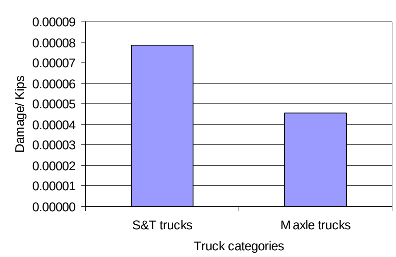
(c) Damage vs. FHWA truck classes



(d) Normalized damage vs. FHWA truck classes

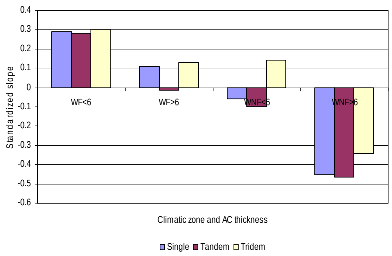


(e) Damage vs. truck categories

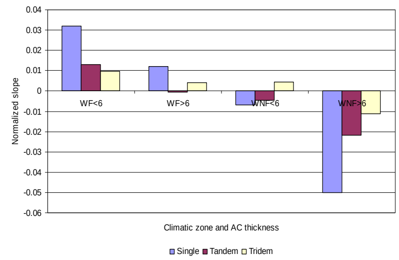


(f) Normalized damage vs. truck categories

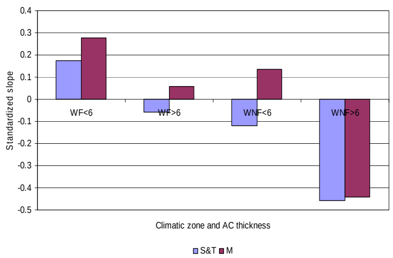
Figure 5 Fatigue damage for different axle/truck configurations-laboratory



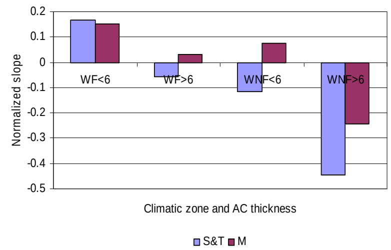
(a) Standardized slope vs. axle configurations



(b) Normalized slope vs. axle configurations



(c) Standardized slope vs. truck configurations



(d) Normalized slope vs. truck configurations

Figure 6 Effect of axle and truck configurations on cracking of flexible pavements-field

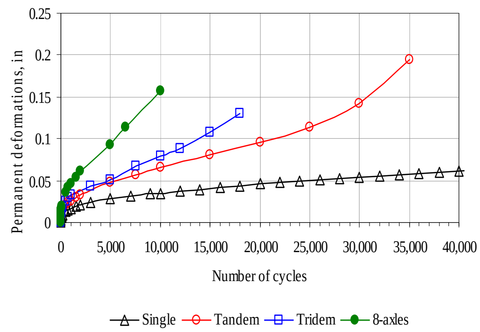
4.2 RUTTING

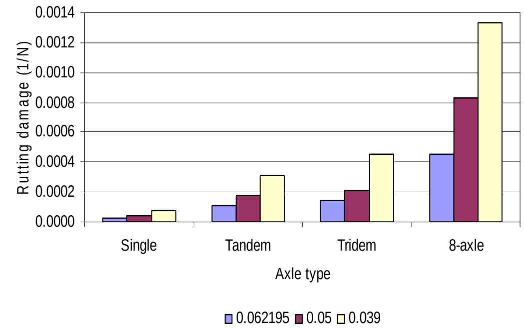
4.2.1 Laboratory Data

Figure 7 (a) shows the cumulative vertical deformation versus number of cycles for different axle configurations in the laboratory for asphalt concrete samples. It can be observed that the number of load repetitions to reach a given permanent deformation decreases with increasing number of axles per axle group. Figure 7 (b) shows the cumulative vertical deformation (rutting) for various axle configurations at different permanent deformations (0.062in, 0.05in, and 0.039in). The figure clearly shows that rut damage increases with increasing number of axles within an axle group. Figures 7 (c), (d) and (e) show the vertical cumulative deformation normalized to the axle load for low, medium and high stress levels. The normalized results do not show any consistent trend, and are therefore inconclusive.

4.2.2 Field Performance Data

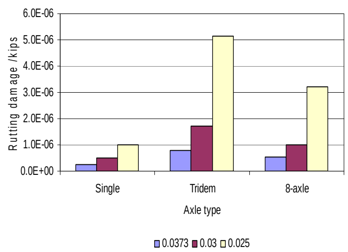
Figure 8 shows the effect of axle/truck configurations on flexible pavement rutting for different climatic zones and AC thicknesses in the field. The effect is shown as the standardized slope of rutting versus axle/truck repetitions (a, c), and as normalized slope with respect to the load carried by the axle/truck (b, d). The results do not show any consistent trend, and therefore are inconclusive. Comparing Figures 7and 8 indicate a weak agreement between the field and laboratory rutting damage for the different axle/truck configurations.

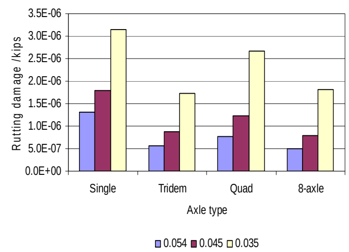


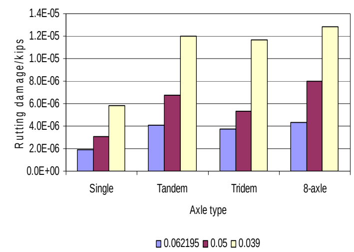


(a) Cumulative vertical deformation vs. number of cycles for different axle configurations-High stress level

(b) Cumulative vertical deformation vs. different axle configurations at rut depth- High stress level





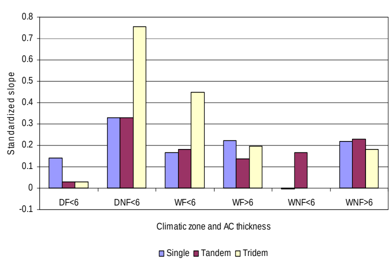


(c) Rutting per kips vs. axle type- Low stress level

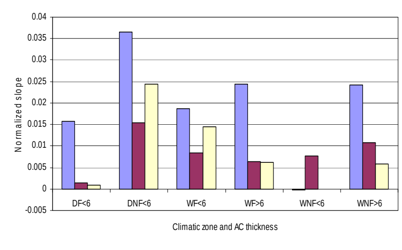
(d) Rutting per kips vs. axle type- Medium stress level

(e) Rutting per kips vs. axle type- High stress level

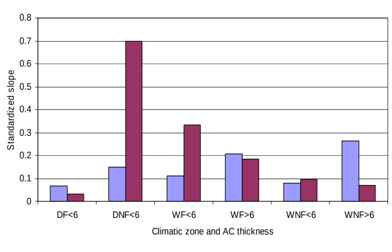
Figure 7 Effect of axle configurations on rutting of flexible pavements- Laboratory



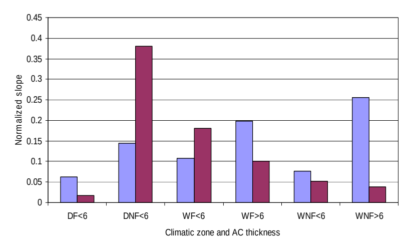
a) Standardized slope vs. axle configurations



b) Normalized slope vs. axle configurations



c) Standardized slope vs. truck configurations



d) Normalized slope vs. truck configurations

Figure 8 Effect of axle and truck configurations on rutting of flexible pavements-field

CONCLUSION

The following conclusions can be drawn from the laboratory test results:

- The dissipated energy method is very useful in determining the fatigue damage caused by multiple axle groups because it directly accounts for the interaction between axles without the need for simplifying assumptions.
- Fatigue damage caused by multiple axles, when normalized by the load they carry, decreases with increasing number of axles per axle group. Therefore, multiple axles are more economically efficient from the point of view of damage caused by the amount of goods transported.
- Rutting damage caused by multiple axles increases with increasing number of axles per axle group. When normalized to the load each axle carry, the results were inconclusive.

There were no conclusive results on the effect of axle/truck configuration on fatigue and rut damage when using performance data from in-service pavements.

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