FATIGUE LIFE PREDICTIONS FOR ASPHALT CONCRETE SUBJECTED TO MULTIPLE AXLE LOADINGS

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ABSTRACT

The Load Equivalency Factor (LEF) and the Truck Factor (TF) are defined as the relative damage of an axle group or a truck to that of a standard axle. In the mechanistic approach, the fatigue damage caused by a given axle configuration is calculated using fatigue equations derived from single haversine or continuous sinusoidal loading pulses. In this paper, the fatigue damage of an asphalt mixture under different axle groups and truck configurations was determined directly from the indirect tensile cyclic load test by using load pulses that are equivalent to the transverse response due to the passage of an entire axle group or truck. In addition, the fatigue damage was obtained for different pavement structures using the SAPSI-M computer program and compared with laboratory results. The pavement fatigue damage and the LEFs/TFs were calculated using three different methods: peak strains, peak-midway strains, and dissipated energy. The results reveal that, in general, the LEFs/TFs based on the peak-midway strain method agree reasonably well with those from the dissipated energy method. On the other hand, the peak strain method overestimates the transverse LEF values.

INTRODUCTION

Load Equivalency Factor (LEF) is defined as the damage of the pavement caused by a given axle relative to the standard 80 kN (18 kip) axle, and has played an important role in mechanistic pavement design. According to Miner's hypothesis, damage is the inverse of the number of load repetitions until failure:

$$Damage = {}^{1}\!/_{N_f}$$

where N_f is the number of load repetitions until failure. In pavement engineering literature, many researchers have tested asphalt concrete mixtures under fatigue and came up with equations that may be used to estimate the N_f corresponding to a given strain or dissipated energy level (e.g., Monismith et al, 1994). These equations have the form:

$$N_f = \alpha_1 \cdot \varepsilon_o^{\beta_1}$$

$$N_f = \alpha_2 \cdot w_o^{\beta_2}$$

where $\varepsilon_o \equiv$ strain

$w_o \equiv$ dissipated energy density

α_i, $\beta_i \equiv$ constants

The equations are typically based on single pulse loading or continuous sinusoidal loading. However, when a vehicle travels over the pavement, a given point in the pavement is subjected to multiple pulses depending on the axle configuration. In addition, a point at the bottom of the asphalt concrete layer undergoes two directional horizontal responses; transverse and longitudinal. Thus the fatigue equations could be developed based on transverse or longitudinal responses (tension or compression-tension). Using a fatigue equation that is developed from transverse responses to estimate the fatigue damage in the longitudinal direction may be inadequate. Furthermore, cracking may initiate at the top of the asphalt concrete, as reported in several studies (Myers et al., 1998). In this analysis, only bottom-up fatigue is considered.

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The objectives of this paper are to: (1) investigate the fatigue damage caused by multiple axle groups and different truck configurations, and (2) compare different methods of predicting fatigue damage. Because of testing limitations, fatigue equations for longitudinal response (compression-tension loading) could not be developed. Therefore the results presented in this paper are limited to transverse response.

METHODS USED

Strain methods

The strain methods use the horizontal strains at the bottom of the AC layer to calculate the fatigue life of the pavement system, using laboratory derived fatigue equations. For multiple axles, the damage is calculated from several critical strains individually and then summed. The difference between the two strain methods lies in the strain values that are input into the fatigue equations. In this paper, only the peak and peak-midway strain methods are considered.

Figure 1 shows typical longitudinal strain time histories under single and tandem axles. The peak method takes only the peak tension part of the strains (designated as ε_p in the figure) to calculate the fatigue life of the pavement system.

The peak-midway strain method accounts for both the peak tensile strain and the peak compressive strain of the longitudinal strain time histories. The difference of the peak tensile and compressive strains (designated as ε_{pm} in Figure 1) is input in empirical fatigue equations to calculate the fatigue life and the damage of the pavement. It should be noted that there is no fatigue testing done with this type of loading pulse.

Figure 2 shows typical transverse strain time histories under single and tandem axles. The peak method is theoretically identical to the peak-midway strain method for the transverse strain under a single axle. However, for transverse strains under multiple axles, this method neglects the interaction between the adjacent axles and treats them as two separate single axles. In other words, it considers the two peak strain values (ε_1 and ε_{p1} in Figure 2 (b)) separately such that it does not differentiate between the tandem axle and two separate single axles.

The peak-midway method, on the other hand, takes the peak tensile strain due to the first axle (shown as ε_1 in Figure 2 (b)) and the difference of the second peak and the valley in between (shown as ε_{pm1} in Figure 2 (b)). Thus, this method considers the interaction between the two axles of the tandem axle.

For the transverse strain time history under a single axle (figure 2 (a)) which only has tension, the peak strain value is input into the fatigue equation to calculate the N_f. For the longitudinal strain under a single (figure 1 (a)) which includes tension and compression, there are two possible inputs into the fatigue equation: Inputting either ε_p or ε_{pm} would result in two different LEF values.

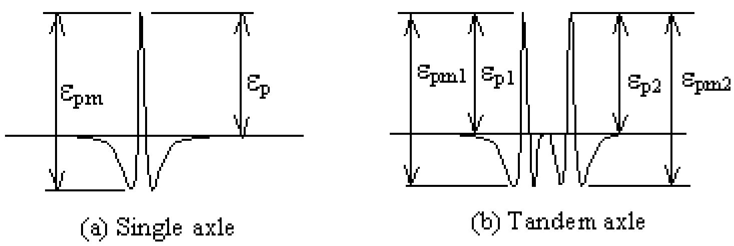


Figure 1. Typical longitudinal strain time histories.

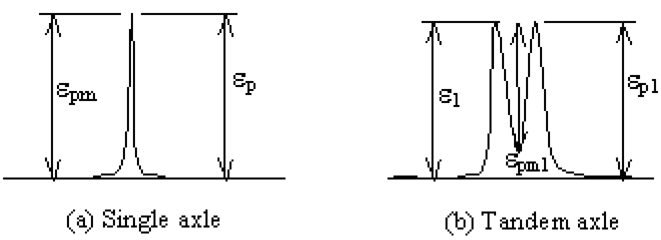


Figure 2. Typical transverse strain time histories.

A better way to do this would be to use a loading pulse similar to what is observed (separately from for transverse and longitudinal directions) to develop the fatigue curves, and then use the corresponding strain values to calculate N_f. In practice, this has not been done. Instead, the transverse or longitudinal strains are frequently input into the fatigue equations that are based on pulse or sinusoidal loading without taking into account the above considerations.

There are several other strain methods of calculating the fatigue life such as the rainflow method. It takes the ranges of the strain values in a time history as input into the fatigue equations and sums up the damage. This method is commonly used for the fatigue of metal under complex response time histories (Gillespie et al, 1993).

Dissipated energy method

Dissipated energy is defined as the area within a stress-strain hysteresis loop. It represents the energy lost in the pavement due to the passage of an axle group. Figures 3 and 4 show the longitudinal and transverse stress-strain loops for single and tridem axles, respectively.

The advantage of this concept is that the dissipated energy can be calculated as a single scalar value and put into the fatigue equations to calculate the damage directly. This procedure eliminates the summation of damage due to several critical strain values that is necessary for the strain methods including the rainflow method. Furthermore, the dissipated energy value captures the totality of the stress-strain response during the passage of the load(s) while the strain values correspond to only one point in time. The method also differentiates between multi axles and several independent single axles naturally.

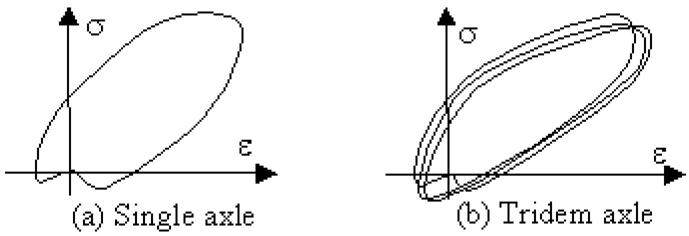


Figure 3. Longitudinal stress-strain hysteresis loop.

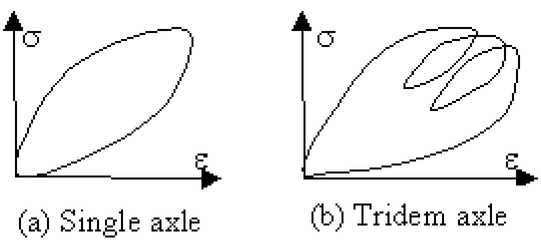


Figure 4. Transverse stress-strain hysteresis loop.

However, similar to the discussion above on strains, if the dissipated energies due to a passage of an axle (single or multiple) in the longitudinal and transverse direction are input into the same fatigue equation they will result in different LEF values, even though both loops correspond to a given axle configuration.

FATIGUE EQUATIONS

Fatigue tests using the Indirect Tensile Cyclic Load Test (ITCLT) have been performed at Michigan State University (El Mohtar, 2003). The details of the laboratory testing are described elsewhere (El Mohtar, 2003, Chatti et al 2004). Thirty-one specimens compacted using the gyratory compactor were tested for fatigue at room temperature. Specimens were tested under different load pulses representing different axle configurations: 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. 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).

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 history at the bottom of the AC layer as predicted by the SAPSI-M computer program [Chatti and Yun,1996] to that at the center of the specimen (calculated using theory). 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 (75%), medium (50%) and low (25%). The interaction level is defined as the peak to valley stress ratio, as shown in Figure 5, and represents different AC layer thicknesses (the thicker the AC, the higher the interaction level).

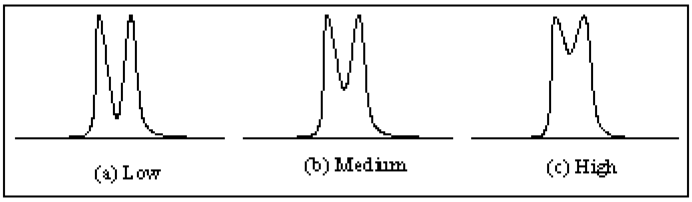
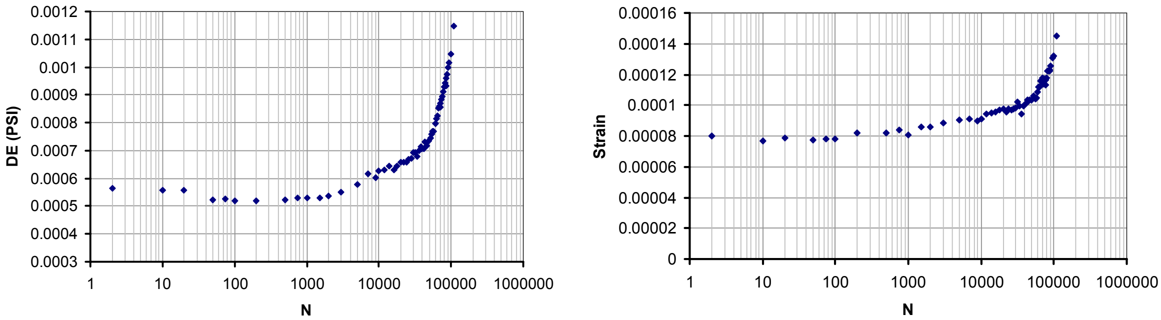


Figure 5. Schematic illustration of different interaction levels.



(a) Dissipated energy versus N (b) Strain versus N

Figure 6. Typical fatigue test results.

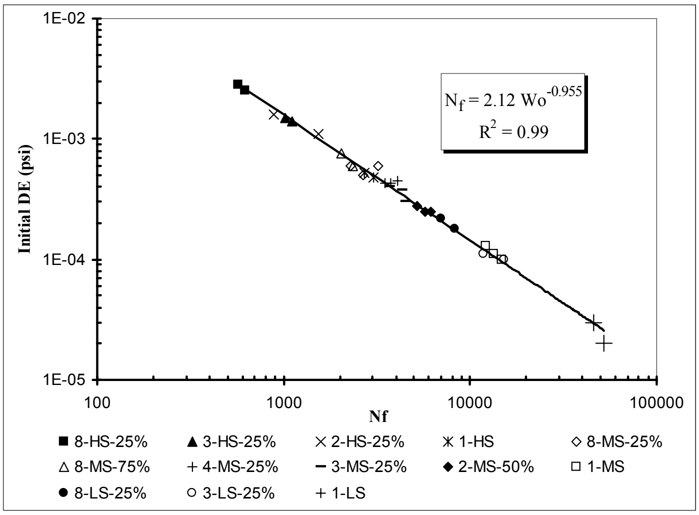


Figure 7. Laboratory results – N_f vs. initial dissipated energy.

During cyclic fatigue testing, the dissipated energy density per cycle initially remains constant, expressing the viscous component of the asphalt mix response. The point at which the dissipated energy density per cycle starts increasing can be interpreted as the initiation of failure, and the corresponding cycle number would be the number of load repetitions to crack initiation [Chatti and El Mohtar, 2004]. Figure 6 shows typical test results of a specimen tested under constant stress mode. Figure 7 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:

$$N_f = 2.12 \times w_0^{-0.955}$$

where N_f is the fatigue life and w_0 is the initial dissipated energy density (in psi). The fact that the fatigue curve based on dissipated energy could be applied irrespective of axle configuration, loading mode and interaction level provide a great advantage to the dissipated energy approach relative to the strain based approach. For multiple axles, the two different strain methods will give different N_f values whereas the dissipated energy method will give one unique N_f value. Thus, comparing the strain methods with the dissipated energy method will allow for determining which strain method works better for estimating the LEF values of multiple axles.

A strain-based fatigue equation was also developed using the same data based on single pulse loading and transverse strain:

$$N_f = 5.97 \times 10^{-7} \times \varepsilon_0^{-2.342}$$

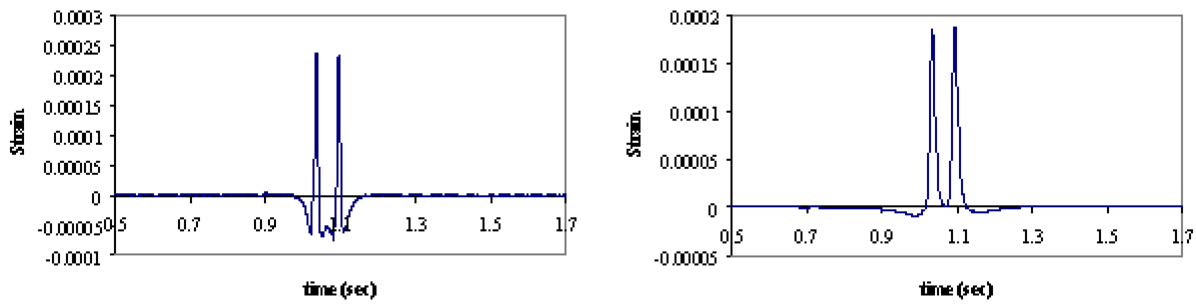
where N_f is the fatigue life and ε_0 is the initial strain.

Fatigue equations based on longitudinal strains or compression-tension loading could not be developed due to the limitations of the testing apparatus.

ANALYSIS

Generating theoretical stress-strain time histories

The stress and strain time histories at the bottom of the asphalt layer were generated using the SAPSI-M computer program (Chatti and Yun, 1996). It is a linear dynamic finite layer program that uses the frequency-based complex response method and the fast Fourier transform algorithm. The model allows for frequency-dependent material properties and models damping using complex moduli. Figure 8 shows typical longitudinal and transverse strain time histories under a tandem axle.



(a) Longitudinal

(b) Transverse

Figure 8. Longitudinal and transverse strain time histories generated by SAPSI-M.

The pavement profiles and the axle configurations used in this paper are summarized in Tables 1 and 2, respectively. All axles presented here are composed of dual tires except for the front steering axle. Table 3 shows the trucks analyzed in this study.

The tire pressure was held constant at 689 kPa (100 psi). As a result, the tire-pavement contact area was varied as the load of the axle varied. To calculate the LEFs, the fatigue life of a standard axle with dual tires and a tire pressure of 483 kPa (70 psi) was also calculated.

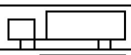
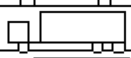
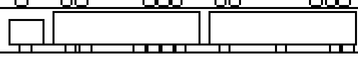
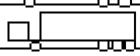
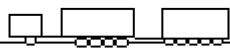
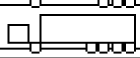
Table 1. Pavement profiles used.

Pavement Profile Type	AC Thickness, mm(in)	AC Modulus, MPa (ksi)	AC Damping Ratio
Thin, Stiff, Low Damping	90 (3.5)	4830 (700)	0.05
Thin, Stiff, High Damping	90 (3.5)	4830 (700)	0.10
Medium, Stiff, Low Damping	203 (8)	4830 (700)	0.05
Medium, Stiff, High Damping	203 (8)	4830 (700)	0.10
Thick, Stiff, Low Damping	305 (12)	4830 (700)	0.05
Thick, Stiff, High Damping	305 (12)	4830 (700)	0.10

Table 2. Axle configurations and loads.

Axle configuration	Load per axle, kN (kips)
Standard axle	80 (18)
Front steering axle	69 (15.4)
Single axle	80 (18)
Tandem1 axle	71 (16)
Tandem2 axle	58 (13)
Tridem axle	58 (13)
Quad axle	58 (13)
5 axles	58 (13)
7 axles	58 (13)
8 axles	58 (13)

Table 3. Trucks analyzed and their gross weights.

Truck No.	Shape	Gross Weight kN (kips)	Truck No.	Shape	Gross Weight kN (kips)
1		149 (33.4)	6		674 (151.4)
2		211 (47.4)	7		718 (161.4)
3		242 (54.4)	8		589 (132.4)
4		300 (67.4)	9		616 (138.4)
5		531 (119.4)	10		674 (151.4)

Results and discussions

As discussed above, the LEF is defined as the damage due to the passage of a given axle relative to a standard axle. That is, using the dissipated energy the LEF is calculated as:

$$LEF_{axle} = \frac{Damage_{axle}}{Damage_{s\tan dard}} = \frac{1/N_{f,axle}}{1/N_{f,s\tan dard}} = \frac{N_{f,s\tan dard}}{N_{f,axle}} = \frac{\alpha_1 \cdot w_{o,s\tan dard}{}^{\beta_1}}{\alpha_1 \cdot w_{o,axle}{}^{\beta_1}} = \left(\frac{w_{o,s\tan dard}}{w_{o,axle}}\right)^{\beta_1}$$

Similarly, using the strain equation the LEF is:

$$LEF_{axle} = \frac{Damage_{axle}}{Damage_{standard}} = \frac{1/N_{f,axle}}{1/N_{f,standard}} = \frac{N_{f,standard}}{N_{f,axle}} = \frac{\alpha_2 \cdot \varepsilon_{o,standard}^{\;\beta_2}}{\alpha_2 \cdot \varepsilon_{o,axle}^{\;\beta_{21}}} = \left(\frac{\varepsilon_{o,standard}}{\varepsilon_{o,axle}}\right)^{\beta_2}$$

These LEF values will be different with regard to which dissipated energy or strain values are used; longitudinal or transverse, as mentioned above. If the longitudinal response value is input into a fatigue equation that was developed using the initial transverse response values, the resulting N_f would not be the same. In addition, the N_f value obtained from the initial strain should be the same as the one that was calculated from the corresponding dissipated energy. To compare the LEF values from SAPSI-M and from the laboratory tests, the N_f from SAPSI-M had to be corrected such that the N_f from strain and dissipated energy is the same, under a single transverse pulse. Using the responses under a single axle loading, the damping ratio of the AC layer was determined by extrapolation (see figure 9) so that the N_f values from the initial strain and the dissipated energy are the same. The corresponding damping ratio was 3.7%. This value is reasonable. In order to incorporate the interaction level for multiple axles, the thicknesses that resulted in 25%, 50%, and 75% interaction were determined by interpolation (see figure 10).

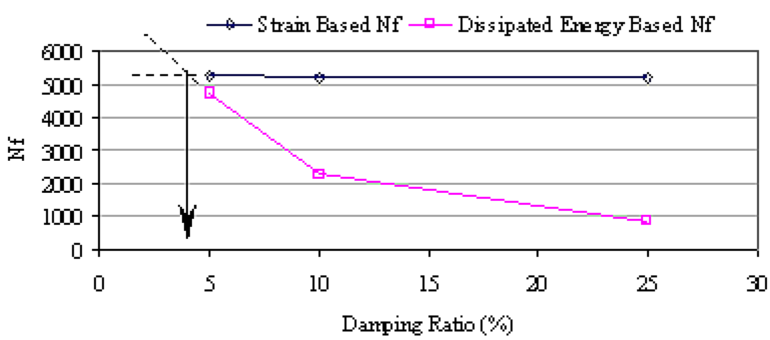


Figure 9. Extrapolation of damping ratio.

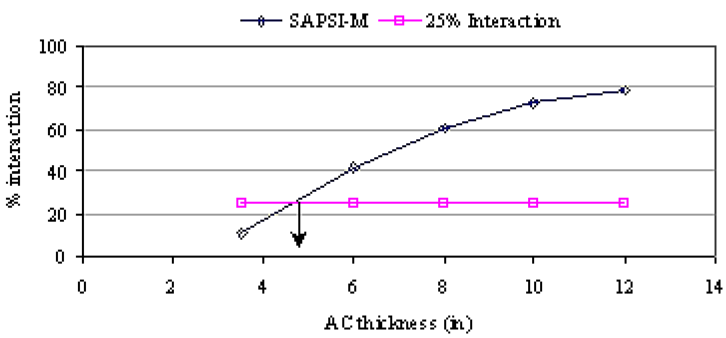
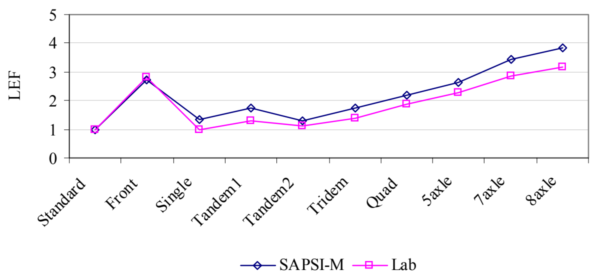
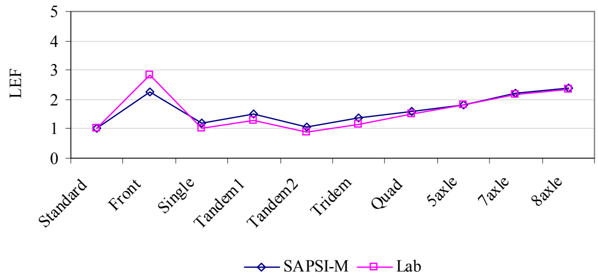


Figure 10. Interpolation of AC thickness (25% interaction).

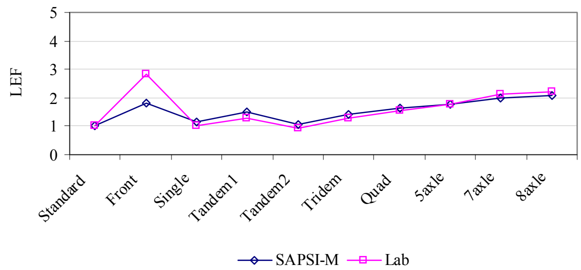
The thicknesses were 122, 193, and 264 mm (4.9, 7.7, and 10.4 in.). The calculated LEF values (using dissipated energy) for these thicknesses with 3.7% damping ratio are shown in figure 11. As can be seen from the figure, the LEF from SAPSI-M are, in general, slightly higher than those from the laboratory testing, with the ratios of 1.19, 1.07, and 1.02 for 25%, 50% and 75% interaction, respectively. The figure indicates that fatigue damage from multiple axles is significantly lower than single axles given the load they carry and higher interaction level leads to lower damage.



(a) 25% interaction



(b) 50% interaction



(c) 75% interaction

Figure 11. Comparison of LEF values from SAPSI-M and laboratory results.

Figure 12 shows the truck factors (TF) calculated for the trucks shown in table 3. The interaction level was kept constant at 25%. The TF values from SAPSI-M are higher than the laboratory results. This is expected since the LEF values from SAPSI-M are higher than the laboratory LEF values.

Note that, trucks 1 through 4 have truck factors that are close to 4.0.

For multiple axles, different methods of estimating the LEF can be used. Figures 13 and 14 show the transverse LEF values calculated from three methods (dissipated energy, peak-midway strain and peak strain methods), using laboratory data and SAPSI-M results respectively. The peak strain method estimates the LEF values fairly well for single and tandem axles. However, for multiple axle groups that have 3 or more axles, the peak method starts to significantly overestimate the LEF values. This is because the peak method does not account for the interaction between the axles. Thus, the higher the interaction level, the more the peak strain method overestimates the LEF. On the other hand, the peak-midway strain method estimates the LEF value reasonably well as compared to the peak strain method, although it underestimates the fatigue damage relative to the dissipated energy method.

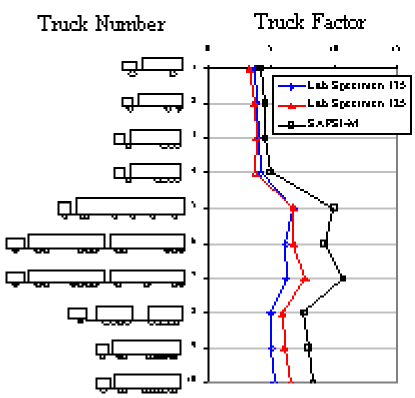
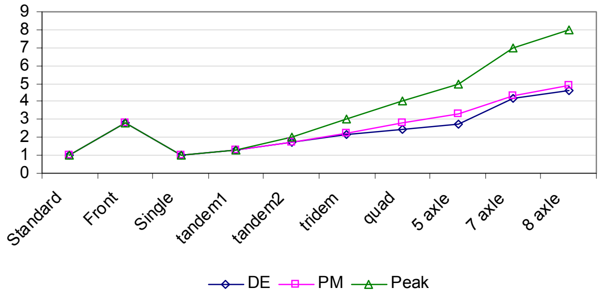
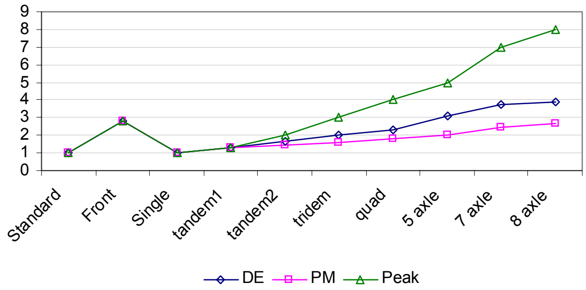


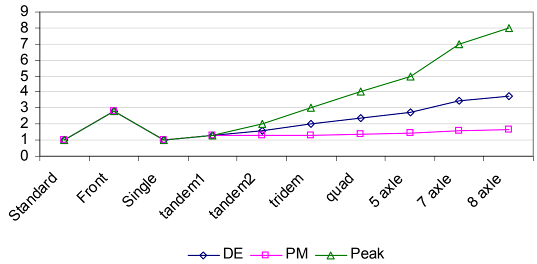
Figure 12. Truck factors.



(a) 25% interaction

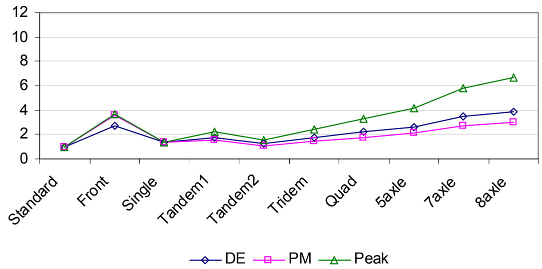


(b) 50% interaction

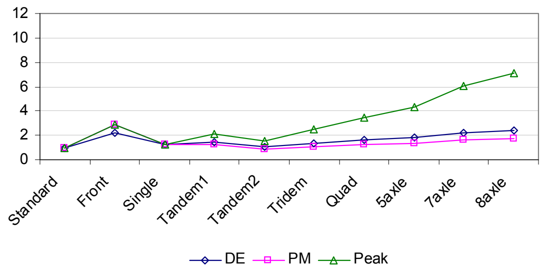


(c) 75% interaction

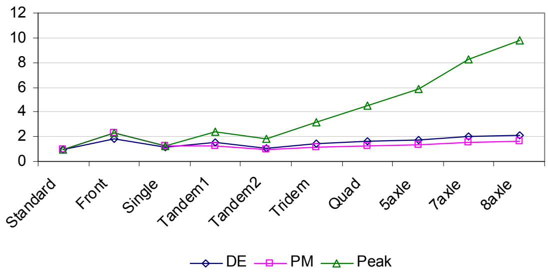
Figure 13. Comparison of transverse LEF values from different methods for 25% interaction.



(a) 25% interaction



(b) 50% interaction



(c) 75% interaction

Figure 14. Comparison of transverse LEF values from different methods (SAPSI-M).

CONCLUSION

In this paper, the transverse LEF/TF values from the laboratory test results and the SAPSI-M computer program were compared. It showed that, the SAPSI-M based LEF/TF values agreed well with those from the laboratory results. For multiple axle groups, the peak-midway strain method agrees better with the dissipated energy method than the peak strain method. On the other hand, the peak strain method overestimates the transverse LEF values. This is because the peak strain method does not account for the interaction between the axles for the transverse response.

The results presented in this paper are based on fatigue equations developed using transverse pulse loadings. Longitudinal response based fatigue equations could not be developed due to testing limitations. It is strongly recommended that similar analysis be conducted using fatigue equations developed from longitudinal pulse loadings.

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