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MECHANISTIC CALCULATION OF LOAD EQUIVALENCY AND TRUCK FACTORS FOR FATIGUE DAMAGE OF HOT MIX ASPHALT USING STRAIN AREA METHOD

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ABSTRACT

Among several pavement distress types, fatigue and rutting are the main distresses of flexible pavements. To accurately assess the amount of damage that trucks with multiple axle groups cause to these flexible pavements, a summation methodology is imperative. Several methods have been used to sum the pavement damage due to multiple axle groups, researchers have used continuous methods, as well as discrete methods. The continuous strain area method is a very good candidate for calculating the fatigue damage. Applying this method on the laboratory strain pulses proved superior to the discrete method. The characteristics of the mechanistic strain pulse differs from the laboratory strain pulse, which indicates that the mechanistic strain area method for calculating the Axle Factors (AFs) needs to be calibrated with the laboratory-derived AF values. The calibrated power was obtained by minimizing the Sum of the Square Error (SSE) between both AFs that involved iteration over trial values. This study employed two pavement cross sections, thin and thick, for analysis of the mechanistic strain area. The Load Equivalency Factors (LEFs) and Truck Factors (TFs) for multiple axle and truck configurations were calculated using the calibrated mechanistic strain area method. The results showed that combining truck axles in a large axle group reduces the fatigue damage significantly (by about 50%) compared to the same number of individual axles. Moreover, wide-base tires impose more fatigue damage to the pavements than conventional dual tires bearing the same load and tire pressure.

KEYWORDS: Fatigue Damage, KENLAYER, Axle Factors, Load Equivalency Factor, Truck Factors and Mechanistic Strain Area Method.

الحساب الميكانيكى للاحمال المعادلة ومعاملات الشاحنات الناتج عن الكلال للخلطات الاسفليه باستخدام طريقه مساحة الانفعال

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الملخص

من أنواع عيوب الرصف العديدة ، يعد الكلال والتخدد من العيوب الأساسية للأرصفة المرنة. من أجل إجراء تقييم دقيق لمقدار الضرر الذي تسببه الشاحنات ذات مجموعات محاور متعددة لهذه الأرصفة المرنة، فمن الضروري اتباع منهجية جمع الضرر الناتج للعيوب. وقد تم استخدام عدة طرق لجمع أضرار الرصف بسبب تعدد مجموعات المحاور، ومنها استخدام الباحثون لطرقًا متصلة، بالإضافة إلى طرق منفصلة. تعد طريقة مساحة الانفعال المتصلة مرشحًا جيدًا لحساب ضرر الكلال الناتج عن الأحمال المتعددة لتلك المحاور. أثبت تطبيق هذه الطريقة على نبضات الضغط المختبري تفوقه على الطرق المنفصلة. تختلف خصائص نبض السلالة الميكانيكية عن نبضة السلالة المختبرية، مما يشير إلى أن طريقة مساحة الانفعال الميكانيكية لحساب عوامل المحاور (AFs) تحتاج إلى معايرة بقيم AFs المشتقة من المختبر. تم الحصول على اس المعايرة عن طريق تقليل مجموع الخطأ المربع (SSE) بين كلا من عوامل المحاور المشتقة من المعمل والمحسوبه من مساحة الانفعال المكانيكية. استخدمت هذه الدراسة مقطعين عرضيين للرصف، رفيع وسميك، لحساب مساحة الانفعال الميكانيكي. تم حساب معاملات الاحمال المعادلة (LEFs) ومعاملات الشاحنات (TFs) لتكوينات المحاور والشاحنات المتعددة. أظهرت النتائج أن دمج محاور الشاحنات في مجموعة محاور متعددة يقلل من ضرر الكلال بشكل ملحوظ (بحوالي 50%) مقارنة بنفس العدد من المحاور الفردية. علاوة على ذلك، فإن الإطارات ذات القاعدة العريضة تسبب ضررًا أكبر للأرصفة مقارنة بالإطارات المزدوجة التقليدية التي تحمل نفس الحمولة وبنفس ضغط الإطارات .

الكلمات المفتاحية: ضرر الكلال، KENLAYER، عوامل المحاور، الاحمال المعادله، معاملات الشاحنات، طريقه مساحة الانفعال الميكانيكي

1. INTRODUCTION

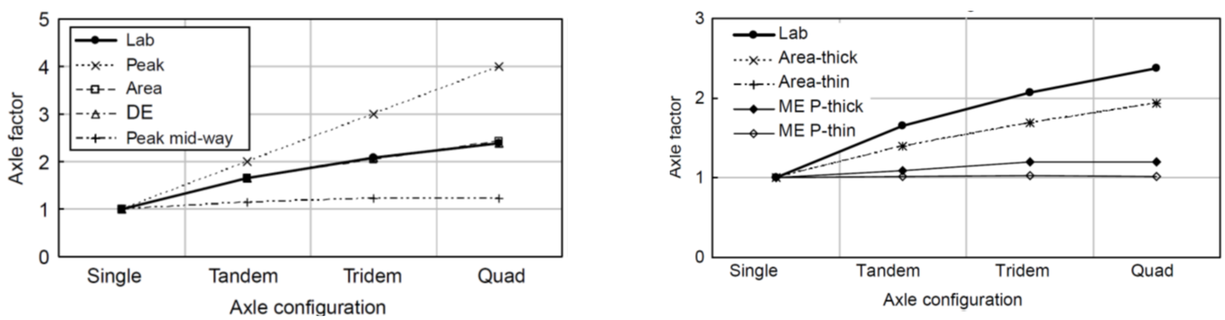
Among several pavement distress types, fatigue and rutting are the main pavement distresses of flexible pavements. The new Mechanistic-Empirical Pavement Design Guide (M-EPDG) [1] established under NCHRP Study 1-37A no longer relies on the equivalent axle load concept and predicts the pavement distresses directly using axle load spectra. Truck traffic is decomposed into axles based on their configurations and weights to calculate the resulting pavement damage for each axle, then summing the resulting damage from each axle configuration. To evaluate the pavement damage caused by heavy multiple axles trucks a large study was done for the Michigan Department of Transportation (MDOT) to investigate the effect of Michigan multi-axle trucks on pavement distress [2]. The State of Michigan has larger trucks with multiple axles (up to 11 axles), comprised of larger axle groups (up to 8 axles). The study included fatigue and rutting distresses for flexible pavement, as well as fatigue and faulting for rigid pavement. The fatigue and rutting for large axle groups were evaluated by comparing their Axle Factors (AF) to the same axle numbers as an individual axle.

Several methods have been used to sum the pavement damage due to multiple axle groups. A study was conducted to evaluate methods for predicting asphalt concrete pavement fatigue and rut damage after being subjected to multiple axle loads [3]. The study evaluated three discreet methods and four continuous methods for both fatigue and rutting damage. The discreet methods are peak, peak mid-way, and last peak for the multiple axle strain pulse. The continuous methods are integration of the strain pulse, area of the strain pulse, strain rate, and dissipated energy. When applying these methods to the laboratory strain pulses resulting from Indirect Tensile Cyclic Load Test (ITCLT) for fatigue [4], the continuous methods, strain area and dissipated energy, aligned exceptionally well with the laboratory results since they account not only for the peak strain values but also for the entire strain pulse. On the other hand, the peak and peak mid-way methods displayed a lack of agreement with the laboratory results despite their long-time use by researchers for multiple axles [5].

Figure 1.a shows the comparison of AFs using several damage summation methods with laboratory-obtained values of AF. The peak strain method overestimates the AF, with values exactly proportional to the number of axles, meaning the method does not consider the interaction of the strain pulses. This indicates that the method falsely deals with the axle groups as individual axles. Meanwhile, the peak mid-way method underestimates the AF for multiple axle groups where it adds very little damage from the consecutive axles in the axle group to the first axle peak strain. This indicates that the discrete methods do not capture the holistic characteristics of the strain pulse of multiple axles. Conversely, the continuous methods, strain area and dissipated energy, account for entire properties of the multiple axle strain pulse and their AF calculations match the laboratory-

derived AF values exactly. This concludes that fatigue damage calculations for multiple axles should be done using continuous damage methods, like strain area or dissipated energy.

When applying the continuous damage methods to the mechanistic analysis, the dissipated energy method requires using dynamic mechanistic analysis [6] to calculate the stress-strain time histories and the area within the stress-strain hysteresis loop. This type of analysis is not widely used by the practitioners and requires more advanced analysis. The strain area for stationary multiple axle loads can be easily calculated using the software program KENLAYER [5], which considers the pavement layer as a linear elastic material. Figure 1.b compares AF values from laboratory analyses to AFs from mechanistic analyses (KENLAYER), using several damage summation methods. These methods include the strain area and the Mechanistic - Imperial Pavement Design Guide (MEPDG) procedure for determining the strain under multiple axles. The calculated strain from these various methods were used to calculate the AFs for fatigue damage and compare it to the resulting laboratory AFs. The continuous strain area method yielded the closest AFs to the laboratory-derived AFs. Applying the strain area on the laboratory strain pulse matched the laboratory AFs exactly, whereas applying the strain area on the mechanistic strain pulse from KENLAYER underestimated the AFs.



(a) (b)

Fig. 1: Comparison of AFs with Laboratory-Derived AF Values and Mechanistic Analysis, where a) Laboratory calculations of AFs using several methods and b) Laboratory calculation of AFs compared to several mechanistic methods [3].

Figure 2 illustrates the strain pulse from the laboratory and the mechanistic analysis using KENLAYER for single and quad axles. The characteristics of the mechanistic strain pulse (Figure 2 a and b) differ from the laboratory strain pulse in the following:

- The laboratory strain pulses have residual strain after releasing the load due to the plastic properties of hot mix asphalt,
- The strain takes some time to reset after releasing the load due to the viscous properties of hot mix asphalt, and
- The peaks that follow the first peak are affected by the previous peaks due to the residual strains.

All of the above characteristics are absent in the mechanistic strain pulses resulting from KENLAYER, see Figure 2 c and d.

The above discussions indicate that the continuous strain area method is a very good candidate for calculating the fatigue damage due to multiple axle loads. Applying this method on the laboratory strain pulses proved superior to discrete methods. When using the strain area method for mechanistic pulses resulting from KENLAYER with the same power (0.478) [3], the resulting AFs are underestimated. This indicates that applying the strain area method on mechanistic pulses requires calibration to the laboratory strain pulse due to the natural difference between both pulses, as mentioned above.

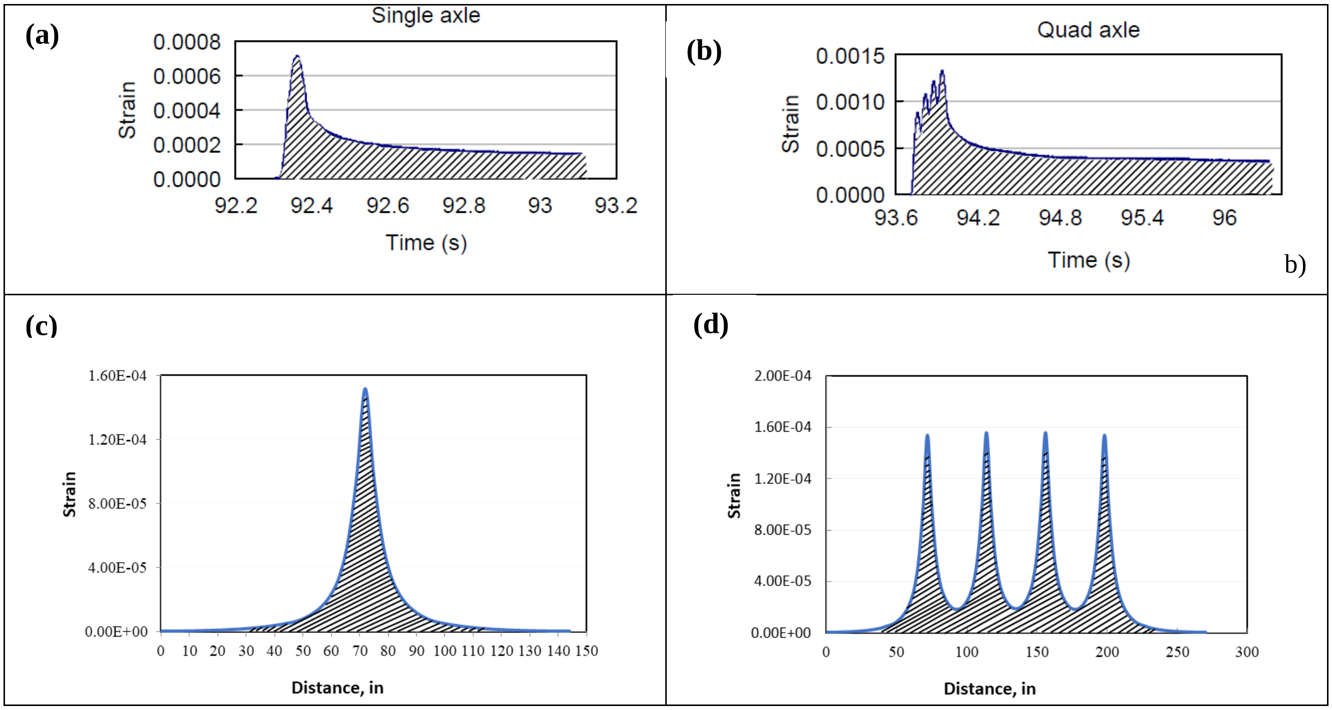


Fig. 2: Strain Area for One and Four Axles from the Laboratory and Mechanistic Analyses where a) Strain Area of Single Axle – Lab, b) Strain Area of Quad Axle – Lab, c) Strain Area of Single Axle – KENLAYER, and d) Strain Area of Quad Axle – KENLAYER. [3].

1. MECHANISTIC ANALYSIS

To calculate the AFs mechanistically, two pavement cross sections were used in this analysis, thin and thick pavement. Table 1 shows the thickness of the pavement layer and the moduli for both thin and thick pavement. The tensile strain pulse at the bottom of the asphalt layer due to single or up to eight axles were calculated using KENLAYER. The single axle load is 13 kips, and the eight-axle load is 8 times the single load (104 kips) as is the case for all other axle configurations, see Figure 3. The tire pressure used for all axles is 100 ksi.

Table 1: Pavement Cross Section and Layer Moduli

Cross-section No.	HMA		Base		Subgrade
	Thickness (in.)[a]	Modulus (psi)[b]	Thickness (in.)	Modulus (psi)	Modulus (psi)
1	8	551,236	36	55,283	23.205
2[c]	4.1	551,236	8.2	55,283	23.205

[a] 1in. = 25.4 mm.
[b] 1in. = 6.89 kPa.
[c] This section is part of the SPS-1 experiment

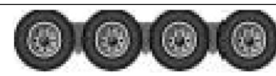
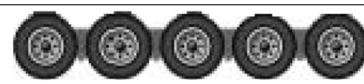
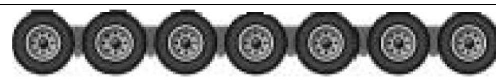
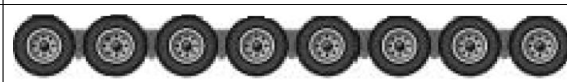
Axle	Load, Kips	Axle Configurations
Single	13	
Tandem	26	
Triden	39	
Quad	52	
Five	65	
Seven	91	
Eight	104	

Fig. 3: Axle Configurations (Single to Eight).

2. CALIBRATION OF MECHANISTIC STRAIN AREA

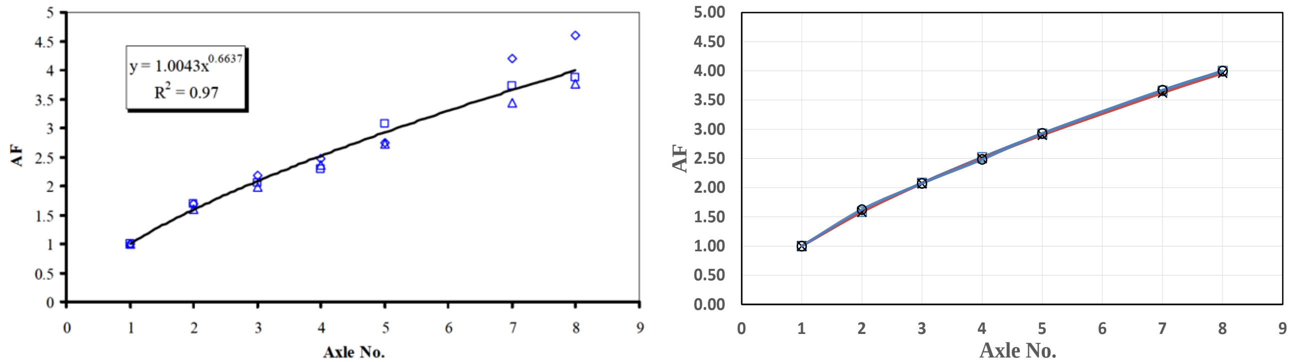
The mechanistic strain pulses for all axle configurations were utilized to calculate the strain area under each pulse by the trapezoidal rules. Similar to AF calculation in the laboratory, the mechanistic AFs for all axle configurations were calculated using the following equation:

$$AF_{Mechanistic} = \left\{\frac{\text{Strain Area of an axle configuration}}{\text{Strain Area of single axle 13kips}}\right\}^{0.478} \tag{1}$$

The power of 0.478 was borrowed from the strain area of the laboratory axle factors. The mechanistic calculated AFs for all axle configurations were compared to the laboratory-derived AF values based on the number of cyclic loads to failure as per the following equation:

$$AF_{Lab} = \frac{Damage\ of\ the\ axle\ group}{Damage\ of\ single\ axle} = \frac{\frac{1}{N_{f\ axle\ group}}}{\frac{1}{N_{f\ single\ axle}}} = \frac{N_{f\ single\ axle}}{N_{f\ axle\ group}} \tag{2}$$

Comparison between mechanistic AFs (equation 1) and laboratory AFs (equation 2) showed that the mechanistic AFs calculated with the power of 0.478, borrowed from the laboratory strain area, underestimates the AFs. This indicates that the mechanistic strain area method for calculating the AFs needs to be calibrated in accordance with the laboratory-derived AF values. The calibrated power was obtained by minimizing the Sum of the Square Error (SSE) between both AFs, using the “Solver” tool from Microsoft Excel. The calibrated power for the mechanistic strain area to calculate AFs is 0.667 with a SSE of zero, indicating that the mechanistic strain pulse can be used to calculate AFs that match the laboratory-derived AF values exactly. Figure 4.a shows the laboratory-derived AF values based on the number of cyclic loads to failure and Figure 4.b shows the calibrated mechanistic AF for thin and thick pavement, as well as the laboratory AFs. The figure shows an exact match between the mechanist AFs for thin and thick pavement and the laboratory AFs.



(a)

(b)

Fig. 4: Calibration of Mechanistic AFs to the Laboratory-Derived AFs where a) Laboratory-derived AF values [2] and b) Calibration of mechanistic AF to the Lab [3].

3. LOAD EQUIVALENCY FACTORS (LEFS)

After calibrating the mechanistic strain area method with the laboratory axle factor, obtaining an exact match and SSE of zero, the fatigue Load Equivalency Factor (LEF) can be calculated using the mechanistic strain area method with the newly calibrated power of 0.667. The tensile strain areas for all axles (single to eight) with conventional and wide-base tires were calculated for thin and thick pavements, shown in Table 1 above. The axles with wide-base tires have the same axle loads shown in Figure 3 but the dual tires were replaced by the new generation of wide-base single tires with a tire pressure of 100 psi [10]. In addition, the tensile strain area for a standard axle load of 18 kips with single axle dual tires was calculated. The LEF for any axle load can be calculated from the following equation:

$$LEF_{Mechanistic} = \left\{\frac{\text{Strain Area of an axle configuration}}{\text{Strain Area of Standard axle (18 kips)}}\right\}^{0.667} \quad (3)$$

The above equation was employed to calculate the LEF for all axle configurations (single to eight) on thin and thick pavement with conventional and wide-base tires. The calculated LEF is illustrated in Figure 5. The results showed the following:

- An eight axle group with conventional tires has a LEF about 3.5 times that of the single axle (not 8 times of the single). These results indicate that grouping the axles reduces the fatigue damage for flexible pavement,
- An eight axle group with wide-base tires has a LEF about 4.5 times that of the single axle (not 8 times of the single),
- For all axle groups, axles with wide-base tires always have a higher LEF, proving more damaging than axles with conventional tires. This indicates that axles with wide-base tires always create more fatigue damage than axles with conventional tires, and
- All axles with conventional and wide-base tires introduce more damage (higher LEF) for thin pavement than for thick pavement.

The LEFs were divided by the load that each axle group carries, as listed in Figure 3. The LEFs per tonnage that each load carries were estimated, as illustrated in Figure 6. The results show that the more axles in the axle group the less damage for all axles and types of pavements. Axles with wide-base tires cause more damage for thin and thick pavement than axles with conventional tires. Comparison between the LEFs for conventional dual tires and wide-base tires showed that the wide-base tires impose on average 44% more fatigue damage for thin pavements than conventional dual tires, whereas this percentage becomes 33% for thicker pavements.

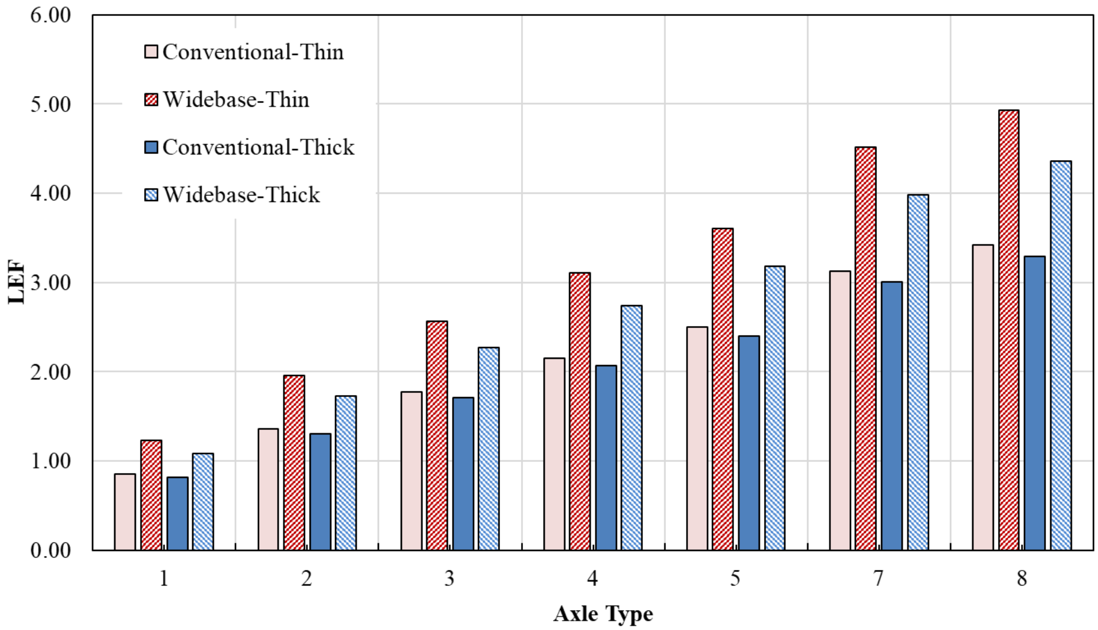


Fig. 5: Load Equivalency Factor (LEF) for Different Axle Configurations

4. TRUCK FACTORS (TFs)

Truck Factors (TFs) still represent one of the major input factors in the pavement design for transportation agencies who still use the AASHTO 1993 pavement design guide. After calibrating the mechanistic strain area method with the laboratory-derived axle factor, yielding an excellent match as shown in Figure 4b, the method was utilized to calculate and compare the fatigue damage due to different truck configurations. All Federal Highway Administration (FHWA) truck classes with large axle groups, up to quad axles, were selected for TF calculation. Table 2 shows the FHWA truck classes, class definitions, axle groups, truck weights, and truck configurations. The table shows seventeen different truck configurations ranging from FHWA class 5 to class 13. The trucks have different axle groups, varying from single to quad axles, and loading weights, ranging from 33.4 kips to 161.4 kips.

The KENLAYER software was used to calculate the transverse tensile strain at the bottom of the asphalt layers due to these axles for both thick and thin pavement systems used in this study, see Table 1. The strains were calculated for trucks with conventional dual tires and trucks with the new generation of wide-base tires. The strain pulses for each axle were developed and compiled from the calculated strain values. Using the superposition for strain pulses comprising the configuration of each axle in the truck, the truck's strain pulses were created. Figure 7 shows the strain pulses of Truck # 17 (FHWA class 13) with conventional dual tires and wide-base tires for thin and thick pavement. The figure shows that the strain values for trucks with wide-base tires is always higher than the strain values of trucks with dual tires for both thick and thin pavement. The strain pulses of trucks with both tire types for thick pavement have more interactions and are wider than the stain pulses for thin pavements.

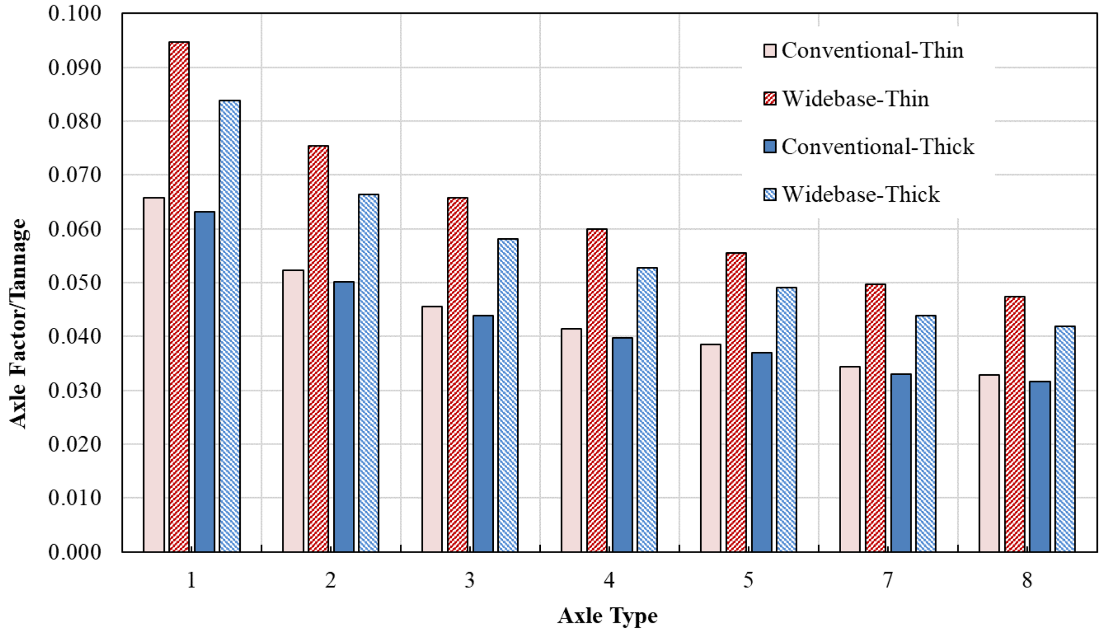


Fig. 6: Load Equivalency Factor (LEF) per Tonnage for Different Axle Configurations

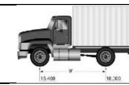
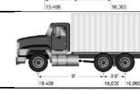
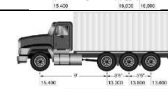
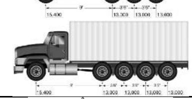
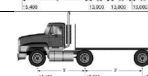
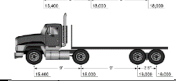
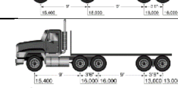
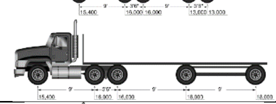
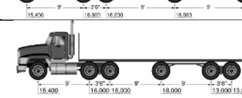
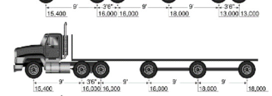
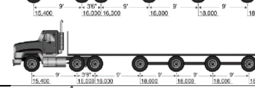
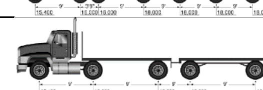
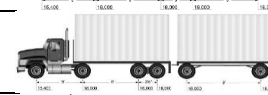
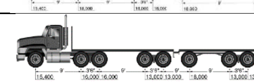
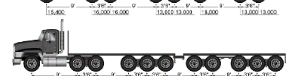
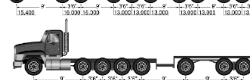
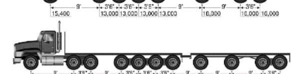
To calculate the TFs due to fatigue damage for all trucks shown in Table 2, the area under the strain pulse for each truck configuration was calculated using the trapezoidal rule. The TFs for all truck configurations shown in Table 2 can be calculated using the equation below:

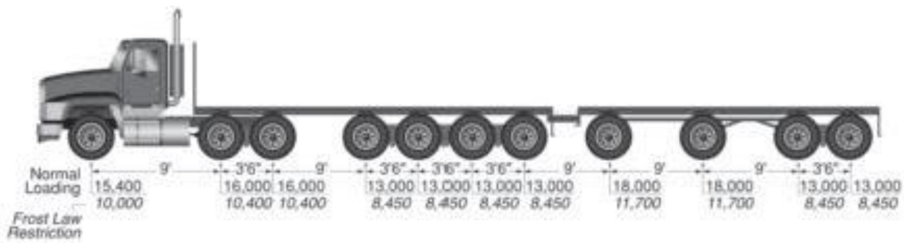
$$TF_{Mechanistic} = \left\{\frac{\text{Strain Area of Truck configuration}}{\text{Strain Area of Standard axle (18 kips)}}\right\}^{0.667} \qquad (4)$$

Figure 8 shows the calculated TFs of all trucks with conventional dual tires and wide-base tires for thick and thin pavements. The figure shows that all trucks impose more fatigue damage to thin pavements than thicker pavements. These results indicate that all truck configurations impose more fatigue damage to thin pavements than thick pavements for both conventional dual tires and wide-base tires. Trucks with wide-base tires always have more fatigue damage than the conventional dual tires for both thin and thick pavement. Comparing the values of fatigue damage of wide-base tires with conventional dual tires indicates that the wide-base tires have an average of about 31% more for thin pavement and 23% more for thick pavement than conventional dual tires. This difference in pavement damage caused by trucks (31% for thin, 23% for thick) is less than what it was for axles (44% for thin, 33% for thick) due to the inclusion of front axle damage in the case of trucks for both tire types.

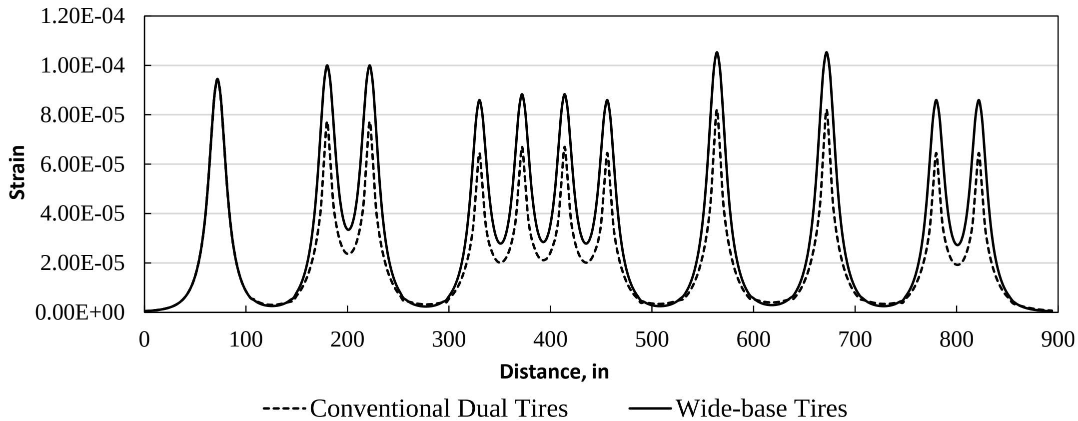
Figure 9 illustrates the calculated TFs for all eighteen truck configurations shown in Table 2 after dividing the TF for each truck over the weight it carries (TF/tonnage). The results have similar outcomes as the TFs shown in Figure 8, however they show the damage per one unit of weight that each truck carries. From these results, one can rank the trucks that have the least damage relative to the load. The trucks with large axle groups always show less damage than the trucks with the same axle numbers individually (not grouped). For the same tire types and pavement thicknesses, trucks # 14 to 18 (with axles grouped) always have less fatigue damage than similar trucks with the same axle numbers and weights but individual axles (not grouped). This indicates that grouping the truck axles prevents more fatigue damage and elongates pavement service life.

Table 2: Information of the Trucks Used in the Study [9]

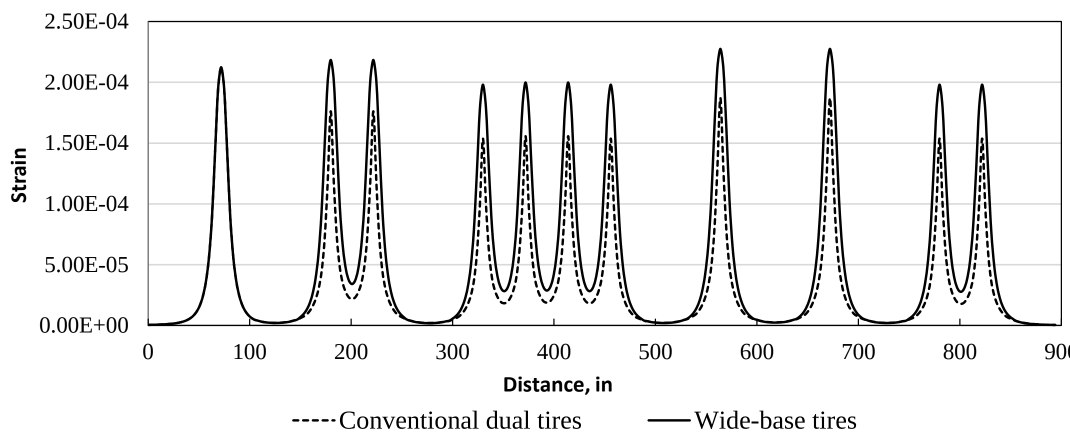
Truck #	FHWA Class Type	Class Definition	Axle Group	Truck Weight, Ib	Example Truck Configuration*
1	5	Two-axle, six-tire, single-unit trucks	1	33,400	
2	6	Three-axle single-unit trucks	1 and 2	47,400	
3	7	Four or more axle single-unit trucks	1, 3, and 4	54,400	
4				67,400	
5	8	Four or fewer axle single-trailer trucks	1 and 2	51,400	
6				65,400	
7	9	Five-axle single-trailer trucks	1 and 2	73,400	
8				83,400	
9	10	Six or more axle single-trailer trucks	1 and 2	91,400	
10				101,400	
11				119,400	
12	11	Five or fewer axle multi-trailer trucks	1	87,400	
13	12	Six-axle multi-trailer trucks	1 and 2	101,400	
14	13	Seven or more axle multi-trailer trucks	1, 2, 3, and 4	117,400	
15				151,400	
16				117,400	
17				161,400	
18				125,400	



a. Truck # 17



b. Thick Pavement



c. Thin Pavement

Fig. 7: Truck 17 Strain Pulse with Conventional Dual Tires and Wide-Base Tires for both Thin and Thick Pavements

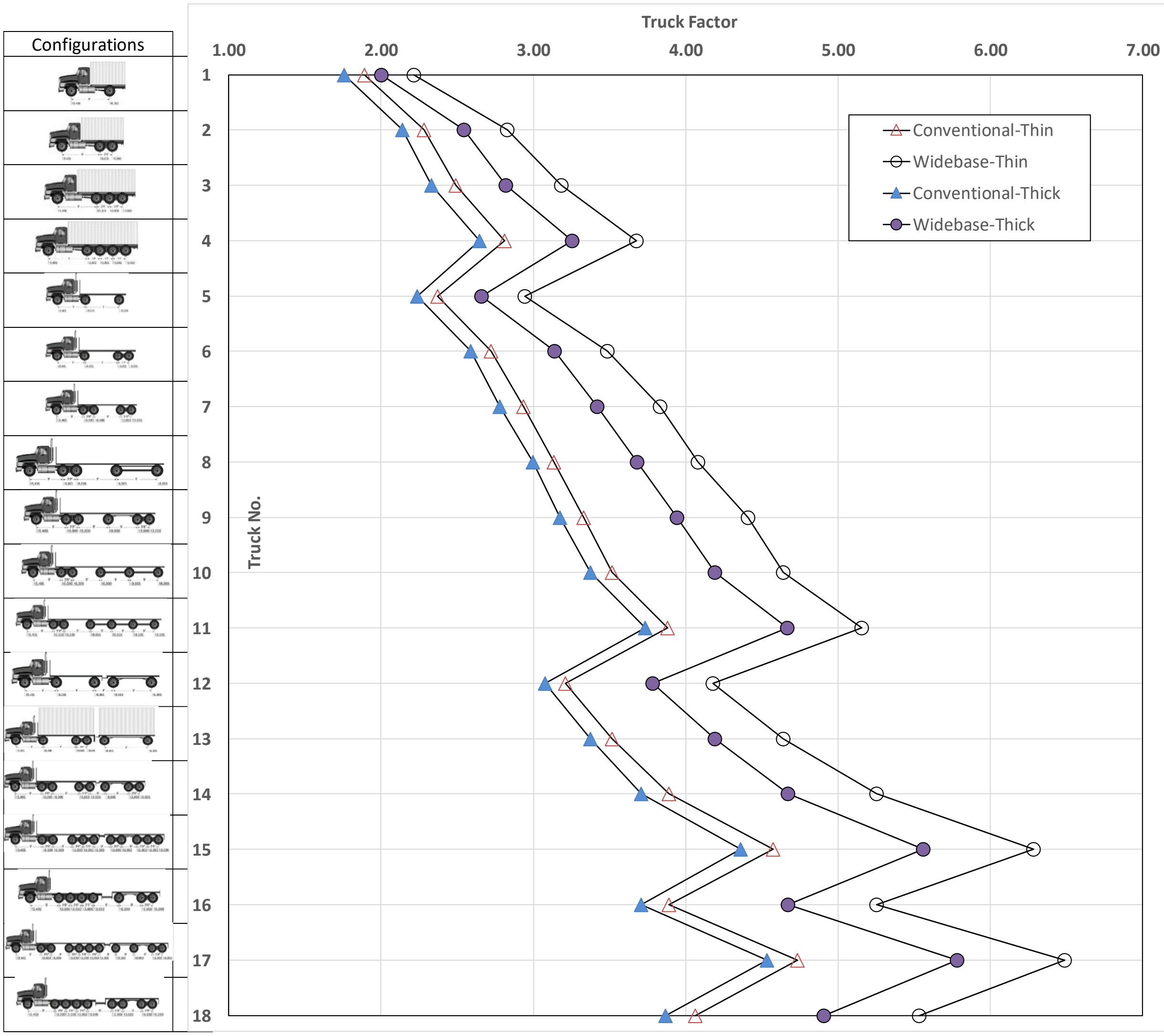


Fig. 8: TFs of Trucks with Conventional Dual Tires and Wide-base Tires for Both Thin and Thick Pavements

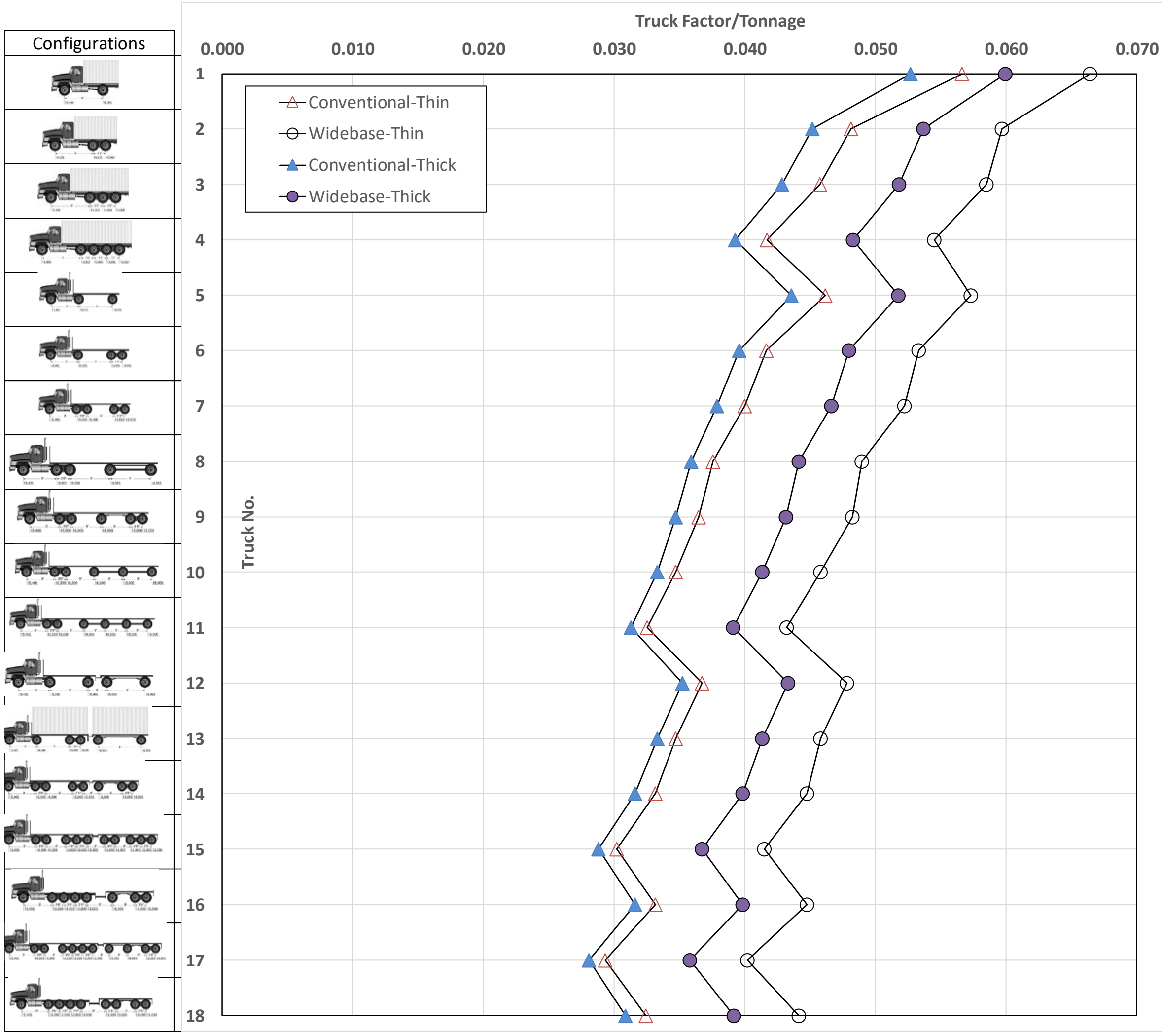


Fig. 9: Tfs/Tonnage of Trucks with Conventional Dual Tires and Wide-Base Tires for Both Thin and Thick Pavements

5. CONCLUSION

There are several damage summation methods that can be used to calculate the fatigue damage of hot mix asphalt due to heavy multiple axle loads, the strain area is one of these methods. The mechanistic strain areas developed using KENLAYER software were calibrated using the laboratory-derived AFs and showed an excellent match to them with zero SSE.

The strain area method was utilized to calculate the LEFs for different axle configurations, as well as TFs for different truck configurations. The main conclusions of the study are as follows:

- The mechanistic strain area method is similar to the dissipated energy method but is easier to use as a continuous damage summation method that captures all characteristics of the strain pulse as opposed to the discrete peak and peak mid-way methods,
- Combining truck axles in large axle groups reduces the fatigue damage significantly (by about 50%) compared to the same number as individual axles,

- Wide-base tires impose greater fatigue damage to the pavement than conventional dual tires that carry the same load and have the same tire pressure,
- For the same axles or trucks, thin pavement shows more fatigue damages than thicker pavement, and
- Trucks with large axle groups show less fatigue damages than trucks with the same number of axles but have individual axles with the same weights.

6. REFERENCES

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