Comparison between Flexible Pavement Damage Due to Conventional and Wide-Base Tires of Heavy Multiple Axles

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Abstract: Trucks are considered one of the most important means in transporting. Recently, the tire designers introduced new wide-base tires to replace the conventional dual tires system. The objective of this study is to investigate flexible pavement damage due to different heavy multiple axle configurations with wide-base tires. Several axle configurations including single, tandem, tridem and quad with conventional and wide-base tires were considered in this study. Two flexible pavement sections were analyzed, thick and thin pavement sections with thicknesses and material properties representing majority of the pavement cross-sections. To quantify and compare the damage for thick and thin pavement sections due to heavy axle load configurations, the forward analyses were conducted using KENLAYER program to calculate the pavement response. The horizontal tensile strain at the bottom of the hot mix asphalt and the vertical compressive strain on top of the subgrade and at the middle of each pavement layers as well as the six consecutive sub-layers of the subgrade soils were calculated from the structural model. These pavement responses were utilized in the performance models to calculate the two main pavement distress, fatigue cracking and pavement surface rutting. The strain area model for fatigue and VESYS rutting model for rutting were utilized to calculate the pavement damage. The Axle Factors were calculated for each axle configurations to compare the pavement damage due to axles with conventional and wide-base tires. The results indicate that axle loads with wide-base tires impose more fatigue and rutting damage than axles with conventional tires.
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Key words: Wide-base tire, dual tire, pavement rutting, pavement fatigue, pavement damage, multiple axles

1. Background

The 21st century witness enormous trading activities due to the economic alliances between the countries. This is in return increased the transportation activities on the road networks. Heavy trucks have major share in transporting freights. Recently, the truck industry introduces the wide-base tires which replacing the conventional tires to reduce fuel consumption, tire cost and repair, emission and noise, and recycling impact of scrap tires. Also, using the wide-base tire increase hauling capacity, ride and comfort, and improve handling, braking, and safety.

Since the introduction of wide-base tires, researchers started to compare the contact area, contact stress, the pavement response and damage effect on the pavement of both conventional and wide-base tire. For two types of wide-bases (385/65R22.5 and 425/65R22.5) at a constant load, the tire inflation pressure variation primarily affected the contact stresses in the central region of the contact area; the higher the inflation pressure, the greater the contact pressures in this central region. The contact pressures in outer portions of the tires were essentially not affected. In contrast, at a constant inflation pressure, the tire load variation explicitly influenced the contact stresses in the outer regions of the contact area; the higher the load, the higher those stresses. The maximum contact stress was still located at the center of the contact area, as **Yap, 1988** reported in a similar study. He compared the tire load increase due first to an inflation pressure increase and then to a tire load increase for a 11-24.5 radial tire, a 11R24.5 radial tire and a 385/65R22.5 wide-base tire (all manufactured by Goodyear). The wide-base tires exhibited higher increase in the contact stresses in the case of the increase of the inflation pressure, but they had the lowest increase as the tire load increased. Despite this fact, in both cases wide-base tires had higher vertical contact stresses. **Myers *et al.*, 1999** measured the three components of the contact stresses under various truck tires. Results were presented for the vertical and transverse contact stresses for a bias ply tire and R299 radial tire (for both load 25 KN and inflation pressure 115 psi), and M844 wide base radial tire (load 41.7 KN and inflation pressure 115 psi). The results indicate that, the vertical and transverse contact stresses are higher for wide-base tires because wide-base tires have a higher load per tire ratio than any other type of tire. The distribution of the vertical contact stresses was also not uniform. The maximum value was found to occur at the center of the contact area and equal to approximately 2.3 times the inflation pressure. Also, it is observed that the maximum vertical stresses of the wide-base tire are about 1.5 times greater than those of the bias ply and radial tires. With respect to the transverse stresses, again the wide-base tires exhibit higher values in the central region of the contact area. Maximum transverse stress (of the wide-base tire) is about one third of the maximum vertical contact stress. It should be noted that the relationship between pavement response (stress, strain, and deflection) are not linear relationship with the pavement performance (Fatigue, rutting, etc.) which urge for quantifying the pavement damage due to these axles with wide-base tires.

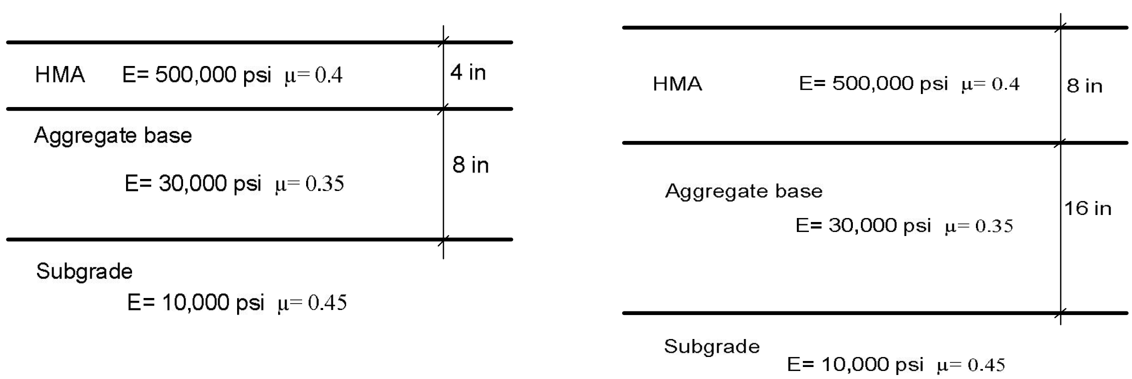
Al-Qadi *et al.*, 2002, measured the pavement response for dual tire and new wide-base tire with the same tire pressure at Virginia Smart Road Test Facility. The results showed that the newly developed wide-base tire induce approximately the same horizontal strain under the hot mix asphalt layer as do equivalent dual tires. Therefore, they expect the same fatigue damage for both newly developed tires and dual tires. In contrary, the vertical compressive stresses induced by wide-base tire are greater on the upper hot mix asphalt layers of the tested pavement. The difference diminishes with depth and become negligible at the bottom of the subbase layer.

Kim *et al.*, 2005, used plane-strain two-dimensional and three-dimensional static and dynamic finite element analyses to assess the larger stresses generated by wide-base tires and their effect on the subgrade. They compared between the response of conventional and wide-base tires under elastic-plastic conditions, wide-base tires induce approximately four times larger permanent strains in the pavement layers than conventional tires. Therefore, design of a pavement using Load Equivalency Factor (LEF) values for dual tires leads to overestimation of the pavement design life.

Since the relation between the pavement response and pavement damage is not linear, researchers have investigated the pavement response and predicted the pavement damage to determine the effect of wide-base tires on pavement damage. **Sebaaly and Tabatabaee, 1992** investigated the effects of tire pressure, tire type, axle load, and axle configuration under actual truck loading and highway speed on instrumented test sections. The various tire types are tested against the 11R22.5 wide base tire to evaluate their relative damage to pavements. The results showed that the wide-base single tires consistently have significantly higher strains and deflection than dual tires. The fatigue and rutting damage factors for the wide-base single tires range from 1.5 to 1.7 and from 1.2 to 2.0 for the single and tandem axles, respectively.

1.1 Damage Calculation Due to Multiple axle loads

Several laboratory fatigue tests such as simple fracture, support fracture, direct axial, diametral, triaxial, fracture tests, and wheel tracking tests were performed to determine the fatigue damage due to traffic loads, (**Matthews *et al.*, 1993**). Researchers stated the basic concept of each test where some of these tests were stresses-controlled while others were strain-controlled. However, all of these tests have been performed using either a single pulse with rest period or a continuous sinusoidal load. Similar to pavement fatigue, several trials have been made to predict pavement rutting based on laboratory experiments (**Ayres, 2002**); however all of these trials were based on single load pulse. In reality, the pavement is subjected to multiple load pulses due to the passage of large axle group trucks.



a) Thin section

b) Thick section

Figure 1: Thicknesses and material properties of thick and thin pavement

Due to the fact that the damage resulting from multiple axle load were not correctly characterized since there were no laboratory tests based on multiple pulses. Recently, a massive laboratory tests simulating the multiple axle loads for both flexible and rigid pavement are conducted at Michigan State University.

Salama and Chatti, 2011 got advantages of these tests and evaluated fatigue and rut damage prediction methods for asphalt concrete pavements subjected to multiple axle loads. Different summation methods of calculating pavement damage caused by multiple axles were evaluated using laboratory data, with the evaluation criterion being the degree of agreement with the measured laboratory performance. They concluded that for fatigue damage, dissipated energy and strain area methods have an excellent agreement with the laboratory determined axle factors. For rutting damage, the peak strain method has good agreement with the laboratory determined axle factors. In this study, strain area and peak strain methods will be used to calculate the fatigue and rutting damage of pavement, respectively. The damage of pavement were calculated for thick and thin pavement with thicknesses and material properties as shown in Figure 1 a and b. The axle factor of fatigue and rutting damage can be calculated from strain area and peak strain equations as illustrated in the following sections.

1.1.1Fatigue

Fatigue is one of the main distress types in flexible pavements. The main pavement response that causes fatigue cracking in pavement is the tensile strain at the bottom of the hot mix asphalt. KENLAYER computer program will be used to calculate the horizontal tensile strain at the bottom of the hot mix asphalt layer under the stander axle and all axles considered in the study (single, dual, tridom and quad) with conventional dual tires and wide-base tires, **Huang, 1993**. Hence, strain area proven that it is the most candidate method to quantify the fatigue damage. Equation 3.1 shows the number of fatigue cycles until failure using strain area method. To compare the damage due to multiple axle relative to the stander axle, fatigue strain area model will be used to calculate the Axle Factors (AF).

$$N_f = 18.865 * A_o^{-0.478} \quad (1)$$

Where:

N_f = is the number of cycles to failure, and

A_o = is the initial area under the strain curve for stander axle or any axle or truck.

and

AF = Damage of axle / Damage of the stander axle

$$= N_{f\,\text{std axle}} / N_{f\,\text{axle or truck}} = (A_{o\,\text{std axle}} / A_{o\,\text{axle or truck}})^{-0.478} \quad (2)$$

1.1.2 Rutting

Similar to fatigue, rutting is one of the main distress types in flexible pavements. The main pavement response that causes pavement rutting is the vertical compressive strain. KENLAYER computer program will be used to calculate the vertical compressive strain on top of the subgrade layer, at the middle of the hot mix asphalt layer, at the middle of the base layer and at the middle of the subsequent six subgrade layers each with thicknesses of 40 inches until the vertical compressive strain becomes negligible and no resultant permanent deformation due to truck load.

To calculate the total rutting at the pavement surface (rutting in HMA plus rutting in base plus rutting in subgrade), VESYS rutting model is the most appropriate model which has this capability, Moavenzadeh, 1974. Equation 3.7 shows the form of the model.

$$\rho_p = h_{AC}\frac{\mu_{AC}}{1-\alpha_{AC}}\left(\sum_{i=1}^{K}(n_i)^{1-\alpha_{AC}}\left(\varepsilon_{ei,AC}\right)\right) + h_{base}\frac{\mu_{base}}{1-\alpha_{base}}\left(\sum_{i=1}^{K}(n_i)^{1-\alpha_{base}}\left(\varepsilon_{ei,base}\right)\right) + h_{SG}\frac{\mu_{SG}}{1-\alpha_{SG}}\left(\sum_{i=1}^{K}(n_i)^{1-\alpha_{SG}}\left(\varepsilon_{ei,SG}\right)\right) \quad (3)$$

Where:

ρ_p = total cumulative rut depth (in the same units as the layer thickness),

I = subscript denoting axle group,

K = number of axle group,

H = layer thickness for HMA layer, combined base layer, and subgrade layer,

n = number of load applications, assume $n = 1*10^6$ (one million repetitions)

$_e$ = compression vertical elastic strain at the middle of the layers,

μ = permanent deformation parameter representing the constant of proportionality between plastic and elastic strain, and

α = permanent deformation parameter indicating the rate of change in rutting as the number of load applications increases.

Since the rutting calculation using VESYS model will be used for relative comparison for different axles with conventional and wide-base tires, Table 1 shows an average values for permanent deformation parameters which was presented in previous research, Salama, 2005.

Table 1: Average values of permanent deformation parameters

Pavement layer	α	μ
HMA	0.65	0.8
Base	0.7	0.4
Subgrade	0.75	0.025

The rutting damage factors for axles can be calculated from equation (3.8). However, the truck factor will be calculated by summing the axles factor of the truck axle.

$$\text{Damage factor} = \text{Rutting}_{(\text{any axle})} / \text{Rutting}_{(\text{stander axle})} \quad (4)$$

1. Research Procedure

The following table summarizes the research methodology in term of axle and truck configuration, the forward analysis software, the performance model, and axle load values that will be used to calculate the pavement damage due to conventional tire and wide-base tire. Figure 2 shows the flow chart of research plan which satisfy the research objectives.

Table 2: Summary of the research methodology

Item	Availability	Considered in the research
Axle configuration	Single to eight axle group	Single to quad axle
Axle load values	Different axle load values	Single =10 ton, Tandem = 20 ton, Tridem =30 ton, and Quad = 40 ton
Forward analysis software	Several MLET and FEM software	KENLAYER (MLET)
Fatigue model	Several fatigue models	Strain area model
Rutting model	Several Rutting models	Subgrade rutting using AI model
		Hot mix asphalt using Peak strain model
		Total rutting at the pavement surface using VESYS model

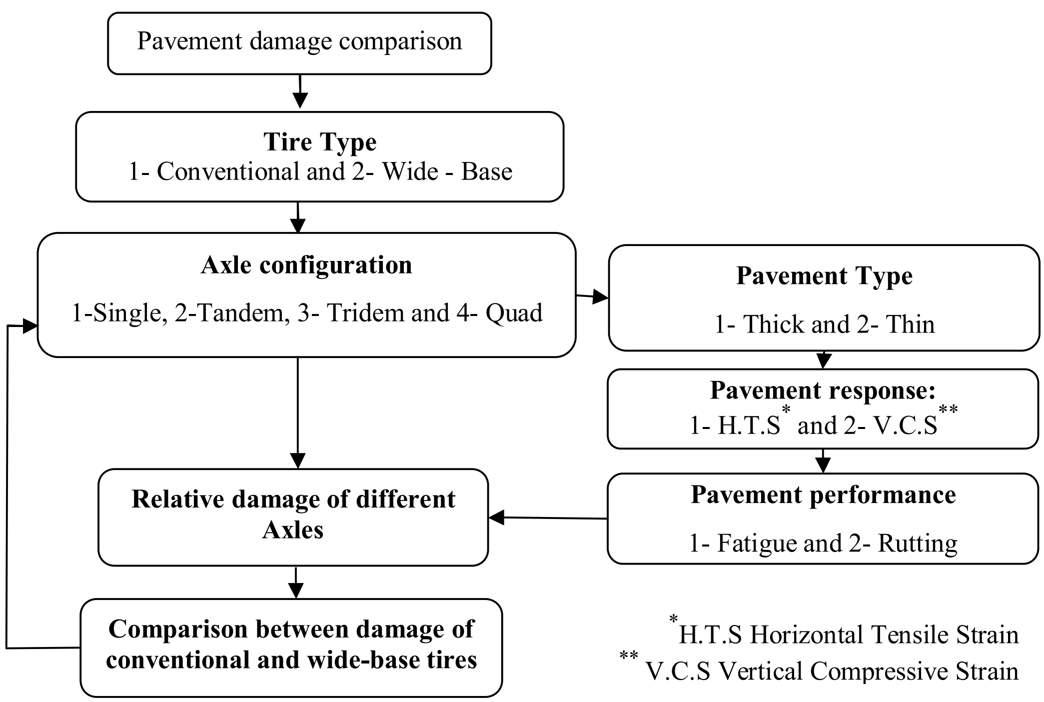


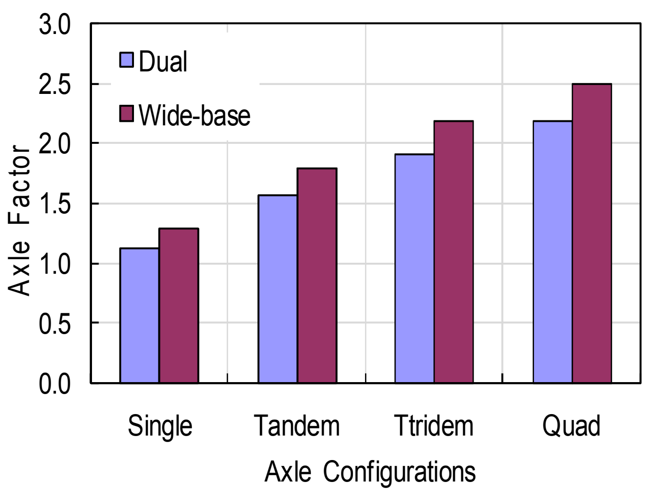
Figure 2: Flowchart of the analysis

3. Analysis and Discussions

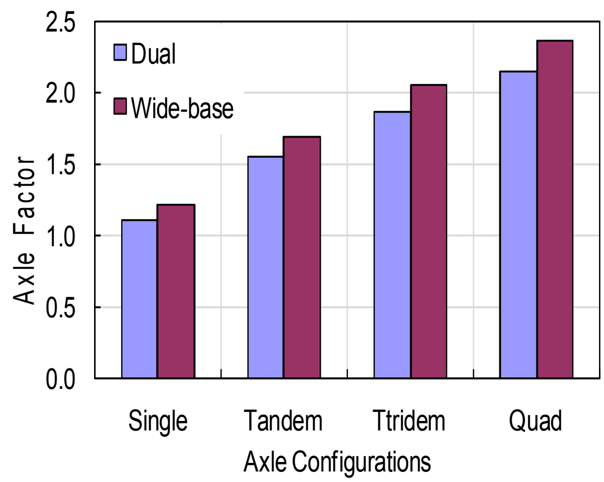
Figures 3 a and b shows the Axle Factor calculated from the strain area method for single, tandem, tridem and quad axle with dual and wide-base tires for both thin and thick pavements. The results show that the wide-base tires impose more fatigue damage for both thin and thick pavements. Almost similar trend of increasing in magnitude observed for the four axle types for thin and thick pavements. The increase in the fatigue damage under wide-base tire due to the larger area under the strain pulse which resulting from smaller surface contact area of the wide-base tire than the dual tire, see Figures 3 a and b. The increase in fatigue damage due to axles with wide-base tires are 9.9%, 9.0%, 10.2%, and 9.8% for single, tandem, tridem and quad axles, respectively. Whereas for thin pavement, these percentages of increase in fatigue damage are 15.2 %for single and 14.7% for tandem, tridem and quad axles.

Figures 4 a and b shows the calculated total surface rutting Axle Factors due to different axles with dual and wide-base tires for thick and thin pavements. The results show that the Axle Factors for thick pavements due to axles with conventional and wide-base are very close and there is no significant difference between the rutting damage. On the other hand, these differences are relatively higher in the thin pavement which indicates that axles with wide-base tires cause more rutting damage than axles with conventional tires. The wide-base tire cause more rutting damage in the thin pavement since the thin hot mix asphalt do not provide enough protection for the sub-layers especially the aggregate base to sustain the heavy axle loads. The percentages of rutting damage increase for thick pavements due to axles with wide-base tires are 16.7, 4.7, 4.2, and 4 for single, tandem, tridem and quad axles, respectively. These results indicate that increasing the number of axles within an axle group decreasing the rutting damage. For Thin pavement, these percentages become 31.3, 21.6, 21.1, and 20.9 for single, tandem, tridem and quad axles, respectively.

Comparing the overall increase in the fatigue damage resulting from axles for thin and thick pavements due to the wide-base tires indicate that the wide-base tires impose more fatigue damage ranges between 9 % and 10.2 % with average 9.7 % in compare to fatigue damage with dual tires for thick pavements whereas this percentage ranges between 14.7 % and 15.2 % with average 14.8 % for the thin pavements, see Figure 5. Whereas comparing the overall increase in the total surface rutting damage resulting from axles for thin and thick pavements due to the wide-base tires indicate that the wide-base tires impose difference in the overall rutting damage ranges between 4 % and 16.7 % with average 7.4 % in compare to dual tires for thick pavements whereas this percentage ranges between 20.9 % and 31.3 % with average 23.7 % for the thin pavements, see Figure 5.

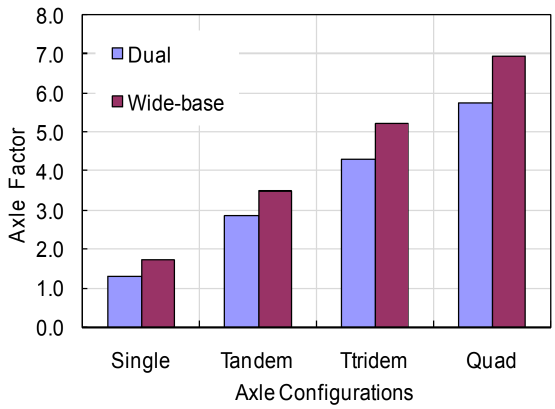


a) Thin pavement

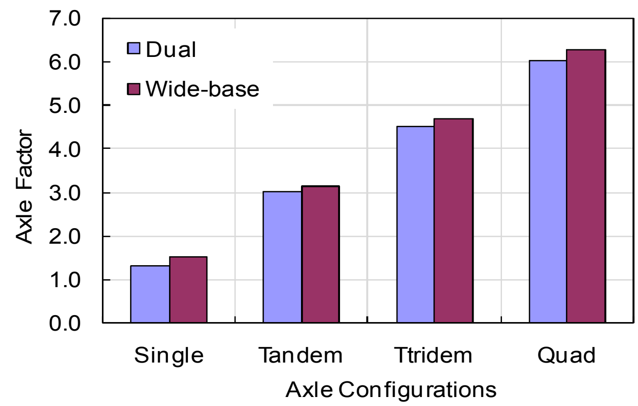


b) Thick pavement

Figure 3: Fatigue axle factors

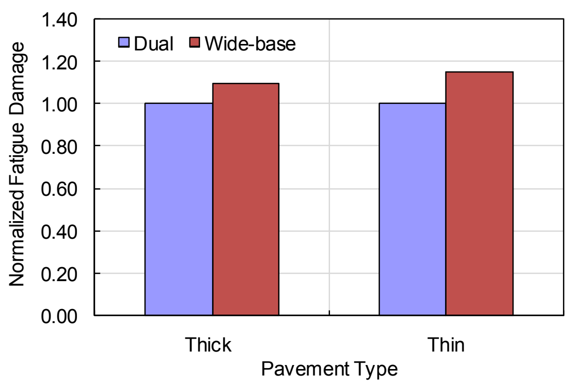


a) Thin pavement



b) Thick pavement

Figure 4: Rutting axle factors



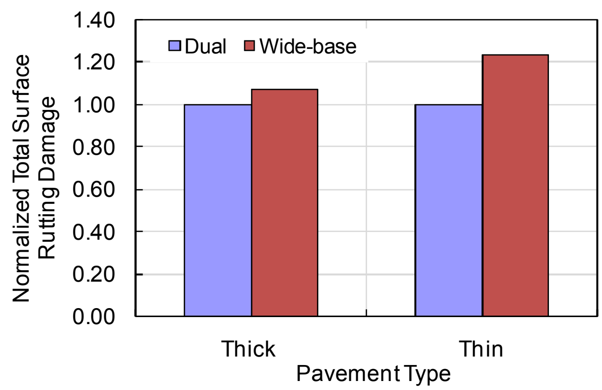
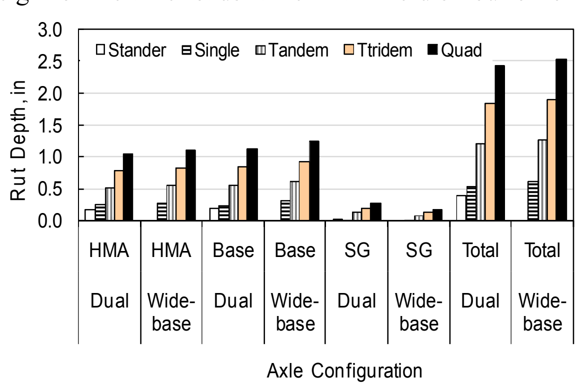
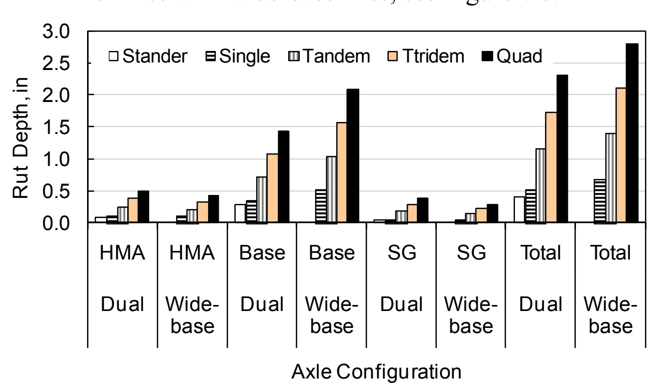


Figure 5: Normalized average fatigue and rutting damage for thick and thin pavement

Figure 6 a and b shows the total surface rutting and the layer rutting due to different axle configuration with dual and wide-base tires for both thin and thick pavements. Figure 6 a shows that the resulting layers rutting in thick pavement due to axles with dual or wide-base are almost the same. This indicates that the rutting is more affected by the total weight of the axle loads rather than the distribution of the load underneath the tires, as long as the weak layers are protected by the hot mix asphalt. Unlike thick pavement, thin pavement has no enough hot mix asphalt to protect the base layer to carry heavy axle loads. Hence axles with wide-base tires create more rutting damage in the base layer than axles with dual tires which resulting in more total rutting damage due to axles with wide-base tires, see Figure 6 b.



a) Thick pavement



b) Thin pavement

Figure 6: Total and layer rut depth due to different axle configurations

4. Conclusion

This study involves mechanistic evaluation of flexible pavement damage due to axle loads with wide-base tires. The analysis includes comparisons between pavement damage due to axle loads with wide-base tires and axle loads with conventional tires. The pavement damage includes fatigue and total surface rutting damages. Based on the analysis of fatigue and rutting damage due axle loads with conventional and wide-base tires for thin and thick pavement, the following conclusions are drawn:

- In general, axle loads with wide-base tires impose more fatigue and rutting damage than axles with conventional tires.
- Axles with wide-base tires impose an average 9.7 % (from 9 % to 10.2%) fatigue damage more than the axles with conventional tires for thick pavements whereas this percentage become on average 14.8 % (from 14.7 to 15.2 %) for the thin pavements.
- Axles with wide-base tires impose on average 7.4 % (4% to 16.7%) rutting damage more than the axles with conventional tires for thick pavements whereas this percentage become on average 23.7 % (20.9 % to 31.3 %) for the thin pavements.
- An overall agreement between the layer rutting damage resulting from total surface rutting approach (VESYS rutting model) with subgrade and hot mix asphalt rutting.

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