Determination of Legal Axle and Truck Loads with Wide-Base Tires

Hassan Salama[1], Mahmoud Solyman[2] and Ahmed Shehata[1]

[1]Civil & Environmental Engineering Department, Al Azhar University, Egypt
[2] Construction Engineering and Utilities Department, Zagazig University, Egypt
elsaied2000@yahoo.com

Abstract: Trucks are considered one of the most important means of transportation. Recently, the tire designers introduced new wide-base tires to replace the conventional dual tires system. Previous studies indicated that these types of tires increase the pavement damage. This study aims to estimate the legal equivalent loads of different axle and truck configurations with wide-base tires which impose the same pavement damage as the conventional dual tires. Several axle configurations including single, tandem, tridem and quad as well as fifteen Egyptian truck configurations were considered in this study. Thick and thin pavement sections with thicknesses and material properties representing majority of the pavement cross-sections were analyzed. To quantify and compare the damage for thick and thin pavement sections due to heavy axle load configurations, forward analyses were conducted using KENLAYER program to calculate the pavement response. The horizontal tensile strains at the bottom of the hot mix asphalt and the vertical compressive strains 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 responses were utilized in the performance models to calculate the two main pavement distresses, fatigue cracking and pavement rutting. The Axle Factors were calculated for each axle configurations with wide-base and conventional tires then relationships between axle weights and axle factors were developed for axles with dual tire. The weights of axle with wide-base tires that produce the same damage were calculated from these relationships. Then, using simple linear regression analysis, different relationships between the weights of axles with dual and wide-base tires were developed. Using these relationships, legal loads for axles and trucks with wide - base tires that create the same fatigue and rutting were estimated.

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1. Introduction

Recently, the truck industry introduced the wide-base tires which replacing the conventional tires to reduce tire cost and repair, emission and noise, and recycling impact of scrap tires. Also, using the wide-base tire increase hauling capacity, ride comfort, and improve handling and braking. However, this type of tire has impact on the pavement response and damage.

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 dual and wide-base tire. Yap, 1988, 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. 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 a bias ply tire and R299 radial tire, and M844 wide base radial tire. 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 of vertical contact stresses of the wide-base tire 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.

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 static and dynamic finite element analyses to assess the larger stresses generated by wide-base tires and their effect on the subgrade in compare to the pavement response under the dual tires 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. Pavement Damage Calculation Due to Axle Loads with Conventional and Wide-base Tires

The fatigue damage due to traffic loads were determined through several laboratory fatigue tests such as simple fracture, support fracture, direct axial, diametral, triaxial, fracture tests, and wheel tracking (Matthews *et al.,* 1993). 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.

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.

1.1.1. Fatigue

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 was 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, tandem, tridem 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 1 shows the number of fatigue cycles until failure using strain area method. To compare the damage due to multiple axles 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.

From the above equation the Axle Factor can be calculated as follows:

AF = Damage of axle / Damage of the stander axle = $N_{f\,\text{std axle}} / N_{f\,\text{axle or truck}}$

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

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 was used to calculate the vertical compressive strain at the middle of the hot mix asphalt layer, middle of the base layer and at the middle of subsequent six subgrade layers each with thicknesses of 40 inches until the vertical compressive strain became negligible. Based on the calculated vertical strain VESYS rutting model was used to calculate the total rutting at the pavement surface (Moavenzadeh, 1974). Equation 3 shows the form of the model.

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

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 indicating the rate of change in rutting as the number of load applications increases.

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

Salama, 2005 presented varies values for the permanent deformation parameters (and μ). Averages of these values were used in this study as below:

- HMA layer: 0.65 and μ = 0.8
- Base layer : 0.70 and μ = 0.4
- Subgrade layer: 0.75 and μ = 0.025

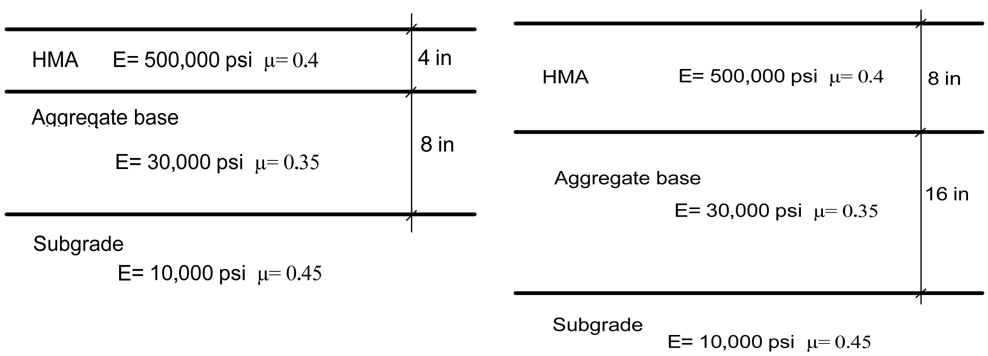
The rutting damage factors for axles can be calculated from equation 4.

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

2. RESEARCH PARAMETERS AND PROCEDURE

This section presents the research parameters that have been used in the analysis such as, axle loads, Axle and truck configurations, forward analysis software, performance model, and axle load values that will be used to calculate the pavement damage due to conventional tire and wide-base tire:

- Axle configuration: Single to quad axle
- Axle load values: Different axle load values
- Trucks configuration: Fifteen Egyptian truck configurations according to Egyptian Code for Urban and Rural Road Works, 2007
- Truck Axle load values: Single =13 ton, Tandem = 20 ton, Tridem =30 ton, and Quad = 40 ton
- Forward analysis software: KENLAYER which is based on Multilayer Elastic Theory (MLET)
- Fatigue model: Strain area model
- Rutting model: VESYS model for total rutting at the pavement surface
- Pavement configuration: Thin and thick with thicknesses and material properties as shown in Figure 1.



a) Thin section b) Thick section

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

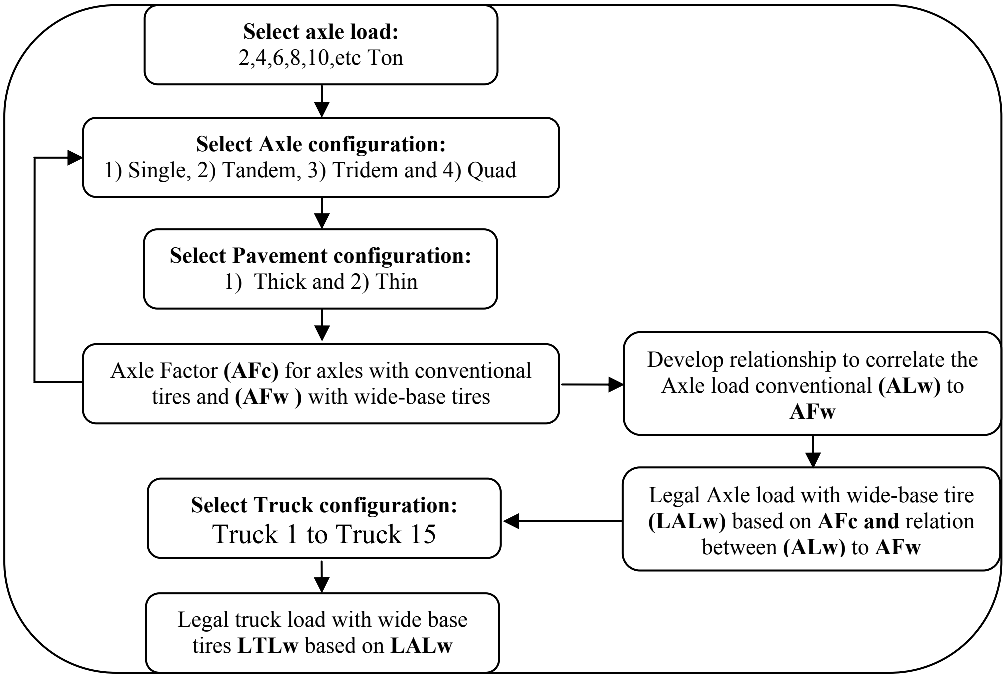


Figure 2: Flowchart of work plan

3. Analysis and Discussions

In the following sections the legal equivalent axle load for axles with wide-base tires that impose the same fatigue and rutting damage will be estimated and discussed. The legal load will be estimated for single, tandem, tridem and quad axle configurations at different axle load values as well as the fifteen Egyptian truck configurations.

3.1. Single Axle Load

3.1.1. Fatigue

KENLAYER computer program was utilized to calculate the horizontal tensile strain at the bottom of the hot mix asphalt layer under single axle loads with conventional and wide-base tires. The area under the resulting strain curves was calculated along with the standard axle and single axle load with different load values. Fatigue model based on the strain area was employed to calculate the axle factors of single axles, see Equation 2. The axle factors based on fatigue damage for single axle loads from 4 to 15 ton are shown in Table 1. A relationship between single axle loads with wide-base tire and its fatigue axle factors for thin and thick pavement was developed, see Figure 3. The following Equations illustrate these relationships.

$$LW_{Thin} = 4.822 * AF_W^{\,2.834} \quad (5)$$

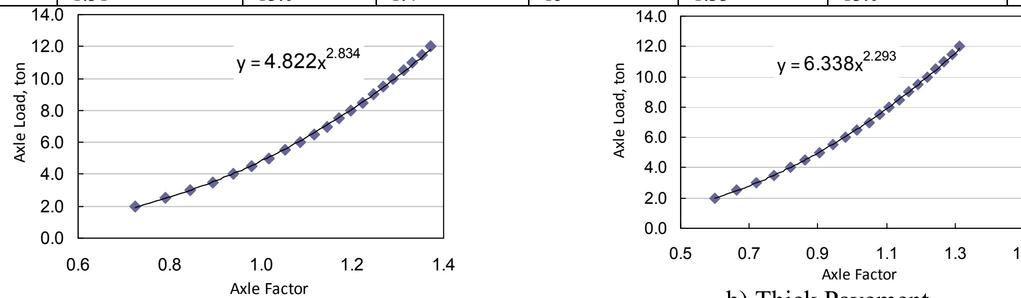
$$LW_{Thick} = 6.338 * AF_W^{\,2.293} \quad (6)$$

Where: LW is the single axle load with wide-base tire and AF_W is its fatigue axle factors.

Table 1: Single axle loads with dual and wide-base tires and its fatigue axle factors

Thin Pavement				Thick Pavement			
Axle load (ton)	Axle factor (AF_c)	Axle load (ton)	Axle factor (AF_w)	Axle load (ton)	Axle factor (AF_c)	Axle load (ton)	Axle factor (AF_w)
Dual		Wide-base		Dual		Wide-base	
4	0.79	2.0	0.72	4	0.72	2.0	0.60
5	0.86	3.0	0.85	5	0.81	3.0	0.72
6	0.92	4.0	0.94	6	0.88	4.0	0.82
7	0.98	5.0	1.02	7	0.94	5.0	0.91
8	1.03	6.0	1.09	8	1.00	6.0	0.98
9	1.08	7.0	1.14	9	1.05	7.0	1.05
10	1.12	8.0	1.20	10	1.11	8.0	1.11
11	1.17	9.0	1.25	11	1.16	9.0	1.17
12	1.20	10.0	1.29	12	1.20	10.0	1.22
13	1.24	11.0	1.33	13	1.25	11.0	1.27
14	1.28	12.0	1.37	14	1.29	12.0	1.31

15	1.31	13.0	1.4	15	1.33	13.0	1.35



a) Thin Pavement b) Thick Pavement

Figure 3: Single axle load with wide-base tire versus its fatigue axle factors

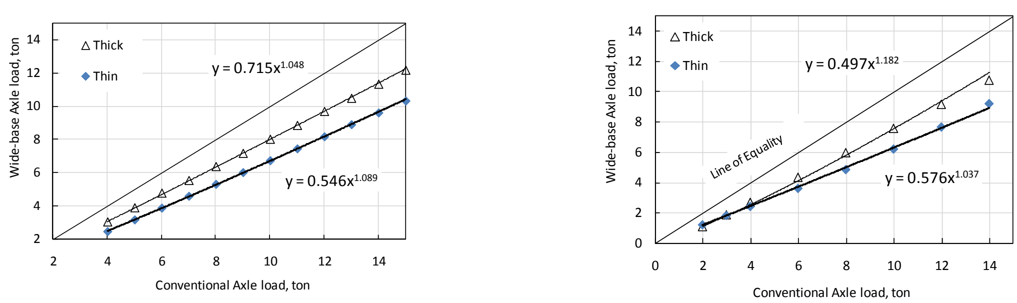
The above Equations were utilized to calculate the single axle loads with wide-base tires that impose the same fatigue damage to the pavement resulting from axle load with conventional dual tire. For any axle load with conventional tire the axle factor for conventional tires (AF_c) will be determined from Table 1, then substitute this value in equation 5 or 6 based pavement thickness to estimate the equivalent axle load with wide-base tire. For example, to find axle load with wide-base tires that impose the same fatigue damage of axle load with conventional dual tires equal 10 ton for thin pavement, from Table 1 AF_c at 10 ton axle load, dual tire and thin pavement is 1.124, substituting 1.124 in equation 5, the resulting axle load with wide – base will be 6.72 ton. Similarly, the axle loads with wide- base tires equivalent to axle loads with conventional tires from 4 to 15 ton were estimated

A relationship between the single axle load with wide-base tire and the load of conventional tire that cause the same pavement fatigue damage was developed for both thin and thick pavement. Figure 4-a illustrates these relations for thin and thick pavement and the following Equations are resulting from these relationships.

$$LW_{thin} = 0.546\ LC^{1.089} \quad (7)$$

$$LW_{thick} = 0.715\ LC^{1.048} \quad (8)$$

Where, LW is the single axle load with wide-base and LC is the single axle load with conventional tire. Equations 7 and 8 can be used to convert any single axle loads with conventional tires to single axle load with wide-base tires that cause the same fatigue damage. Figure 4-a shows that the legal load of single axle with wide-base tire for thick pavement is higher than of that for thin pavement and both are lower than the legal load of the axles with conventional dual tires.



a) Fatigue Damage b) Rutting Damage

Figure 4: Single axle load with wide-base tire versus single axle load with dual tires

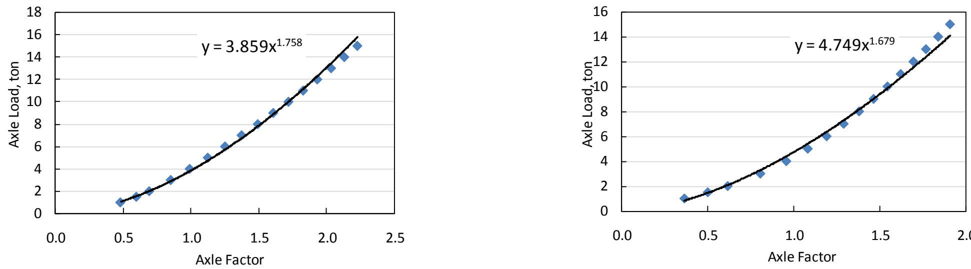
3.1.2. Rutting

Similar to the fatigue, the rutting axle factors were calculated from equations 3 and 4 for single axle load from 1 to 15 ton with conventional and wide-base. The calculated values were used to develop a relationship between single axle loads with wide-base tire and their rutting axle factors as shown in Figure 5. The following Equations illustrate these relationships.

$$LW_{Thin} = 3.859 * AF_W^{1.758} \quad (9)$$

$$LW_{Thick} = 4.749 * AF_W^{1.679} \quad (10)$$

Where: LW is the single axle load with wide-base tire and AF_W is its rutting axle factor. The above Equations were utilized to calculate the single axle loads with wide-base tires that impose the same rutting damage to the pavement following the same procedures explained in fatigue damage in section 4.1.1.



a) Thin Pavement b) Thick Pavement

Figure 5: Single axle load with wide-base tire versus its rutting axle factors

Relationships between single axle load with wide-base tires and load of conventional tires that cause the same pavement rutting damage was developed for both thin and thick pavement. Figure 4-b illustrates these relations for thin and thick pavement. The following Equations are resulting from these relationships.

$LW_{thin} = 0.576\ LC^{1.037}$ (11)

$LW_{thick} = 0.497\ LC^{1.182}$ (12)

Where, LW is the single axle load with wide-base tire that cause the same rutting damage as single axle load with conventional dual tire LC. The above Equations can be used to determine the same axle load with wide-base tire that impose the same rutting damage. The results indicate that for all axle loads and both thick and thin pavement the loads that can be carried with wide- base tires are less than those with conventional dual tires but thick pavement can carry more axle load with wide-base tires than thin pavement.

3.2. Tandem, tridem and quad Axle Load

The same procedures of estimating legal load of single axle with wide –base tires were applied for tandem, tridem and quad axles and the outcome is presented below.

3.2.1. Fatigue

As mentioned above, the axle factors for fatigue damage were calculated from equation 2 and the results were used to develop equations relating axle load with axle factors for axles with wide-base tires. Equations 13 and 14 show these relations of tandem axles for thin and thick pavement.

$LW_{Thin} = 3.758 * AF_W^{2.834}$ (13)

$LW_{Thick} = 5.914 * AF_W^{2.301}$ (14)

Where: LW is the tandem axle load with wide-base tire and AF_W is its fatigue axle factors. The above Equations were utilized to calculate the tandem axle loads with wide-base tires that impose the same rutting damage to the pavement then a relationship between the tandem axle load with wide-base tire and the load of conventional tire that cause the same pavement fatigue damage was developed for both thin and thick pavement. Figure 6-a illustrates these relations for thin and thick pavement. Equations 15 and 16 are resulting from these relationships.

$LW_{thin} = 0.513\ LC^{1.090}$ (Tandem – Thin) (15)

$LW_{thick} = 0.684\ LC^{1.053}$ (Tandem – Thick) (16)

Where, LW is tandem axle load with wide-base tire that cause the same fatigue damage as tandem axle load with conventional dual tire LC. The above Equations can be used to determine the tandem axle with wide-base tires that cause the same fatigue damage.

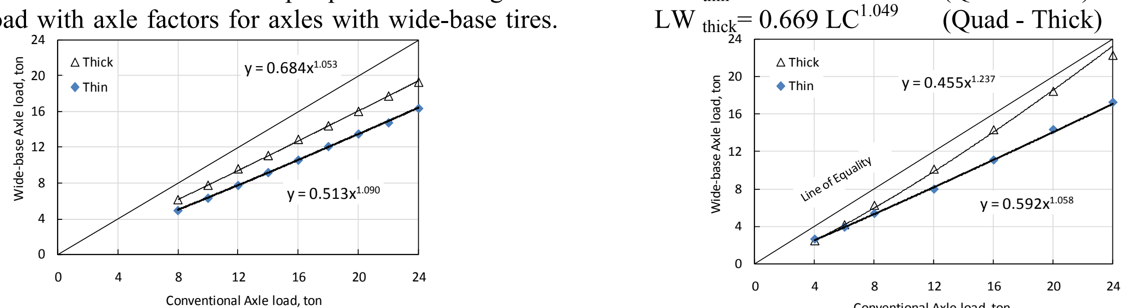
Using the same sequences, the relationships for tridem and quad axle loads that relate the axle loads with wide-base tires which cause the same fatigue damage as conventional tires were developed as shown below. Figure 7 illustrates these relationships.

$LW_{thin} = 0.483\ LC^{1.097}$ (Tridem -Thin) (17)

$LW_{thick} = 0.678\ LC^{1.049}$ (Tridem -Thick) (18)

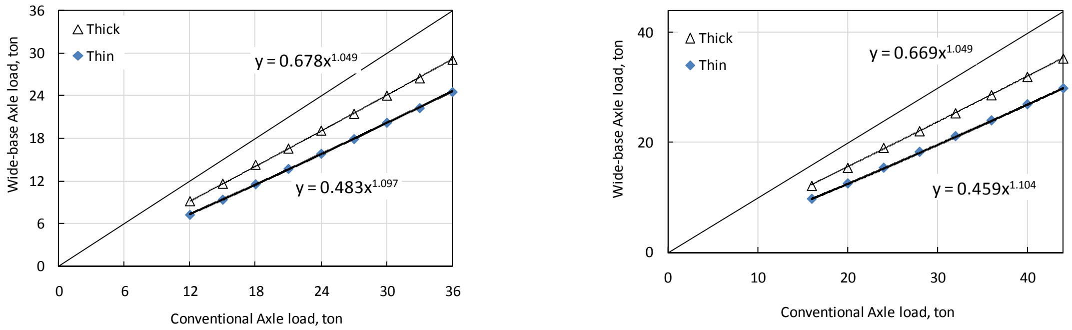
$LW_{thin} = 0.459\ LC^{1.104}$ (Quad - Thin) (19)

$LW_{thick} = 0.669\ LC^{1.049}$ (Quad - Thick) (20)



a) Fatigue Damage b) Rutting Damage

Figure 6: Tandem axle load with wide-base tire versus tandem axle load with dual tires



a) Tridem axle b) Quad axle

Figure 7: Axle load with wide-base tire versus axle load with dual tires – Fatigue

3.2.2. Rutting

The axle factors for rutting damage were calculated from equations 3and 4, then and the results were used to develop the following equations for thin and thick pavement.

$LW_{Thin} = 2.244 * AF_W^{1.771}$ (21)

$LW_{Thick} = 2.982 * AF_W^{1.627}$ (22)

Where: LW is the tandem axle load with wide-base tire and AF_W is its rutting axle factors.

Similar to fatigue, a relationship between the tandem axle load with wide-base tire and the load of conventional tire that cause the same pavement rutting damage was developed for both thin and thick pavement. Figure 6-b illustrates these relations and the following Equations are resulting from these relationships for thin and thick pavement.

$LW_{thin} = 0.592\ LC^{1.058}$ (Tandem – Thin) (23)

$LW_{thick} = 0.455\ LC^{1.237}$ (Tandem – Thick) (24)

Where, LW is the tandem axle load with wide-base tire that cause the same rutting damage as tandem axle load with conventional dual tire LC. Figure 6.b indicates that there are no significant differences between the tandem axle loads with conventional tires and those of wide-base tires that cause the same rutting damage for thick pavement. This is due to the fact that the vertical compressive strain resulting from both tire configurations becomes close in the peak values under multiple axles loads.

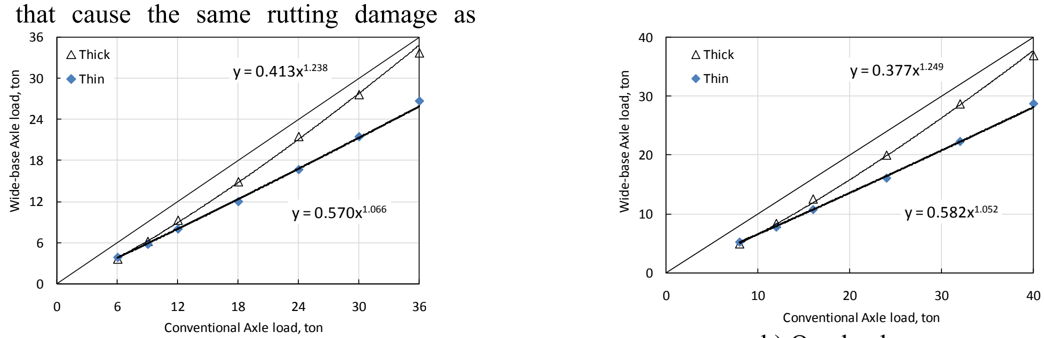
Similar to rutting relationships for single and tandem axles, the relationships between axle loads with wide-base tires which cause the same fatigue damage as conventional tires were developed as shown below. Figure 8 shows the graphical representations of these Equations.

$LW_{thin} = 0.570\ LC^{1.066}$ (Tridem -Thin) (25)

$LW_{thick} = 0.413\ LC^{1.238}$ (Tridem -Thick) (26)

$LW_{thin} = 0.582\ LC^{1.052}$ (Quad - Thin) (27)

$LW_{thick} = 0.377\ LC^{1.249}$ (Quad - Thick) (28)



a) Tridem axle b) Quad axle

Figure 8: Axle load with wide-base tire versus axle load with dual tires – Rutting

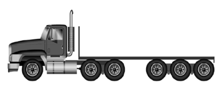
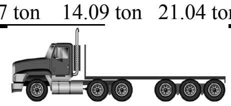
3.3. Calculation of Axle Loads with Wide-Base Tires

This section is dedicated to develop summary table that have the relationships between legal axle loads with wide-base tires and their corresponding weight for axles with conventional tires which have the same fatigue and rutting damage for both thin and thick pavements. The developed equations in this study were utilized to determine the load for all axle configurations with wide-base tires, see Table 2. The legal axle loads with wide-base tires can be used to compose the legal load of any truck configurations that have a combination of single, tandem, tridem, and quad axles. As an example, trucks 10 (Egyptian configuration) were used to convert their legal axle load with conventional tires to axle loads with wide-base tires that will cause the same fatigue and rutting damage for both thin and thick pavements, see Table 3. The resulting axle loads showed that the rutting axle loads of with wide-base tires are higher than that for fatigue.

Table 2: Corresponding legal axle loads of wide-base tires for fatigue and rutting damage

Axle type	Equation		Axle load, ton		
	Fatigue damage	Rutting damage	Conv.	Wide-base Fatigue Damage	Wide-base Rutting Damage
Single	$LW_{thin}= 0.546\ LC^{1.089}$	$LW_{thin}= 0.576\ LC^{1.037}$	13	8.92	8.23
	$LW_{thick}= 0.715\ LC^{1.048}$	$LW_{thick}= 0.497\ LC^{1.182}$		10.51	10.31
Tandem	$LW_{thin}= 0.513\ LC^{1.090}$	$LW_{thin}= 0.592\ LC^{1.058}$	20	13.43	14.09
	$LW_{thick}= 0.684\ LC^{1.053}$	$LW_{thick}= 0.455\ LC^{1.237}$		16.03	18.51
Tridem	$LW_{thin}= 0.483\ LC^{1.097}$	$LW_{thin}= 0.570\ LC^{1.066}$	30	20.15	21.04
	$LW_{thick}= 0.678\ LC^{1.049}$	$LW_{thick}= 0.413\ LC^{1.238}$		24.03	27.84
Quad	$LW_{thin}= 0.459\ LC^{1.104}$	$LW_{thin}= 0.582\ LC^{1.052}$	40	26.94	28.20
	$LW_{thick}= 0.669\ LC^{1.049}$	$LW_{thick}= 0.377\ LC^{1.249}$		32.06	37.78

Table 3: Example for equivalent truck load with conventional and wide-base tires for Fatigue and rutting damage

Axle type / Pavement type	Truck configuration	Total truck weight, ton	
		Fatigue Damage	Rutting Damage
Conventional Tires	 7 ton 20 ton 30 ton	57	
Wide-base tire (Thin pavement)	 Fatigue 7 ton 13.43 ton 20.15 ton Rutting 7 ton 14.09 ton 21.04 ton	40.58	42.13
Wide-base tire (Thick pavement)	 Fatigue 7 ton 16.03 ton 24.03 ton Rutting 7 ton 18.51 ton 27.84 ton	47.06	53.35

4. Conclusions

This study is focusing on the conversion of the axle loads with conventional tires to wide-base tires which cause the same fatigue and rutting damage. The analysis involved developing relationships between axle loads at different load values and the axle factors for axle configurations including single, tandem, tridem, and quad axles. Then, the axle loads with wide base-tires that have the same axle factors were determined for fatigue and rutting damage. In general, the results showed that the thick pavement can carry more axle loads for fatigue and rutting for all axle configurations. The axle loads with wide-base tires that cause the same fatigue and rutting damage is less than the same axle loads with conventional tires. However, axle loads with wide-base tires for fatigue appear to be less than the ones for rutting damage for all configurations as indicated in the total gross weight of the trucks. Moreover, for rutting damage, the load of the axles with wide-base tires become closer to the load for the same axles with conventional tire as the number of axles increase within the axle group.

The reason for axle loads with wide-base tires is less for fatigue damage that for rutting is refer to the critical response of fatigue damage is the tensile strain at the bottom of the asphalt layer which is close to the surface where the strain due to wide-base tire is larger than the conventional tires. On contrary, the critical response for rutting damage is the vertical compressive strain at the middle of pavement layers where the deeper the layer the vertical compressive strain for wide-base and conventional tires become closer in values due to the strain distributions with depth.

Corresponding author
Mahmoud Solyman
Construction Engineering and Utilities Department, Zagazig University, Egypt
elsaied2000@yahoo.com

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