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Flexible Pavement Damage Due to The Legal and Illegal Axle Loads

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ملخص البحث

تعتبر الشاحنات من اهم وسائل النقل الموجودة فى مصر. وهناك أنواع مختلفة من عربات النقل ذات أحمال واشكال محاور مختلفة, والتى تسبب انواع مختلفة من ضررالرصف. الهدف الأساسى من هذا البحث هو عمل مقارنة بين الضرر الذى يحدث فى الرصف المرن نتيجة أحمال المحاور القانونية والغير قانونية. تم دراسة عدة محاور مثل محاور أحادية، ثنائية، ثلاثية، وكذلك رباعية. وتم إختيار نوعين من القطاعات الإسفلتية بالطرق المصرية، طريق القاهرة-الأسكندرية (الزراعى) وطريق القاهرة-دمياط بسماكات وخصائص مواد ممثلة لمعظم قطاعات الأسفلت المرن وتم أختيار هذان الطريقان لأنهما يسهمان بقوة فى عملية نقل البضائع فى مصرويستقبلان معظم عربات النقل ذات أحمال المحاور العالية. لكى يتم تحديد ومقارنة الضرر فى القطاعين السابقين نتيجة أحمال المحاور القانونية والغير قانونية, تم عمل تحليلات لحساب الإنفعال (Strain) فى الطبقات المختلفة للأسفلت بواسطة برنامج KENLAYER. وبواسطة هذا البرنامج تم حساب إنفعال الشد الطولى اسفل الطبقة السطحية وإنفعال الضغط الرأسى عند منتصف الطبقة السطحية ومنتصف طبقة الأساس وكذلك عند منتصف ست طبقات متتابعة من طبقات الأرض الطبيعية سمك كل طبقة متر واحد. تم إستخدام هذه الإنفعالات لحساب التلف نتيجة الكلال Fatigue والتخدد Rutting و تم إستخدام طريقة مساحة الإنفعال Strain area لحساب الكلال ونموذج VESYS لحساب التخدد. وتم حساب معامل المحاور Axle Factors لكل أشكال المحاور المختلفة.

ABSTRACT

Trucks are considered one of the most important means in transporting in Egypt. Different truck types with varying axle configurations cause different types of pavement distresses. The objective of this study is to make a comparison between the flexible pavement damage due to the legal and illegal axle loads. Several axle configurations including single, tandem, tridem and quad axle were considered in this study. Two flexible pavement sections were analyzed from two Egyptian roads, Cairo-Alex (agric) and Cairo-Damietta roads with thicknesses and material properties representing majority of the pavement cross-sections. These two roads were chosen because they contribute strongly in the process of moving goods in Egypt and they hosts most of trucks with heavy multiple axle loads. To quantify and compare the damage for the two pavement sections due to the legal and illegal axle loads, 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 layer and the vertical compressive strain at the middle of the HMA, base, and six 40-in subsequent layers of subgrade under different axle configurations were calculated. 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.

1. INTRODUCTION

Truck traffic is a major factor in pavement design because truck loads are the primary cause of pavement distresses. This study aims to make a comparison between the flexible pavement damage due to the legal and illegal axle loads. The prediction of flexible pavement failure has been empirically developed by correlating the multi-layered elastic theory results with the results of field tests such as the AASHO Road Test. The two main concerns with flexible pavements are fatigue cracking and rutting. Fatigue cracking is mainly caused by the accumulation of horizontal tensile strain at the bottom of the hot mix asphalt layer. Rutting (vertical permanent deformation) is generally known to be induced by the accumulation of vertical compressive strains on the top of the subgrade layer due to the repetition of traffic loadings.

2. BACKGROUND

There are several models to investigate the fatigue and rutting pavement damage resulting from single and multiple axle loads. Numerous fatigue models have been formulated based on laboratory testing and calibrated with the field performance and accelerated pavement testing. Some of the well-known equations include those developed by Asphalt Institute (AI) and Shell:

$$N_f = 0.0796 * \varepsilon_t^{-3.291} * E_{ac}^{-0.854}$$ (AI) (Shook, 1982) (1)

1 $$N_f = 0.0685 * \varepsilon_t^{-5.671} * E_{ac}^{-2.364}$$ (Shell) (Claussen, 1977) (2)

Where

N_f = the number of load repetitions to fatigue failure,

ε_t = the horizontal tensile strain at the bottom of the HMA layer, and

E_{ac} = the dynamic modulus of elasticity of asphalt concrete.

2

Monismith, (1992) presented a set of equations translating mechanical response to pavement performance as the basis of mechanistic-empirical (M-E) pavement design. Equations, called performance equations, have been developed to empirically relate the number of cycles to failure, N_f, for a given measured or calculated pavement response.

$N_f = k_1 (1/\varepsilon_t)^{k_2}$ (3)

Where

N_f = Number of cycles to failure,

□□□□□□□□□□□□□□□= Measured pavement response, and

k_1, k_2 = Empirical constants, $k_1 = 2.831{*}e^{-6}$ and $k_2 = 3.148$.

There are two mechanistic modeling approaches have been developed by Huang 1993, to predict rutting. The first approach is referred to the subgrade strain model, while the second approach considers permanent deformation within each pavement layer. The most widely used equation in the first approach is:

$$N_d = f_4\,(\square_v)^{-f5} \qquad (4)$$

Where:

N_d = number of allowable load applications,

f_4, f_5 = constants determined from road tests or field performance studies, and

□□□□□□□□□□□□□□□□□□□□□□$_v$ = vertical compressive strain on top of the subgrade.

The VESYS rutting model (Moavenzadeh, 1974) was derived so that each term of the equation corresponds to one pavement layer with two unique permanent deformation parameters (□ and □). The form of the model is more applicable for use in this research as shown below (Ali and Tayabji, 2000 and Ali *et al.* 1998).

$$\rho_{\mathrm{p}} = h_{\mathrm{AC}} \frac{\mu_{\mathrm{AC}}}{1\text{-}\alpha_{\mathrm{AC}}} \left(\sum_{i=1}^{K} (n_i)^{1-\alpha_{\mathrm{AC}}} \left(\varepsilon_{ei,\mathrm{AC}}\right)\right) + h_{\mathrm{base}} \frac{\mu_{\mathrm{base}}}{1\text{-}\alpha_{\mathrm{base}}} \left(\sum_{i=1}^{K} (n_i)^{1-\alpha_{\mathrm{base}}} \left(\varepsilon_{ei,\mathrm{base}}\right)\right)$$
$$+ h_{\mathrm{SG}} \frac{\mu_{\mathrm{SG}}}{1\text{-}\alpha_{\mathrm{SG}}} \left(\sum_{i=1}^{K} (n_i)^{1-\alpha_{\mathrm{SG}}} \left(\varepsilon_{\mathrm{ei,SG}}\right)\right)$$

(5)

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,

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

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

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

Ullidtz's, 1987 literature review shows that the subgrade strain models (AI and Shell models) are based on unreasonable assumptions, since they only account for subgrade rutting while neglecting upper pavement layer rutting. He also, reported that the subgrade rutting in the AASHO road test was only 9% of the total surface rutting as shown in Table 1.

Table 1: Percent layer distribution of rutting (Ullidtz, 1987)

Pavement layer	Percent observed rutting
Asphalt concrete	32
Base	14
Subbase	45
Subgrade	9

2.1 Damage Calculation Due to Multiple axle loads

Several laboratory fatigue and rutting tests were performed to determine the fatigue and rutting damage due to traffic loads, Matthews et al, 1993 and Ayres, 2002. However, all of these tests were based on a single load pulse with rest period. In reality, the pavement is subjected to multiple load pulses due to the passage of large axle group trucks.

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.

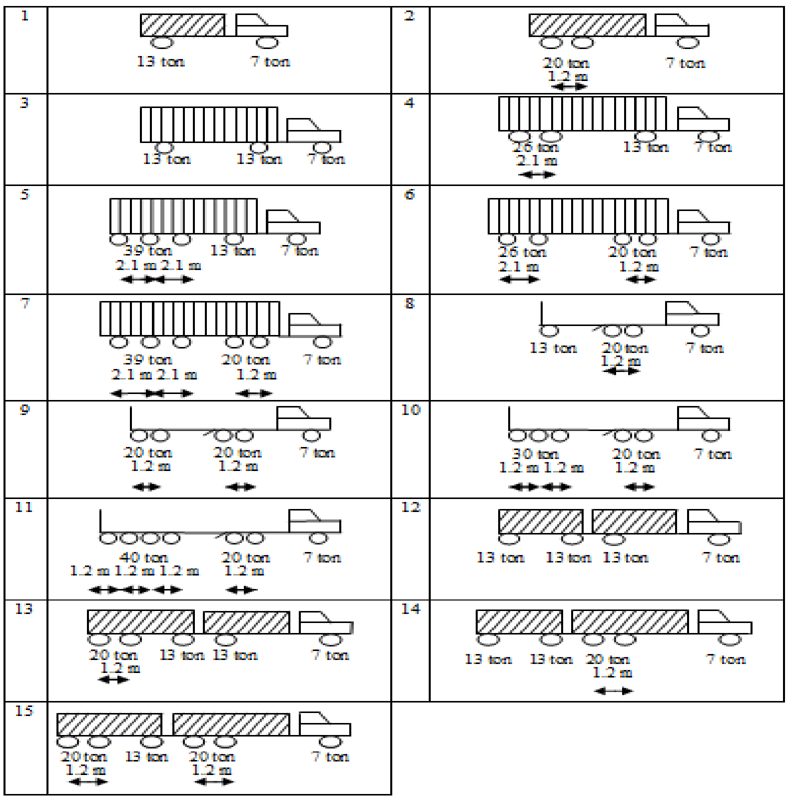
2.1.1 KENLAYER Computer Program

The KENLAYER computer program was developed by Huang (1993). KENLAYER can be applied only to flexible pavements with no joints or rigid layers. The backbone of KENLAYER is the solution for an elastic multilayer system under a circular loaded area. The solutions are superimposed for multiple wheels, applied iteratively for nonlinear layers, and collocated at various times for viscoelastic layers. As a result, KENLAYER can be applied to layer systems under single, tandem, tridem axles only with each layer behaving differently, linear elastic, nonlinear elastic, or viscoelastic. KENLAYER can be applied to a maximum of 19 layers with output at 10 different radial coordinates and 19 different vertical coordinates, or a total of 190 points. For multiple wheels, in addition to the 19 vertical coordinates, solutions can be obtained at a total of 25 points by specifying the x and y coordinates of each point. Damage analysis can be made by dividing each year into a maximum of 12 periods, each with a different set of material properties. Each period can have a maximum of 12 load groups, either single or multiple. The damage caused by fatigue cracking and permanent deformation in each period over all load groups is summed up to evaluate the design life, The KENLAYER computer program consider truck speed equal zero (Huang 1993).

3. METHODOLOGY OF RESEARCH

There are several axle configurations which vary from single axle to eight-axle group. However, majority of the axle configurations that are existing over the Egyptian road network are single, tandem, tridem and in rare situations quad axle. This study will include analysis of single, tandem, tridem, and quad axle configuration. Similar to axle configurations, there is several truck configurations are exist worldwide. In this study, the main concern is the truck configurations that are using the Egyptian road network. All truck configurations included in the Egyptian Code for Urban and Rural Road Works will be considered in the analysis. Table 2 shows the fifteen truck configurations.

Table 2: Egyptian axle/truck configurations and axle load



3.1 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 will be used to calculate the horizontal tensile strain at the bottom of the hot mix asphalt layer under the standard axle and all axles considered in the study (single, tandem, tridem and quad) due to the legal and illegal axle loads. To calculate the axle factors for different axle configurations, the strain area fatigue model was used since it is the closest damage compared with the laboratory test. Equation 6 shows the strain area of the fatigue model. It should be noted that the model in close agreement with the laboratory results, however since the model was not calibrated on a field performance data, it should not be used to calculate actual fatigue life of a pavement system on service. Hence, the model will be used to calculate the relative fatigue damage due to the legal and illegal axle loads. To compare the damage due to the legal and illegal axles relative to the standard axle, fatigue strain area model will be used to calculate the Axle Factors (AF).

$$N_f = 18.865 * A_o^{-0.478} \qquad (6)$$

Where:

N_f = is the number of cycles to fatigue failure, and

A_o = is the initial area under the strain curve for standard axle or any axle group.

and

AF = Damage of axle / Damage of the standard axle

$$= N_{f\,\text{std axle}} / N_{f\,\text{axle}} = (A_{o\,\text{std axle}} / A_{o\,\text{axle}})^{-0.478} \qquad (7)$$

3.2 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 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 8 shows the form of the model.

$$\rho_\text{p} = h_\text{AC}\frac{\mu_\text{AC}}{1\text{-}\alpha_\text{AC}}\left(\sum_{i=1}^{K}(n_i)^{1-\alpha_\text{AC}}\left(\varepsilon_{ei,\text{AC}}\right)\right) + h_\text{base}\frac{\mu_\text{base}}{1\text{-}\alpha_\text{base}}\left(\sum_{i=1}^{K}(n_i)^{1-\alpha_\text{base}}\left(\varepsilon_{ei,\text{base}}\right)\right) + h_\text{SG}\frac{\mu_\text{SG}}{1\text{-}\alpha_\text{SG}}\left(\sum_{i=1}^{K}(n_i)^{1-\alpha_\text{SG}}\left(\varepsilon_\text{ei,SG}\right)\right) \qquad (8)$$

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),

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

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

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

The only concern about the VESYS rutting model is that the model has a permanent deformation parameters □□and□□□ that are section specific and rely on the material properties and environmental condition of that pavement section. In this study, the VESYS rutting model will be used to compare the rutting damage due to the legal and illegal axles and not intention of predicting the actual rut depth due to these axles. Several studies were conducted to calibrate the permanent deformation parameters of VESYS rutting models, Salama 2005 summarized all of these studies. In this study, the permanent deformation parameters value were chosen as an average based on Kenis and Wang, 1997 study. Table 3 shows the permanent deformation parameter for VESYS rutting model.

Table 3: Values of □ and □□(Kenis and Wang, 1997)

Pavement layer	□	□
HMA	0.65	0.8
Base	0.7	0.4
Subgrade	0.75	0.025

The rutting Axle Factors (AFs) were calculated from the following Equation.

$$\text{Rutting AFs} = \text{Rut Depth}_{\text{axle}} / \text{Rut Depth}_{\text{standard axle}} \quad (9)$$

The following table summarizes the research methodology in term of axle configuration, axle loading, the forward analysis software and the performance model that will be used to calculate the pavement damage due to the legal and illegal axle loads for different axle configurations.

2.1 *Table 4: 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	Legal axle load, 12.5 % over load, 25 % over load, 50 % over load, and Maximum over load.
Forward analysis software	Several MLET and FEM software	KENLAYER (MLET)
Fatigue model	Several fatigue models	Strain area model
Rutting model	Several Rutting models	Total rutting at the pavement surface using VESYS model

In our study, strain area and peak strain methods will be used to calculate the fatigue and rutting damage of pavement, respectively. To investigate the flexible pavement damage due to the legal and illegal axle loads. Two flexible pavement sections were analyzed from two Egyptian roads, Cairo-Alex (agric) and Cairo-Damietta roads. The thicknesses and material properties of pavement layers for the two roads are shown in Table 5 the properties include modulus of elasticity (E) and Poisson ratio (μ).

Table 5: Thicknesses and material properties of pavement layers for the two roads

Cross-sections	HMA			Base			Subgrade	
	Thickness, in	E, psi	μ	Thickness, in	E, psi	μ	E, psi	μ
Cairo-Alex (agric)	4	500000	0.4	10	30000	0.35	10000	0.45
Cairo-Damietta	4.4	500000	0.4	16	30000	0.35	10000	0.45

It is worth mentioning that the filed data of axle loads was limited to the over axle loads only, as there were no records for the illegal axle loads. Table 6 shows the over axle loads for the illegal axle loads which considered in our study.

Table 6: The over axle loads for the illegal axle loads

Loading Conditions	Axle Loads (ton)						
	Single	Single	Tandem	Tandem	Tridem	Tridem	Quad
full load (Legal)	13	10	26	20	39	30	40
12.5 % over load	15	11.25	30	22.5	45	33.75	45
25 % over load	16.5	12.5	33	25	49.5	37.5	50
50 % over load	20	15	40	30	60	45	60
maximum over load	23	17.5	46	35	69	52.5	70

4. ANALYSIS AND DISCUSSIONS

4.1 Fatigue

Table 7, Table 8, Table 9, Table 10 and Table 11 shows the Axle Factors (AFs) of fatigue damage calculated from the strain area method due to different axle configurations (single, tandem, tridem and quad) for the two Egyptian roads, Cairo-Alex (agric) and Cairo-Damietta roads due to the legal and illegal axle loads. The illegal axle loads which considered in this study are 12.5 % over load, 25 % over load, and 50 % over load and maximum over load. The results show that the fatigue damage increasing with the increased the axle load because the area under the tensile strain pulse is increasing with the increased the axle load.

Table 7: Axle Factors of fatigue damage due to different axle configurations for the two roads due to legal axle load

Axle configurations	Axle load ton (kips)	Load / tire ton (kips)	Tire pressure (psi)	Cairo-Alex (Agric)			Cairo- Damietta		
				$A_0 * 10^{-5}$ (in^2)	N_f	AF	$A_0 * 10^{-5}$ (in^2)	N_f	AF
Standard	8.18 t (18.0 kips)	2.05 t (4.500 kips)	80	476.5	242	1	410.2	261	1
Single	13.00 t (28.60 kips)	3.25 t (7.150 kips)	120	745.8	196	1.24	642.3	210	1.24
Tandem	26.00 t (57.20 kips)	3.25 t (7.150 kips)	120	1488.1	140	1.72	1281.4	151	1.72
Tridem	39.00 t (85.80 kips)	3.25 t (7.150 kips)	120	2227.2	116	2.09	1918.2	124	2.09
Single	10.00 t (22.00 kips)	2.50 t (5.500 kips)	120	611.6	215	1.13	525.6	231	1.13
Tandem	20.00 t (44.00 kips)	2.50 t (5.500 kips)	120	1221.5	154	1.57	1048.9	166	1.57
Tridem	30.00 t (66.00 kips)	2.50 t (5.500 kips)	120	1829.8	127	1.90	1571.4	137	1.90
Quad	40.00 t (88.00 kips)	2.50 t (5.500 kips)	120	2436.3	111	2.18	2092.7	119	2.18

Table 8: Axle Factors of fatigue damage due to different axle configurations for the two roads due to 12.5 % over load

Axle configurations	Axle load ton (kips)	Load / tire ton (kips)	Tire pressure (psi)	Cairo-Alex (Agric)			Cairo- Damietta		
				$A_0 *10^{-5}$ (in^2)	N_f	AF	$A_0 *10^{-5}$ (in^2)	N_f	AF
Standard	8.18 t (18.0 kips)	2.05 t (4.500 kips)	80	476.5	242	1	410.2	261	1
Single	15.00 t (33.00 kips)	3.75 t (8.250 kips)	120	832.3	186	1.31	717.5	199	1.31
Tandem	30.00 t (66.00 kips)	3.75 t (8.250 kips)	120	1661.1	133	1.82	1431.5	143	1.82
Tridem	45.00 t (99.00 kips)	3.75 t (8.250 kips)	120	2486.4	110	2.20	2143.6	118	2.20
Single	11.25 t (24.75 kips)	2.81 t (6.187 kips)	120	669.3	206	1.18	575.7	222	1.18
Tandem	22.50 t (49.50 kips)	2.81 t (6.187 kips)	120	1336.6	148	1.64	1148.8	159	1.64
Tridem	33.75 t (74.25 kips)	2.81 t (6.187 kips)	120	2002.5	122	1.99	1721.3	131	1.99
Quad	45.00 t (99.00 kips)	2.81 t (6.187 kips)	120	2666.5	106	2.28	2292.5	114	2.28

Table 9: Axle Factors of fatigue damage due to different axle configurations for the two roads due to 25 % over load

Axle configurations	Axle load ton (kips)	Load / tire ton (kips)	Tire pressure (psi)	Cairo-Alex (Agric)			Cairo- Damietta		
				$A_0 *10^{-5}$ (in^2)	N_f	AF	$A_0 *10^{-5}$ (in^2)	N_f	AF
Standard	8.18 t (18.0 kips)	2.05 t (4.500 kips)	80	476.5	242	1	410.2	261	1
Single	16.50 t (36.30 kips)	4.125 t (9.075 kips)	120	893.8	180	1.35	771	193	1.35
Tandem	33.00 t (72.60 kips)	4.125 t (9.075 kips)	120	1784.7	129	1.88	1538.3	138	1.88
Tridem	49.50 t (108.90 kips)	4.125 t (9.075 kips)	120	2672	106	2.28	2303.9	114	2.28
Single	12.50 t (27.50 kips)	3.125 t (6.875 kips)	120	725.1	199	1.22	624.2	213	1.22
Tandem	25.00 t (55.00 kips)	3.125 t (6.875 kips)	120	1448.1	142	1.70	1245.7	153	1.70
Tridem	37.50 t (82.50 kips)	3.125 t (6.875 kips)	120	2169.8	117	2.06	1866.7	126	2.06
Quad	50.00 t (110.00 kips)	3.125 t (6.875 kips)	120	2889.4	102	2.37	2486.4	110	2.37

Table 10: Axle Factors of fatigue damage due to different axle configurations for the two roads due to 50 % over load

Axle configurations	Axle load ton (kips)	Load / tire ton (kips)	Tire pressure (psi)	Cairo-Alex (Agric)			Cairo- Damietta		
				$A_0 *10^{-5}$ (in^2)	N_f	AF	$A_0 *10^{-5}$ (in^2)	N_f	AF
Standard	8.18 t (18.0 kips)	2.05 t (4.500 kips)	80	476.5	242	1	410.2	261	1
Single	20.00 t (44.00 kips)	5.00 t (11.00 kips)	120	1032.5	168	1.45	890.9	180	1.45
Tandem	40.00 t (88.00 kips)	5.00 t (11.00 kips)	120	2061.1	120	2.01	1777.6	129	2.01
Tridem	60.00 t (132.00 kips)	5.00 t (11.00 kips)	120	3086.5	99	2.44	2663.9	106	2.44
Single	15.00 t (33.00 kips)	3.75 t (8.250 kips)	120	832.3	186	1.31	717.5	199	1.31
Tandem	30.00 t (66.00 kips)	3.75 t (8.250 kips)	120	1662.1	133	1.82	1431.7	143	1.82
Tridem	45.00 t (99.00 kips)	3.75 t (8.250 kips)	120	2490.9	110	2.20	2145.7	118	2.20
Quad	60.00 t (132.00 kips)	3.75 t (8.250 kips)	120	3317.6	96	2.53	2858.9	103	2.53

Table 11: Axle Factors of fatigue damage due to different axle configurations for the two roads due to maximum over load

Axle configurations	Axle load ton (kips)	Load / tire ton (kips)	Tire pressure (psi)	Cairo-Alex (Agric)			Cairo- Damietta		
				A_0 *10^{-5} (in^2)	N_f	AF	A_0 *10^{-5} (in^2)	N_f	AF
Standard	8.18 t (18.0 kips)	2.05 t (4.500 kips)	80	476.5	242	1	410.2	261	1
Single	23.00 t (50.50 kips)	5.75 t (12.65 kips)	120	1145.9	159	1.52	989.1	171	1.52
Tandem	46.00 t (101.20 kips)	5.75 t (12.65 kips)	120	2287.5	114	2.12	1973.3	123	2.12
Tridem	69.00 t (151.80 kips)	5.75 t (12.65 kips)	120	3426.7	94	2.57	2958.3	101	2.57
Single	17.50 t (38.50 kips)	4.375 t (9.625 kips)	120	934.3	176	1.38	806.1	189	1.38
Tandem	35.00 t (77.00 kips)	4.375 t (9.625 kips)	120	1865.8	126	1.92	1608.4	135	1.92
Tridem	52.50 t (115.50 kips)	4.375 t (9.625 kips)	120	2796.4	104	2.33	2411	111	2.33
Quad	70.00 t (154.00 kips)	4.375 t (9.625 kips)	120	3725.3	90	2.67	3213	97	2.67

Table 12 shows the Axle Factors percentage of fatigue damage due to different axle configurations for the two Egyptian roads, Cairo-Alex (agric) and Cairo-Damietta roads due to the legal and illegal axle loads. The results show that the fatigue damage increasing with an average of 4.9 % with the increased axle loads about 12.5 %, and the fatigue damage increasing with an average of 8.7 % with the increased axle loads about 25 %, and the fatigue damage increasing with an average of 16.3 % with the increased axle loads about 50 % and the fatigue damage increasing with an average of 22.6 % with the increased axle loads to a maximum over load.

Table 12: Axle Factors percentage of fatigue damage due to different axle configurations for the two roads due to legal and illegal axle loads

Axle configurations	Legal axle	12.5 % over load		25 % over load		50 % over load		Max over load	
		Cairo-Alex (Agric)	Cairo-Damietta	Cairo-Alex (Agric)	Cairo-Damietta	Cairo-Alex (Agric)	Cairo-Damietta	Cairo-Alex (Agric)	Cairo-Damietta
Single	1	1.050 (5.0 %)	1.050 (5.0 %)	1.084 (8.4 %)	1.084 (8.4 %)	1.164 (16.4 %)	1.164 (16.4 %)	1.224 (22.4 %)	1.224 (22.4 %)
Tandem	1	1.051 (5.1 %)	1.051 (5.1 %)	1.088 (8.8 %)	1.088 (8.8 %)	1.164 (16.4 %)	1.164 (16.4 %)	1.228 (22.8 %)	1.228 (22.8 %)
Tridem	1	1.050 (5.0 %)	1.050 (5.0 %)	1.088 (8.8 %)	1.088 (8.8 %)	1.163 (16.3 %)	1.163 (16.3 %)	1.228 (22.8 %)	1.228 (22.8 %)
Quad	1	1.046 (4.6 %)	1.046 (4.6 %)	1.087 (8.7 %)	1.087 (8.7 %)	1.160 (16.0 %)	1.160 (16.0 %)	1.225 (22.5 %)	1.225 (22.5 %)
Average	1	1.049 (4.9 %)		1.087 (8.7 %)		1.163 (16.3 %)		1.226 (22.6 %)	

4.2 Rutting

Table 13, Table 14, Table 15, Table 16 and Table 17 shows the Axle Factors (AFs) of total surface rutting damage due to different axle configurations (single, tandem, tridem and quad) for the two Egyptian roads, Cairo-Alex (agric) and Cairo-Damietta roads due to the legal and illegal axle loads. The results show that the rutting damage increasing with the increased the axle load because increased axle load increases the vertical compressive strain and that gave more total surface rutting damage.

Table 13: Axle Factors of total surface rutting damage and total layer rut depth due to different axle configurations for the two roads due to legal axle load

Axle configurations	Axle load ton (kips)	Load / tire ton (kips)	Tire pressure (psi)	Cairo-Alex (Agric)					Cairo-Damietta				
				HMA rut (in)	Base rut (in)	SG rut (in)	Total rut (in)	AF	HMA rut (in)	Base rut (in)	SG rut (in)	Total rut (in)	AF
Standard	8.18 t (18.00 kips)	2.05 t (4.500 kips)	80	0.076	0.312	0.04	0.428	1	0.089	0.355	0.031	0.475	1
Steering	7.00 t (15.40 kips)	3.50 t (7.700 kips)	120	0.118	0.438	0.038	0.594	1.39	0.138	0.464	0.028	0.63	1.33
Single	13.00 t (28.60 kips)	3.25 t (7.150 kips)	120	0.113	0.492	0.064	0.669	1.56	0.132	0.562	0.049	0.743	1.56
Tandem	26.00 t (57.20 kips)	3.25 t (7.150 kips)	120	0.235	1.016	0.228	1.479	3.46	0.276	1.19	0.196	1.662	3.5
Tridem	39.00 t (85.80 kips)	3.25 t (7.150 kips)	120	0.352	1.524	0.342	2.218	5.18	0.414	1.784	0.294	2.492	5.25
Single	10.00 t (22.00 kips)	2.50 t (5.500 kips)	120	0.122	0.388	0.049	0.559	1.31	0.14	0.439	0.038	0.617	1.3
Tandem	20.00 t (44.00 kips)	2.50 t (5.500 kips)	120	0.266	0.891	0.291	1.448	3.38	0.31	1.084	0.256	1.65	3.47
Tridem	30.00 t (66.00 kips)	2.50 t (5.500 kips)	120	0.399	1.337	0.436	2.172	5.07	0.466	1.626	0.384	2.476	5.21
Quad	40.00 t (88.00 kips)	2.50 t (5.500 kips)	120	0.531	1.782	0.582	2.895	6.76	0.621	2.168	0.512	3.301	6.95

Table 14: Axle Factors of total surface rutting damage and total layer rut depth due to different axle configurations for the two roads due to 12.5 % over load

Axle configurations	Axle load ton (kips)	Load / tire ton (kips)	Tire pressure (psi)	Cairo-Alex (Agric)					Cairo-Damietta				
				HMA rut (in)	Base rut (in)	SG rut (in)	Total rut (in)	AF	HMA rut (in)	Base rut (in)	SG rut (in)	Total rut (in)	AF
Standard	8.18 t (18.00 kips)	2.05 t (4.500 kips)	80	0.076	0.312	0.04	0.428	1	0.089	0.355	0.031	0.475	1
Steering	7.50 t (16.50 kips)	3.75 t (8.250 kips)	120	0.116	0.464	0.041	0.621	1.45	0.136	0.493	0.03	0.659	1.39
Single	15.00 t (33.00 kips)	3.75 t (8.250 kips)	120	0.107	0.56	0.074	0.741	1.73	0.126	0.644	0.057	0.827	1.74
Tandem	30.00 t (66.00 kips)	3.75 t (8.250 kips)	120	0.225	1.157	0.264	1.646	3.85	0.268	1.364	0.227	1.859	3.91
Tridem	45.00 t (99.00 kips)	3.75 t (8.250 kips)	120	0.338	1.736	0.395	2.469	5.77	0.402	2.047	0.34	2.789	5.87
Single	11.25 t (24.75 kips)	2.812 t (6.187 kips)	120	0.118	0.432	0.056	0.606	1.42	0.137	0.491	0.042	0.67	1.41
Tandem	22.50 t (49.50 kips)	2.812 t (6.187 kips)	120	0.26	0.993	0.327	1.58	3.69	0.307	1.213	0.288	1.808	3.81
Tridem	33.75 t (74.25 kips)	2.812 t (6.187 kips)	120	0.391	1.49	0.491	2.372	5.54	0.461	1.82	0.432	2.713	5.71
Quad	45.00 t (99.00 kips)	2.812 t (6.187 kips)	120	0.521	1.987	0.654	3.162	7.39	0.614	2.426	0.576	3.616	7.61

Table 15: Axle Factors of total surface rutting damage and total layer rut depth due to different axle configurations for the two roads due to 25 % over load

Axle configurations	Axle load ton (kips)	Load / tire ton (kips)	Tire pressure (psi)	Cairo-Alex (Agric)					Cairo-Damietta				
				HMA rut (in)	Base rut (in)	SG rut (in)	Total rut (in)	AF	HMA rut (in)	Base rut (in)	SG rut (in)	Total rut (in)	AF
Standard	8.18 t (18.00 kips)	2.05 t (4.500 kips)	80	0.076	0.312	0.04	0.428	1	0.089	0.355	0.031	0.475	1
Steering	8.00 t (17.60 kips)	4.00 t (8.800 kips)	120	0.114	0.49	0.043	0.647	1.51	0.134	0.523	0.032	0.689	1.45
Single	16.50 t (36.30 kips)	4.125 t (9.075 kips)	120	0.104	0.609	0.081	0.794	1.86	0.123	0.704	0.062	0.889	1.87
Tandem	33.00 t (72.60 kips)	4.125 t (9.075 kips)	120	0.219	1.259	0.29	1.768	4.13	0.262	1.492	0.249	2.003	4.22
Tridem	49.50 t (108.90 kips)	4.125 t (9.075 kips)	120	0.329	1.889	0.435	2.653	6.2	0.398	2.291	0.399	3.088	6.5
Single	12.50 t (27.50 kips)	3.125 t (6.875 kips)	120	0.114	0.476	0.062	0.652	1.52	0.133	0.543	0.047	0.723	1.52
Tandem	25.00 t (55.00 kips)	3.125 t (6.875 kips)	120	0.256	1.094	0.363	1.713	4	0.304	1.342	0.32	1.966	4.14
Tridem	37.50 t (82.50 kips)	3.125 t (6.875 kips)	120	0.384	1.641	0.545	2.57	6	0.456	2.013	0.48	2.949	6.21
Quad	50.00 t (110.00 kips)	3.125 t (6.875 kips)	120	0.512	2.188	0.727	3.427	8.01	0.607	2.684	0.64	3.931	8.28

Table 16: Axle Factors of total surface rutting damage and total layer rut depth due to different axle configurations for the two roads due to 50 % over load

Axle configurations	Axle load ton (kips)	Load / tire ton (kips)	Tire pressure (psi)	Cairo-Alex (Agric)					Cairo-Damietta				
				HMA rut (in)	Base rut (in)	SG rut (in)	Total rut (in)	AF	HMA rut (in)	Base rut (in)	SG rut (in)	Total rut (in)	AF
Standard	8.18 t (18.00 kips)	2.05 t (4.500 kips)	80	0.076	0.312	0.04	0.428	1	0.089	0.355	0.031	0.475	1
Steering	9.00 t (19.80 kips)	4.50 t (9.900 kips)	120	0.11	0.541	0.049	0.7	1.64	0.13	0.582	0.036	0.748	1.57
Single	20.00 t (44.00 kips)	5.00 t (11.000 kips)	120	0.097	0.719	0.098	0.914	2.14	0.115	0.841	0.075	1.031	2.17
Tandem	40.00 t (88.00 kips)	5.00 t (11.000 kips)	120	0.208	1.49	0.351	2.049	4.79	0.251	1.783	0.302	2.336	4.92
Tridem	60.00 t (132.00 kips)	5.00 t (11.000 kips)	120	0.313	2.234	0.526	3.073	7.18	0.376	2.675	0.453	3.504	7.38
Single	15.00 t (33.00 kips)	3.75 t (8.250 kips)	120	0.107	0.56	0.074	0.741	1.73	0.126	0.644	0.057	0.827	1.74
Tandem	30.00 t (66.00 kips)	3.75 t (8.250 kips)	120	0.248	1.291	0.436	1.975	4.61	0.298	1.597	0.384	2.279	4.8
Tridem	45.50 t (99.00 kips)	3.75 t (8.250 kips)	120	0.372	1.936	0.654	2.962	6.92	0.447	2.395	0.576	3.418	7.2
Quad	60.00 t (132.00 kips)	3.75 t (8.250 kips)	120	0.5	2.582	0.872	3.954	9.24	0.596	3.193	0.768	4.557	9.59

Table 17: Axle Factors of total surface rutting damage and total layer rut depth due to different axle configurations for the two roads due to maximum over load

Axle configurations	Axle load ton (kips)	Load / tire ton (kips)	Tire pressure (psi)	Cairo-Alex (Agric)					Cairo-Damietta				
				HMA rut (in)	Base rut (in)	SG rut (in)	Total rut (in)	AF	HMA rut (in)	Base rut (in)	SG rut (in)	Total rut (in)	AF
Standard	8.18 t (18.00 kips)	2.05 t (4.500 kips)	80	0.076	0.312	0.04	0.428	1	0.089	0.355	0.031	0.475	1
Steering	10.00 t (22.00 kips)	5.000 t (11.000 kips)	120	0.107	0.59	0.054	0.751	1.75	0.127	0.638	0.04	0.805	1.69
Single	23.00 t (50.50 kips)	5.750 t (12.650 kips)	120	0.092	0.811	0.113	1.016	2.37	0.11	0.955	0.087	1.152	2.43
Tandem	46.00 t (101.20 kips)	5.750 t (12.650 kips)	120	0.201	1.68	0.403	2.284	5.34	0.243	2.027	0.347	2.617	5.51
Tridem	69.00 t (151.80 kips)	5.750 t (12.650 kips)	120	0.302	2.519	0.605	3.426	8	0.365	3.04	0.521	3.926	8.27
Single	17.50 t (38.50 kips)	4.375 t (9.625 kips)	120	0.102	0.641	0.086	0.829	1.94	0.12	0.743	0.066	0.929	1.96
Tandem	35.00 t (77.00 kips)	4.375 t (9.625 kips)	120	0.243	1.482	0.508	2.233	5.22	0.293	1.847	0.448	2.588	5.45
Tridem	52.50 t (115.50 kips)	4.375 t (9.625 kips)	120	0.364	2.223	0.763	3.35	7.83	0.44	2.77	0.672	3.882	8.17
Quad	70.00 t (154.00 kips)	4.375 t (9.625 kips)	120	0.486	2.964	1.017	4.467	10.44	0.587	3.693	0.895	5.175	10.89

Table 18 shows the Axle Factors percentage of total surface rutting damage due to different axle configurations for the two Egyptian roads, Cairo-Alex (agric) and Cairo-Damietta roads due to the legal and illegal axle loads. The results show that the rutting damage increasing with an average of 10.05 % with the increased axle loads about 12.5 %, and the rutting damage increasing with an average of 19.11 % with the increased axle loads about 25 %, and the rutting damage increasing with an average of 37.4 % with the increased axle loads about 50 % and the rutting damage increasing with an average of 54.65 % with the increased axle loads to a maximum over load.

Table 18: Axle Factors percentage of total surface rutting damage due to different axle configurations for the two roads due to the legal and illegal axle loads

Axle configurations	Legal axle	12.5 % overload		25 % overload		50 % overload		Max load	
		Cairo-Alex (Agric)	Cairo-Damietta	Cairo-Alex (Agric)	Cairo-Damietta	Cairo-Alex (Agric)	Cairo-Damietta	Cairo-Alex (Agric)	Cairo-Damietta
Single	1	`1.096 (9.6 %)	`1.10 (10 %)	1.176 (17.6 %)	1.184 (18.4 %)	1.346 (34.6 %)	1.364 (36.4 %)	1.50 (50 %)	1.533 (53.3 %)
Tandem	1	1.1025 (10.25 %)	1.1075 (10.75 %)	1.1885 (18.85 %)	1.1995 (19.95 %)	1.374 (37.4 %)	1.3945 (39.45 %)	1.543 (54.3 %)	1.572 (57.2 %)
Tridem	1	1.1035 (10.35 %)	1.107 (10.7 %)	1.19 (19 %)	1.215 (21.5 %)	1.375 (37.5 %)	1.394 (39.4 %)	1.544 (54.4 %)	1.571 (57.1 %)
Quad	1	1.093 (9.3 %)	1.095 (9.5 %)	1.185 (18.5 %)	1.191 (19.1 %)	1.367 (36.7 %)	1.38 (38 %)	1.544 (54.4 %)	1.567 (56.7 %)
Average	1	1.1005 (10.05 %)		1.1911 (19.11%)		1.374 (37.4 %)		1.5465 (54.65 %)	

5. CONCLUSIONS AND RECOMMENDATIONS

This study involves flexible pavement damage due to the legal and illegal axle loads. The pavement damage includes fatigue and total surface rutting damages. Based on the analysis of fatigue and rutting damage due axle loads for two flexible pavement sections from two Egyptian roads, Cairo-Alex (agric) and Cairo-Damietta roads, the following conclusions are drawn:

- The fatigue damage increasing with the increased the axle load because the area under the tensile strain pulse is increasing with the increased the axle load.
- The fatigue damage increasing with an average of 4.9 % with the increased axle loads about 12.5 %, and the fatigue damage increasing with an average of 8.7 % with the increased axle loads about 25 %, and the fatigue damage increasing with an average of 16.3 % with the increased axle loads about 50 % and the fatigue damage increasing with an average of 22.6 % with the increased axle loads to a maximum over load.
- The rutting damage increasing with the increased the axle load because increased axle load increases the vertical compressive strain and that gave more total surface rutting damage.
- The rutting damage increasing with an average of 10.05 % with the increased axle loads about 12.5 %, and the rutting damage increasing with an average of 19.11 % with the increased axle loads about 25 %, and the rutting damage increasing with an average of 37.4 % with the increased axle loads about 50 % and the rutting damage increasing with an average of 54.65 % with the increased axle loads to a maximum over load.
- Laboratory and field investigation can be conducted to validate the mechanistic investigation of this research.
- Inventory of pavement layer thicknesses for road network can be conducted to determine the distributions of the structure integrity of the road network.
- Further research should be considered the vehicle speed because the strains decrease as the speed of the vehicle increases.

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