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Structural and Economical Effect of Over Weight Trucks on Asphalt Pavement

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Abstract: The general authority of road, bridges, and land transportation (GARBLT) specify the limitation of truck loads that run on Egyptian highways. Many trucks violate these limits by loading additional weights to decrease the transportation unit cost. This behavior causes severe deterioration to the pavement. Such violating trucks are charged by eventually little penalties compared to the damage they cause to the pavement. The objectives of this study is to evaluate the effect of increasing axle load, due to overloaded trucks, on the pavement life and to estimate a critical load that makes a boundary between penalized loads and the unallowable loads by developing a relationship between the number of load repetition to failure and axle load. The research used the KENPAVE software to calculate the horizontal tensile strain occurring at the bottom of the asphalt layer and the vertical compressive strains occurring at the top the subgrade soil due to the different axle loads. The calculated strains are then utilized to estimate the number of load repetitions to failure due to fatigue cracking using the Asphalt Institute (AI) method. Finally, relationships relating the predicted numbers of load repetitions with axle load and tire pressure were developed using regression analysis. In this study, Cairo - Alexandria desert highway was used as a case study.

***Key words**: Asphalt pavement; Axles loads; KENPAVE; Overweight trucks; Structural effect.*

Background

Overloading of trucks is a serious problem in developing countries. It results in high axle and wheel loads which have a devastating effect on the pavement structure. A research done by Molenaar [1] described the results of a rather extensive axle and wheel load survey that took place in Ghana. The study showed that overloading should be considered as a serious economical crime especially when dealing with thin road structures that are sensitive to overloading or dealing with low budgets for rehabilitation and maintenance. The only effective policy to the author's opinion was to unload the overloaded truck on site. He also added that increasing the asphalt thickness to reduce the stresses and strains in the lower layers is a costly and most probably not really an effective solution. Luskin and Michel [2] reported that allowing extra weight for a given type of truck can cause substantial pavement damage because of the increase in the axle weights.

Zhang and Tighe [3] examined the relative damage of pavements induced by tridem and trunnion axle load groups. The analysis was conducted with typical structures of both flexible and rigid pavements by first analyzing the mechanistic responses of pavements to tridem and trunnion axle groups. They concluded that the pavement wear increases with the increase of axle weight, number of axle loadings, and the spacing within axle groups. They also found that pavement impacts are influenced by vehicle suspensions, tire pressure, and tire type. The study also showed that vehicle-specific characteristics are less important to pavement deterioration than pavement type and axle weight. The break-up of pavements is usually caused by fatigue.

To make appropriate decisions on deciding the overloading limits of various axle configurations, highway agencies need to understand the impact of these axle groups in terms of their damage to pavement. This could be achieved through applying the appropriate pavement performance models, which will be discussed in the following section.

Problem Statement and Objectives

Overloaded trucks can cause excessive damage to pavement structures, such as worn surface, rutting, potholes, etc. These deteriorated pavements can, in turn, result in increased accident potential. To reduce the cost of maintenance, it is desirable to enforce the legal load to keep the pavements in good conditions as long as possible. Without active enforcement, the amount of overloading will increase leading to rapid deterioration of pavement. Local authorities in Egypt usually charge the violating trucks by eleven pounds as a flat penalty rate for every ton exceeding the legal load limit.

The objectives of the study were to investigate and analyze the effect of axle load increase of overweight trucks on the pavement life and to develop proper strategies dealing with overweight problem, either by enforcing a categorized penalty for the violating trucks according to the damage they cause to the pavement, or by unloading the violating trucks if a critical load is exceeded.

Research Methodology

The two most common failure modes of asphalt pavements used in design are fatigue cracking caused by tensile strain at bottom of the asphalt layer and rutting related to vertical (compression) strain at

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top of subgrade soil. These two parameters were used to assess the overload effects in this study. They were calculated using the KENPAVE software taking into account the tire pressure. The calculated strains were used in the fatigue cracking and rutting models introduced by the Asphalt Institute (AI) to estimate the number of load repetitions to failure.

The proposed analysis was applied to the Cairo-Alexandria desert road as a case study with tire pressure varying from 80 to 150*psi* (551.6 to 1,034.3*kPa*), while increasing the allowable axle load by 50, 100, and 200%. The pavement structural data for this road was collected from General Authority of Road, Bridges and Land Transportation (GARBLT). The trucks were weighted on a typical traffic day along two sections on Cairo-Alexandria desert road between 10:00AM and 12:00 Noon for the first section and from 1:00 to 3:00PM for the second section.

The collected data were statistically analyzed to determine the representative truckload traveling the road. Typical truck configurations commonly operated on the road were used in the analysis. These configurations were determined either from documentary data available in the related authorities or collected from field. By using sensitivity analysis, the obtained relationships were grouped together including tire pressure (P), the critical load for rutting ($L_{cr\ rutting}$), the critical load for fatigue ($L_{cr\ fatigue}$), the number of allowable load repetitions for rutting ($N_{cr\ rutting}$), and the number of allowable load repetitions for fatigue ($N_{cr\ fatigue}$).

Regression analysis using SPSS was employed to develop a model correlating the number of load repetitions as a dependent variable with the actual truck load as an independent variable where the tire pressure was considered. By substituting the surveyed truck loads in this model, the allowable number of load repetitions to failure can be estimated.

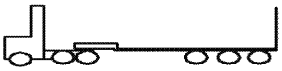
Data Analysis

The collected truck data were statistically analyzed to determine the truck weights commonly operating on the road. The average representative truck load is estimated using SPSS software through drawing relationships between the load and its frequency for each type of truck moving on the road. The whole truck fleet being surveyed was therefore categorized according to type, number of axles, axle configuration, sum of axle weights, and the representative truck load, as shown in Table 1.

Based on GARBLT [4] specifications, single front axles are given a limited standard weight of 7*tons*, while single dual axles are limited to 13*tons*. For dual tandem axles, the axle weights are limited to 20*tons*. The summations of axles are then summed up giving the standard truck weight that should not be exceeded.

Configuration of Considered Axle Types

The different axle configurations used in this study are single axles (I), dual axles (II) with dual spacing (Y) 30*cm*, and dual tandem axles (III) with tandem spacing (X) 150*cm*. An example of the axle distribution for truck Type 9 is shown in the corresponding figure as follows:



Axle configuration of truck Type 9	=**I**	**III**	**II II II**
Axle weight (*ton*)	=7	20	3 * 13
Total truck weight (*ton*)	=7+20+39	=	66

For the rest of the trucks, the distribution is illustrated in Table 1.

Table 1 summarizes the actual weights of these overloaded trucks during the field survey and the results of their statistical analysis. The representative truck load varies from a truck type to another according to the field survey.

Prediction of Fatigue Cracking and Rutting

Using the traffic data along with the axle load, tire pressure, and pavement structure criteria, the KENPAVE software was used to calculate the horizontal tensile strain (ε_t) at the bottom of the asphalt layer and the vertical compressive strain (ε_c) at the top of the subgrade layer, and the total damage ratio induced due to the number of load repetitions.

The pavement strains were then used to predict the pavement performance using the AI models. The pavement performance was evaluated in terms of number of allowable load repetitions to failure with respect to fatigue cracking and rutting. The AI suggested the following fatigue cracking performance model [5]:

$$N_f = 0.0796 * \varepsilon_t^{-3.291} |E^*|^{-0.854} \tag{1}$$

Where,

N_f = the number of load repetitions with respect to fatigue,

ε_t = the tensile strain at the bottom of asphalt concrete (AC) layer, and

Table 1. Quantification of Trucks Weights Operating on Cairo-Alexandria Desert Road.

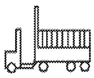
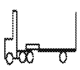
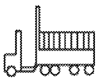
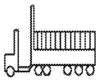
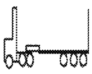
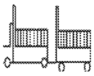
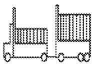
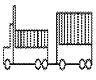
	Type 1	Type 4	Type 6	Type 7	Type 8	Type 9	Type 11	Type 12	Type 14
Truck Type									
Number of Axles	2	4	3	4	5	5	4	4	4
Axle Configuration	I+II	I+3*II	I+III+II	I+III+2*II	I+III+3*II	I+III+3*II	I+3*II	I+2*II+III	I+2*III+II
Sum of Axle Weights (*ton*)	20	46	47	53	57	66	46	53	60
Number of Trucks Surveyed at Section 1	129	36	6	8	18	5	11	42	21
Number of Trucks Surveyed at Section 2	177	95	8	12	14	7	16	107	53
Total Trucks	306	131	14	20	32	12	27	149	74
Representative Truck Load (*ton*)	36	55	57	65	70	70	55	62	70

Table 2. Number of Load Repetitions in Terms of Fatigue Failure.

Failure Mode	Tire Pressure (*psi**)	Axle Load (*ton*)											
		Single				Single Dual				Dual Tandem			
		7	10.50	14	21	13	19.50	26	39	20	30	40	60
Fatigue Failure (×E6)	80	10.0	6.8	5.4	4.8	5.57	3.9	2.0	1.27	9.6	6.9	2.87	1.72
	100	6.66	4.13	3.0	2.4	3.94	2.2	1.46	0.89	7.1	5.38	2.2	1.23
	125	6.5	2.6	1.75	1.27	2.9	1.94	0.85	0.48	5.46	4.04	1.32	0.7
	140	3.89	2.13	1.2	0.87	2.55	1.66	0.583	0.33	4.62	3.37	0.91	0.48
	150	1.28	1.22	1.18	0.785	0.85	0.7	0.622	0.335	1.61	1.31	1.0	0.504
Rutting Failure (×E6)	80	490.0	124.0	36.8	9.6	151.0	34.7	11.3	2.1	476.0	259.0	27.5	5.77
	100	440.0	107	30	7.27	68	39.5	10.0	1.91	437.0	242.0	39.0	13.1
	125	439.0	395	25.5	5.76	130.0	53.8	7.33	0.481	415.0	228.0	22.5	4.37
	140	386.0	89.6	15.3	3.46	31.6	14.2	4.4	0.89	408.0	224.0	13.5	2.62
	150	29.3	25.3	22.7	4.89	151.0	6.79	6.79	1.33	492.0	59.0	21.2	4.0

*1*psi* = 6.895*kPa*

|E*| = the dynamic modulus of the asphalt mixture in *psi* (1*psi* = 6.895*kPa)*.

The rutting model considered in the AI manual is shown in Eq. (2) [5].

$$N_d = f_4\, \varepsilon_c^{-f_5} \quad (2)$$

Where,

N_d = the number of load repetitions with respect to rutting,

ε_c = the compressive strain at the top of subgrade, and

f_4 and f_5 = material constants equal to $1.365\text{x}10^{-9}$ and 4.477, respectively.

The pavement responses, in terms of tensile and compressive strains are estimated for tire pressures varying from 80 to 150*psi* (551.6 to 1,034.3*kPa*), and for axles with overloading by 50, 100, and 200% for each of the single axles, dual axles, and dual tandem axle. These calculated responses were applied in the AI models to obtain the allowable number of load repetition to failure due to fatigue and rutting.

The properties of pavement layers used in the analysis were gathered data values from GARBLT [4]. The estimated modulus values for subgrade, base, and AC layers were 2.4E6, 5.5E6, and 5.8E6*kPa*, respectively. Typical pavement layer thicknesses were used, including 25, 7, and 5*cm* for base, binder, and wearing surface (AC=12*cm*), respectively. The considered poison's ratios were 0.30, 0.35, and 0.40 for AC layer, base, and subgrade layers, respectively. These properties were assumed to be constant along the road. The axle group configuration, distance between axles in the x-direction and y-direction, and the tire inflation pressure were obtained from field measurements.

KENPAVE Analysis for the Considered Axle Loads and Tire Pressures

Table 2 presents the results of sensitivity analysis conducted to estimate the effect of tire pressure on the relationships between axle load and number of load repetitions. This table is divided into three groups for different axle configurations (single, dual, and dual tandem). In each of these groups, different axle loadings were considered. The considered axle loads are the maximum allowable load from GARBLT, 50% overloading, 100% overloading, and 200% overloading. The results were then used to develop relationships between the axle load and number of load repetitions to failure for single, dual, and dual tandem axles. Through these relationships, the number of load repetitions and tire pressure could be accurately studied. Detailed explanation of this table is discussed in the following section.

Effects of Axle Load and Axle Configuration on Pavement Age

Figs. 1(A) and 1(B) present the relationships between the axle load and the corresponding number of load repetitions to failure due to rutting and fatigue cracking respectively, for different tire pressures. These figures show that increasing axle load significantly decreases the allowable number of load repetitions due to both fatigue and rutting.

Fig. 1(B) shows that the tire pressure does not have significant effect on the number of load repetitions determined from the rutting model. The main reason could be because the number of load repetitions due to rutting is related to the compressive strains above the subgrade. Such strain is not affected by tire pressure but only affected by the value of the axle load. On the other hand, Fig. 1(A) shows that for the same axle load, increasing the tire pressure decreases the allowable number of load repetitions due to fatigue failure.

Since the allowable number of load repetitions due to fatigue is mainly correlated with the tensile strain under the asphalt layer, then the tire pressure variation has more severe effect on upper pavement layers (AC Layer). The main explanation for this phenomenon is that increasing the tire pressure decreases the tire contact area with pavement. This leads to increasing the contact stress with pavement. Accordingly, the tensile strain under the pavement increase leading to decreasing the allowable number of load repetitions.

Figs. 1(C) and 1(D) present the same data for tandem axles while, Figs. 1(E) and 1(F) present the data for tandem axles with dual tires. From those figures it can be noticed that for the same axle load, the number of load repetitions increases with changing the configuration

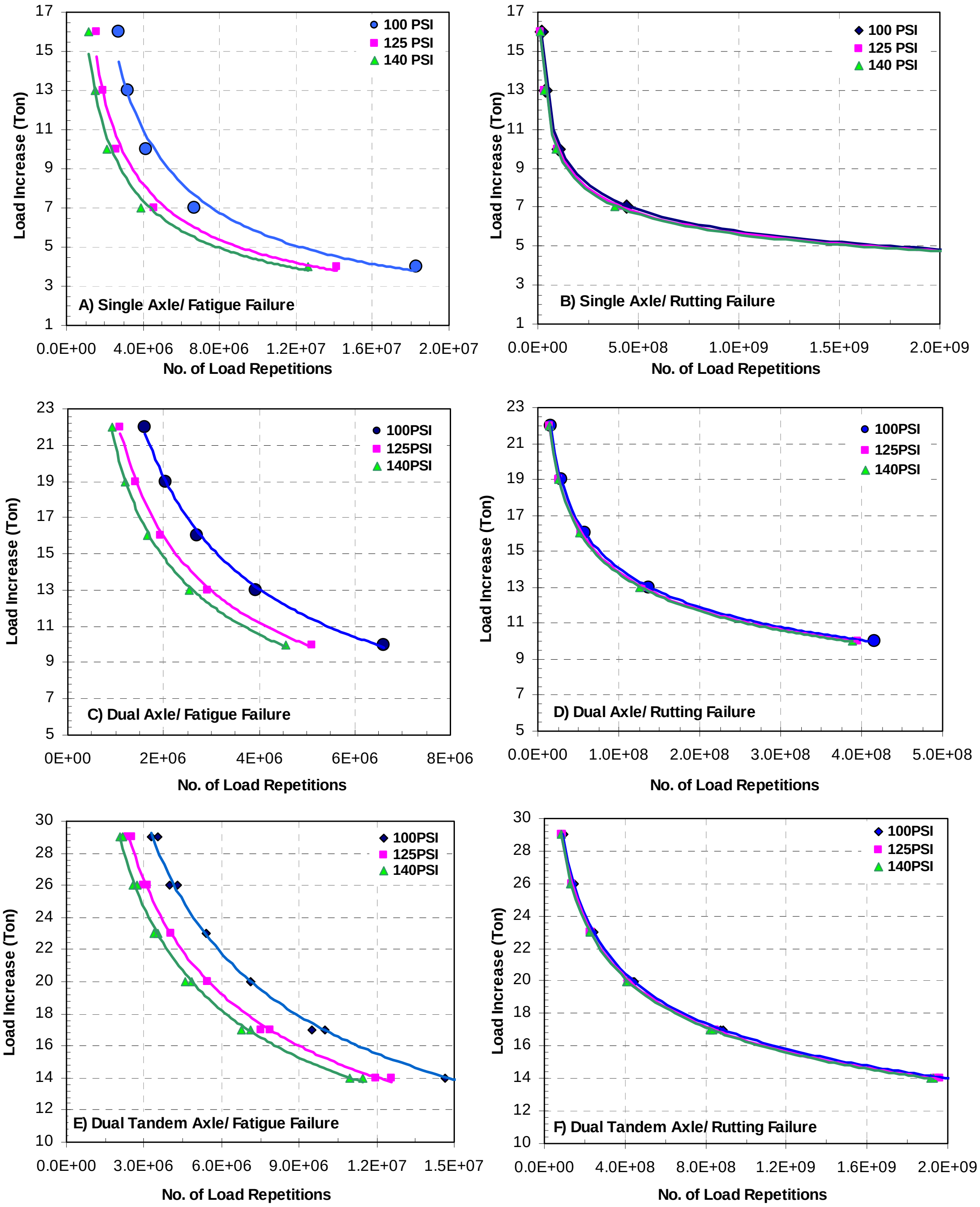


Fig. 1. Relationship between the Axle Load Value for Different Tire Pressures and the Number of Load Repetitions to Failure; Due to Different Axle Configurations and Failure Modes: (A) Fatigue Failure Single Tire, (B) Rutting Failure Single Tire, (C) Fatigue Failure Dual Tire, (D) Rutting Failure Dual Tire, (E) Fatigue Failure Dual Tandem Tires, and (F) Rutting Failure Dual Tandem Tires. Note: 1*psi* = 6.895*kPa*.

from single axles with single tires to tandem axles with dual tires. From these results, the use of dual tandem axles is recommended since trucks with this configuration produce less strains and stresses on the pavement and therefore causes less damage to the pavement.

The combined effects of varying tire pressures and overloading on the number of load repetitions to failure are also presented in Figs. 1(A) through 1(F). For single axles, it is noticed that when the axle load increases by 200%, this results in a reduction in the number of load repetitions to failure by more than 50%. For both single dual and dual tandem tires, the number of load repetitions decreases by approximately 70% or more when increasing the axle load by 200%. Meanwhile, increasing tire pressure results in a reduction in the number of load repetitions to failure due to fatigue. For a single axle tire, the number of load repetitions decreases to 87% of its value as the tire pressure increases from 80 to 150*psi* (551.6 to 1,034.3*kPa*).

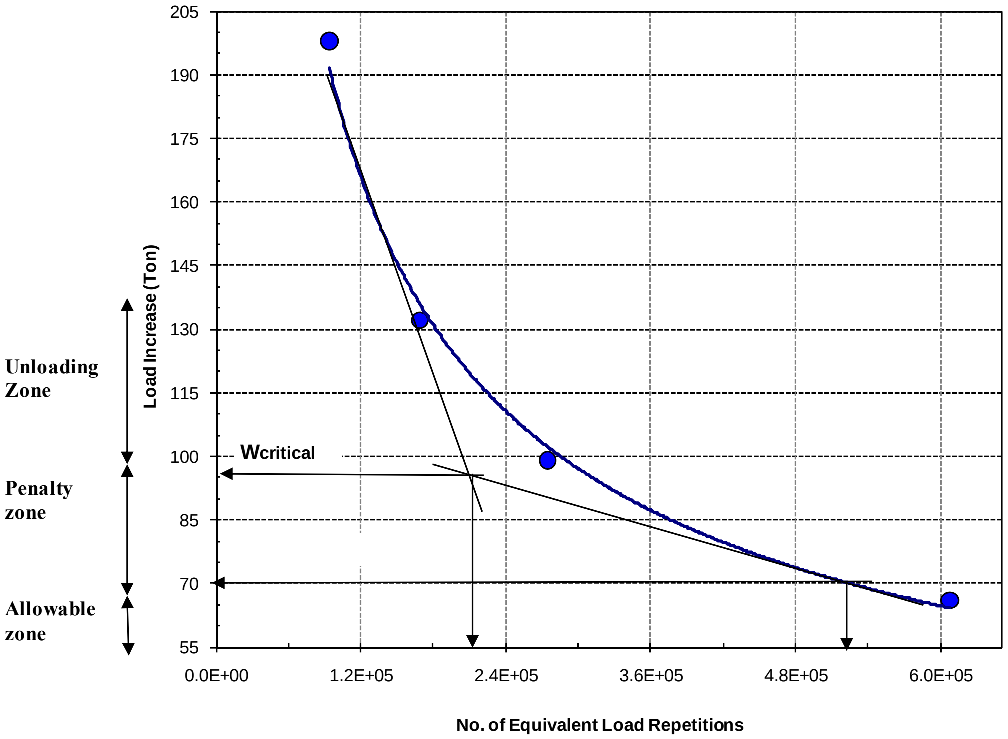


Fig. 2. Graphical Identification of the Critical Axle Load.

The same effect can be noticed for dual and dual tandem axles due to the change of projected area. It is also noticed that the number of load repetitions for single axles are less than those ones for dual and dual tandem axles. Finally, it can be easily noticed from all curves that when the load increases gradually, inverse proportional curves reach a point where there is a sudden decrease in the allowable number of load repetitions that may lead to premature failure of the pavement.

Critical Load Estimation

Since the penalty charge for violating trucks are usually estimated per the whole truck weight not the axle weight. Therefore, it is necessary to estimate the critical load for the whole truck per truck type. Unfortunately, the KENPAVE software predicts only the number of load repetitions corresponding to each axle group separately and does not bring the equivalent number of load repetitions that represents the whole truck. Therefore, relationships between the number of load repetitions and axle loads are graphically presented as shown in Fig. 2 to represent the whole truck due to the following concept.

If we follow the estimation of the design hour volume (DHV) concept, the researchers had decided that when using average hourly volume is inadequate design and the maximum peak hour is not economical. So the hourly volume used in design should be decided upon not to be very much so usually by using 30th highest hourly volume of the year, the 30 highest hour volume (HHV) is approximately 15% of the average daily traffic (ADT) and this percentage tends to be constant year after year. From the previous discussion DHV is a representation of the peak hour traffic, usually for the future. Likewise for the critical load, it was suggested because taking the maximum load would not be economical and taking the average load would be inadequate By using the critical load method and suggested tire pressure, the pavement would last for specified number of years according to design.

Therefore, the same concept used in estimating the DHV is followed to identify a certain value as the equivalent load to be considered as "the critical load". The points chosen to draw the tangent lines are the points determined from the output of the KENPAVE program which had been substituted in Eq. (3) [6].

$$\text{Damage } (D_r) = \sum_{i=1}^{p} \sum_{j=1}^{m} \frac{n_{ij}}{N_{ij}} \tag{3}$$

Where:
D_r = damage ratio at the end of a year, N_{ij} = allowable number of load repetitions based on the fatigue and rutting models, and n_{ij} = the predicted number of load repetitions for load j in period i.

Since the relationship between the axle load and the damage ratio is linear. Therefore, the damage occurring due to each truck can be summed up for each axle. By inversing the damage ratio the allowable number of trucks can be estimated. This concept is used to estimate the equivalent number of load repetitions per truck type [6]. It could be noticed that such curve is similar to the curve used for the determination of the thirtieth highest hour volume from traffic volume hourly variation.

The presented curve in Fig. 2 is divided into three zones; allowable zone, penalty zone, and unloading zone. The allowable load separates the penalty zone from the allowable zone, while the estimated critical load separates the unloading zone from the penalty zone as shown in the figure. It could be clearly noticed that the penalty grading zone lies in between $W_{critical}$ (W_{cr}) and $W_{allowable}$ (W_{all}).

Table 3. Estimated Critical Load Values $L_{critical}$ (L_{cr}) and Corresponding Number of Load Repetitions to Failure $N_{critical}$(N_{cr}) for Different Truck Types and Tire Pressures.

Truck Type	Truck Load(*ton*)		Tire Pressure	Fatigue		Rutting	
	Allowable	Representative	(*psi**)	L_{cr}	N_{cr}(×E5)	L_{cr}	N_{cr}(×E6)
1	20	29	80	35	16.5	23	64.0
			100	35	14.0	23	63.0
			110	33	7.9	23	65.0
			125	31	7.0	22	62.0
			140	32	5.5	23	63.0
			150	31	3.1	22	61.0
4	46	75	80	74	6.8	58	6.0
			100	73	4.3	58	6.0
			110	73	3.7	58	5.5
			125	70	3.0	58	5.5
			140	67	2.3	57	5.6
			150	66	2.0	57	5.3
6	47	76	80	73	13.6	61	14.0
			100	73	8.5	60	11.0
			110	74	6.7	60	10.0
			125	70	5.0	61	11.0
			140	68	4.6	58	10.0
			150	67	4.2	59	11.0
7	53	85	80	85	8.5	91	4.2
			100	80	4.5	96	3.7
			110	78	4.0	92	3.7
			125	78	3.2	95	3.7
			140	77	2.4	93	3.8
			150	76	2.2	92	3.9
8	66	102	80	98	5.9	85	2.3
			100	96	3.7	85	2.5
			110	94	3.2	88	2.2
			125	98	2.3	87	2.3
			140	95	1.9	87	2.3
			150	95	1.7	87	2.3
9	66	70	80	104	5.8	66	21.0
			100	103	3.8	66	20.0
			110	98	2.4	66	19.0
			125	97	2.1	65	18.0
			140	97	1.8	65	18.0
			150	96	1.15	66	18.0
11	46	75	80	71	6.8		6.0
			100	73	4.3	58	6.0
			110	73	3.7	58	5.5
			125	70	3.0	58	5.5
			140	67	2.3	58	5.6
			150	64	2.0	57	5.3
12	53	62	80	78	7.8	58	40.0
			100	84	5.8	58	38.0
			110	81	3.4	58	39.0
			125	80	3.2	57	37.0
			140	82	2.4	57	40.0
			150	87	1.25	57	39.0
14	60	70	67	91	9.0	67	16.0
			67	96	6.8	67	15.0
			67	92	4.8	67	13.0
			66	95	4.0	66	14.0
			66	93	2.4	66	15.0
			66	92	1.3	66	15.0

$^*1psi = 6.895kPa$

Beyond the critical load $W_{critical}(W_{cr})$, the exceeding load will cause quick deterioration to the pavement and should be treated as an unacceptable load for which the truck should be unloaded.

The estimated critical load values and corresponding number of load repetitions to failure for different truck types and different tire pressures are summarized in Table 3 for both fatigue and rutting failure modes. This table consists of 8 columns. Column one represents the truck type based on the truck fleet moving on Cairo-Alexandria desert road. Column 2 represents the allowable truck load based on the Egyptian government regulations. Column 3 shows the representative field truck load, which was estimated through analysis done by SPSS program using field survey data. Column 4 represents the tire pressure varying from 80 to 150*psi* (551.6 to 1,034.3*kPa*). Column 5 shows the critical load estimated based on the concept shown in Fig. 2. Column six is the output from KENPAVE program which is the number of load repetitions with respect to fatigue. Columns 7 and 8 represent the same data as columns 5 and 6 but for the rutting data.

Table 3 shows that for truck type 1, the allowable load (20*ton*) is less than the measured representative truck load (29*ton*), which, in turn, is less than the critical truck load obtained from the developed relationships between load and number of load repetitions. Furthermore, when the tire pressure increases (from 80 to 150*psi* (551.6 to 1,034.3*kPa*)), the gap between the critical load and the allowable load increases. The table also shows that the number of load repetition with respect to rutting is not seriously affected by tire pressure, and tire pressure has significant influences on fatigue cracking in asphalt layer.

Regression Analyses

Regression analysis using SPSS was performed to establish models that describe relationships among the numbers of load repetitions to failure and the whole truck (N), the truck load (L) and the tire pressure (P) for Cairo-Alexandria desert road. The prediction models are developed for both rutting and fatigue and are summarized in Table 4. The coefficient of correlation and significance are also presented in the table.

As shown in Table 4, data show good correlations among the three parameters with respect to fatigue; however, for rutting, low coefficients of correlation among these parameters are observed. Therefore the models listed in Table 4 for fatigue are recommended for use to predict pavement performance with tire pressure taken into consideration.

Deciding the Suitable Violation Penalty

To estimate the imposed penalty, the total cost of constructing the road should be known. The following formula developed by Ethiopian roads authority (ERA) [7] is being simplified to estimate such penalty as follows:

$$\text{Fine}/km = \frac{Cost\ of\ road\ /\ km}{Number\ of\ load\ repetitions\ /\ truck} \tag{4}$$

Using Eq. (4) and by knowing the cost of Cairo-Alexandria desert road from GARBLT, the fines that the driver must pay for violating the allowable load until he reaches the critical state can be estimated for different truck types and considering different tire pressures. Table 5 explains the fine calculation for truck Type 1 with different tire pressures. To study how the fines would be collected the truck effects with respect to both rutting and fatigue on the pavement need to be considered. The number of load repetitions induced from rutting and/or fatigue is an important factor to be used for calculating the suitable fine for the violating truck. The numbers of load repetitions with respect to rutting and fatigue in both summer and winter should be estimated and used as the minimum.

N_{cr} and L_{cr} for both rutting and fatigue are illustrated, taking into consideration climatic conditions by applying a low tire pressure

Table 4. Interrelationship between Number of Load Repetitions (N_{cr}), Truck Load (L_{cr}), and Tire Pressure (P) for Cairo-Alexandria Desert Road.

Truck Type	Fatigue Models	Rutting Models
1	$N_{cr}=33793.027*L_{cr}-19319.5*P+2066136$ $R^2 = 0.932$, Sig = 0.018	$N_{cr}=-824933*L_{cr}-1417943*P+ 2.3e8$ $R^2 = 0.83$, Sig = 0.067
4	$N_{cr}=-24149.8*L_{cr}-8204.192*P+ 030862$ $R^2 = 0.975$, Sig = 0.004	$N_{cr} = -262291*L_{cr}-13631.3* P + 2.2e7$ $R^2 = 0.79$, Sig = 0.096
6	$N_{cr}=-69831.4*L_{cr}-18922.3*P+ 7868125$ $R^2 = 0.965$, Sig = 0.007	$N_{cr}=327462.3*L_{cr}-27246.6*P+5225018$ $R^2 = 0.477$, Sig = 0.378
7	$N_{cr}=-10317.1*L_{cr}-8716.786*P+2257764$ $R^2 = 0.866$, Sig = 0.049	$N_{cr} = -2952.03* P +4180197$ $R^2 = 0.153$, Sig = 0.444
8	$N_{cr}=9598.501*L_{cr}-5557.816*P+1654.17$ $R^2 = 0.923$, Sig = 0.021	$N_{cr}=-83389.3*L_{cr}+1711.409*P+9328747$ $R^2 = 0.679$, Sig = 0.182
9	$N_{cr}=3666.397*L_{cr}-6448.933*P+ 669165$ $R^2 = 0.925$, Sig = .021	$N_{cr}=-128408*L_{cr}-220679 * P + 4.4e7$ $R^2 = 0.52$, Sig = 0.33
11	$N_{cr}=-24149.8*L_{cr}-8204.192*P+ 030862$ $R^2 = 0.975$, Sig = 0.004	$N_{cr} = -262291* L_{cr}-13631.3*P+ 2.2e7$ $R^2 = 0.79$, Sig = 0.096
12	$N_{cr}=2918.502*L_{cr}-9114.537*P+ 229141$ $R^2 = 0.929$, Sig = 0.019	$N_{cr}=-129609*L_{cr}-476594*P+ 7.9e7$ $R^2 = 0.79$, Sig = 0.09
14	$N_{cr}=4975.776*L_{cr}-10830.2*P+ 1280635$ $R^2 = 0.985$, Sig = 0.002	$N_{cr} = -293053 *L_{cr}-278644*P + 6.3e7$ $R^2 = 0.56$, Sig = 0.56

Table 5. Fine Estimation for Truck Type 1.

Tire Pressure (*psi*[*])	Truck Load (*ton*)	No. of Allowable Load Repetitions (×E6)	Estimated Fine (LE/*km*)
80	20	3.75	None
	21	3.53	0.22
	22	3.34	0.23
	23	3.17	0.24
	24	3.02	0.25
	25	2.87	0.27
	26	2.74	0.28
	27	2.62	0.29
	28	2.51	0.30
	29	2.41	0.32
	30	2.32	0.33
	31	2.23	0.34
	32	2.15	0.36
	33	2.07	Unload
100	20	2.20	None
	21	2.10	0.36
	22	2.01	0.38
	23	1.94	0.40
	24	1.86	0.41
	25	1.79	0.43
	26	1.73	0.44
	27	1.67	0.46
	28	1.62	0.47
	29	1.57	0.49
	30	1.52	0.50
	31	1.48	0.52
	32	1.43	Unload

[*] 1*psi* = 6.895*kPa*

value of (100*psi* (689.5*kPa*)) in summer and a high tire pressure value of (150*psi* (1,034.3*kPa*)) in winter. The representative number of load repetitions is taken as the least between those from fatigue and rutting as the most critical one to estimate the optimum fine. It should be noted that such fine estimates should only be considered in the penalty grading zone. Above the critical load, such formula should not be applied and the violating trucks must be unloaded by authorities to prevent premature pavement deterioration.

It is worth mentioning that fatigue has more significant effects than rutting in reducing the pavement life. Therefore, it is recommended to design against overloading by considering a suitable factor of safety. The fines calculation for truck Type 1 is illustrated in Table 5. Such calculation takes into consideration the variation of tire pressure that affects both the critical load and number of load repetitions. Applying those estimated fines will help solving the overweight truck problem by discouraging truckers to upload overweighs. It develops a controlling system that stops the violating trucks from continuous deterioration of the pavement.

Conclusions

Based on this study, the following can be concluded:

- For the same axle load, the allowable number of load repetitions to failure increases with changing the configuration from single to dual tandem, respectively. Based on that the use of dual tandem axles is recommended.
- A new concept has been developed, namely the critical truck load (L_{cr}), based on which the trucks are either to be allowed, penalized or enforced to unload the overweight load before crossing the roads.
- The fatigue cracking at the bottom of AC layer is likely to be controlling factor for estimating penalty due to its sensitivity to both overloading and tire pressure, while rutting is sensitive to overloading but not to tire pressure.

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