Load equivalence factors as function of axial loads and tire pressure for design of flexible pavemet

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Heavy load application is considered the major reason of pavement distresses. In the last decades, many researchers have obtained damage of road resulted from repeated loads application to highway pavements based primarily on the intensity and frequency of axle loads. However, it is now widely accepted that tire pressure plays a major role on pavement distresses. As the axle load and tire pressure of heavy vehicles has increased, the need to evaluate the effects of heavy axle load and high tire pressure on pavement performance becomes urgent. The main objective of this paper is to evaluate the effect of the axle loads and tire pressures on the determination of Load Equivalency Factors (LEF) and consequently their effect on flexible pavement design. The results showed that, the influence of tire pressure on asphalt pavement depends on axle load. At high to intermediate axle loads, high tire pressure can cause significant increase in LEF. On the other hand, at low axle load, variation of LEF with tire pressure becoms insignificant. At the same tire pressures and axle loads, increased subgrade elastic modulus has insignificant influence on LEF. The fatigue and rutting coefficents, *m* and *b* in the LEF equations are not affected by the type of soil and were found to equal 5 under the circumstances at hand. Regression equations were obtained to simplify the determination of LEF as a function of axle loads, contact pressure and subgrade elastic modulus.

يعتبر تأثير أحمال وحدات السير العالية على طبقات الرصف من الأسباب الرئيسية التى تؤدى الى الانهيارات به. لذا أتجه كثير من الباحثين الى دراسة تأثير كلا من تكرار ومقدار الأحمال المحورية على الانهيارات التى تحدث بطبقات الرصف المرن . ونظرا لاختلاف ضغوط أطارات العجل فقد وجد أنه يلزم دراسة مدى تغير قيم ضغوط أطارات العجل علاوة على مقدار الأحمال المحورية على سلوك طبقات الرصف. لذا أتجه هذا البحث الى دراسة مدى تأثر معامل الحمل المكافئ بتغير قيم كلا من ضغط أطارات العجل وأحمال وحدات السير وذلك لأنواع مختلفة من تربة التأسيس. وبتحليل النتائج التى تم التوصل أليها وجد أن تأثير ضغط أطارات العجل على معامل الحمل المكافئ يتوقف على قيم أحمال المركبات. كذلك أوضحت النتائج أن ثابتى التخدد والتعب التى تستخدم فى حساب مقدار معامل الحمل المكافئ تتوقف على المتغيرات المختلفة محل الدراسة. أوضحت النتائج أن قيم هذه الثوابت تبلغ ٥ باستخدام المتغيرات التى استخدمت بالبحث. واخيرا تم استنباط علاقة رياضية تربط بين معامل الحمل المكافئ والمتغيرات المختلفة وهى الأحمال المحورية وضغط الاطارات ومعامل المرونة لتربة التأسيس.

Keywords: Axle load, Tire pressure, Pavement design, Fatigue, Equivalent axle load

1. Introduction

During the last few years excessive damages were observed on several highway, mostly on high volume major roads. The reasons behind can be manifold: mixture desing, high temperature in summer, change in traffic load, etc. Recently, with the development of vehicles manufactures, many heavy trucks were spread all over the world. For example, in Egypt, there are many types of heavy vehicles of 6-axles of total weight ranging from 42 to 52 ton [1]. These heavy vehicles have a bad effect on pavement responses.

The effects of high tire inflation pressure on flexible pavement have been widely accepted as an important factor for flexible pavement design. The Asphalt Institute has adopted an Equivalent Axle Load (EAL) adjustment factor for tire pressure in its asphalt pavement thickness design manual [2]. Contact pressure is assumed to be equal to tire inflation pressure for pavement design purpose. It is because that heavy truck usually uses high tire pressure and thus it is more detrimental to pavements. The use of tire inflation pressure as the contact pressure is therefore on the safe side [3, 4]. To reflect the actual load application on pavements, the effects of axle loads and tire pressures must be evaluated. This paper aims at investigating the effects of high tire pressures and heavy axle loads on pavement response, and to determine the Equivalent Single Axle Load (ESAL) of some vehicles (trucks) type in Egypt.

The detrimental effects of high tire contact pressure on flexible pavement were examined by computing the tensile strain at the bottom of asphalt layer and the compressive strain at the top of subgrade. Comparing the ESAL manifested the effects of heavy axle load and high tire pressure on the design of flexible pavement. This goal can be achieved by using the theory of layered system as well as software computer program, BASIR program.

2. Layered systems

Layered systems with a number of layers have been studied by many researchers and mathematicians. Burmister [5] presented the first layered theory analysis with specific application to the problem of pavement design. The layered system considered and the boundary conditions imposed in the Burmister solution are shown in fig. 1. The pavement was represented as a layered system, each layer represenented as a different material and characterized by a modulus of elasticity. While the assumption of using an elastic modulus to represent paving materials has often been criticized, the real value of layered theory to serve as a foundamental guide to pavement desing has never been full demonstrated in the technical literature.

3. Flexible pavement design criteria

In pavement design and analysis, loads on the surface of the pavement produce two strains which are believed to be critical for design purposes. These are:

1. The horizontal tensile strain, εt , on the underside of the lowest asphalt-bound layer,
2. The vertical compressive strain, εc , at the top of subgrade layer.

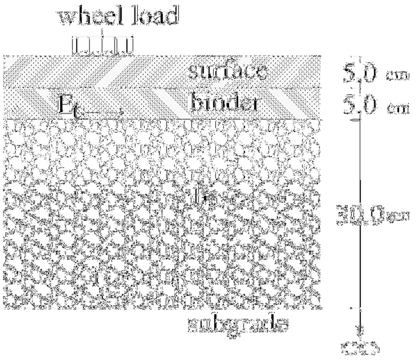

Fig. 1. strain in flexible pavement system.

Fig. 1 shows the pavement structure sysytem and the locations of horizontal tensile strain, εt and the vertical compressive strain, εc.

If the horizontal tensile strain, εt, is excessive, cracking of the surface layer will occur, and the pavement distresses due to fatigue. If the vertical compressive strain, εc, is excessive, permanent deformation occurs at the surface of the pavement structure from overloading the subgrade, and the pavement distresses due to rutting. In this study, the horizontal tensile strain, εt and the vertical compressive strain, εc will be detremine at different factors.

3.1. Fatigue criteria

The relationship between fatigue failure of asphalt concrete and tensile strain εt , at the bottom of asphalt layer is represented by the number of load repetitions in the following form [6]:

$$Nf = k\,(1/\varepsilon t\,)^{m}\;. \qquad (\text{`}1)$$

Nf is the number of load repetitions to failure,
εt is the tensile strain at the bottom of asphalt layer, and
k,m is the coefficients depending on the thicknesses and properties of layers. Their values vary from 3 to 6 [8].

3.2. Rutting criteria

The relationship between rutting failure and compressive strain εc, at the top of subgrade is represented by the number of load applications as follows [6]:

$$Nc = a\,(1/\varepsilon c)^{b}\,\cdot \tag{2}$$

Nc is the number of load applications,
εc is the vertical compressive strain at the top of subgrade, and
a,b are the coefficients depending on the thicknesses and properties of layers. Their values vary from 3 to 6 [8].

4. Varibles used in this investigation

In the present study, five axial load levels and tire pressures are selected. These loads and tire pressures are 60, 70, 80, 90 ,100 kN and 0.5, 06, 0.7, 0.8, and 0.9 MPa, resprctively. Moreover, three values for the modulus of deformation of subgrade represent the soil in the most locations in Egypt. These values are 50, 100, 150 MPa.In the following section, the infuence of different variables on Load Equivalency Factor (LEF) will be discussed.

5. Load equivalency factors

An equivalent axle load factor defined as the damage per pass to a pavement by the axle in question relative to the damage per pass of a standard axle load, usually the 18-kip (80 kN) single axle load applied to the pavement on two sets of dual tires. Pavement design is based on the total number of passes of the standard axle load during the design period, which is defined as the Equivalent Single-Axle Load (ESAL).

6. Equivalency axial load factors based on fatigue criteria

The Equivalent Axle Load Factor (EALF) on the basis of fatigue failure with the same material is the ratio of NfS to Nfl [8]:

$$ALEF = (N_{fS}\,/N_{fl}) = [k(1/\varepsilon_{tss})^{m}\,]\,/\,[k(1/\varepsilon_{tij})^{m}\,] = (\varepsilon_{tij}\,/\,\varepsilon_{tss}\,)^{m}\;. \tag{3}$$

NfS is the number of repetitions to failure of standard load and pressure,
Nfl is the number of repetitions to failure of arbitrary load and pressure,
εtss is the maximum tensile strain at the underside of asphalt layer under the standard single axle load of 80 kN and a tire inflation pressure of 80 psi (550 kPa),
εtij is the maximum tensile strain at the underside of asphalt layer for the i axle load and j tire inflation pressure, and
m fatigue coefficient, and m was chosen ranging between 3 and 6 in this research [5,6].

7. Equivalency axial load factors based on rutting criteria

The equivalent axle load factor on the basis of rutting failure with the same material is the ratio of Ncs to Ncl [8]:

$$EALF = N_{cs}\,/N_{cl} = [a(1/\varepsilon_{css})^{b}\,]\,/\,[a(1/\varepsilon_{cij})^{b}\,] = (\varepsilon_{cij}\,/\varepsilon_{css}\,)^{\,b}\;. \tag{4}$$

Ncs is the number of standard load and pressure applications,
Ncl is the number of arbitrary load and pressure applications,
εcss *is* the maximum vertical compressive strain at the top of subgrade under the standard single axle load of 80 kN and a tire inflation pressure of 80 psi (550 kPa),
εcij *is* the maximum vertical compressive strain at the top of subgrade for the i axle load and j tire inflation pressure, and
b is the rutting coefficient b was chosen ranging between 3 and 6 in this research [5,6].

8. Fatiuge and rutting coefficients

One of the main objectives of this study is to determine the constant m and b to be used to determine the load equivalent factors, LEF, in the design of fexible pavement thickness. Many researches were conducted for this purpose, resulting in values for m and b ranging from 3 to 6 [5,6]. Therefore, in this research the coefficients m and b were chosen ranging between 3 and 6. In order to deduce the suitable value of these cofficients, the LEF given by ASSHTO specifications [9] was used to compare the LEF produced by using different values of coefficients and different modulus of deformation of subgrade and constant single axial load, 80 kN and tire pressure 0.5 MPa. Figs. 3 to 8 indicate a comparison between different curves of LEF using m and b coefficients and AELF AASHTO reference curve. From these groups of LEF curves and statisitic analysis between them, it can be seen that AELF curve using *m* or *b* coeeficients is equal to 5 in the nearst cuve to AELF AASHTO curve. Therefore, it can be concluded that, the ideal fatigue and rutting coefficients value was equal to 5 under the varibles used in this study.

9. Effect of tire pressure on equivalency axial load factors

It was difficult to measure the tire inflation pressure of different trucks on Egyptian road network, thus a survey was made to collect data from the drivers and from stations that repair tires and adapt tire pressure on Cairo-Alex. agriculture highway and Cairo –Alex. desert highway. Analysis of survey data showed that the average tire pressure for single axles with single and dual tires is about 0.80 MPa (≈ 8.0 bar) and for tandem and triple axles is about 9.0 MPa (≈ 9.0 bar). In case of high axle loads, the contact pressure is smaller than the inflation tire pressure, thus contact pressure is supposed to be 90% of tire pressure in this investigation.

The elastic multi-layer analysis program BISAR [7] ,developed by Shell, was used to determine the levels of stress and strain in the flexible pavement under increased tire pressures and axle loads. The geometry of axle structure along with the locations for the determination of maximum strains are illustrated in fig. 2.

In this study, the pavement was characterized as three – layers elastic and four-layers elastic system as outlined in table 1. The modulus of deformation of subgrade as well as Poisson's ratios are assumed values according to pervious studies [10]. Modulus of deformation of subgrade for wearing-and binder courses were calculated from the following eq. (11):

$$E = 15000 - 7900 \log (t) \,. \tag{5}$$

Where:

t is the pavement temperature, °C, and

E is modulus of deformation of subgrade, MPa

Pavement temperature was assumed for wearing course about 45 °C and for binder course 40 °C. This assumption is based on a study performed by Egyptian road network. It was assumed also that base course was constructed from good quality materials with CBR > 80%.

10. Variation of equivalency axial load factor with tire pressure and axial load

The combined effects of tire pressure and axle load on the Load Equivalency Factor (LEF) were evaluated based on the critical stresses and strains in the pavement. The maximum tensile strain at the bottom of asphalt layer and the maximum vertical compressive strain at the top of subgrade determined by computer BISAR program, the equivalent factors with reference to any tire and axle load can be computed using eqs. (3) and (4).

The maximum tensile strain at the bottom of asphalt layer was used to calculate the equivalency factor due to fatigue, *Eft*. Similarly, the maximum vertical compressive strain on the top of subgrade was used to calculate the equivalency factor due to rutting, *Efc*. Tables 2 and 3 present the equivalency factors due to the two failure modes, *Eft* and *Efc*, for single axle with dual tires. The greater equivalency factors of *Eft* and Efc were represented the LEFs for this pavement component.

It can be noticed from table 2 that, if *Eft* is the greater equivalency, increases in tire pressure are accompanied by increases in equivalent factor *Eft*. This is because *Eft*'s would certainly be influenced by tire pressure. In cases where *Efc* is the greater equivalency, the change in *Efc* with tire pressure is almost negligible. This is reasonable because the compressive strain at the top of subgrade, being over 0.40 m from pavement surface, is relatively insensitive to tire pressure. Oppositely, the compressive strain is very sensitive to axle loads.

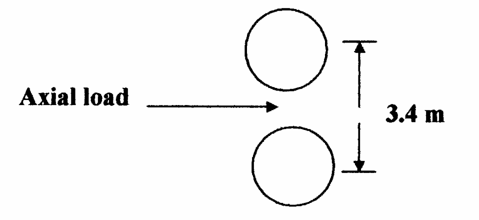

Fig. 2. points used for determination of max strains.

Table 1
Layered elastic representations

Four- layers	Thick.	Elastic modulus, *E*, MPa	Poisson's ratio,*u*
wearing course,mm	50	2000	0.35
binder course,mm	50	2300	0.35
Crushed aggregate base, mm	300	600	0.37
Subgrade	Infinite	50, 100, 150	0.45

Table 2
LEFs as a function of axle loads and tire pressure for single axles at different subgrade elastic modulus (Case fatigue coefficient m= 5)

Single axle load, kN	Tire contact pressure (MPa)				
	0.50	0.60	0.70	0.80	0.90
			E subgrade = 50 Mpa		
60	0.46	1.61	3.05	5.11	7.96
70	0.66	1.72	3.42	5.95	9.58
80	1.00	1.77	3.71	6.73	10.96
90	1.32	1.77	3.82	7.07	11.97
100	2.07	2.72	3.82	7.42	12.77
			E subgrade = 100 Mpa		
60	0.40	2.305	4.34	7.40	11.2
70	0.65	2.54	4.98	8.60	13.76
80	1.00	2.62	5.41	9.71	15.71
90	1.89	2.62	5.71	10.44	17.51
100	2.62	2.62	5.71	10.94	18.66
			E subgrade = 150 Mpa		
60	0.27	2.57	4.95	12.37	13.88
70	0.70	2.82	5.68	15.53	14.20
80	1.00	3.00	6.16	18.37	15.53
90	1.63	3.00	6.32	19.72	17.72
100	2.65	3.00	6.50	21.00	18.10

Table 3
LEFs as a function of axle loads and tire pressure for single axles at different subgrade elastic modulus (Case rutting coefficient b= 5)

Single axle load, kN	Tire contact pressure (MPa)				
	0.50	0.60	0.70	0.80	0.90
			E subgrade = 50 Mpa		
60	0.55	0.30	0.32	0.33	0.34
70	0.69	0.60	0.62	0.68	0.71
80	1.00	1.09	1.20	1.27	1.31
90	1.66	1.87	2.03	2.16	2.3
100	2.61	2.94	3.26	3.46	3.7
			E subgrade = 100 Mpa		
60	0.29	0.31	0.33	0.65	0.68
70	0.56	0.62	0.68	0.77	1.70
80	1.00	1.14	1.24	4.35	5.26
90	1.67	1.88	2.06	2.22	2.49
100	2.57	2.96	3.28	3.64	4.12
			E subgrade = 150 Mpa		
60	0.28	0.32	0.34	0.36	0.37
70	0.56	0.62	0.69	0.73	0.76
80	1.00	2.94	1.23	1.32	1.38
90	1.65	1.87	2.07	2.25	2.39
100	2.54	2.97	3.32	3.58	3.85

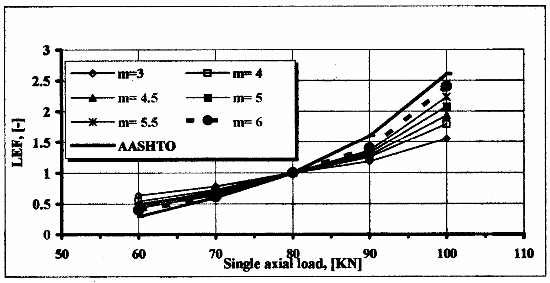

Fig. 3. LEF versus single axial load at *Et* and *E* = 50 [MPa].

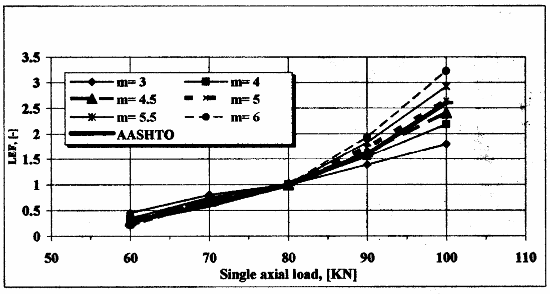

Fig. 5. LEF versus single axial load at *Et* and *E* = 150 [MPa].

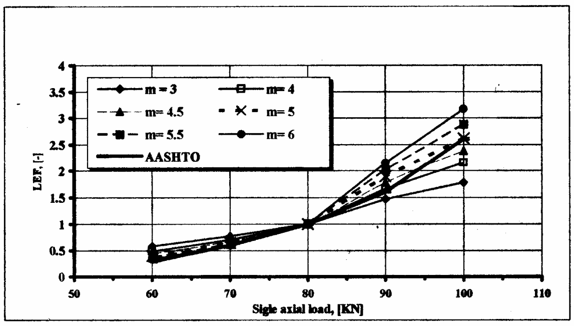

Fig. 4. LEF versus single axial load at *Et* and *E* = 100 [MPa].

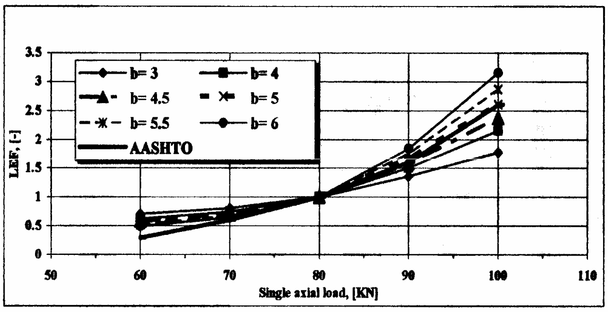

Fig. 6. LEF versus single axial load at [c*t]* and *E* = 50 [MPa].

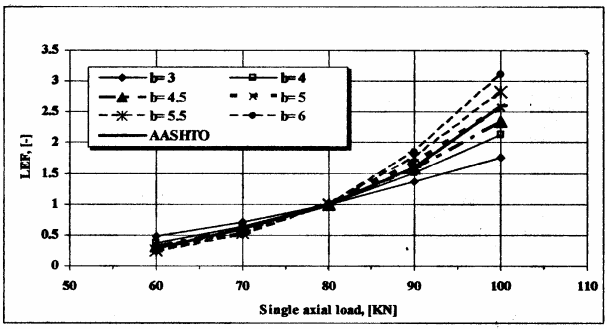

Fig. 7. LEF versus single axial load at [c*t*] and *E* = 100 [MPa].

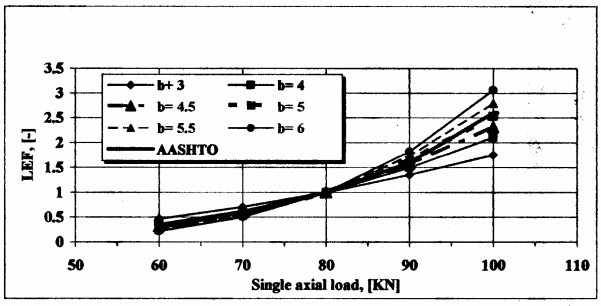

Fig. 8. LEF versus single axial load at [c*t*] and *E* = 100 [MPa].

It can be concluded that the effect of increased tire pressure on asphalt pavement depends on axle load. At high to intermediate axle loads, high tire pressure can cause marked increase in *Efc*. On the other hand, at low axle loads, variation of *Efc* with tire pressure becomes insignificant.

11. Relationship between LEF using bisar program and LEF using AASHTO specification

Linear regression was performed between the biggest values of calculated LEFs in the two cases, fatigue and rutting, at 0.50 Mpa tire pressure at different modulus of deformation of subgrade in the one side and another side the AASHTO LEFs values. It was found that very strong correlation between the calculated LEFs and AASHTO-LEFs. The regression equations is as follows:

$$Y=P\,X+F. \qquad (6)$$

Where,
X = AASHTO- LEFs,
Y= LEF using BISAR computer program, P and F are constants.

Table 4 represents the two constants P and F and the correlation coeffocient. From this table, it can be concluded that at lower modulus of deformation of subgrade, 50 Mpa, the rutting constant "*P*" becams higher than those in other modulus of elasticity. On the other hand, no specific trend can be seen for the variation of the coefficient P with increasing in the modulus of deformation of subgrade.

Table 4
represents the two constants *P*, *F* and the correlation coeffocient.

E	εt		
	P	*F*	Corr. Coeff.
50	+1.1531	-0.121	0.97
100	+0.9823	-0.071	0.98
150	+0.9730	-0.617	1.00

12. Relationship between the LEF and variables

Multi-regression analysis was fulfilled to obtain the relationships between LEFs and axle loads, tire contact pressure and subgrade elastic modulus for axle loads. The achieved relations is as follows:

$$LEF = -34.51 + 7.7\,Pt + 0.263\,P + 7.6\,Log\,E\,. \qquad (7)$$

LEF	is the Load equivalency factor,
Pt	is the tire contact pressure (MPa),
P	is the axle load (kN), and
E	modulus of deformation of subgrade (MPa) correlation coefficient is equal to 0.9.

13. Estimating of equivalent axle loads (EALs)

In order to estimate the effect of increasing tire pressure for different axle loads, an adjustment factor is introduced. This factor is defined as the ratio of LEF for tire pressure in question to the LEF for standard tire pressure of 0.5 MPa [4].

Table 5
Truck factors as a function of tire pressure and subgrade elastic modulus for different vehicles in egypt

Truck type, load (ton)	Truck Factor				
	Tire contact pressure (MPa)				
	0.50	0.60	0.70	0.80	0.90
	E= 50 MEPa				
SUT 16 t, (6, 10)	1.10	2.48	4.28	6.76	10.01
TST 26t, (6,10,10)	1.65	3.35	5.51	8.41	12.06
TST 36t, (6, 10, 10, 10)	2.20	4.22	6.74	10.06	14.11
	E =100 MPa				
SUT 16 t, (6,10)	0.93	3.15	5.53	8.99	13.17
TST 26t, (6, 10, 10)	1.46	3.99	6.72	10.58	15.14
TST 36 t, (6, 10, 10, 10)	1.99	4.83	7.91	12.17	17.11
	E= 150 MPa				
SUT 16 t	0.80	3.38	6.13	13.90	15.83
TST 26t, (6, 10, 10)	1.33	4.19	7.31	15.43	17.78
TST 36 t, (6, 10, 10, 10)	1.86	5.00	8.49	16.96	19.73

Note; SUT is single unit truck and TST is tractor semi-trailer

$$EAL = ADTi \times TF \times Gr \times Fd \times 365 . \qquad (8)$$

Where,
$ADTi$ is the first year annual average daily Traffic,
TF is the truck factor,
Gr is the growth factor for a given growth Rate, and
Fd is the design lane factor.

Truck Factors (TF) were calculated as a function of tire pressure and modulus of deformation of subgrade for 3 types of trucks on Egyptian road network. These factors are shown in table 5. It was found that the subgrade elastic modulus has no significant influence on these factors. Thus, the truck factors could be determined for each truck type as a function of tire pressure using linear regression as follows:

$$TF = 0.491 + 0.0276\, Pt . \qquad (9)$$

Where,
Pt is the tire pressure correlation coefficient is equal to 0.94.

14. Conclusions

According to the analysis done herein, the following could be concluded:

1. As the axle load increases, high tire pressure can cause significant increase in the equivalent axle load factor. In that case, fatigue failure is the prevailing failure mode. On the other hand, as the single axle load continues to increase, the failure mode turns to a rutting one and, in this case the effect of increase in tire pressure can be ignored.
2. The fatigue and rutting coefficients, m and b in the LEF equations are not affected by the type of subgrade soil and were found to equal 5 under the circumstances at hand.
3. The influence of high tire pressure on asphalt pavement depends on axle load. At low to intermediate axle loads, high tire pressure can cause remarkable increase in LEF. At high axle loads, variation of equivalency factor with tire pressure can be neglected. At the same tire pressures and axle loads, increased modulus of deformation of subgrade has insignificant influence on LEFs.
4. LEFs can be determined as a function of axle loads (P), tire contact pressure (Pt) and modulus of deformation of subgrade (E) from the following regression equation:

$$LEF = -34.51 + 7.7\, Pt + 0.263\, P + 7.6 \log E.$$

5. LEFs can be calculated using the truck factor (TF) as a function of tire pressure (Pt).

This factor can be calculated according to the following form:

$TF = 0.491 + 0.0276\, Pt$.

6. The effect of subgrade elastic modulus on EAL depends on tire pressure. At high tire pressures, there is marked decrease of EAL with increasing subgrade elastic modulus. At low tire pressures, the effect of subgrade on EAL becomes insignificant. At the same subgrade type, high tire pressures can cause significant increase in total EAL.
7. The designer of flexible pavement must take into account both tire pressure and vehicles axial load. The procedure presented in this paper introduces a new additional design tool to improve the strurctural pavement section design.

References

[1] Egyptian Code for Urban and Rural Roads, Part 6 “Highway Structure Design” (1998).
[2] Asphalt Institute, “Thickness Design – Asphalt Pavement for Highways and Streets” Ninth Edition, The asphalt Institute, Manual Series No. 1 (MS-1) (1991).
[3] AASHTO Guide for Design of Pavement Structures, 1993. American Association of State Highway and Transportation Officials, Washington, DC (1993).
[4] W. H. Huang et al. “Effects of Heavy Vehicles and Tire Pressure on Flexible Pavement Design in Taiwan”, Paper Submitted for Presentation and Publication at the 80 th Annual Meeting in January 2001 of the transportation Research Board, Washington, D.C. (2001).
[5] D. M. Burmister "The Theory of Stresses and displacement in Layered Systems and Applications to the Design of airport Runways," Proceedings. Highway Research Board. Vol. 23, pp. 126-149 (1943).
[6] S. W. Hudson and S.B., Seeds “Evaluation of increased Pavement Loading and Tire Pressures”, Transportation Research Record 1207, pp. 197-206 (1998).
[7] BISAR, Computer Program, “Bitumen Structure Analysis in Roads”, Koninklijke Shell – Laboratorium, Amsterdam (1972).
[8] O. K. Kim et al., “Effect of Increased Truck Tire Pressure on Asphalt Concrete Pavement”, Journal of Transportation Engineering, ASCE, Vol. 115 (4), pp. 329-350 (1989).
[9] L/B. Roger and J. B., Kenneth " Highway Engineering Handbook", building and Rehabilitating the intrastructure, chapter three, pp. 3.13- 3.22 (1995).
[10] J. Hothan, “Zum Einfluss der Zugspannungsaufnahmenfähigkeit in ungebundenen Tragschichten auf die Anstrengung von Asphaltbefestigungen- Eine Modell-Untersuchung” – Dissertation, Universität Honnover (1986).
[11] F. Wellner, “Grundlagen zur Bemessung Flexibler Strassenkonstruktionen mit Tragschichten ohne Bindemittel”, - Dissertation, TU-Dresden (1995).

Received July 2, 2003
Accepted July 23, 2003