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The Effects of Truck Axle Loads and Tire Pressure on the Responses of Flexible Pavement

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ABSTRACT
In recent years, overinflated tire pressure and the consequence of increased heavy vehicles` axle loads on flexible pavements responses have become a major source of worry, because of the higher stress levels induced within the flexible pavement which leads to extra damage. As a result, this research aims to assess the performance of the flexible pavement under varied axle loads and tire pressures of different trucks in Egypt. The 3D-Move V2.1 analysis program is a tool used to calculate the stresses and strains within pavement layers. The main conclusions that can be drawn from the analysis of the results is that there is a direct relation between pavement responses in terms of vertical strain z-z ($\varepsilon_{z\text{-}z}$), normal strain x-x ($\varepsilon_{x\text{-}x}$), and vertical displacement (V_d) with each of tire pressure and axle load. Furthermore, the pavement responses are affected more by load than tire pressure. The $\varepsilon_{z\text{-}z}$ is influenced not only by vertical stresses, but also by normal and radial stresses and the elastic modulus of the layer. Also, vertical strain developed at the bottom of the asphalt layer and the subgrade is not affected significantly by tire pressure. In addition, the effects of tire pressure on the horizontal strain at the bottom of the asphalt layer is much more than on the compressive strain above the subgrade. The important conclusion is increasing of wheel loads have a greater impact on rutting deterioration than fatigue. However, increasing tire pressure has a greater impact on fatigue deterioration than rutting.

Keywords: *Truck axial loads, tire pressure, rutting and fatigue damage, flexible pavement responses, and 3D-Move V 2.1.*

1. Introduction

Trucks are a major consumer of the pavement structure because they apply the highest loads to the road surface. Among heavy trucks, all do not cause equal damage because of variations in wheel load (static and dynamic), number and location of axles, types of suspensions, number of wheels, tire type and inflation pressure, and other factors. Heavy trucks are increasing in the diversity of their design and use. New configurations, new suspensions, new tire types, and higher inflation pressures are changing the loads imposed on the pavement surface.

In recent years, the effects of increased truck tire pressures on flexible pavement performance have become a subject of great concern. Various researchers have used analytical methods to attribute decreased fatigue life, increased rutting, and accelerated serviceability loss to the effects of increased tire pressure [1-3].

The effects of tire pressure on flexible pavement response and performance were evaluated [4] using data from the first phase of research at the FHW A Pavement Testing Facility. The response evaluation included measuring surface deflections, surface strains, and strains at the bottom of the asphalt layer for various combinations of load and tire pressure. The response evaluation showed tire pressure had little effect on the measured responses at all load levels. Increasing the tire pressure from 76 to 140 psi accounted for only a 2- to 10-percent increase in surface deflection, surface strain, and strain at the bottom of the asphalt layer.

The results of pavement analysis using KENLAYER program [5] showed that the influence of increased tire inflation pressure on asphalt pavement depends on axle load. At low to intermediate axle loads, the increase in tire pressure causes marked increase in EALF, while fatigue failure is the predominant failure mode. At high axle loads, the failure mode turns to rutting and, in such case the variation of EALF with tire pressure becomes insignificant. The EALFs at the operational level of tire contact pressure of 130 psi along with the legal values of axle loads were found approximately twice and triple the AASHTO factors for single and tandem, respectively. The effects of tire pressure on the pavement response and failure life of pavement were evaluated [6]. The research uses the ELSYM5 software and pavement materials conditions to estimate the tensile strains occurring under the asphalt concrete (AC) layer and the compressive strains above the subgrade surface. The calculated strain is then utilized to estimate the number of load repetitions to failure due to fatigue cracking and rutting using the asphalt institute (AI) method.

Overinflated tire pressure and the effect of increased heavy vehicles` axle load on flexible pavements responses have been evaluated in this research [7] that aims to evaluate the effects of various tire inflation pressures on the determination of tire contact/footprint area for flexible pavement. A survey to collect data on current levels of tire inflation pressure was carried out at two major expressways in Klang Valley, Malaysia and a full-scale experiment was then conducted on a heavy vehicle with 1:1:2 axle configuration, 10 R 20 tire size and attached trailer with constant axle load. The data showed that the operational levels of tire inflation pressure of heavy vehicles in that area were as high as 827 kPa (120 psi) compared to the assumed tire inflation pressure of 700 kPa (102 psi) used for pavement design in Malaysia. Comparison between actual tire-pavement contact area and tire contact area calculated using conventional circular method showed a difference as high as 79%. KENPAVE linear elastic program was used to analyze the effects of measured actual tire-pavement contact area and the results was compared using conventional circular tire contact area. It was found that high tire inflation pressure produces less contact area (actual), giving more detrimental effect on the flexible pavement compared to the conventional circular tire contact area method. However, it was also found that the temperature of tires when the heavy vehicles are operational give less significant impact on tire inflation pressure for the Malaysian climate.

Moreover, the weak pavement section was more affected than strong section with increased tire pressure with changing the configuration from single to tandem axle. The pavement design life is generally governed by fatigue failure with respect to tire pressure. Tire pressure has no significant effects on rutting life compared to fatigue life, which is highly sensitive to pressure levels.

On Texas highways, an increase in the number of permitted oversized and overweight loads have been found. The motor carrier industry uses a number of tire sizes in transporting oversized and overweight loads. Tire inflation pressures for these transports are often higher than those used for regular line hauling to match the higher wheel loads of the overweight truck or trailer. In evaluating the structural adequacy of pavements to applied wheel loads, existing practice typically assumes the tire pressure to be uniform over the contact area with magnitude equal to the inflation pressure. This analysis ignores the differences in tire footprints among various tire types. To determine the effects of these differences, researchers investigated existing procedures for predicting pavement response to applied surface tractions at the tire-pavement interface [8]. A specific objective was to establish how tire contact stresses may be modeled in existing layered elastic programs to better approximate the effects of non-uniform tire contact pressure distributions, and account for differences in tire construction, tire load, and tire inflation pressure on predicted pavement response. To this end, researchers assembled a data base of measured tire contact stresses and performed a comparative evaluation of methods for representing tire contact pressure distributions in existing models to predict performance-related pavement response variables.

A computer program called TireView was developed that provides estimates of tire contact area as a function of tire type, tire load, and tire inflation pressure and predicts the stress distribution at the tire-pavement interface based on polynomial interpolations of measured tire contact stresses in the data base. A method for predicting pavement response using layered elastic analysis is proposed that is based on the predicted tire contact area. Alternatively, the predicted tire contact pressure distribution from Tire View may be used in a finite element program for applications where a more rigorous analysis is desired.

2. Aim and Research Significance

The aim of this study was calculating and analyzing the flexible asphalt pavement responses for the same pavement section and material properties at different axle loads and tire pressure. Moreover, the cumulative damage of the pavement structure as a result of increasing axle loads and tire pressure were obtained. The computer software 3D-Move 2.1 analysis help us to solve and analyzing dynamic response of different axle loads and tire pressures taking into consideration the following:

1- Layer thickness 2- Elastic modulus 3- Poisson's ratio 4- Damping ratio 5- Unit weight 6- Soil type

3. Experimental Program

The 3-D move v.2.1. was used to perform the calculations of this project. In the following, some information's about this program will be discussed.

A- Description of 3-D Move V2.1 program

The analytical model (3D-Move) adopted here to undertake the pavement response computations uses a continuum-based finite-layer approach. The 3D-Move analysis model can account for important pavement response factors such as the moving traffic-induced complex 3D contact stress distributions (normal and shear) of any shape, vehicle speed, and viscoelastic material characterization for the pavement layers. This approach treats each pavement layer as a continuum and uses the Fourier transform technique. Therefore, it can handle complex surface loadings such as multiple loads and non-uniform tire contact stress distribution. Since the tire imprint can be of any shape, this approach is suitable to analyze tire imprints, including those generated by wide-base tires [9, 10].

The finite-layer method is much more computationally efficient than the moving load models based on the finite element method [11,12]. This is because often times the pavements are horizontally layered and pavement responses are customarily required only at a few selected locations and for such problems the finite layer approach of 3D-Move Analysis is ideally suited. Since rate-dependent material properties (viscoelastic) can be accommodated by the approach, it is an ideal tool to model the behavior of asphalt concrete (AC) layer and also to study pavement response as a function of vehicle speed. Frequency-domain solutions are adopted in 3D-Move Analysis, which enables the direct use of the frequency sweep test data of HMA mixture in the analysis. Many attempts that included field calibrations (e.g., Penn State University test track, Mn/Road and UNR Off-road Vehicle study) that compared a variety of independently-measured pavement responses (stresses, strains, and displacements) with those computed have been reported in the literature [13]. These verification studies have validated the applicability and versatility of the approach .

B- Characterization of Asphalt Materials

The asphalt layer material can be characterized as a linear elastic or a viscoelastic material. The dynamic modulus, |E*|, is required for the viscoelastic analysis.

4. Test Results and Discussion

A. Effect of wheel load and tire pressure on V_d

The effect of wheel load and tire pressure on V_d at the observed points asphalt concrete surface (AC surface), bottom of asphalt layer (AC bottom) and Top of subgrade (subgrade surface) were depicted on Figs. 1 to 3. It can be observed that, at constant tire pressure, the vertical displacement increases with increasing the wheel load for all loading cases and at all observed points. Moreover, the increase in V_d values from the least and largest loading case [4000 Ib-90 psi and 5500 Ib-130 psi] were 39, 39, and 35 % at AC surface, AC bottom, and subgrade surface respectively. Even though, at constant wheel loads, the increase in V_d with changing tire pressure is a small, insignificant increase, as the greatest increase among the smallest and largest tire pressure [90:130] psi is less than 3.7% .

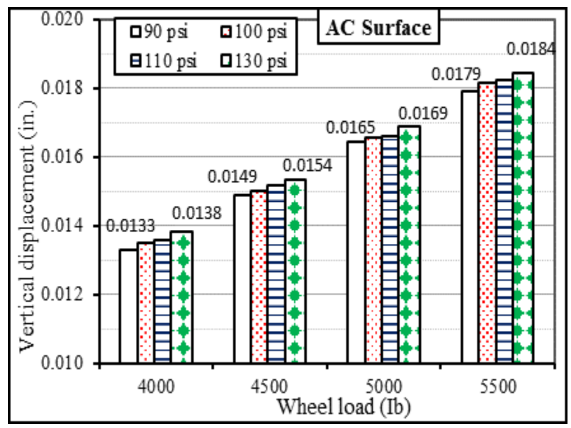

Fig. 1. Effect of wheel load and tire pressure on V_d at AC surface

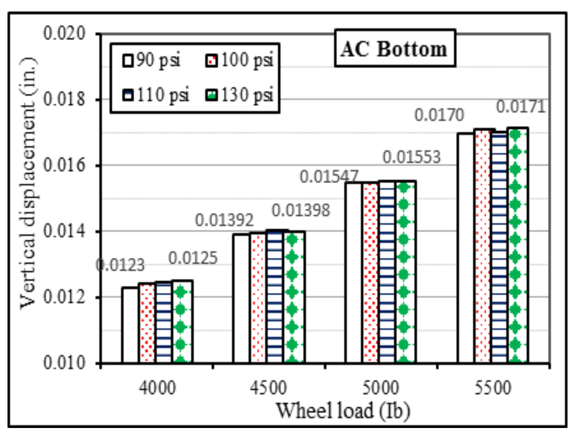

Fig. 2. Effect of wheel load and tire pressure on V_d at AC bottom

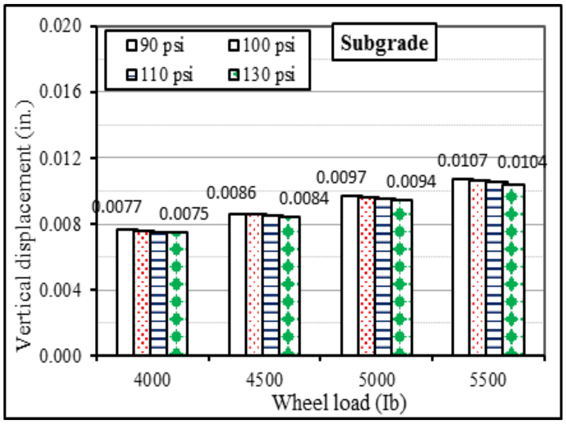

Fig. 3. Effect of wheel load and tire pressure on V_d at subgrade

At subgrade surface, it is noted that the general trend of the vertical displacement values decreases with increasing tire pressure in all cases of wheel loads. However, as mentioned previously, it increases with increasing wheel loads when tire pressure is fixed. The decrease in the vertical displacement values could be linked to the decrease in radius of the contact pressure circle. Where it is clear from (1), the radius R decreases as tire pressure increases provided that the wheel load is constant.

$$R = \sqrt{\frac{P}{\pi \rho}} \qquad (1)$$

Where:
R = radius of pressure contact area
P = Wheel load   ρ = Tire pressure

B. Effect of wheel load and tire pressure on ε_{x-x}

Table 1 and Figures 4 to 6 show the effect of wheel load and tire pressure on ε_{x-x} at the observed points. It is noteworthy mentioning that the developed strains at AC surface were compression as indicated via positive values in fig. 4. However, tensile strains were developed at both of AC bottom and subgrade surface as displayed via negative numbers in Figs. 5 and 6. From the three figures, it can be revealed that the ε_{x-x} increases for all values with increasing wheel load at constant tire pressures. Furthermore, at constant wheel load, the ε_{x-x} increases with increasing tire pressure.

Table 1. ε_{x-x} (in micro strain) at observed points

AC Surface				
Tire pressure (psi)	**Wheel load (Ib)**			
	4000	4500	5000	5500
90	300	319	338	355
100	315	335	355	375
110	328	352	370	390
130	357	379	400	421
AC bottom				
Tire pressure (psi)	**Wheel load (Ib)**			
	4000	4500	5000	5500
90	- 207	- 220	- 234	- 245
100	- 215	- 230	- 245	- 259
110	- 224	- 241	- 255	- 270
130	- 239	-256	- 274	- 290
Subgrade				
Tire pressure (psi)	**Wheel load (Ib)**			
	4000	4500	5000	5500
90	- 117	- 128	- 140	- 152
100	- 119	- 130	- 142	- 155
110	- 121	- 134	- 145	- 157
130	- 127	- 138	- 149	- 162

Numerically, at the AC surface, AC bottom, and subgrade surface, the increases in ε_{x-x} values from the least and greatest loading cases [4000 Ib-90 psi and 5500 Ib-130 psi] were 40, 40, and 38 percent, respectively. Also, it can be revealed that at constant wheel load, the increase rate of ε_{x-x} between the lowest and highest values of tire pressure [90 and 130] was significant, with an average value of 18%, at both observed points AC surface and AC bottom. As for the subgrade surface, the rate of increase was not as significant as it was on the AC layer where the values of the rate of increase were around 8%.

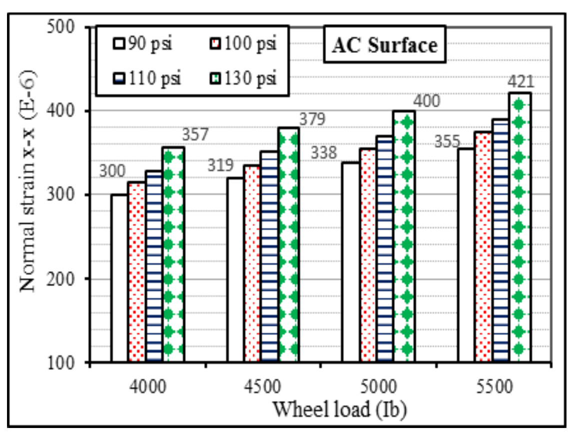

Fig. 4. Effect of wheel load and tire pressure on ε_{x-x} at AC surface

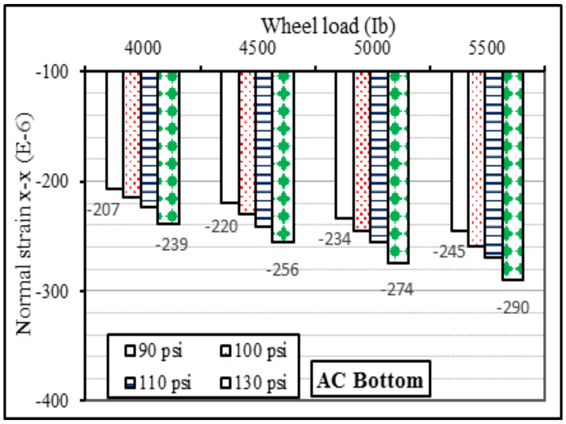

Fig. 5. Effect of wheel load & tire pressure on ε_{x-x} at AC bottom

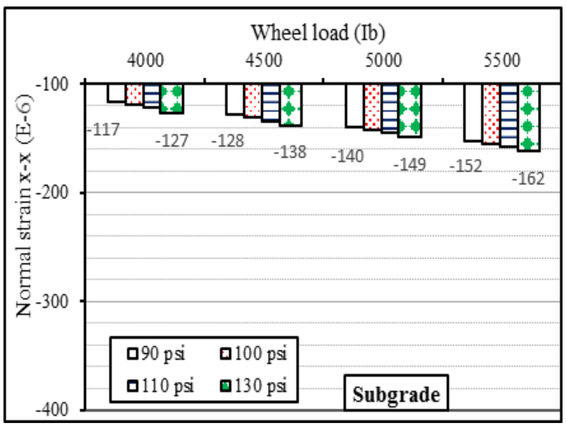

Fig. 6. Effect of wheel load and tire pressure on ε_{x-x} at subgrade

C. Effect of wheel load and tire pressure on ε_{z-z}

Table 2 and Figures 7 to 9 show the effect of wheel load and tire pressure on ε_{z-z} at the observed points. Form displayed results, one can observe the direct relation between the ε_{z-z} and each of tire pressure and wheel load, as the ε_{z-z} increases regularly as one increases and the other is held constant. Also, it can be noticed that the values of the ε_{z-z} dramatically decreased at AC bottom, then increased again at subgrade layer to almost the values of AC surface. The reason for this could be attributed to the vertical strains z-z of pavement layers not only affected by the vertical stress z-z but affected also by normal and radial stresses and layer's elasticity moduli (E).

Table 2. ε_{z-z} (in micro strain) at observed points

AC Surface				
Tire pressure (psi)	**Wheel load (Ib)**			
	4000	4500	5000	5500
90	243	250	251	257
100	270	271	278	279
110	289	295	299	306
130	336	341	346	351
AC bottom				
Tire pressure (psi)	**Wheel load (Ib)**			
	4000	4500	5000	5500
90	89	97	105	113
100	91	100	108	117
110	92	102	110	119
130	95	105	114	123
Subgrade				
Tire pressure (psi)	**Wheel load (Ib)**			
	4000	4500	5000	5500
90	241	269	299	324
100	242	270	299	329
110	243	274	299	329
130	246	274	302	331

Numerically, increases rate in ε_{z-z} from the least and greatest case of loading were 44, 38, and 37 percent, respectively, at the AC surface, AC bottom, and subgrade surface. Figure 7 shows that the increasing rate is significant between the lowest and highest tire pressure, at each case of wheel load, with an average value of 38%. However, as for AC bottom and subgrade surface, figures 8 and 9 indicates the non-significant increasing rate with an average value around 3%.

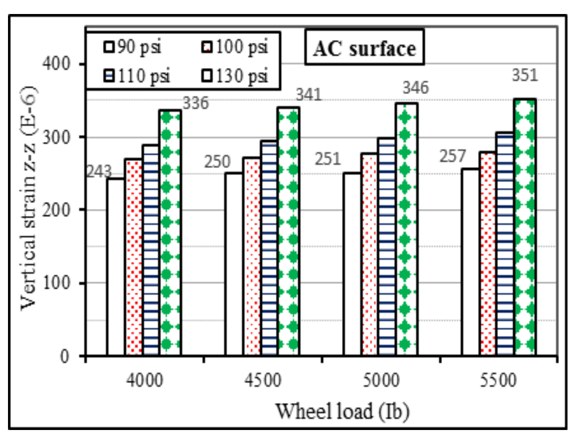

Fig. 7. Effect of wheel load and tire pressure on ε_{z-z} at AC surface

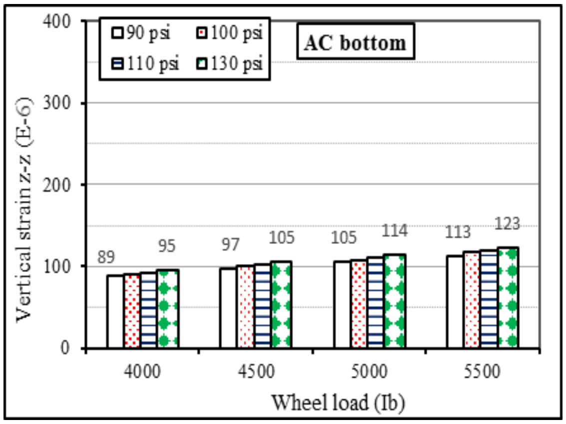

Fig. 8. Effect of wheel load and tire pressure on $\varepsilon_{z\text{-}z}$ at AC bottom

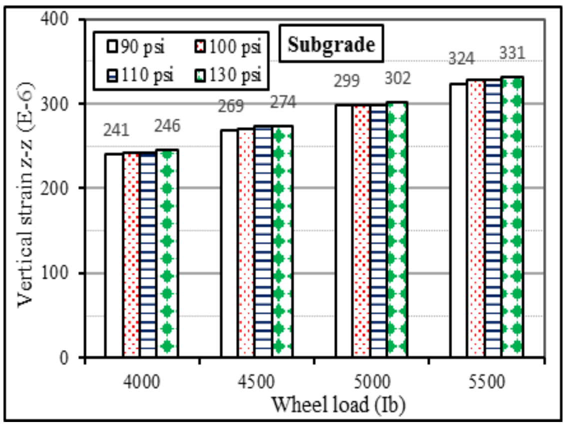

Fig. 9. Effect of wheel load and tire pressure on $\varepsilon_{z\text{-}z}$ at subgrade

D. Effect of wheel load and tire pressure on fatigue and rutting damage

Loads on the pavement's surface produce two kinds of strains that are thought to be critical for design purposes. These are the normal tensile strain x-x (ε_x) at the bottom of asphalt layer and the vertical compressive strain z-z (ε_z) at the top of subgrade layer. The 3D Move V2.1, a computer program, was used to determine the two critical strains as displayed in Tables 1 and 2. If ε_x is too high, the surface layer cracks and the pavement degrades due to fatigue, whereas if ε_z is too great, permanent deformation occurs at the surface of the pavement structure due to subgrade overloading resulting in rutting of pavement. The following damage analysis was carried out for both fatigue cracking and permanent deformation, rutting.

The tensile strains ε_x generated at AC bottom, presented in Table 1, were used for calculating the needed number of load repetition N_f for mitigating cracks by fatigue. The estimated N_f was calculated from the proposed (2) by Asphalt Institute [14]. The equation represents the relationship between fatigue failure of asphalt concrete and tensile strain εx at AC bottom. The vertical compressive strains ε_z generated at subgrade surface, which were displayed in Table 2, were also used to calculate the frequency of loads N_{rut} for mitigating of rutting appearance. The estimated N_{rut} was specified from (3) - according to Asphalt Institute [14] - that provides the relationship between the vertical compressive strain ε_z at subgrade surface and failure by rutting.

$$N_F = 0.0796\left(\frac{1}{\varepsilon_X}\right)^{3.291}\left(\frac{1}{E}\right)^{0.854} \qquad (2)$$

Where:
N_f = Number of load repetitions to prevent fatigue cracking.
ε_x = Tensile strain at the bottom of asphalt layer.
E = Elastic modulus of asphalt layer.

$$N_{rut} = 1.365\times10^{-9}\left(\frac{1}{\varepsilon_X}\right)^{4.477} \qquad (3)$$

Where:
N_{rut} = Number of load repetitions to prevent rutting deformation.
ε_z = Vertical compression strain at subgrade surface.

Table 3 shows the number of load repetitions for fatigue and rutting at all selected loading conditions. The N_f values were calculated at the modulus of elasticity of the asphalt layer E equal to 2E+5 psi.

In order to express the extent of deterioration through the pavement layers as a result of increasing the wheel loads or tire pressure, an equivalent wheel load index (EWLI) was calculated and used for this purpose. Equations 4 and 5 introduce these two indices for fatigue and rutting respectively. It should be mentioned that the lowest case of loading 4000 Ib (90 psi) was taken as a reference case only for the purpose of comparison.

$$EWLI^{f} = \left(\frac{\varepsilon_x^{0}}{\varepsilon_x^{1}}\right)^{3.291} \qquad (4)$$

$$EWLI^{r} = \left(\frac{\varepsilon_z^{0}}{\varepsilon_z^{1}}\right)^{4.477} \qquad (5)$$

Where:
$EWLI^{f}$ = Equivalent wheel load index for fatigue
ε_x^{0} = Normal tensile strain x-x at AC bottom for loading case 4000 Ib (90 psi)

ε_x^1 = Normal tensile strain x-x at AC bottom for any loading case

$EWLI^r$ = Equivalent wheel load index for rutting

ε_z^0 = Vertical compressive strain z-z at subgrade surface for any loading case

ε_z^1 = Vertical compressive strain z-z at subgrade surface for any loading case

Table 3. Load repetitions to fatigue and rutting for all the selected cases of loading

Load repetition for fatigue (N_f)				
Tire pressure (psi)	Wheel load (Ib)			
	4000	4500	5000	5500
90	3.2E+6	2.6E+6	2.1E+6	1.8E+6
100	2.8E+6	2.2E+6	1.8E+6	1.5E+6
110	2.4E+6	1.9E+6	1.6E+6	1.3E+6
130	2.0E+6	1.6E+6	1.3E+6	1.0E+6
Load repetition for rutting (N_{rut})				
Tire pressure (psi)	Wheel load (Ib)			
	4000	4500	5000	5500
90	2.15E+7	1.32E+7	8.20E+6	5.72E+6
100	2.11E+7	1.29E+7	8.20E+6	5.34E+6
110	2.08E+7	1.21E+7	8.20E+6	5.34E+6
130	1.96E+7	1.21E+7	7.84E+6	5.20E+6

Figures 10 and 11 show the equivalent wheel load index (EWLI) for fatigue and rutting, respectively. It is observed from two figures that the deterioration of pavement by fatigue or rutting increase with increasing both of wheel load and/or tire pressure. Fatigue damage increased by 67% (100*[1-0.33]) between the lowest and highest loading condition, while rutting damage occurred by 76%. An increase in tire pressure from 90 to 130 psi resulted in a decrease in the number of repetitions to failure N_f by about 38, 32, 27, 24 % respectively for 4000, 4500, 5000, and 5500 Ib wheel load. While, N_{rut} decreased by 9, 5, 2 and 3 % at the same wheel loads.

In all cases of fixed wheel load, increasing tire pressure resulted in significant deteriorations through fatigue as opposed to minor deteriorations through rutting. When tire pressures are constant, however, the situation has flipped, meaning that with increased wheel load, rutting deterioration is greater than fatigue deterioration.

In summary, it can be revealed that increasing wheel loads has a greater effect on rutting deterioration than on fatigue deterioration. While increasing tire pressure has a greater impact on fatigue deterioration than it does on rutting.

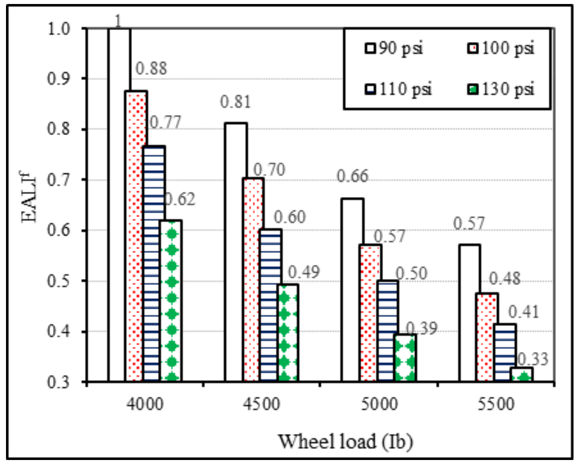

Fig. 10. Equivalent wheel load index for fatigue

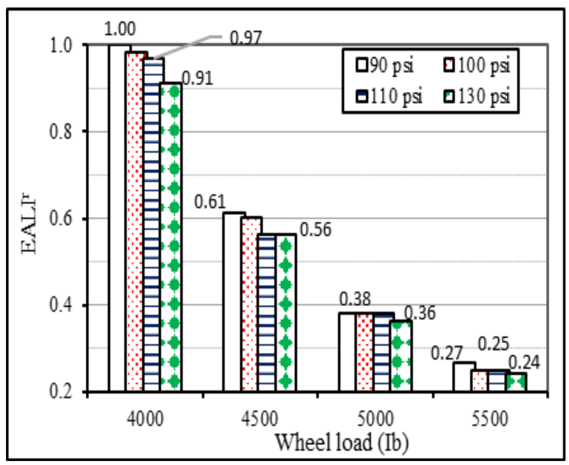

Fig. 11. Equivalent wheel load index for rutting

5. Conclusions

Based on the methodology and analysis of results for this study, the following conclusions can be drawn:

- There is a direct relation between the three measured pavement responses ($\mathcal{E}_{z-z}$, $\mathcal{E}_{x-x}$, and vertical displacement) with each of tire pressure and wheel load.
- The pavement responses were affected more by load than by tire pressure.
- A decrease in V_d values with an increase in tire pressure can be associated with a decrease in the contact pressure radius.

- The effect of changing tire pressure on ε_{x-x} at the subgrade was not as significant as it was on the asphalt layer.
- The vertical strain z-z dramatically reduced at AC bottom, then increased again at subgrade surface to nearly the values of AC surface.
- Vertical strains z-z within pavement layers are influenced not only by vertical stresses, but also by normal and radial stresses and the elastic modulus of the layer.
- Unlike at the pavement surface, the change in tire pressure has no significant effect on ε_{z-z} at the bottom of the asphalt layer and the subgrade.
- The effects of tire pressure on the horizontal strain at the bottom of the asphalt layer is much more than on the compressive strain above the subgrade.
- Fatigue damage increased by 67% between the minimum and maximum case of loading, while the rutting damage increased by 76%.
- Increased wheel loads have a greater impact on rutting deterioration than fatigue. However, increasing tire pressure has a greater impact on fatigue deterioration than rutting.

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