Effects of Truck Tire Pressure on Fatigue and Rutting of Flexible Pavements

Abdullah I. Al-Mansour*, Abduraof H. Al-Qaili**

*professor of transportation, Civil Engineering Department, College of Engineering, King Saud University, Riyadh, KSA
**graduate student, Civil Engineering Department, College of Engineering, King Saud University, Riyadh, KSA

Abstract: In the past, damage resulted from load application to highway pavements focused primarily on the magnitude and frequency of axle loads. In recent years, the effect of increased truck tire pressure on flexible pavements responses has become a subject of great concern. The tire inflation pressure of trucks causes severe deterioration to the pavement and thus reduce its life. This paper aims to evaluate the effects of tire inflation pressure on the pavement response and failure life of pavement. 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. Keywords: Fatigue life, Rutting life, Tensile strain, Compressive strain, Flexible pavement, ELSYM5, Tire inflation pressure.

I. Introduction:

Structural failure of flexible pavements has more spread in many roads as a result of the drastic changes in truck axle loads as well as tire pressures. Important findings of a recent study have concluded that tire pressure has more significant effect on rutting tendency of surface asphalt layer than wheel loads [1]. In the past, damage resulted from load application to highway pavements focused primarily on the magnitude and frequency of axle loads. In recent years, the effect of increased truck tire pressure on flexible pavements responses has become a subject of great concern. Analytical study to investigate the effects of truck tire pressure on pavement responses found that tire pressure was significantly related to tensile strain $\varepsilon_t$ at the bottom of the asphalt layer and stresses near the pavement surface for both the thick and thin pavements [2]. However, tire pressure effects on vertical compressive strain $\varepsilon_c$ at the top of the subgrade were minor, especially in a thick pavement. The increased rutting, decreased fatigue life and accelerated serviceability loss of the pavement have been attributed to the effect of increased truck tire pressure as well as increased axle loads [3, 4].

Existing practice assumes the tire pressure to be uniform over the contact area. The size of contact areas then calculated depending on the contact pressure. The contact pressure is greater than tire pressure for low-pressure tires, because the wall of tires is in compression and the sum of vertical forces due to wall and tire pressure must be equal to the force due to contact pressure. On the other hand, the contact pressure is smaller than tire pressure for high pressure tire, since the wall of tires is in tension [5]. A computer program called TireView was developed that provides estimates of tire contact areas 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 interpolation of measured tire contact stresses [6]. In pavement analysis, tire pressure on the surface of the pavement produces two strains which are believed to be critical for design purposes. These are: the horizontal tensile strain $\varepsilon_t$ at the bottom of the asphalt layer and the vertical compressive strain $\varepsilon_c$ at the top of the subgrade layer. If the horizontal tensile strain $\varepsilon_t$ is excessive cracking of the surface layer will occur, and the pavement distresses due to fatigue. If the vertical compressive strain $\varepsilon_c$ is excessive, permanent deformation occurs on the surface of the pavement structure from overloading the subgrade and the pavement distresses due to rutting [8, 9].

II. Problem Statement:

Tire inflation pressure of trucks can cause excessive damage to pavement structure, such as cracking, rutting, potholes, etc. The deterioration of pavements can, in turn, results in reducing pavement service life and increased accident potential. To reduce this effect, it is important to enforce the legal tire pressure to keep the pavement in good conditions as long as possible. Without active enforcement, the amount of tire pressure will increase leading to rapid deterioration of pavement.
III. Objective:
The primary objective of this study is to estimate and analyze the effects of tire pressure on pavement responses and to determine the number of load repetitions to pavement failure. This will provide a mean to:
1. Investigate the flexible pavement performance due to variation of tire pressure.
2. Predict the design life of the flexible pavement at different tire pressure levels.
3. Perform sensitivity analysis of the variation in tire pressure levels.

IV. Pavement Failure Criteria
In pavement analysis, loads on pavement surface produce two strains. These are the horizontal tensile strain, \( \varepsilon_t \), at the bottom of the asphalt layer and the vertical compressive strain, \( \varepsilon_c \), at the top of the subgrade layer. The two strains are believed to be critical for design purposes. The two critical strains are determined using computer program ELSYM5. Damage analysis was performed for both fatigue cracking and permanent deformation as follows:

Fatigue failure:
The relationship between fatigue failure of asphalt concrete and tensile strain \( \varepsilon_t \), at the bottom of asphalt layer is represented by the number of repetitions as suggested by Asphalt Institute in the following form:

\[
N_f = 0.0796 \left( \frac{1}{\varepsilon_t} \right)^{3.291} (1/E_1)^{0.854}
\]

Where:
- \( N_f \): Number of load repetitions to prevent fatigue cracking
- \( \varepsilon_t \): Tensile strain at the bottom of asphalt layer.
- \( E_1 \): Elastic modulus of asphalt layer.

Rutting failure:
The relationship between rutting failure and compressive strain at the top of subgrade is represented by the number of load applications as suggested by Asphalt Institute in the following form:

\[
N_r = 1.365 \times 10^{-9} \left( \frac{1}{\varepsilon_c} \right)^{4.477}
\]

Where:
- \( N_r \): Number of load repetitions to limit Rutting
- \( \varepsilon_c \): Vertical compressive strain at the top of Subgrade

V. Methods of Analysis
Two typical pavement cross sections are considered for analysis. The first represents, in general, a strong section used in major roads, while the second section represents a weak section used in minor (agriculture) roads. Theses typical sections were selected based on the Saudi Arabia Specifications of Roads. Flexible pavement is typically taken as a multi-layered elastic system in the analysis of pavement response. Materials in each layer are characterized by a modulus of elasticity (E) and a Poisson’s ratio (\( \mu \)). The structural properties of the investigated pavement sections are shown in Table 1.

Loading conditions evaluated included two axle configurations, and four tire pressure levels. The two axle configurations were a dual tired single axle and a dual tired tandem axle. Tire loads used were 14,350 lb per tire for a dual tired single axle whereas for a dual tired tandem is 11,050 lb per tire. Tire pressures of 80, 100, 120 and 130 psi were used. The dual tire is approximated by two circular plates (with variable radius according to axle load and tire pressure) and spaced at 13.6 in. center to center. The tandem axles are represented by two axles spaced 48-in. center to center. The geometry of axle’s configuration along with the locations for the determination of maximum strains are illustrated in Fig.1. A circular tire

<table>
<thead>
<tr>
<th>Section</th>
<th>layer</th>
<th>Thick. (in)</th>
<th>E(psi)</th>
<th>( \mu )</th>
</tr>
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<tbody>
<tr>
<td>(1)</td>
<td>surface</td>
<td>2</td>
<td>600,000</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Asphalt base</td>
<td>4</td>
<td>600,000</td>
<td>0.35</td>
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<tr>
<td></td>
<td>Granular base</td>
<td>12</td>
<td>15,000</td>
<td>0.40</td>
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<td></td>
<td>Subgrade</td>
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<td>10,000</td>
<td>0.45</td>
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<tr>
<td>(2)</td>
<td>surface</td>
<td>2</td>
<td>600,000</td>
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<td>Granular base</td>
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<td>Subgrade</td>
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<td>0.45</td>
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</table>
A circular tire imprint is assumed and the radius of contact is calculated as follow:

\[ a = \sqrt{\frac{P}{\pi \rho_t}} \]

Where:
- \( a \): Radius of contact
- \( P \): Wheel load
- \( \rho_t \): Contact pressure.

Evaluation points were determined depending on failure criteria and axle configuration. In asphalt concrete pavements, the failure criteria were fatigue and rutting, therefore strains at the bottom of the asphalt concrete and top of subgrade were used to determine the load repetitions to failure for fatigue and rutting respectively. Strains directly under a tire, under the tire edge, between the dual tires and between the axles were calculated for the dual tandem axle configuration. For the single axle configuration, the strains under a tire, under the tire edge, and between the tires were determined. Only the largest strain found for each loading condition was used in determining the load repetitions to failure. Other strains were not considered.

![Fig. 1. Geometry of axles configuration](image)

**Determination of strains:**

Determination of horizontal tensile strain at the bottom of asphalt concrete and vertical compressive strains at the top of subgrade were determined using the ELSYM5 computer software program developed by the Federal Highway Administration. ELSYM5 uses elastic layer theory to calculate the stresses and strains at specified points in multi-layer pavement systems. Input variables were material properties, loading condition, and points of evaluation.

**Number of load repetitions to failure:**

For each pavement section and loading condition, the strains at the selected points of interest were calculated using the ELSYM5 program. Using the strain calculated by ELSYM5 and the Asphalt Institute failure formulas, the number of load repetitions to failure for each combination of pavement section and loading condition was determined.

**VI. Results**

The results of the conducted analysis are discussed in the following sections:

**Effect of tire Pressure on pavement responses:**

It can be seen from Figure 2 that the relationship between horizontal strain at the bottom of the asphalt surface and tire pressure levels is nearly linear for the single axle, while it is obviously nonlinear with tandem axle in strong section. The figure shows that the effect of tire pressure was more evident in the range of 90–110 psi for both single and tandem axles. Also, the horizontal strain at bottom asphalt surface increased significantly
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with increasing tire pressure. There is about 100% increase in horizontal strains with single axle where is 75% with dual axle due to increasing tire pressure from 80 to 130 psi.

Figure 3 show the variation in the horizontal strains with tire pressure for the weak section. The relationship is nearly nonlinear for single axle and linear for tandem axle. The result detects 22% increase in horizontal strains with single axle whereas 50% with tandem axle due to increase in tire pressure from 80 to 130 psi. Figure 4 and 5 show the relationship between compressive strain above the subgrade and tire pressure levels. The effect of the tire pressure is not very significant on the compressive strain above the subgrade compared to the horizontal strain at the bottom of the asphalt surface.

Fig. 2. Horizontal strain at the bottom of the asphalt surface with tire pressure for strong section.

Fig. 3. Horizontal strain at the bottom of the asphalt surface with tire pressure for weak section.

Fig. 4. Compressive strain above the subgrade with tire pressure levels for strong section.
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**Fig. 5.** Compressive strain above the subgrade with tire pressure levels for weak section.

**Effect of tire pressure on fatigue life:**

Figs. 6 and 7 explain the trends of the predicted number of load repetitions to failure \( N_f \) (fatigue life) for the strong section and weak section, respectively. It is shown that fatigue life \( N_f \) generally decreased with increased tire pressure levels, and the magnitude of the reductions were highest in the range of 80 – 120 psi. Fig. 6 shows that the number of repetitions to failure \( N_f \) for the tandem axle on the strong section decreased from \( 4 \times 10^6 \) to \( 1 \times 10^6 \) due to increase in tire pressure from 80 to 120 psi. The number of load repetitions to failure for single axle reduced from \( 6 \times 10^6 \) to \( 1 \times 10^6 \) as a result of increasing tire pressure from 80 to 120 psi. The corresponding reduction of the number of load repetitions to failure for the single axle and tandem axle for the weak section were 34 and 63%, respectively. The effects of tire pressure levels on the number of load repetitions to failure is more for the strong section than for the weak section.

**Fig. 6.** Estimated number of load repetitions to failure \( N_f \) for varying tire pressure levels for the strong section.

**Fig. 7.** Estimated number of load repetitions to failure \( N_f \) for varying tire pressure levels for the weak section.
Effect of tire pressure levels on rutting life:

The number of load repetitions due to rutting is related to the compressive strain above the subgrade. Figs. 8 and 9 show that the tire pressure levels do not have significant effect on the number of load repetitions determined from the rutting model. The rutting life increased as a result of decreasing tire pressure from 80 – 130 psi by about 3 and 10 % for single axle and tandem axle, respectively on strong pavement section. The rutting life increased by about 32 and 21 % for the single axle and the tandem axle, respectively on weak section with the decrease in tire pressure from 130 – 80 psi. The number of load repetitions due to rutting is related to the compressive strain above the subgrade.

Fig. 8. Estimated Load Repetitions to Failure \( N_r \) for Varying tire inflation pressure in strong section

![Fig. 8. Estimated Load Repetitions to Failure \( N_r \) for Varying tire inflation pressure in strong section](image)

Fig. 9. Estimated Load Repetitions to Failure \( N_r \) for Varying tire inflation pressure in weak section

![Fig. 9. Estimated Load Repetitions to Failure \( N_r \) for Varying tire inflation pressure in weak section](image)

VII. Conclusion

This preliminary study indicated that reducing tire pressure will reduce pavement strains and extend pavement service life. Tire pressure affects both fatigue and rutting failure. Based on the methodology and analysis of results for this study, the following conclusions are drawn:

- Horizontal strain at the bottom of the asphalt layer and compressive strain above the subgrade increase with increase in tire pressure. 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 magnitude of the tire pressure effects on the horizontal strain at the bottom of the asphalt layer and compressive strain above the subgrade was mainly noticed in the range of 80 – 120 psi.
- An increase in tire pressure from 80 – 120 psi will result in decrees in the number of repetitions to failure \( N_f \) for the tandem axle by about 75% and 84 % for the single axle on a strong pavement section. The corresponding reduction of the number of load repetitions to failure for the single axle and tandem axle for the weak section were 34 and 63%, respectively. This indicates that the effect of tire pressure on the strong section was more than on the weak section.
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- 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 tire pressure.
- Tire pressure has no significant effects on rutting life compared to fatigue life, which is highly sensitive to pressure levels.

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References: