The Effect of Axle Overloading and High Tire Pressure on Flexible Pavement Structure

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Abstract: - Axle overloading and high tire pressures on the highways and motorways in Pakistan are one of the reasons that cause early pavement deterioration. There are numerous sections on the national highway on which trucks are reposted to be operating at 40-80 percent higher tire pressure than the legal limit, and the axle overloading is 30 percent greater than the legal axle load limit. This research aims at determining the effect of axle overloading and high tire pressure on the flexible pavement structure and derive the truck factors for trucks in order to quantify the damage to the pavement due to a single pass of 2-axle, 3-axle, 4-axle, 5-axle, and 6-axle truck using the results reported in the Pilot Axle Load Survey conducted by the National Transport Research Centre. In order to determine the effect of axle overloading and high tire pressure, a theoretical linear elastic mechanistic empirical analysis for different axle configurations was performed using KENLAYER and regression models were developed to find the Equivalent Axle Load Factor (EALFs) for the fatigue cracking, and permanent deformation. It was found that the EALFs were mostly controlled by permanent deformation distress criterion. The EALFs and the truck factors were highly influenced by the axle loads rather than the tire pressure. The 3-axle truck was found to be the most damaging truck followed by 6-axle truck, 5-axle truck, 2-axle truck, and 4-axle truck.

Key-words: - axle loads; overloading; equivalent axle load factors; pavement distresses; Pakistan

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1 Introduction

Axle weight overloading and high tire pressure are some of the significant issues on the 268935 km long highway network of Pakistan [1]. With increased axle load causing high tire pressure, the Load Equivalency Factors or Equivalent Single Axle Load (ESALs) also increase, causing an increase in pavement responses (deflection, strains, and stresses) and can affect the fatigue life of pavements [2]. Determining load equivalency factors (EALFs) is critical in pavement design and rehabilitation as underestimation of the damage from the axle loads on the pavement would result in early failure. The EALF represents the ratio of the allowable number of load repetitions by a single pass of a standard axle load, such as 18-kip single axle load, to the allowable number of load repetitions by any other load and axle configuration that would produce the same reduction in the serviceability life of a flexible pavement. A study by the National Transport Research Centre (NTRC), conducted in 1995, indicates that 43% of the trucks were loaded above the axle load limits of 12 tons [3]. Therefore, to prevent premature pavement failure, it is necessary to determine the impacts of increased axle loading and tire pressures in terms of

ESALs, which would be one of the primary inputs in the pavement design.

The National Highway Authority (NHA) Pakistan has defined the allowable axle load limits for each axle type which are shown in Table 1. However, NHA has also allowed axle overloading up to 30 percent higher than the legal axle load limits, and a penalty is only imposed on the truck whose Gross Vehicle Weight (GVW) is higher than 30 percent overloading. The axle load limits, inclusive of 30% overloading margin, are also shown in Table 1.

Table 1:Vehicle classification and allowable GVW (Source: NHA)

Truck Type	Truck Configuration Code	Allowable Gross Weight (tons)	Allowable Overloaded Gross Weight (tons)
2-Axle Single	1.2	17.5	22.75
3-Axle Tandem	1.22	27.5	35.75
4-Axle Single-Tandem	1.2-22	39.5	51.35
5 -Axle Tandem-Tandem	1.22-22	49.5	64.35
6-Axle Tandem-Tridem	1.22+222	58.5	76
Front tire inflation pressure = 100 psi			
Rear tire inflation pressure = 120 psi			

Based upon the prevalent problem of overloading of trucks in Pakistan, the current study was aimed at fulfilling the following objectives. Firstly, to study the effect of axle overloading and increased tire inflation pressure on flexible pavement performance from the results of the Pilot Axle Load Survey on National Highways (N-5) in 2017. Secondly, to derive truck factors based on theoretical mechanistic-empirical analysis of flexible pavement structure using KENLAYER (KENPAVE) software and use the results to develop regression model to create Equivalent Axle Load Factors (EALFs). These factors can be used to identify the amount of damage to the pavement due to a single pass of 2-axle, 3-axle, 4-axle, 5-axle, and 6-axle truck. The methodology followed, and the models developed, in this study would be helpful for design engineers and academicians, who are facing the same problems in their region, to improve the pavement design procedures with more practical values.

The data utilized in this study was collected in 2017 by NTRC, which works under NHA, Pakistan. The details of the survey and its data are available in the following references [1, 4]. Only two pavement distress modes are used in the present study: the fatigue cracking and permanent deformation (rutting). Previous literature suggests that these stresses are found to be the most common in flexible pavements in Pakistan as well as other countries [5-7]. The Asphalt Institute's criteria for fatigue cracking and permanent deformation are used for the analysis. The AASHTO Equivalent Axle Load Factor (EALF) used is only for structural number 5 which is the ideal/maximum for pavement design.

The rest of this paper is organized as follows. Section 2 shows a review of the literature used in order to set up the research objective of this project. Section 3 presents the methods being employed to achieve the objectives. Section 4 presents the regression models, and the final EALF and truck factors, which are developed and derived in this study, are presented, and discussed in section 5 presents. Lastly, section 6 contains conclusions and recommendations, based on this research.

2. Literature Review

In this section, the literature review focuses on three research topics: the effect of axle load on the flexible pavement response, the effect of tire pressure on the pavement response, and the effect of axle configurations on the pavement responses. Finally, a conclusion of the reviewed literature is drawn at the end of this section.

2.1 AASHTO Equivalent Axle Load Factor (EALF) and Equivalent Single Axle Load (ESAL)

The EALF is defined as the damage per pass to a pavement by an axle load and its configuration (single, tandem, or tridem) relative to the damage per pass of a standard axle load, usually the 18-kips single-axle load [8]. The EALF represents the mixed traffic or mixed axle loads and axle configurations of different vehicle types in terms of a single design axle load. The traffic loads applied to any pavement structure determine the pavement's service life. The initial concept of EALF was given by the AASHO road test conducted in the late 1950s and early 1960s. The 18 kips single-axle load was selected as the standard axle load because it was the maximum legal load in most states of the United States of America at the time of the AASHO road test [9].

The test results from the AASHO road test were used to obtain an empirical equation to find EALF. These EALF were published in the AASHO

American Association of State Highway and Transportation Officials (AASHTO) Interim Guide for Design of Pavement Structures in 1972 and in all subsequent editions of the AASHTO Design Guide [10, 11]. The EALF from the AASHO road tests represented that with an increase in axle load and axle load repetitions, the damage to pavement structure also increased. Therefore, the determination of equivalent axle load factors and the number of axle load repetitions is critical in the design of any pavement structure and forecasting the best estimate of future traffic loads on the pavement structure over a design period becomes necessary. The AASHTO EALFs are used to convert different axle configurations and traffic loads in a traffic stream on a pavement system to 18-kip equivalent single axle loads (ESALs). The number of axle load repetitions for any axle configuration (single, tandem, or tridem) is multiplied by its EALF to obtain the equivalent damage based on 18-kips single-axle load. A sum of the equivalent damage of all axle loads, and variable axle configurations in a traffic stream over a design period is termed as the ESALs. Underestimating the ESALs will lead to early pavement failure for the design period while overestimation of ESALs will cause over-designed pavement structures. In general, the EALF of any axle load and axle configuration in terms of load repetition is given by Equation (1).

$$\text{EALF}=\frac{\text{N}_{18}}{\text{N}_{\text{X}}} \quad (1)$$

Where, N_{18} is the number of load applications of 18-kips standard axle load, and N_x = the number of load applications of the axle load and axle configuration in question.

The AASHTO EALF for the flexible pavement is dependent upon the load on the axle, the axle configuration, the terminal serviceability index, and the structural number for the flexible pavement.

The following limitations have been identified with regards to application EALFs. Firstly, they fail to account for the varying tire contact pressure on the pavement structures. The increase in tire pressure causes increase in the primary pavement responses (surface deflections, strains, and stresses) and causes early fatigue failure in pavements [2].

Since the AASHTO EALFs are based on empirical model, they are theoretically valid for the environment, vehicle characteristics, tire pressure, tire type, suspension system, and material properties used in the AASHO road test. The conditions of AASHO road tests are given in detail in the following reference [12]. The extrapolation and use of AASHTO EALF for the environment and material properties other than the one used in the test becomes questionable.

2.2 Effect of Axle Load and Axle Configuration on the Flexible Pavement Responses

In 2005, the Ministry of Transport in Egypt issued a new regulation for increasing the legal axle load limits from 10 tons to 13 tons for single axle, 16 tons to 22 tons for tandem axle, and 22 tons to 30 tons for tridem axle. Osman et al. [13] evaluated such an impact of increasing the legal load limit on the truck factors for different truck types. The research considers six two-axle load limits, three enforcement levels, and two cases of freight weight transportation. They found that an increase in axle load limit increased the damage to the pavement structure by 200 to 300 percent for regardless of the axle load configuration. The Equivalent Standard Axle Loads (ESALs) increased by 75-136%. This study also reported that the increase in ESALs required 2.1 cm to 4.6 cm increase in asphalt layer thickness depending on restrictions on vehicle overloading and the freight volumes.

Pais et al. [14] evaluated the effect of heavy vehicle overloading in terms of pavement life using Weight-in-Motion (WIM) data collected on Portuguese motorway for five years (2006 to 2010). The study documented truck factors for different heavy vehicles applied on a set of pavement structures with five varying thicknesses of asphalt base layer: 10 cm to 30 cm with 5 cm increment having 5,000 MPa stiffness, and five different subgrade resilient moduli (40 to 120 MPa with 20 MPa increment) having 20 cm thickness. They analysed the truck factors for four different scenarios two of which were the vehicles that are overloaded, and the vehicles operating at maximum legal axle load on each axle.

To find the truck factors for different vehicle classifications, Pais et al. [15] used French Pavement Design guide [16]. These researchers concluded that, by increasing the asphalt layer thickness, the damage to pavement due to vehicle overloading reduces. Truck factors did not change significantly with variation in the subgrade stiffness. Another significant result found by Pais et al. [14] is that vehicles with maximum legal axle load on all axles caused more pavement damage than overloaded vehicles since a significant number of vehicles were overloaded on one or more axles rather than on all axles.

Rys et al. [17] evaluated the effect of vehicle overloading on fatigue life of pavement structure. A regression model was developed to find the equivalent axle load based on 100 kN single axle with dual wheels equivalent standard axles taking into account the axle load distribution, and the percentage of overloaded vehicles. Fatigue cracking at the bottom of the asphalt layer was considered as the distress mode. The results showed that the increase of vehicle overloading from 0 to 20% decreases the fatigue life of the pavement by 50%, and just 10% decrease in the overloaded vehicles may increase the service life of the pavement by 4 to 6 years.

Rys et al. [18] created a model to evaluate vehicle load equivalency factors for Polish Catalogue for flexible pavements. The load equivalency factors were adjusted to account for the impact of maximum legal axle load limit, overloaded vehicles, increase in vehicle gross vehicle weight in the future, and the coefficient of dynamic vehicle loads. The results were compared to AASHTO EALF equation (1993 method), the fourth-power law, LCPC 1998 method, and mechanistic-empirical approach. The study concluded that a high correlation exists between the percentage of overloaded vehicles and the load equivalency factors. Also, the vehicle dynamic loads, and increase in the maximum legal axle load would increase the load equivalency factors. They also concluded that load equivalency factors estimated from mechanistic-empirical methods were higher than those estimated from a fourth power law, AASHTO 1993 and LCPC 1998 methods.

Raheel et al. [19] (2018) used the Pais et al. [14] model with similar assumptions to evaluate pavement damage in terms of ESALs and truck factor variation with asphalt base layer thickness and subgrade resilient modulus on National Highway (N-5) based on WIM data for the year 2012. They found that truck factors decreased by 47% with a 100% increase in asphalt layer thickness. However, the truck factors did not vary significantly by increasing the subgrade stiffness modulus. These researchers also found that vehicle axle configuration also plays a significant role in truck factor variation. 2-axle trucks were 3.33 times more damaging than 3-axle trucks and 5.45 times than 6-axle semi-trailers.

2.3 Effect of Tire Pressure on the Flexible Pavement

The effect of tire pressure on the flexible pavement is one of the most important topics of research in the pavement industry. Limited research has been conducted to incorporate the effect of tire pressure in the design of flexible pavement.

Bonaquist et al. [20] compared the pavement responses for three combinations of load (9.4 kips,14.1 kips, and 19 kips), three tire pressures (76 psi, 100 psi, and 140 psi), and two tire types (radial, and bias ply). Two pavement cross-sections were used; 5inches asphalt layer and 5 inches granular layer; 7 inches of asphalt layer, and 12 inches of granular layer. These researchers concluded that at all load levels, the tire pressure accounted for only 2 to 10 percent increase in the vertical deflection, surface strain, and tensile strains at the bottom of asphalt layer. Though, at high temperature, the section traffiked with thinner asphalt thickness at 140 psi tire pressure incresed the rutting.

The findings of Bonaquist et al. [20] can be backed by Wang, et al. [21] who developed a three dimensional finite element model to determine the tensile strain at the bottom of asphalt layer, and the compressive strain and shear strain near the surface of Hot Mix Asphalt (HMA) layer under high tire pressure for airfield flexible pavement. A realistic tire-pavement interaction area was incorporated into the model. The pavement section consisted of a 5 inch. thick asphalt surface layer, a 17 inch. thick econocrete base layer, a 25 inch. thick uncrushed aggregate subbase layer ,and the subgrade. Two levels of tire wheel load were used as in A 380 wheels; 61.3 kips, and 52.5 kips. The tire pressures used were 210 psi, and 245 psi. Wang et al. [21] concluded that increase in maximum pavement responses (strains) was mainly due to increase in wheel load rather than increased tire inflation pressure. Similar results were reported by Roginski

[22] that for wheel load varying from 40 kips to 55 kips upto a tire pressure of 240 psi, no serious damage was observed for the three flexible pavements with varying asphalt layers).

Zhang et al. [23] developed performance-based fatigue cracking model using the AASHO Road Test data for traffic characteristics differing from the AASHO Road Test. Two flexible pavement cross-sections with same material properties, and same granular layer thickness were used. The asphalt layer thickness used were 3 inches and 6 inches. Zhang et al. [23] reported that at constant load with increased tire pressure from 75 psi to 120 psi, the pavement structure with 3 inch aphalt thickness was subjected to more pavement damage than the 6 inch. asphalt thickness regardless of any axle configuration. The maximum damage was caused by super single tires followed by the single axle with dual wheels. The single axle with single wheel produced 49 to 69 percent greater damage compared to the AASHTO EALF for 3 inch, and 39 to 57 percent greater damage for 6 inch HMA layer compared to the AASHTO EALFs.The damage caused by single axle with dual wheels compared to the AASHTO EALF was 50 to 56 percent greater for a 3 inch. asphalt layer, and 17 to 18 percent greater for a 6 inch. asphalt layer thickness.

Similarly, a study conducted by Al-Mansour [24] reported that, with increase in tire pressure from 80 to 130 psi, the pavement structure with 2 inch HMA layer thickness produced least number of load repetitions than the pavement structure with a 6 inch asphalt layer.

2.4 Role of Current Research

In the AASHO Road Test [12] (AASHO 1962), tire inflation pressures ranged from 483 to 550 kPa (70 to 80 psi). In Pakistan, according to Pilot Axle Load Survey conducted by NTRC [1, 4], trucks are being operated at tire inflation pressures higher than the legal limit of 827 kPa (120 psi), which can go as high as 900 to 1,365 kPa (130 to 198 psi). These are higher than those considered in most of the previous studies. From the literature review, it can be concluded that the overloaded vehicles and those operating at maximum legal load, at all axles, would produce greater damage than the vehicles overloaded at a single axle. An axle load increase induces greater horizontal tensile strains at the bottom of the asphalt layer that, in turn, decreases the pavement fatigue life. Also, the variation in the subgrade stiffness does not significantly increase the values of equivalent axle load factors.

The literature review also shows that higher tire pressures for asphalt layer thickness, ranging from an inch up to 3 inches, can potentially impose more damage to pavements. The EALF models did not consider tire inflation pressure. Hence, the current research develops regression models and factors based on the observed tire pressures to address the above-mentioned limitations.

3. Methodology

This section discusses the methodology adopted in this research. As mentioned earlier, regression models were developed to estimate the EALF when a pavement is subjected to varying axle load and tire pressure for different axle configurations. With the developed models, the impact on the primary pavement responses was evaluated. Furthermore, the resulting EALFs were then used to quantify the damage due to trucks as per axle load survey results from NTRC and the NHA’s allowable 30 percent gross vehicle weight overloading. Figure 1 presents the general research approach adopted in this research.

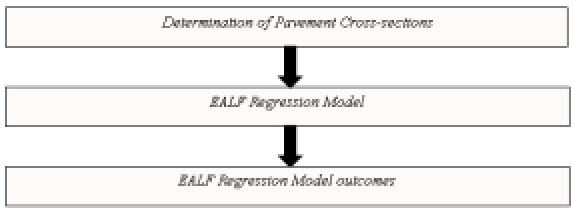

Figure 1: Research Methodology

3.1 Data Acquisition

Results obtained from Traffic Count Survey on N-5, and Axle Load Survey on N-5 conducted by NTRC in 2017 are used as inputs for this research. The NHA conducted a Pilot Axle Load Survey in 2017 on National Highway (N-5) at five weigh stations; Mulla Mansoor, Sangjani, Eminabad, Rohri, and Pipri weigh stations. It was found that a significant number of trucks had Gross Vehicle Weight more than 30% of the permissible weight limit. In some sections, the extent of overloading was found to be alarming, e.g., 87 % of 3-Axle trucks (1191 out of 1369 3-Axle trucks) had more than 40 tons of gross weight at Eminabad Weighing Station [1]. The allowable tire pressure is 100 and 120 psi for front and rear axles, respectively. It was found that trucks operating on N-5 had 40 to 80% higher tire pressure than permissible limits of 120 psi.

From the Traffic Count Survey on N-5 Report, the Northbound and Southbound Average Annual Daily Traffic (AADT) is obtained from the traffic counts at five locations along N-5 namely, Pabbi (Nowshera to Peshawar), Gujranwala (Lahore to Gujranwala), Khanewal (Khanewal to Okara), Rohri (Sukkur to Bahawalpur), and Pipri (Karachi to Thatta). The report also concluded that the AADT is distributed almost equally in both Northbound and Southbound directions, as shown in table 2 [4].

Table 2. AADT in Northbound and Southbound directions for the year 2017

S.No.	Location ID	AADT in Both Directions (Veh/Day)
1	N-5 @ Pabbi	48,328
2	N-5 @ Gujranwala	76,239
3	N-5 @ Khanewal	23,819
4	N-5 @ Rohri	2,363
5	N-5 @ Pipri	19,874

From the Axle Load Survey on N-5, the data used as inputs are the percentage gross vehicle weight distribution and tire inflation pressure on each axle of 2-axle, 3-axle, 4-axle, 5-axle, and 6-axle trucks, and the percentage of overloaded trucks based on WIM and Static Weigh data analysis on the five weigh stations, mentioned above.

3.2 Determination of Pavement Thickness

The Association of State Highway and Transport Officials (AASHTO) Design Guide 1993 is the most widely used method to design flexible pavements in Pakistan. The traffic data is one of the critical inputs for any pavement design. The AASHTO Design Guide uses the concept of ESAL to quantify the damage caused by the traffic to the pavement structure. To determine the ESALs, the EALF is summed together for a given design period for a spectrum of vehicles on a highway. The EALF converts the mixed axle configuration (single, tandem, and tridem) for the vehicles and quantifies the damage per pass of the axle configuration into a reference standard axle load, usually 18 kips. The AASHTO Design Guide uses the EALF for flexible pavement developed by the results of the AASHO Road Test in 1962 with tire inflation pressure ranging from 70 psi to 80 psi and determined from Equations (2) – (4). Equation (2) is empirical; therefore, it uses US Customary units as inputs instead of SI units.

$$EALF=\frac{W_{t18}}{W_{tx}}=10^{-\left[4.79\log(18+1)-4.79\log(L_x+L_2)+4.33\log L_2+\frac{G_t}{\beta x}-\frac{G_t}{\beta_{18}}\right]} \quad (2)$$

$$G_t=\log\left(\frac{4.2-P_t}{4.2-1.5}\right) \quad (3)$$

$$\beta_x=0.40+\frac{0.081\ (Lx+L_2)^{3.23}}{(SN+1)^{5.19}L_2^{3.23}} \quad (4)$$

where W_{t18} is the 18 kips single-axle load repetitions in time t, and W_{tx} is the number of load repetitions of axle load ‘x’ in time t. Lx is axle load ‘x’ applied on the axle, L_2 is axle code for the type of axle on which the load ‘x’ is applied; 1 for single axle, 2 for tandem axle, and 3 for tridem axle, Pt is the Terminal serviceability, SN is the Structural Number of the flexible pavement, G_t is a function of Pt, and β_{18} is the β value when L_x is 18 kips. Therefore, Equation (5) is used to calculate ESALs per truck or truck factor for any truck configuration.

$$TF=\sum_{i=1}^{m}(EALF_i\times n_i) \quad (5)$$

where EALFi is the EALF for the ith-axle load group, n_i is the total number of repetitions for the ith axle load group, and m is the number of axle load groups.

3.2.1 Truck Factors

The NTRC [3] truck factors are still used in flexible pavement designs to determine the design ESALs. Table 3 lists the NTRC-1995 truck factors for loaded vehicles. These truck factors are derived from the AASHTO Pavement Design Guide 1986 using Equation (2) with an SN value of 5, and terminal serviceability of 2.5.

Table 3. The truck factors used in Pakistan for flexible pavement design (Source: [5])

Truck Type	Truck Configura tion Code	NTRC-1995 Loaded Truck Factors	Empty Truck Factors*
2-Axle	1.2	4.67	0.07
3-Axle	1.22	8.84	0.1
4-Axle	1.2-22	10.35	0.41
5-Axle	1.22-22	10.9	0.41

6-Axle	1.22+222	10.9	0.41

*The empty truck factor values are based on practice. NTRC-1995 did not contain truck factors for unloaded trucks

Since NHA allows 30 percent gross vehicle overloading, Equation (2) was used to calculate the EALF for overloaded vehicles with an SN value of 5 and the terminal serviceability index of 2.5. The calculated EALF for each axle of each truck type were summed together to obtain truck factors using Equation (5). The final truck factors for the 2-axle, 3-axle, 4-axle, 5-axle, and 6-axle trucks were obtained by averaging the truck factor of each truck type at Mulla Mansoor weigh station, Sangjani weigh station, Eminabad weigh station, Rohri weigh station, and Pipri weigh station for both northbound and southbound directions. The calculated truck factors are given in Table-4.

Table 4. Truck Factors derived for 30 percent GVW overloaded vehicles from Equation (5)

Truck Type	Truck Configuration Code	30 percent GVW Overloaded Truck Factors
2-Axle	1.2	14.62
3-Axle	1.22	12.05
4-Axle	1.2-22	29
5-Axle	1.22-22	25.33
6-Axle	1.22+222	25.02

3.2.2 Determination of ESALs

Three cross-sections were derived from the 1993 AASHTO Pavement Design Guide for the five study locations (shown in Table 2) given in pilot axle load survey report [1]. The cumulative ESALs were calculated for each location from Equation (6).

$$ESAL=\sum_{i=1}^{n}(TF_i \times AADT_{io}) \times G \times D_L \times D_D \times Y \times 365 \quad (6)$$

Where TFi is the truck Factor of the vehicle 'i', AADTio is the Average Annual Daily Traffic of the vehicle 'i' for the base year. Y is the design period, D_L is the lane distribution, and D_D is the direction distribution factor. For the growth factor, a growth rate of 5 percent was assumed for all vehicles. The base year was 2021, and the end of the design period year was 2030. D_L was taken as 0.7 from AASHTO Flexible Pavement Design Guide, and D_D was taken as 0.5 taken from [1].

The pavement thickness for each location was calculated for two cases:

- Case-I: There are 90 percent of vehicles loaded within the legal load limit and 10 percent empty vehicles. Therefore, the truck factors given in Table 3 were used to calculate the cumulative ESALs.
- Case-II: There are 10 percent empty vehicles, 25 percent vehicles loaded within legal load limit, and 65 percent vehicles carrying 30 percent or more GVW. Therefore, the truck factors given in Table 3 and Table 4 were used to calculate the cumulative ESALs. The highest cumulative ESALs were obtained at the Rohri section for both cases, while the lowest ESALs were obtained at the Pabbi section.

Figure 2 shows the cumulative ESALs for the two cases at each location.

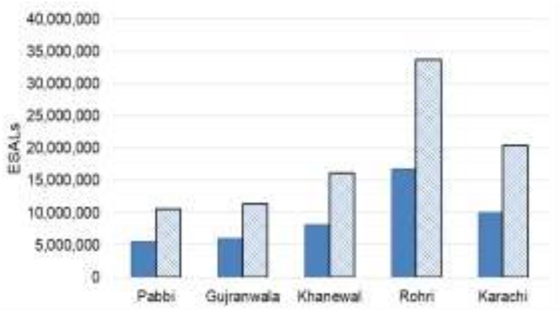

Figure 2: Comparison of ESALs for the Pabbi, Gujranwala, Khanewal, Rohri, and Karachi

3.2.3 Pavement Design

In order to compute the pavement thickness at each location, the AASHTO Pavement Design Guide, 1993 flexible design procedure in employed. The design variables used were,

- W_{t18} = Cumulative 18 kips equivalent single axle load repetitions
- California Bearing Ratio (CBR) of Subgrade, %
- M_R = resilient modulus of the subgrade, psi = $2555xCBR^{0.64}$
- R = reliability of the pavement design
- Z_R = standard normal deviate based on reliability
- S_o = standard deviation
- P_i = initial serviceability index
- P_t = terminal serviceability index
- ΔPSI = Difference between the initial serviceability index P_i and terminal

serviceability index P_t at the end of the design period [11].

- E_1 = Elastic modulus of Asphalt concrete base course, psi
- E_2 = Elastic modulus of aggregate base course, psi
- E_3 = Elastic modulus of granular subbase course, psi
- a_1 = layer coefficient of asphalt concrete layer, per inch
- a_2 = layer coefficient of the aggregate base layer, per inch

The aggregate base course is assumed as to be untreated therefore Equation (7) is used to calculate the layer coefficient, a_2

$$a_2=0.249(\log E_2)-0.977 \quad (7)$$

a_3 = layer coefficient of granular subbase course, per inch

The layer coefficient of granular subbase course is calculated from Equation (8).

$$a_3=0.227(\log E_3-0.839) \quad (8)$$

m_2 = drainage coefficient of aggregate base course layer

m_3 = drainage coefficient of granular subbase course layer

The drainage coefficients were selected from [11]. The drainage conditions are assumed to be fair with 5-25% of time exposure of pavement to moisture levels approaching saturation.

SN = Structural number of pavements, which is computed by Equation (9).

$$SN=a_1D_1+a_2D_2m_2+a_3D_3m_3+\ldots+a_nD_nm_n \quad (9)$$

The AASHTO Flexible Pavement equation [Equation (10)] is used to find the pavement thickness of each section.

$$\log W_{t18}=Z_R S_o+9.36\log(SN+1)-0.20+\frac{\log\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.4+\frac{1094}{(SN+1)^{5.19}}}+2.32\log M_R-8.07 \quad (10)$$

Following are the values for design parameters:

CBR	10
M_R	11,000 psi [from Eq.**Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**], Poisson ratio = 0.45
P_i	4.2
P_t	2.5
ΔPSI	1.7
R	95%
Z_R	-1.645
S_O	0.45
E_1	400,000 psi, Poisson ratio = 0.30
E_2	30,000 psi, Poisson ratio = 0.35
E_3	17,000 psi, Poisson ratio = 0.35
a_1	0.42 /inch [11]
a_2	0.140/inch [from Eq.(7)]
a_3	0.120/inch [from Eq.(8)]
m_2	1
m_3	1

The pavement thickness for both cases at the study locations are shown in Table 5. For case I, the pavement cross section is the same for Pabbi, Gujranwala, Karachi, and Khanewal. For case II, Pabbi, and Gujranwala have the same pavement cross-section. Karachi and Khanewal have the same pavement cross-section. For case II, the cross-section of Pabbi, and Gujranwala remains the same, while for Khanewal, Rohri, and Karachi, the HMA binder course increased by an inch. Therefore, from Tables 5, only three cross-sections C1 (Total Thickness=27inches), C2 (Total Thickness=28inches), and C3 (Total Thickness=29inches) were used for the analysis.

3.3 Development of EALF Regression Models

Four axle configurations were analyzed: single axle with single wheel, single axle with dual wheels, tandem axle with dual wheels, and tridem axle with dual wheels. To characterize the impact of varying load and tire inflation pressure for these configurations, a mechanistic-empirical analysis was employed. Depending upon the pavement failure criterion employed, the mechanistic analysis determines the sensitivity of primary pavement responses for the material properties, layer thicknesses, wheel load, tire pressure, and axle configuration. The primary responses to be analyzed are the tensile strain at the bottom of HMA layer, and the compressive strain at top of the subgrade. The empirical approach is based on the statistical analysis of the results determined from the mechanistic analysis. Following are the steps to create regression models to develop the equivalent axle load factors.

Table 5: Pavement layer thickness at each location

Location	Required SN	Provided SN	Thickness (in.)				
			Asphalt Wearing Course	Asphalt base course	Aggregate Base Course	Granular Subbase Course	Total Pavement Thickness
Case-I							
Pabbi	5.955	6.420	2	8	9	8	27
Gujranwala	6.216	6.420	2	8	9	8	27
Khanewal	6.075	6.420	2	8	9	8	27
Rohri	6.682	6.840	2	9	9	8	28
Karachi	6.171	6.420	2	8	9	8	27
Case-II							
Pabbi	6.244	6.420	2	8	9	8	27
Gujranwala	6.307	6.420	2	8	9	8	27
Khanewal	6.567	6.840	2	9	9	8	28
Rohri	7.215	7.260	2	10	9	8	29
Karachi	6.755	6.840	2	9	9	8	28

(1) Sensitivity analysis for the three pavement cross-sections for each axle configuration. For each cross-section, axle loads were varied from 2 kips to 100 kips for tridem axle, and 2 kips to 90 kips for the other three axle configurations. Tire pressure varied from 70 kips to 200 kips for each axle load, and axle configuration.

(2) For each axle configuration, a regression model was developed for the type of pavement distress criterion employed. Use R^2 to determine the best fit for the regression models.

(3) Using ANOVA to validate the significance of the model.

(4) Using EALF regression models to quantify the damage caused by a single passage of 2-axle, 3-axle, 4-axle, 5-axle, and 6-axle trucks for the 30% GVW overloading of vehicles, and the damage due to GVW distribution for the trucks as reported in NTRC [1]

The effect of axle configuration, axle load and tire pressure on the primary pavement responses will be discussed later in section 4.

3.4 Comparison of Truck Factors

The truck factors for 2-axle, 3-axle, 4-axle, 5-axle, and 6-axle trucks were compared for three scenarios.

- *Scenario 1*: Truck factors using 30 percent overloaded axle load limit, and [1] axle load distribution percentage using EALFs derived from Equation (2) using SN value of 5 and terminal serviceability of 2.5.
- *Scenario 2*: Truck factors using 30 percent overloaded axle load limit, and [1] axle load distribution percentage using EALFs derived from the regression models; and
- *Scenario 3*: Truck factors from the NTRC Axle load Survey 2017 results using EALFs derived from the regression models.

The truck factors derived from the above three scenarios were compared to the truck factors given by NTRC in 1995.

4. Development of EALF Regression Models

EALF Regression models were developed, using the results obtained from sensitivity analysis for the three cross-sections shown in Table 5, with the help of KENLAYER computer program. This program is developed by Dr. Yang Huang. The cross-sections were subjected to tire inflation pressure varying from 70 kips to 200 kips for a range of axle load ranging from 2 kips to 110 kips for tridem axles, and 2 kips to 90 kips for single axle with single wheel, single axle with dual wheels, and tandem axle with dual wheels.

4.1 Linear Elastic Sensitivity Analysis

The KENLAYER computer program was employed to conduct sensitivity analysis. The method employs the use of damage analysis, as proposed by Huang [8]. The EALF was determined for two pavement distress criteria; the tensile strains developed at the bottom of the Hot Mix Asphalt (HMA) layer (fatigue cracking), and the compressive strains developed at the top of the subgrade (rutting or permanent deformation). The tensile and compressive strains were used to calculate the allowable number of load repetitions from Equation (13), and Equation (14). The Asphalt Institute failure criteria were used for the analysis.

$$N_f = 0.0796\,(\epsilon_t)^{-3.291}(E_1)^{-0.854} \quad (13)$$

$$N_d = 1.365\times10^{-9}(\epsilon_c)^{-4.477} \quad (14)$$

where N_f is the number of allowable load repetitions based to limit horizontal tensile strains at the bottom of the asphalt layer, ϵ_t is the maximum tensile strain at the bottom of the asphalt layer, E_1 is the elastic modulus of the asphalt layer in psi, N_d is the number of allowable load repetitions to limit vertical compressive strains on top of the subgrade, and ϵ_c is the critical compressive strain on top of the subgrade. The allowable load repetitions allow finding the damage ratio due to any axle load and axle configuration. The damage ratio is the ratio between the predicted load repetitions to the allowable number of load repetitions. The damage ratio obtained for the pavement distress criterion employed for any axle load group was divided by the damage ratio of the standard 18 kips single axle with dual wheel load at a tire contact pressure of 70 psi for a single pass to obtain the EALFs as shown in Equation (15) & (16).

$$EALF_T = \frac{D_{RT,k,P,q}}{D_{R80_T}} \quad (15)$$

$$EALF_C = \frac{D_{RC,k,P,q}}{D_{R80_C}} \quad (16)$$

Where $D_{RT,k,P,q}$ is the damage ratio of load group 'k' (single axle with single wheels, single axle with dual wheels, tandem axle with dual wheels, and tridem axle with dual wheels) subjected to wheel load 'p ' with tire pressure 'q' based on fatigue cracking failure criterion. DR_{80T} is the damage ratio due to the standard 18 kips single axle with dual wheels at 70 psi tire contact pressure based on the fatigue cracking failure criterion. $EALF_T$ is the equivalent axle load factor based on the fatigue cracking failure criterion. $D_{Rc,k,p,q}$ is the damage ratio of load group 'k' (single axle with single wheel, single axle with dual wheels, tandem axle with dual wheel, and tridem axle with dual wheels) subjected to wheel load 'p' with tire pressure 'q' based on permanent deformation failure criterion. D_{R80c} is the damage ratio due to the standard 18 kips single axle with dual wheels at 70 psi tire contact pressure based on the permanent deformation failure criterion. $EALF_c$ is the equivalent axle load factor based on the permanent deformation (rutting) failure criterion.

For the analysis, only one period is employed, and the predicted number of load repetitions is assumed as one for each pass for all four axle configurations. The centre-to-centre dual tires spacing is assumed to be 13.5 inches, and the spacing between the two axles of tandem and tridem axle is assumed to be 48 inches. The pavement cross-sections were assumed to be four-layered linear elastic system consisting of asphalt wearing course, asphalt binder course, aggregate base course, granular subbase course, and the subgrade. The material properties for each layer are given under the description of Equation 10.

The linear-elastic system is subjected to the wheel load 'p', calculated from Equation (17), that is assumed to be uniformly distributed over a circular contact area whose radius is assumed to be 'a' that is calculated from Equation (18) where a is the tire contact radius in inches, p is the load on the wheel in lbs., and q is the tire contact pressure in psi. The tire contact pressure is assumed to be equal to tire inflation pressure because heavy axle loads have high tire pressures and more destructive effects on the pavements; the use of tire pressure as the contact pressure is, therefore, on the safe side [8].

$$p = \frac{L}{\propto} \quad (17)$$

Where α is 2 for single axle with single wheel; 4 for single axle with dual wheels; 8 for tandem axle with dual wheels; and 12 for tridem axle with dual wheels.

$$a = \sqrt{\frac{p}{\pi\times q}} \quad (18)$$

Figure 3 shows the pavement response points used for the analysis in KENLAYER. For the single axle with a single tire. The strains were obtained below the wheel, while for the single axle with dual tires, the tensile strain and compressive strain were calculated below the wheel as well as midway between the dual wheels. For the case of tandem, and tridem axle, the primary strain was obtained below the first passing axle. The strain obtained due to the passing of the second or third axle is the difference between the strain due to the passing of the first axle, and the strain developed midway between the axles. These strains, either tensile or compressive, are used to calculate the allowable number of load repetitions for any axle load group.

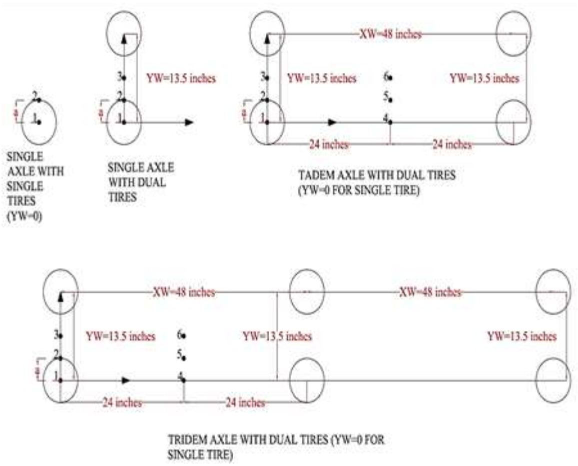

Figure 3: Response points for critical horizontal tensile at the bottom of asphalt layer and vertical compressive strains at top of subgrade

4.2 Effect of Axle Load on the Primary Pavement Responses

The effect on the tensile strain and compressive strain, due to an increase of axle loads on all four load groups, was evaluated. The analysis shows that the tensile strains increase with increasing axle load as well as decrease with an increase in asphalt base course thickness while the compressive strains increase linearly with an increase in axle load. The compressive strains tend to decrease with an increase in asphalt base course thickness by 9 percent. At constant tire pressure (70 psi to 200 psi), the fatigue strains increased by 80-93 percent for single axle with single wheel, 56-81 percent for single axle with dual wheels, 87-96 percent for tandem axle, and 92-97 percent for tridem axles when the axle load (2 kips to 90 kips) is doubled. For the same conditions, the compressive strains increased by a factor of 2 for all axle load groups.

At constant load (2 kips to 90 kips) with tire pressure varying from 70 psi to 200 psi, the following trends were observed,

- The tensile strain increased by a factor of 1.01 to 1.66 for the single axle with single wheels when Asphalt base course thickness is 8 inches, 1.01 to 1.59 when asphalt base course thickness is 9 inch, and 1.01 to 1.53 when asphalt base course thickness is 10 inches. The compressive strains increased by only 9 percent at high axle load and tire pressures.
- For the single axle with dual wheels, the tensile strain increased by a factor of 1.01 to 1.29 when Asphalt base course thickness is 8 inches, 1.01 to 1.26 when asphalt base course thickness is 9 inches, and 1.01 to 1.24 when HMA is 10 inches thick. The compressive strains increase by only 5 percent with varying tire pressure.
- For tandem and tridem axles, the tensile strain increases by 1.01 to 1.16 and 1.01 to 1.1, respectively, regardless of increase of HMA thickness. Also, the increase of compressive strain is minimal with varying pressure, 2.2 percent for tandem axle, and 1.5 percent for the tridem axle.

The plots between axle load for each load group and the primary pavement responses show that the axle load is a predominant parameter that affects the strain as well as allowable load repetitions. Also, the number of load repetitions increase significantly with increase in axle load for all axle load group. The plots also show that the number of load repetitions are also highly correlated with the strain.

4.3 Selection of Regression Models

The factors influencing the EALFs are the axle load, axle configuration, the tensile strain at the bottom of asphalt binder layer, the compressive strain at the top of the subgrade, asphalt layer stiffness, the asphalt layer thickness, stiffness of the granular layers and subgrade, and thickness of the granular layers. The thickness and stiffness of the granular layers are constant. Similarly, the stiffness of both the subgrade and the asphalt layers are also constant. Therefore, these values will not be included in the model. The total asphalt thickness is not considered in the model because the tensile strains and compressive strains are computed from

KENLAYER computer program which already incorporates the pavement layer thickness. Therefore, the regression models developed would be valid for the thicknesses and material properties used in this research, which have been described in the previous sections.

Therefore, the general form of EALF regression model for any axle configuration becomes:

Log ($EALF_T$) = f (log L, log q, log ϵ_t) for fatigue cracking distress criterion; and

Log ($EALF_C$) = f (log L, log q, log ϵ_c) for permanent deformation distress criterion

Where L is the load on the axle in kips, q is the tire pressure in psi, and ϵ_t and ϵ_c are as defined earlier.

For the tandem and tridem axles, the strains due to multiple axles are also taken into account. The strain due to passing of the first axle is the primary strain while the strain due to passing of the second or third axle is the differential strain. Therefore, the EALF models can be written as per Eq. (19) and (20);

$$\text{Log}(EALF_T) = \text{Log } L + \text{Log } P + \text{Log } \epsilon_t + \text{Log } \epsilon_{tdiff.} + \text{Constant} \quad (19)$$

$$\text{Log}(EALF_c) = \text{Log } L + \text{Log } P + \text{Log } \epsilon_c + \text{Log } \epsilon_{cdiff.} + \text{Constant} \quad (20)$$

Where $\epsilon_{tdiff.}$ is the differential tensile strain while ϵ_{cdiff}. is the differential compressive strain. The final form will depend on the level of significance. The NCSS Statistical Software was used to develop the regression models. Table 6 shows the developed regression models for each axle load group for the pavement distress criterion considered. The R^2 values are close to 1 which indicates that the model fits the data very well. To check the significance of the models, ANOVA is performed. The models are tested at 5% significance levels. The selected parameters for the regression models were highly significant at 5% level.

Table 6: EALF Regression models for each axle configuration

Load Group	Log (EALFt)	Log (EALFc)	R^2 for Log (EALFt)	R^2 for Log (EALFc)
SA	-4.826+0.323 log (ϵ_t)+2.761 log(L)+0.350 log(q)	4.42 Log (L)+0.1 Log (q)-5.755	0.9984	0.9999
SASW	-5.623+1.2231og (ϵ_t)+1.660 log(L)+0.601 log(q)	4.028 Log (L)+0.203 Log (q)+0.347 Log (εc)-6.135	0.9935	0.9995
TA	5.730+ 0.711 log (ϵ_t)+2.454 log(L)+0.209 log(q)	-6.173 - 0.968 log (ϵ_c)+ 0.007 log (diff. strain) + 5.394 log(L)+0.023 log(P)	0.9994	0.9999
TRI	-5.753-0.482 log (ϵ_t)+0.701 log (ϵ_{tdiff}) +2.978 log(L)+0.155 log(q)	-4.231-5.481 log (ϵ_c)+1.260 log (ϵ_{cdiff}) +2.978 log(L)+ 0.0134 log(P)	0.9996	0.9999

5. Determination of EALFs and Truck Factors

With the EALF regression models derived, the EALFs for each load group can be determined for tire pressure ranging from 70 kips to 200 kips for axle loads varying from 2 kips to 90 kips for single axle with single wheel, single axle with dual wheels, and tandem axle, and 2 kips to 110 kips for tridem axle. The truck factors were obtained from the EALFs to assess the damage caused by each truck for different case scenarios.

5.1 EALFs for Each Load Group

The EALF governed by fatigue cracking distress criteria increased when the thickness of the asphalt base course layer decreased. Regardless of the asphalt base course thickness, the fatigue cracking is the damage mode over a range of axle loads ranging from 2 kips to 26 kips for single axle with single wheel, 2 kips to 82 kips for single axle with dual wheels, 2 kips to 26 kips for tandem axle, and 2 kips to 42 kips for tridem axles with tire pressures varying from 70 psi to 200 psi. However, the EALF governed by the permanent deformation failure criteria increased with an increase in asphalt base course thickness for all axle load groups. At asphalt base course thickness of 8 inches for constant load with varying tire pressure (70 psi to 200 psi), the following trends were observed;

- the EALF governed by fatigue cracking distress increased from 1.20 times to 1.65 times for single axle with single wheel,1.03 to 1.26 times for single axle with dual wheels,1.02 to 1.24 times for tandem axle, and 1.01 to 1.25 times for tandem axle.
- However, with an increase in asphalt base course layer thickness from 8 inch to 9 inch and 10 inch, the EALF governed by fatigue cracking varied from 1.6 to 1.81 and 1.20 to 1.68 times respectively for single axle with single wheel. For the single axle with dual wheels, the EALF increased from 1.02 to 1.19 times and 1.02 times to 1.17 times. For the tandem axle, the EALF increased from 1.02 to 1.20 times for asphalt base course thickness of 0.23m and 0.25m, respectively. Similarly, for the tridem axle, the EALF increased from 1.05 to 1.16 times, and 1.01 to 1.13 times for 9 inch thick, and 10 inch thick asphalt base course layer.
- For asphalt base course layer thickness of 8 inches, the EALF governed by permanent deformation distress criteria for increased from 1.19 to 1.65 times for single axle with single wheel, 1.06 to 1.25 times for single axle with dual wheels, 1.03 to 1.1 times for tandem axle; and 1.03 to 1.07 times for tridem axles. By increasing the asphalt base course thickness to 9 inches and 10 inches, the EALF increased from 1.18 to 1.73 times and 1.16 to 1.54 times, respectively, for single axle with single wheel;1.05 to 1.23 times, and 1.05 to 1.21 times for single axle with dual wheels.
- For both tandem and tridem axles, regardless of asphalt base course thickness variation, the EALF varies the same as that for 8-inch asphalt base course thickness, explained above.

The EALF are mostly governed by permanent deformation criterion, which is then used for the calculation of truck factors.

5.2 Comparison with AASHTO EALF

A plot of average EALFs and AASHTO EALF with axle load for each axle configuration (in Figure 4 to 7) shows that the EALF for a single axle with dual wheels increased 1.61 times, two times for single axle with single wheel, 1.54 times for tandem axle and 1.2 times for tandem axle. The equivalent axle load factors increased with an increase in axle load.

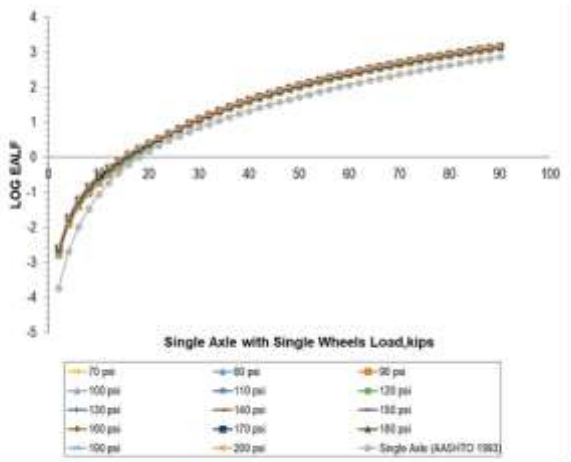

Figure 4: Comparison of regression model EALF and AASHTO EALF with load on single axle with single wheels

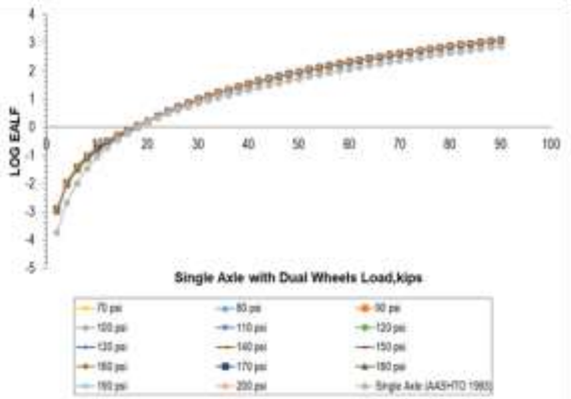

Figure 5: Comparison of regression model EALF and AASHTO EALF with load on single axle with dual wheels

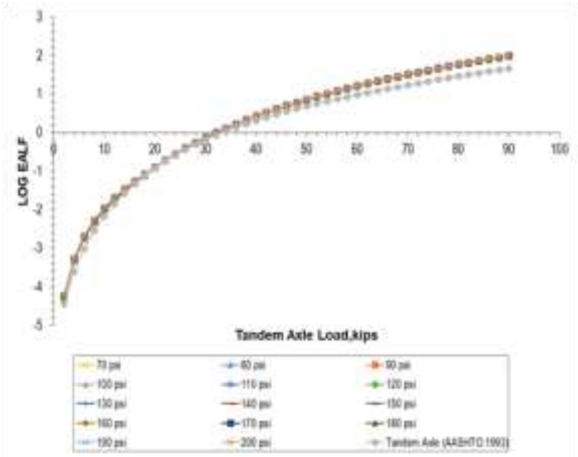

Figure 6: Comparison of regression model EALF and AASHTO EALF with load on tandem axle with dual wheels

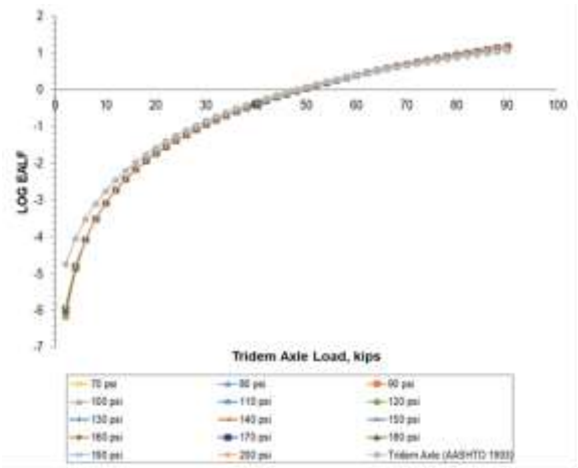

Figure 7: Comparison of regression model EALF and AASHTO EALF with load on tridem axle with dual wheels

5.3 Effect of Overloading

Since the legal rear axle tire pressure as defined by NHA is 120 psi and the vehicles are operating at 150 psi tire pressure, therefore the tensile strain increases by on average 3 percent at constant load. This is because the EALFs are mostly governed by permanent deformation failure, therefore; the impact of increasing tire contact pressure is not very significant. However, the fatigue damage increased by 10 percent for a constant load. Despite any variation of tire pressure, the axle overloading of any load group by 30 percent decreases the fatigue load repetitions by 55 percent, and rutting load repetitions by 69 percent. The 30 percent axle overloading also causes significant damage to the pavement. The ESALs increase by 220 percent for any axle load groups at all pavements cross sections.

5.4 Comparison of Truck Factors

The truck factors do not vary a lot with varying tire pressure. Figure 8 shows the comparison of truck factors obtained at 100 psi front axle tire pressure and rear axle tire pressure varying from 120 psi to 200 psi.

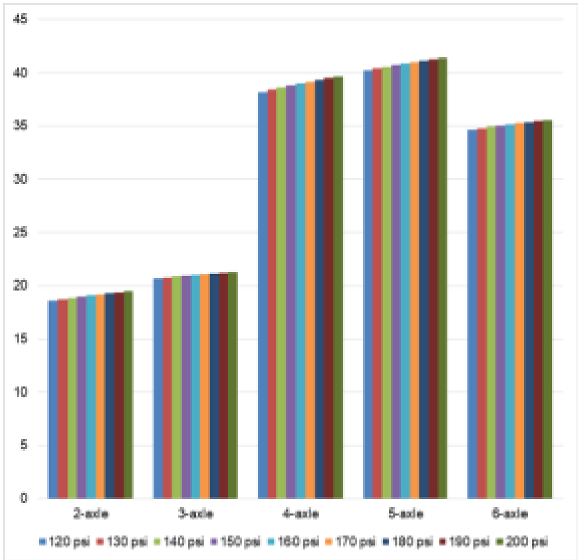

Figure 8: Comparison of truck factors for each truck type with respect to varying tire pressure

Since there is no significant variation of the truck factors with varying tire pressure; therefore, the final truck factors for 30 percent overloaded vehicles were averaged out.

For the GVW, tire inflation pressure, and axle load distribution on each axle given in the NTRC [1] report, the truck factors were obtained from the averaged EALFs. Figure 9 shows the comparison of truck factors for the three scenarios.

- *Scenario 1:* Compared to the For NTRC-1995 truck factors, the truck factors obtained from Equation (2) at 30 percent GVW overloading are 3.13 times greater than the NTRC [3] for 2-axle trucks, 1.36 times greater for 3-axle truck, 2.8 times greater for 4-axle truck, and 2.32 times more damaging for 5-axle, and 6-axle trucks.
- *Scenario 2*: The truck factors obtained from the regression models at 30 percent GVW overloading are 4.2 times greater than the NTRC-1995 truck factor for 2-axle truck, 2.41 times greater for 3-axle truck, 3.83 times greater for 4-axle truck, 3.8 times greater for 5-axle truck, and 3.25 times greater for the 6-axle truck.
- *Scenario 3*: The truck factors obtained from the regression model for NTRC [1] GVW

distribution are 5.69 times greater than the NTRC [3] truck factor for 2-axle truck, 4.77 times greater for 3-axle truck, 1.44 times greater for 4-axle truck, 2.73 times greater for 5-axle truck, and 3.74 times greater for the 6-axle truck.

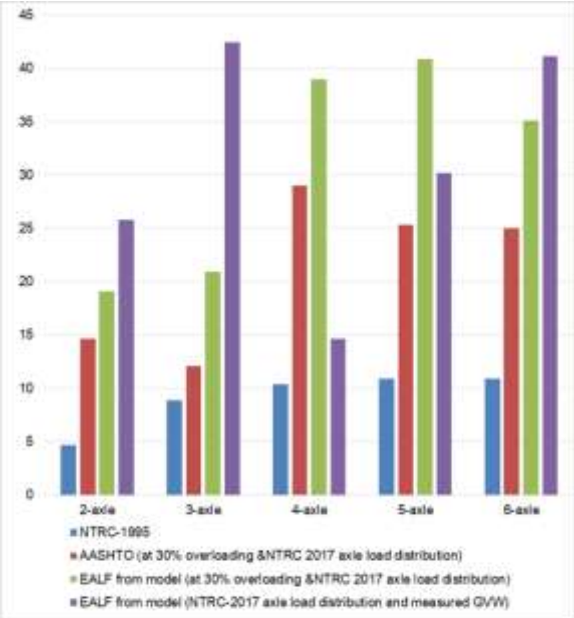

Figure 9: Comparison of truck factors

According to scenario 2, the 3-axle truck causes 1.1 times more damage than a 2-axle truck, while for scenario 3, the 3-axle truck causes 1.6 times more damage than a 2-axle truck. Comparing the situation in scenario 3 that is based on the NTRC [1] report, the 3-axle truck causes more pavement distress than the 6-axle truck. This is because the GVW is distributed at four tire contact area compared to the 6-axle truck whose GVW is distributed at ten tire contact area. Therefore, the 6-axle truck can carry greater GVW while contributing less to pavement damage than the 3-axle truck. The regression analysis shows that the 3-axle decreases pavement life by 80 percent for 1,000,000 passes due to high axle load that contributes to high truck factors.

6. Conclusion and Recommendations

In this study, the results from the Pilot Axle Load Survey conducted by NTRC in the year 2017 were used to find the truck factors for 2-axle, 3-axle, 4-axle, 5-axle, and 6-axle trucks. Truck factors were calculated for three scenarios; using the AASHTO EALF equation to find EALF at 30% axle loading, truck factor determination from theoretical mechanistic analysis at 30% axle overloading, and the truck factor determination from theoretical mechanistic analysis at the GVW reported by NTRC [1]. In addition, EALFs for four axle load configurations were also calculated using damage analysis in KENLAYER. Compared to the AASHTO EALF for SN value of 5 and terminal serviceability index of 2.5, The EALF for a single axle with dual wheels increased 1.61 times, two times for single axle with single wheel, 1.54 times for tandem axle and 1.2 times for tandem axle. The equivalent axle load factors increased with an increase in axle load. A decrease in the thickness of the asphalt base course layer will change the EALF to fatigue cracking failure mode. This concludes that the EALF is dependent upon pavement thickness, material properties, and the pavement distress criteria employed. Any change in these three factors will change the EALF values and failure mode. The EALFs are predominantly controlled by permanent deformation on top of the subgrade layer for all axle load groups. This calls for the review of parameters used for pavement design.

The tensile strain and compressive strain increase linearly with an increase in axle load for all the four axle configurations. Axle configuration plays a significant part in both pavement responses i.e. compressive strain and tensile strain. For the same load on the axle, the single axle with dual wheel produces 1.94 to 2 times greater tensile strain compared to the tandem axle, and 2 to 3 times greater compared to the tridem axle.

High axle loading contributes to a significant decrease in allowable axle load repetitions for all axle load groups. The allowable fatigue load repetitions decreased by 55% for 30% axle load overloading for all of the four axle configurations. NTRC [1] reports that 3-axle trucks were recorded as the most overloaded trucks at N-5 with overloading exceeding 30% at Eminabad weigh station. The impact of the 3-axle truck was theoretically studied using the KENLAYER computer program that shows that a single pass of the 3-axle truck was producing 42.16 ESALs, and just 1,000,000 passes would decrease the pavement life by 80% with failure mode being fatigue cracking.

Increasing the pavement thickness is one of the solutions to control pavement damage, yet it is a very costly practice. Therefore, it is recommended to either modify the properties of the material used in pavement layers such as cement-treated bases to increase the elastic modulus of the layers or switch to rigid pavements for long term pavements.

A nationwide study is required to create mechanistic pavement distress models that would predict the pavement responses and damage with precision for Pakistan's environment. The truck factors and EALFs derived in this study are based on some assumptions. Assumptions other than used in this study will yield different results.

References

[1] NTRC, *Pilot Axle Load Survey on N-5 (Peshawar to Karachi)*, Islamabad: National Transport Research Centre 2017a. Retrieved from www.ntrc.gov.pk: www.ntrc.gov.pk

[2] Bonaquist, R., Surdahl, R., and Mogawer, W., Effect of Tire Pressure on Flexible Pavement Response and Performance. *68th Annual Meeting of the Transportation Research Board*. Washington, D.C., 1989.

[3] NTRC, *Axle Load Study on National Highways*, National Transport Research Centre, 1995. Retrieved from www.ntrc.gov.pk

[4] NTRC, *Pilot Traffic Count Survey on N-5 (Peshawar to Karachi)*. National Transport Research Centre 2017b. Retrieved from www.ntrc.gov.pk, Retrieved 2019, from National Transport Research Centre: http://www.ntrc.gov.pk/

[5] Li, P., Chen, Y., and Xie, Y., Cause Analysis of Asphalt Pavement Rutting on Section N5 in Pakistan. In *1st International Conference on Transportation Infrastructure and Materials*, 2016.

[6] Ragnoli, A., De Blasiis, M. R., & Di Benedetto, A., Pavement Distress Detection Methods: A Review, *Infrastructures*, 3(4), 2018, 58.

[7] Du, Z., Yuan, J., Xiao, F., and Hettiarachchi, C., Application of Image Technology on Pavement Distress Detection: A Review. *Measurement*, 184, 2021, 109900.

[8] Huang, H. Y., *Pavement Analysis and Design*, Upper Saddle River, New Jersey: Pearson Prentice Hall, 2004.

[9] Van Til, C., McCullough, B., Vallerga, B., and Hicks, R, *Evaluation of AASHO Interim Guide for Design of Pavement Structures*, NCHRP, 1972.

[10] AASHTO. *AASHTO Guide for Design of Pavement Structures*, Washington, D.C.: American Association of State Highway and Transportation Officials, 1986.

[11] AASHTO, *AASHTO Guide for Design of Pavement Structures,* Washington,D.C.: American Association of State Highway and Transportation Officials, 1993.

[12] Highway Research Board, *The AASHO Road Test Report 5*, National Academy of Sciences, National Research Council, Publication 954, 1962. Available at https://onlinepubs.trb.org/onlinepubs/sr/sr61e.pdf, accessed on 12th February 2023.

[13] Osman, O., Ghazolly, M., and Mousa, R., Impact of Increasing Legal Axle Loads on Truck Factor in Egypt, *4th International Gulf Conference on Roads*, 2008. Doha, Qatar. doi:10.13140/RG.2.1.2594.1529

[14] Pais, J., Amorim, S.I, and Minhoto, M.J., Impact of Traffic Overload on Road Pavement Performance, *Journal of Transportation Engineering* (139), 2013, 873-879. doi:10.1061/(ASCE)TE.1943-5436.0000571

[15] Pais, J.C., Pereira, P.A., Minhoto, M.J., Fontes, L.P., Kumar, D.S., and Silva, B.T., The Prediction of Fatigue Life using The k1-k2 Relationship, *2nd Workshop on Fourpoint Bending*, University of Minho. Guimarães, Portugal, 2009.

[16] LCPC, *French Design Method for Flexible Pavements*, Paris: Laboratoire central des Ponts et Chausse´es (LCPC), 1994.

[17] Rys, D., Judycki, J., and Jaskula, P., Analysis of Effect of Overloaded Vehicles on Fatigue Life of Flexible Pavements based on Weigh in Motion (WIM) data, *International Journal of Pavement Engineering*, 17(8), 2016a , 716-726.

[18] Rys, D., Judycki, J., and Jaskula, P., Load Equivalency Factors for Polish Catalogue of Typical Flexible and Semi-rigid Pavement Structures, *Transportation Research Procedia*, 2016b, 14.

[19] Raheel, M., Khan, R., Khan, A., Khan, M. T., Ali, I., Alam, B., and Wali, B., Impact of Axle Overload, Asphalt Pavement Thickness and Subgrade Modulus on Load Equivalency Factor using Modified ESALs Equation, *Cogent Engineering*, 5(1), 2018. doi:10.1080/23311916.2018.1528044.

[20] Bonaquist, R.F., Churilla, C.J., and Freund, D.M., Effect of Load, Tire Pressure, and Tire Type on Flexible Pavement Response, *Transportation Research Record* (1207), 1988, 207-216.

[21] Wang, H., Li, M., and Garg, N., Flexible Pavement Responses under Heavy Aircraft and High Tire Pressure Loading, *Transportation Research Record*, 2501(1), 2015, 31–39.

[22] Roginski, M., Effects of Aircraft Tire Pressures on Flexible Pavements and Soil Engineering, *Proc., International Conference on Advanced Characterization of Pavement*, 2007, (pp. 473–1481). Athens, Greece.

[23] Zhang, Z., Kawa, I., and Hudson, W., *Impact of Changing Traffic Characteristics and*

Environmental Conditions on Performance of Pavements. FHWA, 2005.

[24] Al-Mansour, A., and Al-Qaili, A., Effects of Truck Tire Pressure on Fatigue and Rutting of Flexible, IOSR *Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, 15(1), 2018, 57-63.

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