EFFECT OF HEAVY AXLE LOADING ON PAVEMENT PERFORMANCE ON NATIONAL HIGHWAYS NETWORK IN PAKISTAN

By

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ABSTRACT

This study explores the damaging influence of traffic overloading, over inflated truck tires and properties of unbound pavement layers on the performance of flexible pavements. Field data pertaining traffic loading, pavement geomaterials and climatic conditions from Pakistan was analyzed as a case study using the Mechanistic-Empirical (M-E) design framework based on GAMES (General Analysis of Multi-layered Elastic Systems). Results were presented in terms of Relative Damage Factors (RDFs). Based on the analysis of results it was found that the performance of flexible pavements is sensitive to not only traffic loading and tire inflation pressure, but also significantly to the stiffness of unbound pavement layers. The damaging influence of increase in tire pressure keeps on magnifying with each axle load increment. The flexible pavement performance against distresses such as fatigue cracking and rutting is significantly affected by the stiffness of unbound base course and subgrade, respectively. The Design RDF for the Legal axle load (118 kN) and the mean observed axle load (145 kN) on single axle with dual tires, with mean observed tire pressure of 896 kPa was 5.80 and 11.95, respectively. The damage factors derived in this study can be readily used for network level pavement management.

Keywords

Traffic overloading, unbound aggregates, Mechanistic-Empirical Design, Relative Damage Factor, pavement performance.

1. INTRODUCTION

Flexible pavements with hot mix asphalt-concrete (AC) surfacing constitutes the majority of road pavements around the world predominantly due to its low initial/maintenance cost, easy and quick construction, superior riding quality and skid resistance, etc. Flexible pavements are considered to be the most complex among the civil engineering structures. The design and performance considerations of flexible pavements includes a multitude of potentially influencing variables including the complex behavior of pavement geomaterials in each layer, resting on a variety of subgrade soils, under dynamic traffic loads and in an array of climatic conditions. Deficient knowledge or inadequate assembling and/or inappropriate handling of these variables in the design as well as construction stages may adversely affect the performance of flexible pavement structures.

More so due to the phenomenal demand shift towards road transportation options, the enhanced pavement serviceability and longevity demand by the society and the worldwide tendency of funds depletion for construction of new and maintenance of large portfolios of existing ageing road networks, pavement technologists and researchers are concentrating more towards coherent design systems to respond to those demands and for optimal use of resources.

The recent advancement in support technologies - particularly, more sophisticated laboratory and in-situ instrumentation, and much efficient computers now available for general use have indeed facilitated the development of analytical or Mechanistic-Empirical (M-E) design systems which are capable of analyzing variabilities in all the design inputs/conditions (Huang 2004).

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2. ROAD TRANSPORTATION IN PAKISTAN

Road transportation network in Pakistan is not only the lifeline for the country's own economic and social development, it is also an integral part of the greater Asia road network and thus opens-up enormous prospects for trade, cultural exchange and peace in the entire region. Pakistan's road transport system caters to around 92 percent and 96 percent of nationwide passenger and freight traffic, respectively (NHA 2009). The road network comprises of 259,618 kilometers (km), including 179,290 km. of paved and 80,323 km of unpaved roads. Out of the total road network approximately 12,500 km are classified as National Highways and are being administered by an independent federal road agency, the National Highway Authority (NHA). These roads comprise only around 4% of Pakistan's total road network; however, they connect all the major cities and industrial centers around the country and carry more than 80 percent of the country's gross commercial traffic. Therefore the analysis parameters in this study primarily relates to the National Highway system of Pakistan.

In one of the latest study (JICA 2006) the traffic volume on the country's busiest 1800 kms intercity road from the port city of Karachi in the south to Peshawar in the north-west [historically known as grand trunk (GT) road was found to be ranging between 7000 – 23000 vehicles per day with an annual growth rate of around 4%. Composition of cars, buses and trucks was found to be 37%, 24% and 39%, respectively. The truck classification study in Pakistan indicated that 2-axle trucks (with single rear axle on dual tires assembly) dominate the truck types with a share of about 70% in the entire truck fleet in the country (Kamal et al, 2009). More than 90% of trucks carry the pay loads far in excess of standard axle / legal loads.

In order to check and prevent premature failures, the Government of Pakistan has fixed a legal load limit of 118 kN on a single axle with dual tires. A limit of 828 kPa tire inflation pressure has also been fixed accordingly. However, it has been observed in various studies that even these upper limits-beyond the standard axle load of 80 kN and 551 kPa tire pressure – are rarely being followed (e.g., Kamal et al. 2009, JICA 2006, NTRC 1995). These studies reveal that in practice, the load on this axle ranges from 98 kN to as high as 195 kN. In one of the recent study the mean axle load has been observed to be 145 kN. Similarly, the mean tire inflation pressure has been observed to be 896 kPa (NTRC. 1995).

In recent years the newly constructed as well as rehabilitated pavements have shown accelerated deterioration and premature failure causing not only waste of public money but also safety hazard and inconvenience to the road users. The recent road condition survey conducted by NHA (2009), reveals that more than 60% of the network exhibit pavement surface cracking, including more than 23% high severity cracks (crack opening > 10 mm). The survey also indicates that more than 30% of the network has developed permanent deformation (rutting) of various magnitudes. The Remaining Service Life (RSL) data indicate that nearly 46% of the entire network has RSL of not more than 2 years.

The quality of the road infrastructure in Pakistan has severe capacity constraints that obstruct the facilitation and efficient movement of goods to their destination. Poor road maintenance is due to factors such as insufficient funding and overloading of freight vehicles. A 2004-2005 survey of pavement condition on the federal network revealed that 37 percent of the road network was in poor to very poor condition. The maintenance requirement of these roads is significant and toll revenues and roughly half of the government's expenditures on these roads. Provincial roads, which are the primary feeder roads for the National Highway Network, are at the bottom of the road hierarchy system. As a result, the government gives more priority for National Highway investment than provincial road investment. The National Highway Authority responsible to maintain approximately 12,000 Km of main highways and motorways through toll revenues is under pressure to keep-up the maintenance requirements of the country main economic routes. Each year brings revenue deficits to account for compounding maintenance backlog of highways and motorways.

3. PAKISTAN'S TRUCKING FLEET

The trucking sector carries 96 percent of the total freight traffic. While there are a total of 216,119 registered trucks, the Government of Pakistan (GoP) estimates that only 200,500 of these (93 percent) actually operate on roads. Sixty-five to seventy percent of the total truck fleet consists of single or double-axle trucks. The trucking sector is characterized by the presence of a small fleet of owners who generally own less than five vehicles. The trucking sector is highly competitive, characterized by low barriers to entry, many small operators, and low freight rates.

To maintain high revenues, trucks are overloaded, which damages road quality and increases the demand for higher road investment. Lack of enforcement of regulations on safe operation, crew hours, truck modification, and trailer manufacture increase the risk of accidents. According to the GoP's Trucking Policy, by 2007, inefficiencies of the trucking sector were estimated at US$2.62 billion/year, consisting mainly of: (i) US $ 1.04 – 1.57 billion/year in extra fuel costs and diesel subsidies, (ii) US $ 0.52 – 0.61 billion/year in additional road user costs, and (iii) a US$0.44 billion/year contribution to the infrastructure deficit (The World Bank 2012).

The trucking fleet is largely out-dated by several decades and run on underpowered engines. High import tariffs on high capacity multi-axle trucks protect local manufacturers producing low capacity and low-powered trucks and hence prevent the trucking sector from improving its fleet. Over the past 20 years, revenues per km accruing to operators have decreased in real terms by 1.4 percent on average per year. While it might seem unfair to compare Pakistan with these more developed countries, it is with them that Pakistan competes on global markets. Transport time is often lost by trucks needing repairs due to overloading.

4. LEGAL AXLE LOAD LIMITS

The permissible load limits for different types of freight vehicles (Trucks) on our National Highways were subject to series of revisions since the year 2000. Each revision entails approximately 20% of increase in loading limits on our national highways. The damaging effect has been phenomenal as compared to standard axle load of 8-tons to which our roads are being designed and is an internationally accepted norm. The damage caused by excessive load relative to the standard axle follows a damaging effect which is exponential. The exponent of the damaging effect is 4.5 which means that if an axle weighs 16 tons which is double to a standard axle of 8-tons would damage the pavement 22 times compared to standard axle.

The axle load limits initially enforced by NHA and all the subsequent increase in the permissible limits and new suggested ones have been evaluated technically in terms of its damaging effect on our pavements. Equivalent Axle Load Factors (EALF's) i.e. in terms of damage to pavements have been computed for different truck loads by AASHTO and UK's Road Note procedures's and are shown in Figure-1 and Figure-2 below respectively. The graphical presentation below compares the load limits with revisions to this date and it is quite clear that further relaxation in permissible axle loading will drastically reduce pavement life on our national network (S. Khanzada 2013).

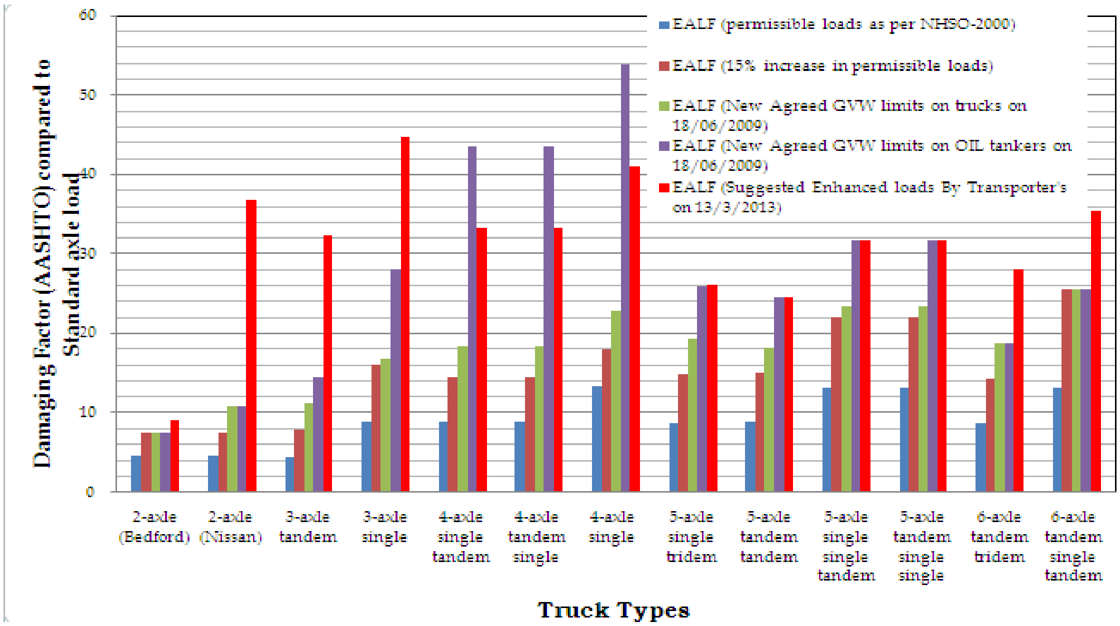

Figure-1: Enhanced Damaging Effect (AASHTO) Due to Revisions in NHA's Legal Load Limit

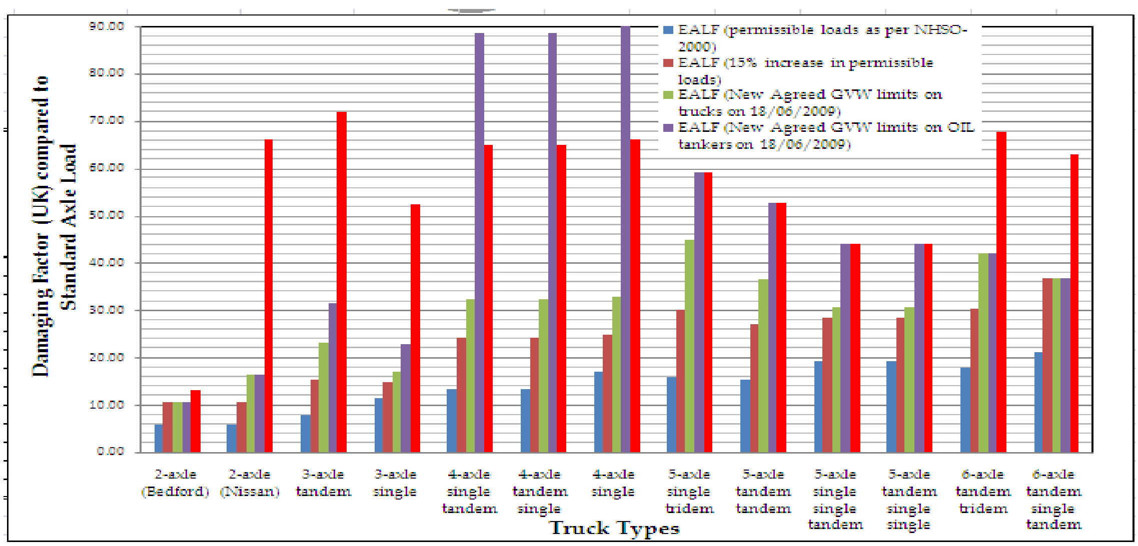

Figure-2: Enhanced Damaging Effect (UK Road Note) Due to Revisions in NHA's Legal Load Limit.

It can be seen from the graphical presentation above that the bars in red colour show the newly suggested permissible load limits. The consequence of this relaxation would translate to pronounce damage to our pavements with escalating maintenance cost. For the last few years, NHA is already facing financial deficit for maintenance needs of its network. The figure below (taken from AMP 2011-2012) shows that 66% of our roads are in fair condition. This implies that two thirds (2/3) of our roads have approached terminal serviceability levels and needed to be upgraded to better levels of serviceability (i.e. Good) if the assets are to be maintained.

5 RESEARCH APPROACH

5.1 *Damage impact analysis*

Damage impact analysis of flexible pavements due to overloading, over inflated truck tires and properties of unbound pavement layers has been conducted using the M-E design framework in this study. In the M-E approach, flexible pavements are modeled as layered elastic systems with infinite lateral dimensions, resting on an elastic subgrade layer of infinite depth. Elastic theory implies that each of the pavement layers and the subgrade can be described by their corresponding elastic modulus "*E*" and Poisson's ratio "μ". Each layer is assumed to be homogeneous and isotropic. Tire loads are commonly assumed as circular loads of uniformly distributed vertical stress, equal to tire inflation pressure. The radius of the circular load is given by the following equation (Papagiannakis and Masad 2008):

$$a = \sqrt{\frac{p}{(i\pi)}} \qquad (1)$$

where, a = contact radius in meter (m), p = vertical load in kN and i = tire inflation pressure in kN/m^2. Critical pavement responses (e.g., stress, strains and deflections) are calculated using theory of elasticity. The analysis parameters employed in this study are discussed in more detail below.

5.2 Pavement Response model

A recently developed analysis tool for layered elastic system capable to assist in M-E design of pavement structures in Japan has been used for this study. The tool named General Analysis of Multi-layered Elastic System (GAMES), provides an excellent combination of analysis features and computation speed for linear elastic layer system and has been found to produce comparable results with a range of other analysis softwares which are used worldwide (Maina et. al. 2008, JSCE 2005). Critical responses analyzed in this study were horizontal tensile strain (ε_t) at the bottom of the asphalt-concrete layer and vertical compressive strain (ε_c) at the top of the subgrade layer as shown in figure-3. These responses were computed for various loading conditions using GAMES. Strains at each point (dots) in the figure were computed and the maximum strain responses were later used as inputs in the distress models (also known as transfer functions for damage analysis).

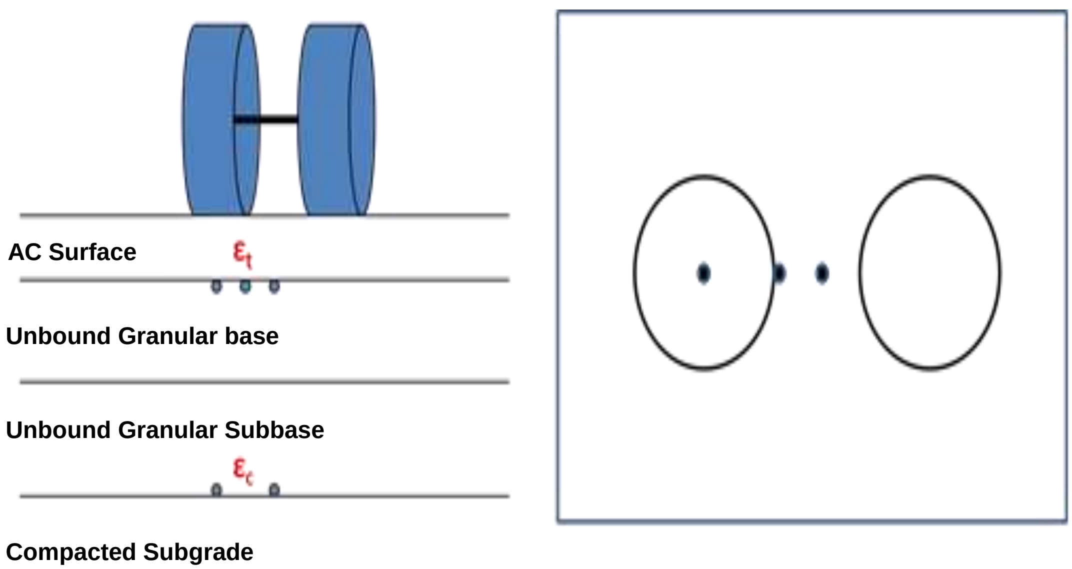

Figure 3: Locations of critical strains under one wheel (with dual tires) of a Single Axle

5.2 *Pavement distress models*

The number of load repetition to failure (N_f) due to maximum ε_t corresponding to bottom-up cracking failure and ε_c corresponding to permanent deformation or rutting failure, were computed for a range of loading conditions using the distress functions proposed by Japan Road Association (JRA). The JRA distress models are basically modified and calibrated version of Asphalt Institute (AI) models (Asphalt Institute 1999). Many different versions of AI models were extensively used in the past for the pavement performance studies. However, capitalizing on the recent advancement in the field of flexible pavement engineering in Japan, the current models suggested by JRA have been used for this study. Moreover, the overall results shown in the later part of this paper were also found to be in agreement with the actual pavement deterioration trends in Pakistan as highlighted in the introduction above, which suggests that the models are generally fit to be used for the Pakistani conditions.

In the M-E design system proposed by JRA, a pavement section is considered to be failed when either 20% of the lane area is cracked and/or the pavement structure exhibits 15 mm of rut depth (JRA 2001). The equation predicting the allowable number of load repetition to fatigue cracking (N_{ff}) is a function of tensile strain (ε_t) and asphalt concrete mix stiffness (modulus) "*E*" according to:

$$N_{ff} = \beta a1 . C . 6.617^{-5} \ . \left(\frac{1}{\varepsilon_c}\right)^{3.291.\beta a2} \left(\frac{1}{E}\right)^{0.854.\beta a3} \qquad (2)$$

$$\text{where,} \quad C = 10^{M} \qquad (3)$$

$$M = 4.84 \left[\frac{VFA}{100} - 0.69\right] \qquad (4)$$

And *VFA* is volume of voids filled with asphalt binder (%). A typical VFA value of 73% as suggested by NHA General Specifications (1998) has been used in this analysis.

$\beta a1 \ . \ \beta a2$ and $\beta a3$ are calibration constants:

$$\beta a1 = Ka \ . \ \beta a1^{/} \qquad (5)$$

Where *Ka* is a correction coefficient for asphalt concrete layer thicknesses (h_{ac}) and is expressed as:

$$Ka = \frac{1}{8.27 \times 10^{-0.11} + 7.83 \ . \ e^{-0.11(hac)}} \qquad (6)$$

The values of $\beta a1 \ . \ \beta a2$ and $\beta a3$ are equal to 5.229x10^4, 1.344 and 3.018, respectively. The equation predicting the allowable number of load repetition to permanent deformation or rutting (N_{fd}) is a function of vertical compressive strain (ε_c) at the top of the subgrade and is expressed as:

$$N_1 fd = \beta s1.(1.365 \times [(10)]\ {}^{\uparrow}(-9).\varepsilon_{\downarrow} c^{\uparrow}(-4.477 * \beta s2) \qquad (7)$$

Where $\beta s1$ and $\beta s2$ are calibration constants equal to 2.134 x 10^4 and 0.819, respectively.

5.3 *Pavement Layer Properties*

Table-1 shows the properties of each layer, assumed for this analysis. The pavement section represents typical design thicknesses and material properties (i.e. generally strong section in the table) utilized in Pakistan for the National Highway design traffic of about 25 million Equivalent Standard Axle Loads (ESALs) over a design life of 10 years, in accordance with AASHTO pavement design method. The elastic moduli of pavement materials have been worked out from the typical California Bearing Ratio (CBR) test values, which is the common test being performed in Pakistan, both in the laboratories and field. The correlations proposed by AASHTO design guide have been used for this purpose.

Table-1: Pavement Layer Properties

Layer	Thickness (cm)	Modulus (MPa)	Poisson Ratio
AC Surface	5	225 - 6850	0.35
AC Base	10		0.35
Aggregate Base	25	Strong layer = 193 Weak layer = 120	0.40
Gran. Sub base	35	Strong layer = 117 Weak layer = 70	0.40
Subgrade	-	Strong layer = 72 Weak layer = 31	0.45

5.4 *Axle Load and Tire Inflation Pressure*

The primary focus of this study was to assess the damaging impact of legal axle load and the observed excess axle load. However, in order to make this study more useful for pavement designers and road administration agencies for rational and economical design of flexible pavements, the analysis variables were enhanced to include a wide range of load and tire pressures as shown in Table-2.

Table-2: load and tire pressure conditions

Analysis Conditions	Range
Axle load	58 kN – 176 kN
Tire inflation pressure	551 kPa – 965 kPa

5.5 *Seasonal variations in Climate*

One of the major advantages of the M-E design approach is the ability to consider climatic condition directly into the design process. The interaction of climatic factors with pavement materials significantly affects the performance of flexible pavements. Particularly, the sensitivity of asphalt concrete mix stiffness (modulus) to temperature variation has been well recognized (AASHTO 2002). Mean monthly air temperatures data, derived from the 60 years` (1931-1990) historical climate data of Pakistan (Khan 2010), has been used in this analysis. The mean monthly pavement temperatures were obtained using the following relation which was originally presented by AI (1999) and also adopted by JRA (2001):

$$M_p = M_a \left[1 + \frac{2.54}{z + 10.16} \right] - \left[\frac{2.54}{9(z + 10.16)} \right] + \frac{10}{3} \qquad (8)$$

where,

M_p : mean monthly Pavement Temperature (°C)

M_a : mean monthly air Temperature (°C)

z : depth below the surface (cm).

The temperature at the upper third point of the AC base layer has been used in this analysis (Huang 2004). A number of AC Temperature-Stiffness (moduli) correlation are available in literature. For this study the stiffness values were worked-out using the correlation established by Scott Wilson pavement engineering, Nottingham, UK (Scott Wilson 1998). Table-3 shows the mean monthly air and mean monthly pavement temperatures and their corresponding AC moduli.

Table-3: AC stiffness (moduli) corresponding to mean monthly temperatures in Pakistan

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Monthly air Temp (^oC)	10	13	17	23	28	31	30	29	27	23	12	10
Mean Monthly Pavement Temp (^oC)	15	18	22	29	35	38	37	36	34	29	17	15
Modulus of AC Layer (MPa)	6850	5290	3560	1450	480	225	300	380	660	1450	5790	6850

6 ANALYSIS OF RESULTS

6.1 *Interpretation of results*

The influence of truck traffic overloading and unbound pavement layers analyzed in this study is presented in terms of Relative Damage Factors (RDFs). RDF can be expressed as the damage caused to a pavement structure by a set of input conditions (i.e. axle loading, tire inflation pressure, material properties and climate) relative to the damage produced by Standard conditions. In this study the standard load and tire pressure were assumed to be the same as suggested by AASHTO guide (i.e. 80 kN load on single axle with a set of dual tires, inflated to 551 kPa each).The RDFs, corresponding to fatigue cracking and permanent deformation or rutting can be expressed as:

$$RDF_f = \frac{N_{ffs}}{N_{ffi}} \qquad (9)$$

and,

$$RDF_d = \frac{N_{fds}}{N_{fdi}} \qquad (10)$$

where, RDF_f is the relative damage factor for fatigue cracking, RDF_d is the relative damage factor for rutting. N_{ffs} and N_{fds} are number of repetition for fatigue cracking and rutting under standard axle loading conditions, respectively. N_{ffi} and N_{fdi} are allowable numbers of repetition for fatigue cracking and rutting under any arbitrary loading conditions, respectively. The larger value between the two RDF values is selected as the Design RDF.

6.2 Effect of axle load and tire inflation pressure

The results show that the performance of flexible pavement is sensitive to not only axle load but also to tire inflation pressure as presented in Figure-4 to Figure-7. Figure-4 shows the effect of axle overloading and tire inflation pressure (Tp) on Asphalt Concrete (AC) fatigue life with Mean Monthly Pavement Temperature (M.M.T). It was observed that the RDF_fs for axle loads between 60 – 90 kN, under all Tp range remained under 2.5.However, the RDF_f sharply increases beyond the 90 kN axle loads. This figure also shows that for any fixed axle load, increasing the Tp resulted in increased RDF_fs. This implies that fatigue performance is highly sensitive to Tp. The phenomenon can be observed even at the standard axle load (80 kN), where the RDF_f increases from 1.0 to 1.66. However, the damaging impact widens for higher axle loads, e.g. at the Legal axle load (118 kN) and the observed axle load (145 kN), the RDF_f increases by 2.3 and 4.6 points, respectively (for Tp ranging from 551 kPa to 965 kPa).

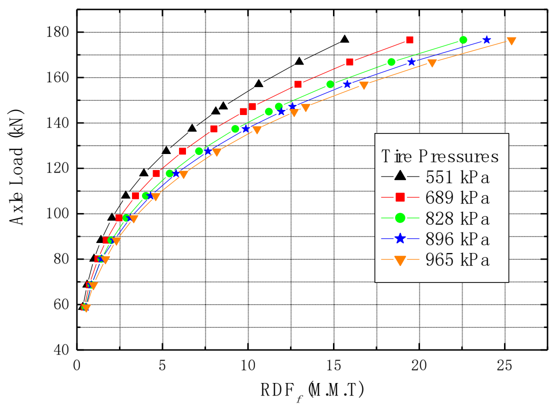

Figure-4 : Relative Damage Factors for Fatigue Failure (RDF_f)

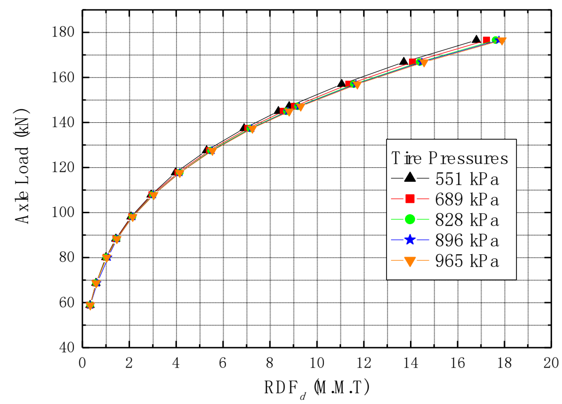

Figure-5 : Relative Damage Factors for Rutting Failure (RDF_d)

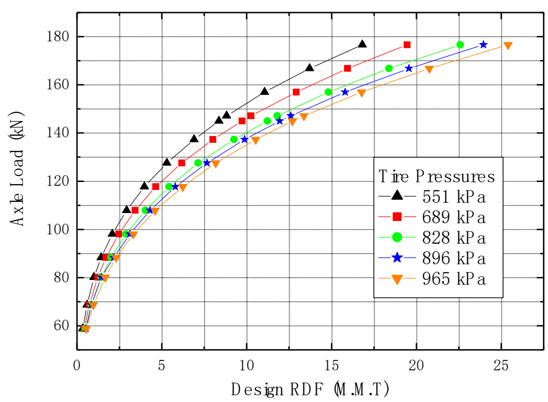

Figure-6 : Representative Design RDFs for all loads and Tp ranges

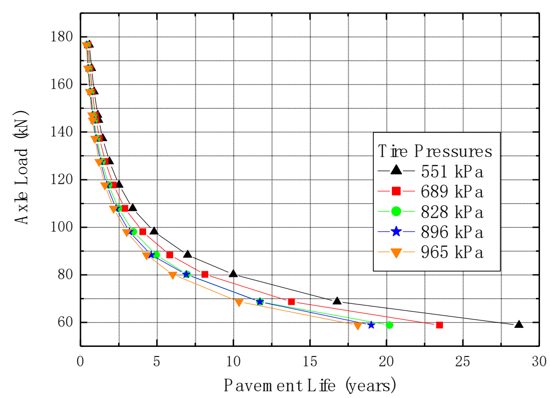

Figure-7 : Effect of axle load and Tire pressure on design life

Figure-5 shows that while the Tp has minimal effect on rutting performance, the axle load has significant effect. This figure also indicates that for the axle load ranging between 60 – 98 kN, the RDF_d remained around 2.0. However, it keeps on increasing until a maximum value of 17.0 at the axle load of 176 kN. The difference in RDF_d s for each individual load increment remained under 1.0, for all Tp`s, which substantiate the observation that Tp has minimal impact on the rutting performance.

Figure-6 shows the Design RDFs for all loads and Tp ranges. The Design RDFs reveal that pavement performance in Pakistan is more sensitive to fatigue failure compared to rutting failure. This result confirms the actual in-service condition of pavements in Pakistan, as revealed by surveys conducted by NHA and mentioned in section-1. Figure-7 summarizes the effect of axle load and Tp on the design life of the pavement structure. The effect on pavement life expectancy due to tire pressure can be observed even at the standard axle load of 80 kN, where the pavement life drops from 10 to 6 years when the Tp was increased from 551 kPa to 965 kPa. At the legal and observed axle loads, the pavement life may be expected to be between 1.5 to 3 years and between 0.8 to 1.2 years, respectively, depending on Tp.

6.3 Effect of stiffness of unbound aggregate layers

Figure-8 and Figure-9 show the influence of stiffness of unbound geo-material and subgrade on AC fatigue and pavement rutting performance, respectively. It was observed that AC fatigue performance is significantly affected by the stiffness of unbound base course and to a lesser extent by subbase layer`s stiffness (figure-8). On the other hand, figure-9 reveals that the pavement rutting performance is almost entirely dependent on the stiffness of subgrade. It may be observed that for weak subgrade, the RDF_d raises to a large value of 88.32 at 176.58 kN axle load and 828 kPa Tp. Finally, figure-10 shows the design RDFs at 828 kPa (legal Tp) under various stiffness of geo-materials :

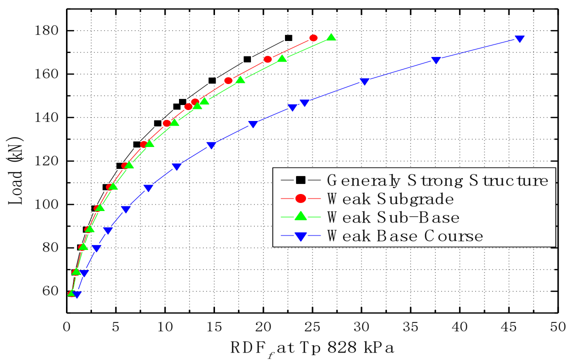

Figure-8 : Effect of geo-materials stiffness on pavement fatigue performance

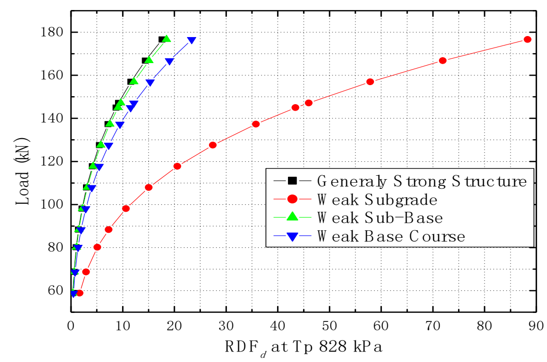

Figure-9 : Effect geo-materials stiffness on pavement rutting performance (Tp 828 kPa)

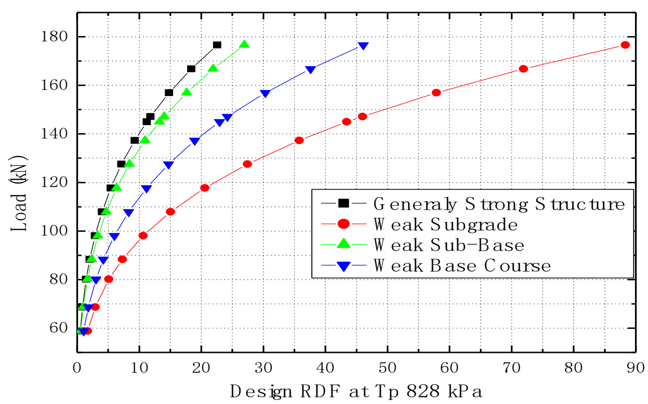

Figure-10 : Design RDFs under various geo-material conditions (Tp 828 kPa)

7 CONCLUSIONS

In this study, the damaging influence of traffic overloading, tire inflation pressure and stiffness of unbound pavement layers on the performance of flexible pavement was analyzed. Conclusions drawn from this study may be summarized as follows:

1) The performance of flexible pavement is sensitive not only to axle loading but also significantly to tire inflation pressure. The damaging influence of increase in tire pressure keeps on magnifying with each axle load increment.

2) With a mean observed tire pressure of 896 kPa, the Design RDF for the legal axle load (118 kN) and the mean observed axle load (145 kN) on single axle with dual tires was found to be 5.80 and 11.95, respectively.

3) The flexible pavement performance against distresses such as fatigue cracking and rutting is significantly affected by the stiffness of unbound base course and subgrade.

4) The damage factors derived in this study can be readily used for network level pavement management.

5) The damaging effect of loads and further relaxation on permissible legal load limits needs no further emphasis. Our road pavements are being punished to phenomenal limits which defy all standard design procedures. The trucking industry is further pushing NHA for relaxations in the axle loading limits. This will escalate our maintenance needs for which resources are stretched to the limits.

6) Strict control of axle loading need to be enforced to safeguard our fragile economy to preserve our future investments. National policy towards this issue should be formulated for zero tolerance.

7) Gradual replacement of ailing trucking fleet should be encouraged through import of multi-axle turbo-diesel trucks on subsidized rates.

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