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Mechanistic-Empirical Study of Sensitivity of Truck Tire Pressure to Asphalt Pavement Thickness in Egypt

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ABSTRACT
Designing, improving and reducing distresses of highway network is an essential responsibility of the roads researchers. Truck tire inflation pressures have steadily increased in the recent decades. 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 main objective of this study is to determine which layer thickness is more sensitive to improve the performance of the flexible pavement with respect to the variation of traffic tire pressure. The performance of pavement will be mentioned by optimum tire pressure measure where fatigue and rutting lives are equal. Moreover, the pavement life will be determined as a function of the tire pressure and the most effective thickness on the performance of the pavement due to the variation of traffic tire pressure. Results demonstrate that, the base course thickness is the key element which can cause a marked decrease in the optimum tire pressure. Moreover, the optimum tire pressure should not exceed 0.80 N/mm^2 with 375.0 mm optimum base thicknesses.

***Keywords* -** Flexible Pavement, KENLAYER , Pavement Life, Pavement Strains, Tire Pressure.

I. INTRODUCTION

1.1 Background

Premature failure of flexible pavements has more circulation in many roads in Egypt as a result of the drastic changes in truck axle loads as well as tire pressures. Important findings of a recent study have indicated that, rutting is the major distress modes surveyed in Egypt due to its high severity and extent levels. Another study concluded that tire pressure has more significant effect on rutting tendency of surface asphalt layer than wheel loads [1]. Analytical study to investigate the effects of truck tire pressure on pavement responses found that tire pressure was significantly related to tensile strain at the bottom of the asphalt layer and stresses near the pavement surface for both the thick and thin pavements. However, tire pressure effects on vertical compressive strain at the top of the subgrade were minor, especially in the 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 [2].

Existing practice assumes the tire pressure to be uniform over the contact area. The size of contact area is then calculated depending on the contact pressure. The contact pressure is greater than tire inflation 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 inflation pressure for high pressure tire, since the wall of tires is in tension. Whatever, a computer program called Tire View was developed that provides estimates of tire contact area as a function of tire type, tire load, and tire inflation pressure and predicts the stress distribution at the tire pavement interface based on polynomial interpolations of measured tire contact stresses in the data base [3].

1.2 Mechanistic- Empirical methods

Almost all of the national highways in Egypt are flexible pavement. Over a few decades, the design of this flexible pavement has been based on empirical method, American Association of State Highway and Transportation Officials (AASHTO) guides for pavement design (AASHTO, 1993). The 1993 AASHTO guide is based solely on the results of the AASHO Road Test from the late 1950s. Moreover, since there has been a phenomenon of overloading in many countries and improvement of material properties quality in flexible pavement design which are not considered in AASHTO 1993, the need for developing improved pavement design and analysis methods is very necessary [4].

The increment of loads and quality of material properties can be evaluated through Mechanistic- Empirical (M-E) method which is based on elementary physics and determines pavement response to wheel loads or environmental condition in terms of stress, strain, and displacement. M-E software like KENLAYER has been developed to facilitate the transition from empirical to mechanistic design methods. The advantages of the M-E design over the empirical methods are it tolerates [5]:

1. Better utilization and characterization of available materials,
2. Improved performance predictions,
3. Relation of material properties to actual pavement performance,
4. Better definition of the existing pavement layer properties.

1.3 Problem statement and research objectives

Vehicle loads are transmitted from the vehicle body through suspension systems and tires to the pavement surface. These loads are distributed through the pavement structure to the subgrade soil. In this tire-pavement interaction system, tires make up the least understood and most controversial aspect. Tire inflation pressure plays an important role in the tire-pavement interaction process. Several survey studies conducted in Egypt and elsewhere in the world found that truck tire inflation pressures have steadily increased in the last several decades. Significant reduction in the tire-pavement contact area occurs due to increased tire pressure, this results in an increase in the tire-pavement contact stress and then more damaging effects to the pavement. Many research efforts were attempted to assess the effects of increased truck tire pressure on flexible pavements, but inconsistent results were obtained from these studies. Thus, the objectives of this study are:

1. To implement the M-E method in flexible pavement design with consideration of traffic loading and pavement cross section properties.
2. To investigate the flexible pavement performance due to overloading and high truck tire pressure.
3. To determine which layer thickness is more sensitive to improve the performance of the flexible pavement with respect to the variation of traffic tire pressure.
4. To study the relation between pavement lives due to tire pressure variation and also predict the pavement life as a function of the tire pressure and the most effective layer thickness.

II. Literature review

Flexible pavements are pavements constructed with bituminous and granular materials. These types of pavements are so named since the total pavement structure deflects/bends under traffic loading. Flexible pavements are layered systems that can be analyzed with Burmister's layer theory (Burmister, 1943) [6]. Flexible pavements structure may be composed of several layers of material with great thickness for optimally transmitting load to the subgrade. These layered systems have high quality materials on the top where stresses are high and low quality materials at the bottom [7].

In (2004) a comprehensive sensitivity analysis of the proposed AASHTO 2002 performance models to the properties of the unbound pavement layers was conducted. The sensitivity analysis includes different types of base materials, base layer thicknesses, hot mix asphalt type and thickness, environmental conditions and subgrade materials. The sensitivity analysis of the AASHTO 2002 model shows that, the base modulus and thickness have significant influence on the international roughness index and the longitudinal cracking. On the other hand the influence of base properties on alligator cracking is about half of the influence of base properties on longitudinal cracking. Surprisingly, all the results show that, the base properties have almost no influence on permanent deformation [8].

In (2005) Heemun Park et.al [9] studied the sensitivity of fatigue and rutting strains to the variation of asphalt binder course and base course thickness and it was concluded that, the percent change in fatigue and rutting strains of asphalt binder course are 2.30 times greater than that in base layer. Moreover, the thickness change in asphalt binder course is very sensitive to the fatigue and rutting strains. In (2006) [10] the new AASHTO 2002 design method for flexible pavement had been applied to understand the pavement performance with respect to the various design parameters. Several important design parameters were selected and were varied one at a time and their effect on the pavement distresses was found. The sensitivity analysis included different amount of traffic loads, base materials, base material thicknesses, surface layer thicknesses and subgrade materials. According to this analysis it was concluded that, the AC bottom up cracking increases with the increase in the AC layer thickness from 2 to 4 inches but then decreases as the AC layer thickness increases beyond 4 inches. On the other hand, AC surface down cracking model is sensitive to all the design parameters considered in the sensitivity analysis in a minor way. However it is very sensitive to the change in AC layer thickness.

Moreover, El-Desouky (2009) [11] provided some useful statistical based models for flexible pavement behavior. The results of a theoretical analysis using the finite element program SAP was utilized in this statistical analysis study. The maximum of surface deflection, tensile strain and compressive strain are the most commonly used criteria for flexible pavement design. Three different AC thicknesses and eight different AC modulus were used to investigate the response of flexible pavement. Based on the theoretical and statistical work presented in this study it was mentioned that, the thickness of asphalt concrete layer was the most important independent variable for the response of flexible pavement followed by the modulus of AC layer.

III. Tire pressure survey in Egypt

In order to guess the actual tire pressure in use, interviews were made on owners of several tire stores in Egypt. It was found that tire inflation pressures used for the majority of trucks are in the range of 120 to 140 psi. Thus, a sample field survey to measure the actual inflation truck-tire pressure was carried out at two rest- stations located on Cairo-Suez road and Cairo-Alexandria desert road. A total of 1618 tires in 117 trucks from different categories were measured for tire inflation pressure. The collected data from the two stations are assembled and presented in Table 1 which illustrates that the tire inflation pressures of trucks in Egypt varies from 93 to 141 psi with mean value of 121 psi and standard deviation of 13.35. An important observation was noticed during measuring the inflation pressure of the assembly dual-tire. It is that, the dual-tire assembly showed difference in inflation pressure between the two tires in the dual-tire assembly ranged from 10 to 50 psi. Moreover, as can be seen in **Table 1** a difference from 20 to 60 psi between inflation pressures of the same truck tires was noticed. This variation in tire inflation pressure may be attributed to the difference between the two tires quality, as it was noticed that the stronger and more durable the tire, the higher the inflation pressure and vice versa [2].

The collected data from the two stations were assembled and presented in **Fig. 1** which shows the distribution of the measured tire inflation pressure of the investigated sample. It can be seen from the Figure1 that 97% of tires operate with tire inflation pressure greater than 80 psi, 59% with tire inflation pressure greater than 120 psi and 2% with tire inflation pressure greater than 140 psi. The fact that cannot be ignored that the majority of truck tires (74%) operates with inflation pressure range from 120 to 140 psi. It is quite obvious that a tire inflation pressure of 80 psi for pavement analysis cannot reflect the field situation. Pavement design based on the standard tire inflation pressure of 80 psi certainly would not suffice. Typically, truck tire contact pressure is approximately 90 % of the tire inflation pressure. So, a conservative value of the operational truck-tire contact pressure of 130 psi (equivalent to the tire inflation pressure of 140 psi.) is recommended in Egypt for pavement analysis and design [2].

IV. Methodology of the study

4.1 Method of data analysis

The method in analyzing the data used in this study is mechanistic empirical method. The main advantage of an M-E design method is that the analysis is based on pavement fatigue and rutting characteristics of all layers, rather than only on the pavement’s surface performance (ride quality). It is based on the mechanistic of materials that relates traffic load to pavement response, such as stress and strain. Mechanistic empirical computer program can be used to run the calculation of stress, strain, and deflection in mechanistic empirical methods. By using this computer program, all the pavement reactions due to the load repetition can be determined more accurately, close to the actual condition [5].

The mechanistic-empirical study of the effects of tire pressure on pavement would require that immediate pavement responses due to tire loading be mechanistically computed for pavement structures, and the long-term pavement performance be related to the computed pavement responses. The problem becomes more complicated when variability is considered for loading, pavement and environmental conditions. During the service life, a piece of pavement may undergo numerous repetitions of truck axles of various types and each axle type is associated with a load spectrum which is the axle volume distribution over the range of axle load [12].

4.2 Finite element and multi-layer models

In a mechanistic-empirical pavement study, asphalt pavement responses due to traffic loading are normally computed with an analytical program either based on a finite element model or a linear elastic multi-layer model. Generally a finite element model offers more potential abilities to handle complicated loading conditions and be configured to realistically characterize pavement responses than a multi-layer model. However the major disadvantage of using a finite element model is its slow computation speeds. The slow computation speed plus demanding requirements for computing resources in processor speed and memory capacity literally prevent the finite element program from being directly used in this study. Although the multi-layer model offers quick computation speeds, however, the quick computation speeds are at the expense of model simplifications, and the oversimplifications that are built into the multi-layer model and the associated traditional tire model may make the computation results quite inaccurate. One major assumption made by the traditional tire model, which is frequently associated with the multi-layer model, is for the tire-pavement interaction process in which tire-pavement contact stress is assumed to be uniformly distributed over a circular contact area, and simply equal to the tire inflation pressure. However, recent studies have demonstrated that the tire-pavement contact stress is far from uniformly distributed and the distribution of contact stress primarily depends on tire pressure, tire load, and tire type. Therefore, a proposed solution to the problem at hand should be able to handle the non-uniform tire-pavement contact stress, resolve the difficulty in the slow computation speeds of the finite element model, and deal with the variability in loading, pavement, and environmental conditions [13].

4.3 Pavement response analysis

Flexible pavement is typically taken as a multi-layered elastic system in the analysis of pavement response. A computer program KENLAYER is used to analyze the distress on the flexible pavement layer. The input for analysis consists of two main parameters: traffic loading and material properties. The structural analysis of flexible pavement for KENLAYER is based on the Burmister layer theory. The fatigue cracking Transport and Road Research Laboratory (TRRL) model was developed after TRRL report 1132, and is based on the field performance of several experimental flexible pavements. A multilayer elastic model was used to calculate the dynamic strains. The accumulation of fatigue damage was calculated based on Miner's hypothesis. Considerable adjustment was needed to correlate between laboratory fatigue relations and field performance [14].

The design life for fatigue could be calculated using the following formula [15]:

Nf= 1.66E-10 (εt) –4.32 …………………. (1)

While the rutting model incorporated in the Transport and Road Research Laboratory is given by the following equation [15]:

Nr = 1.13E-06 (εv) –3.57 ………………. (2)

where:

εt: horizontal tensile strain at the bottom of the asphalt layer;

εv: vertical compressive strain at the surface of subgrade.

4.4 Pavement cross sections

Materials in each layer are characterized by a modulus of elasticity (E) and a Poisson's ratio. In the present study, a typical pavement cross section consists of asphalt layer thickness (h1=100.0 mm) with elasticity modulus (E1=2909.0 N/mm^2), and base layer thickness (h2=300.0 mm) with elasticity modulus (E2=174.0 N/mm2) resting on subgrade with elasticity modulus (E3=58.0 N/mm^2). Different probable cross sections that may be used in Egyptian roads are considered for analysis through varying the reference components by ± 25 % and ± 50 %. Four values of each thickness are considered plus the reference one.

4.5 Traffic loading

Five tire pressures levels are selected. these tire pressures are 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0 (n/mm2) according to survey on cairo-suez road and cairo-alexandria desert road [16]. while standard axle load of 80.0kn are considered .the dual tire is approximated by two circular plates with radius (a).the radius of the contact area (a) can be determined according to the following equation (a = (p/ π.pt) 0.5) and spaced at 340.0 mm center to center.

V. Sensitivity analysis of pavement thickness with respect to optimum tire pressure

Analysis of the suggested pavement cross section with variation of increased tire pressure has been performed using KENLAYER computer program. **Fig. 2** shows the decrease in fatigue pavement life with increasing truck tire pressure especially at higher values of wearing surfaces thickness while the effect of increasing tire pressure hasn't any effect on the performance of rutting life. Moreover, the optimum tire pressure increases with increasing wearing surfaces thickness. For example at h1=50.0 mm the optimum tire pressure is 0.62 N/mm2 while at h1= 75.0 mm the optimum tire pressure is 0.80 N/mm2. This means that 150% increase in wearing surfaces thickness leads to 29.0 % increase in optimum tire pressure.

As shown in Figures 3 and 4, the increased wearing surfaces thickness leads to a significant increase in fatigue life as well as rutting life especially when h1 increase from 100 to 125mm and from 125 to 150 mm.

The variation of increased tire pressure with base course thickness has been shown in Figure 5 which indicates that, unlike rutting pavement life, the fatigue pavement life decreases obviously with increasing truck tire pressure. Moreover, the optimum tire pressure decreases with increasing the base course thickness. For example when the base course thickness increases from 375.0 mm to 450.0 mm the optimum tire pressure decreases by 21.25%.

Figure 5

Fig. 6 shows that the increased base course thickness leads to an increase in fatigue life where this increase can be ignored especially at higher values of tire pressures. While **Fig. 7** shows that the pavement rutting life increases obviously with increasing the base course thickness especially when increase from 300 to 375 and from 375 to 450 mm.

From the previous analysis, it can be concluded that base course thickness is the key element which leads to a decrease in the optimum tire pressure. Moreover, pavement rutting life hasn't any sensitivity to the variation of increased truck tire pressure. On the other hand, the optimum tire pressure should not exceed 0.80 N/mm^2 with optimum h2=375.0 mm.

VI. Relation between fatigue and rutting lives for each surface and base thicknesses

Relation between fatigue and rutting lives for surface thickness ranged between 50 to 150 mm due to different truck tire pressure has been studied and illustrated in **Fig 8**. It has been found that the Nr value increases obviously with the increase in the Nf value where the relation is basically linear and may therefore be expressed as a law:

Nr = n(Nf)+k ……………………….. (3)

Where K is a constant and n is a dimensionless constant representing the tangent of the slop angle. As shown in **Fig. 8** and Table 2, the slop of the curve (n) is a function of the Pt where increases with the increase of the tire pressure for both surface and base thickness variation. **Fig. 9** illustrates the relation between fatigue and rutting lives for base course thickness ranged between 150 to 450 mm due to different truck tire pressure. It can be observed that the effect of increasing of fatigue life value on the performance of rutting life can be neglected especially at higher values of tire pressures where the relation between them is basically polynomial.

In order to explore the influence of the tire pressure, the data in Figures 8 and 9 are represented in Figure 10. From the regression equations, the multiple R2 for wearing surface thickness variation is relatively high (0.92). However, note that there is a big scatter for the regression equation for base course thickness variation (R^2 = 0.102).

VII. Fatigue life as a function of tire pressure and base course thickness

In order to get pavement fatigue life with respect to traffic tire pressure and base course thickness, Data Fit version 9.0 has been applied. The achieved equation for (F.L.) is as follow:

For Fatigue Life:

F.L.=2398857 – 2696342.8 PT+1736.8 H2

R^2=0.82

Where:

F.L.: Pavement Fatigue life;

Pt: tire pressure (N/mm2);

h2: base course thickness (mm).

The reason for determining fatigue life only is that, when the tire pressure and base course thickness increase the fatigue life obviously decreased and increased for each item respectively. While rutting life could not be determined according to tire pressure and base course thickness because of the effect of increased tire pressure and base course thickness on the performance of rutting life can be neglected. Moreover, fatigue life has been determined with respect to base course thickness not to wearing surfaces thickness because of increasing base course thickness leads to a marked decrease in the optimum tire pressure. While increasing wearing surfaces thickness leads to an increase in the optimum tire pressure.

VIII. Conclusions

Based on the methodology and analysis of results of this study the following conclusions were drawn:

1. Pavement fatigue life decreases with increasing in truck tire pressure especially at higher values of wearing surfaces thickness while, pavement rutting life hasn't any sensitivity to the variation of increased truck tire pressure. Moreover, Pavement life for both fatigue and rutting increase with increasing in pavement thickness.
2. The optimum tire pressure increases with increasing wearing surfaces thickness and decreases with increasing the base course thickness where it shouldn't exceed 0.80 N/mm2 with optimum design key element (h2) of 375.0 mm.
3. Relation between fatigue and rutting lives due to surface thickness variation and tire pressure variation is basically linear. While this relation for base course thickness variation can be neglected especially at higher values of tire pressure, where the relation is basically polynomial.
4. Fatigue life can be determined as a function of traffic tire pressure and base course thickness. While rutting life could not be determined according to tire pressure and base course thickness because of the effect of increased tire pressure and base course thickness on the performance of rutting life can be neglected.

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Table 1: Measured inflation tire pressures for different truck types on Egyptian roads [2].

Truck Code	No. of Trucks	No. of Tires	Measurements of tire inflation pressure (psi)			
			Min. value	Max. value	Mean value	Stand. Devi
2D	19	114	74	132	112	15.92
3A	25	250	87	146	121	14.63
2-2	7	98	72	132	113	13.96
2-3	19	342	92	140	122	13.12
3-2	27	486	85	145	120	12.42
3-3	6	132	96	144	125	14.11
2-S1	7	70	80	135	115	13.34
2-S3	5	90	125	146	129	11.14
3-S2	2	36	128	148	130	11.52
Tot. Aver.	**117**	**1618**	**93.2**	**140.9**	**120.8**	**13.35**

Table 2 : The tangent of the slop angle (n) values.

Surface thickness variation (50 to 150mm)	**Truck tire pressure (N/mm^2)**					
	0.5	0.6	0.7	0.8	0.9	1.0
the slop angle (n) values	0.1246	0.1597	0.1862	0.2162	0.2486	0.2592

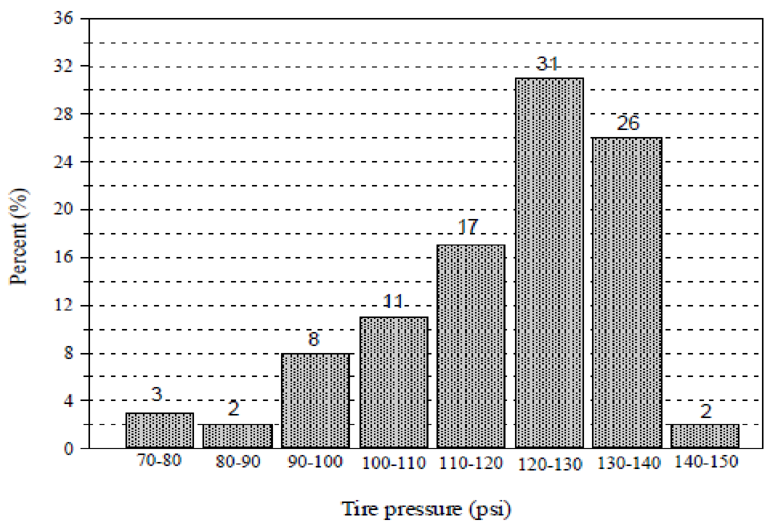


Figure 1: Distribution of measured truck-tire inflation pressures [2].

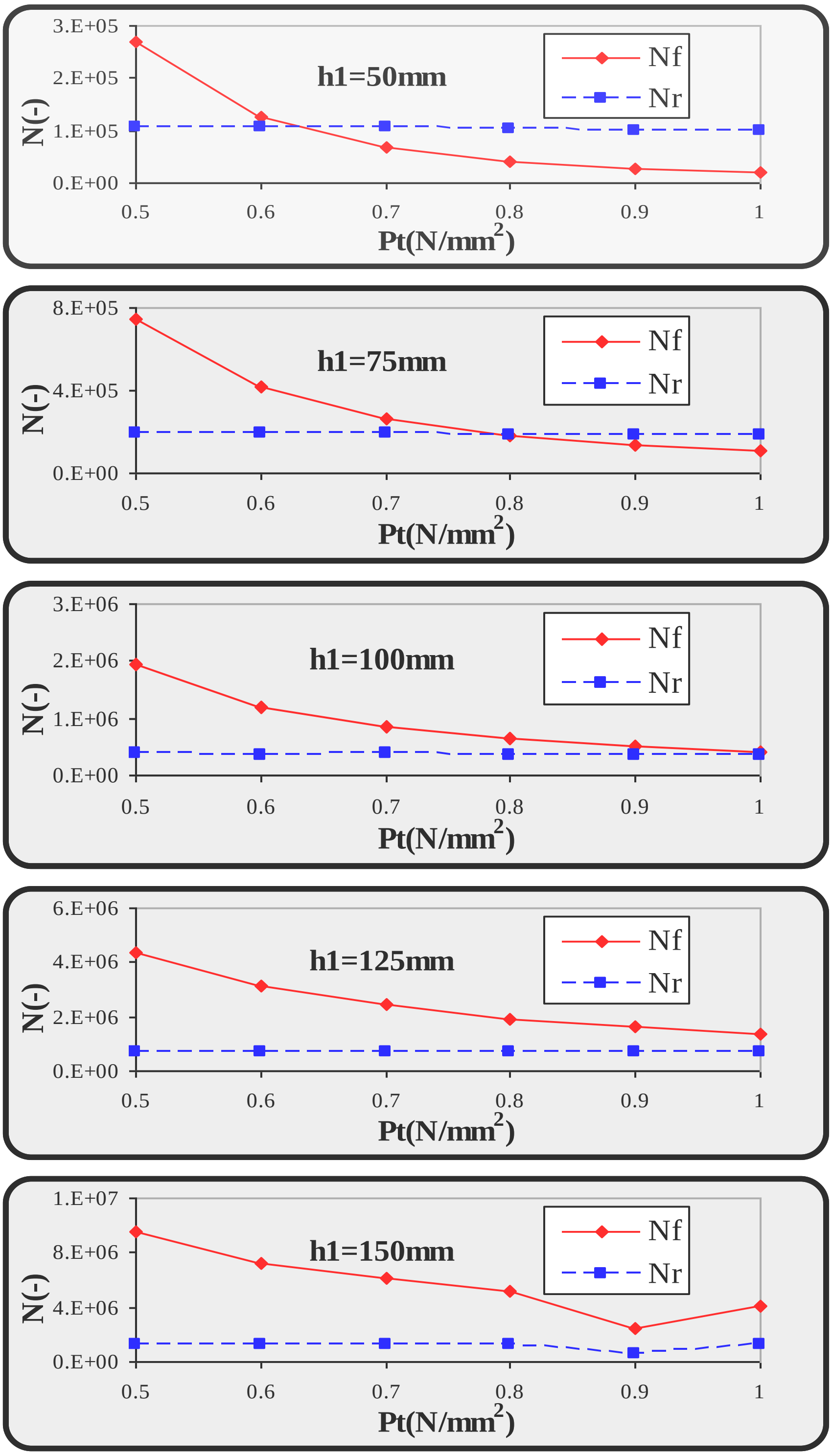


Figure 2: Sensitivity of optimum tire pressure to wearing surfaces thickness.

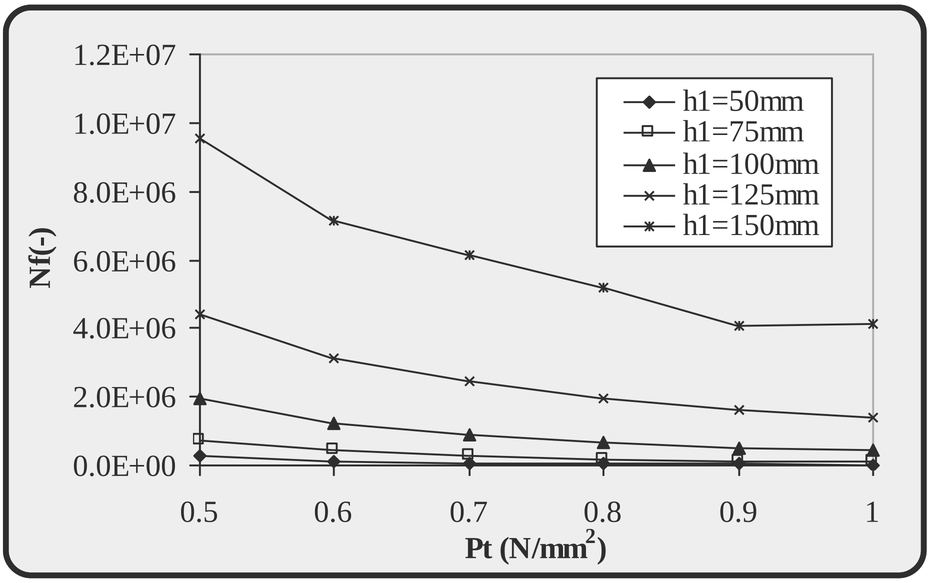


Figure 3: Response of fatigue life due to surface thickness variation.

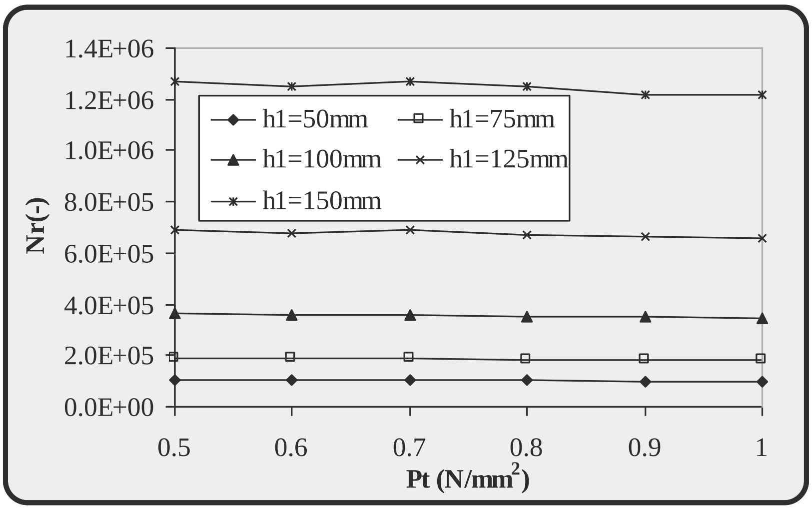
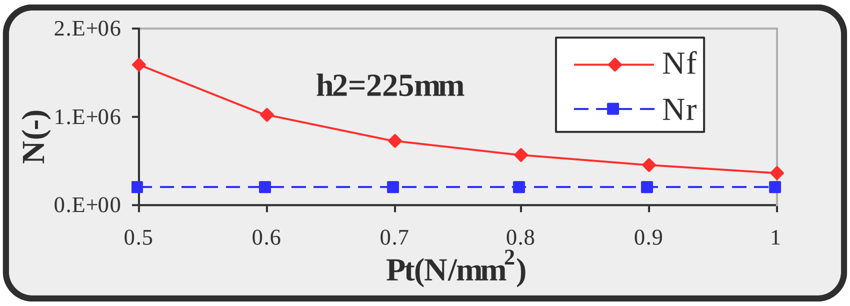


Figure 4: Response of rutting life due to surface thickness variation.



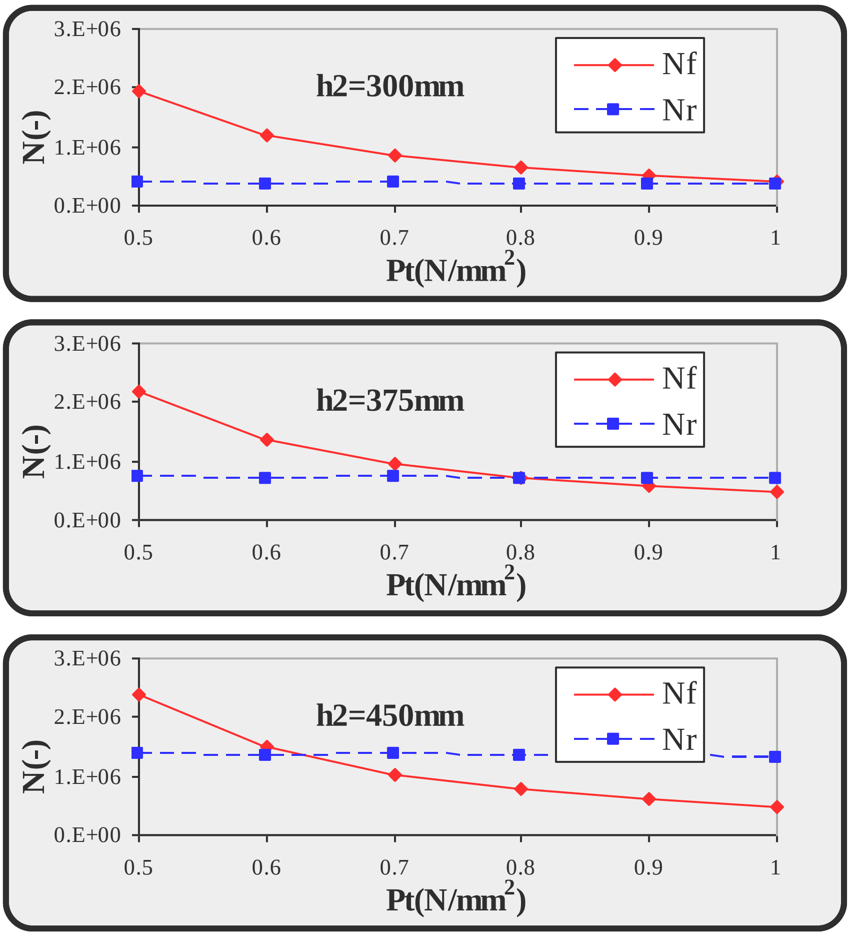


Figure 5: Sensitivity of optimum tire pressure to base course thickness.

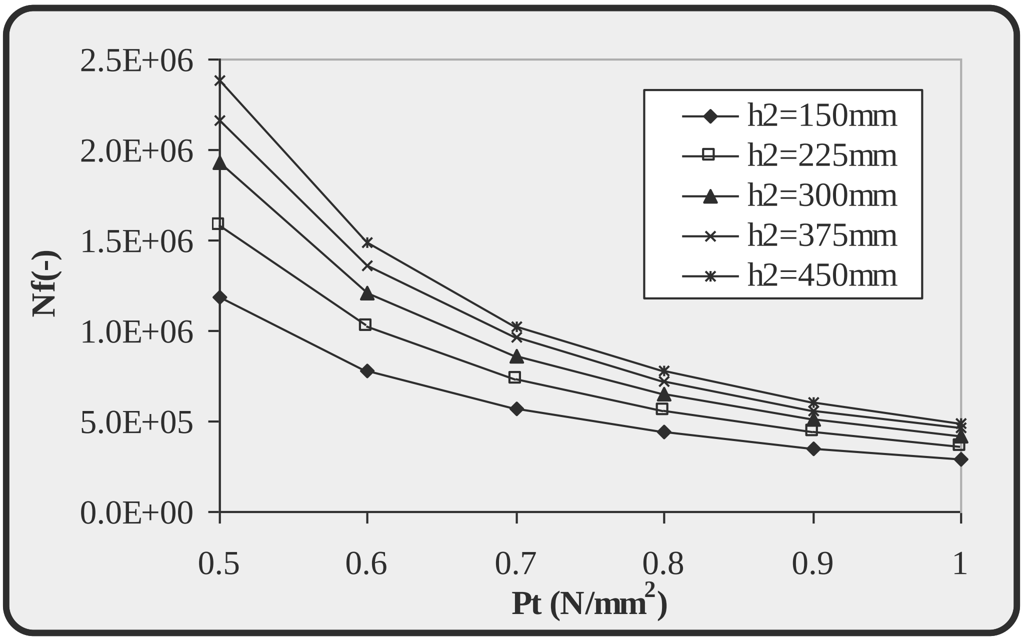


Figure 6: Response of fatigue life due to base course thickness variation.

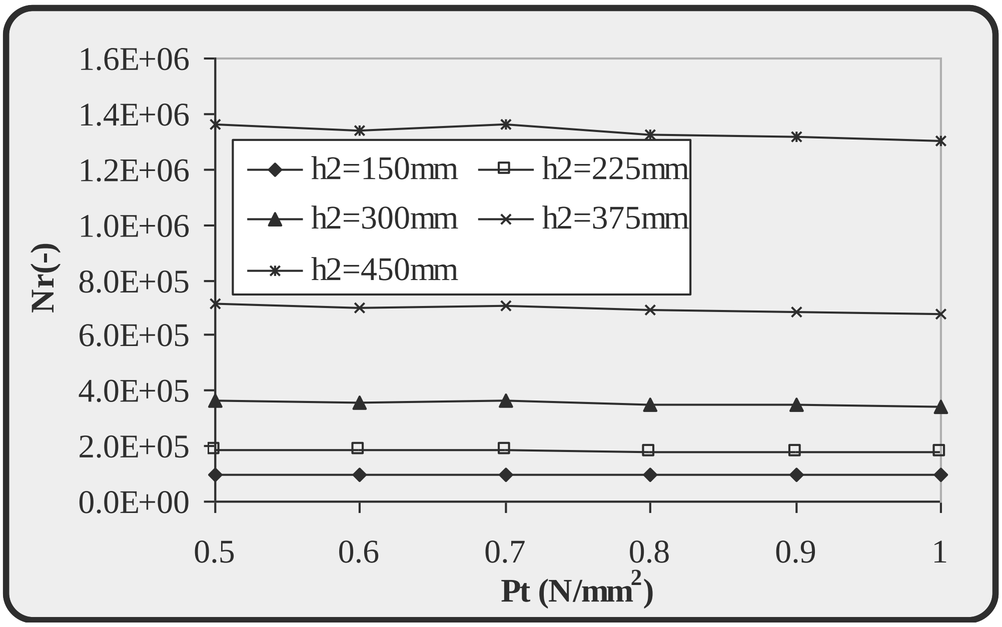


Figure 7: Response of rutting life due to base course thickness variation.

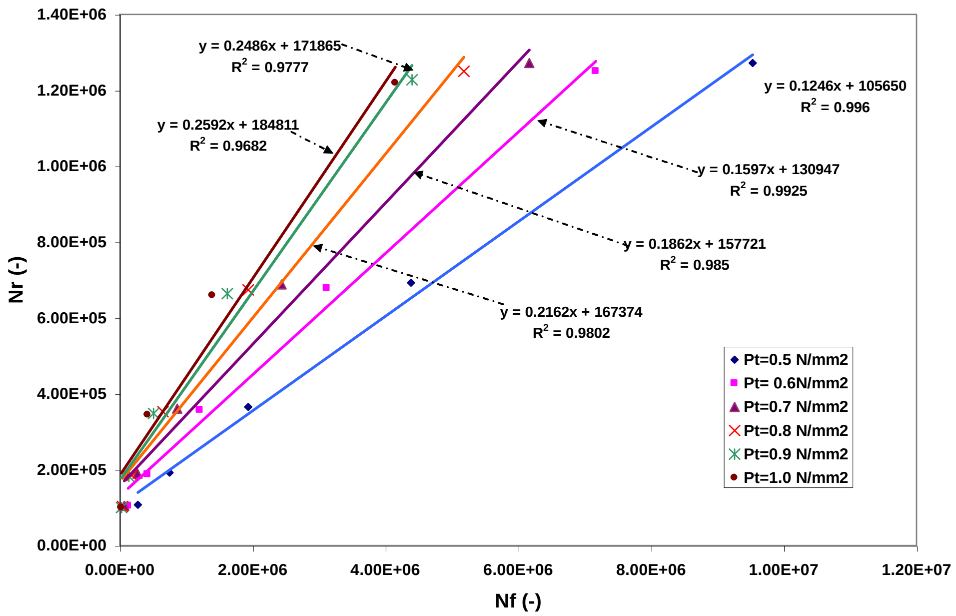


Figure 8: Relation between Nf and Nr for h1 variation

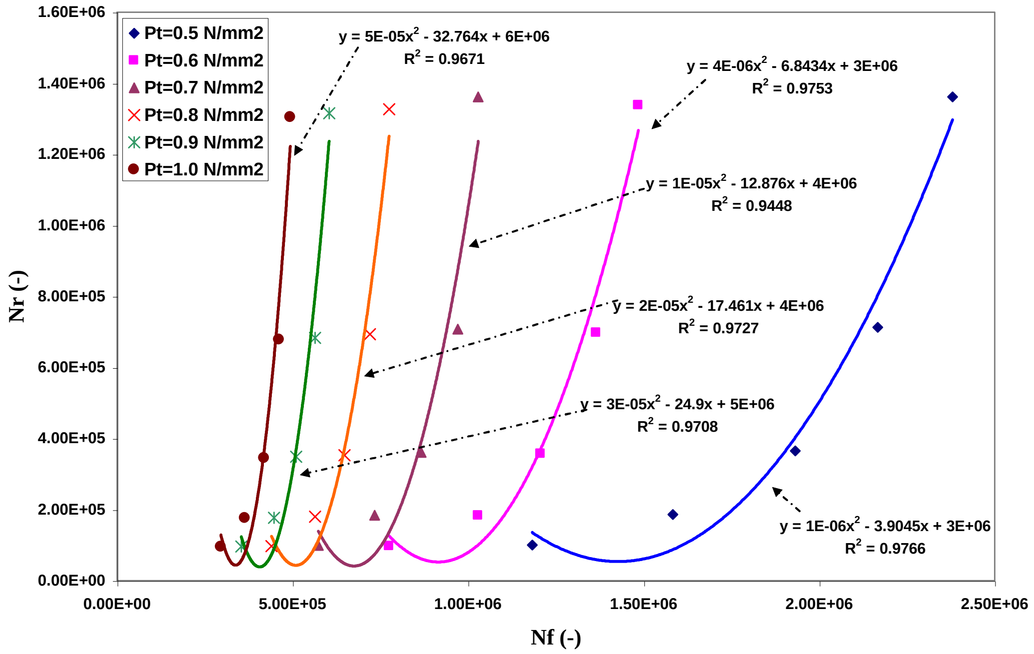


Figure 9: Relation between Nf and Nr for h2 variation.

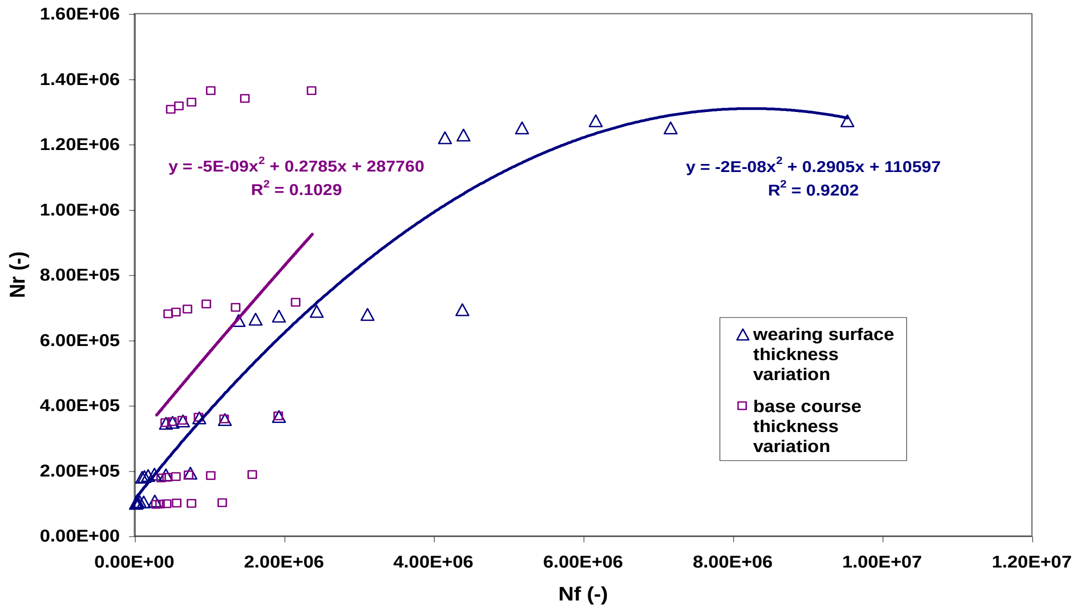


Figure 10: Influence of layers thickness on the relation between pavement lives.