International Journal of the Physical Sciences Vol. 6(21), pp. 5040-5047, 30 September, 2011
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS11.1085
ISSN 1992 - 1950 ©2011 Academic Journals

Full Length Research Paper

Effect of tire footprint area in pavement response studies

Danial Moazami*, Ratnasamy Muniandy, Hussain Hamid and Zainuddin Md. Yusoff

Department of Civil Engineering, University Putra Malaysia, Malaysia.

Accepted 26 July, 2011

The necessity of incorporating realistic non-uniform measured contact stresses, tire footprint area, as well as other non-linear and viscoelastic behaviour within tire-pavement interaction have been suggested by many researchers in order to obtain more reliable pavement responses. However, modeling 3D contact stresses with distribution and other non-linear properties in common pavement design procedure seems difficult and impractical because of the complexity usually involved in this process. Therefore, layered linear elastic theory and average circular contact pressure have been widely used in most common pavement design procedures. In this paper, a simple but acceptable method for predicting pavement responses, in the existing layered linear elastic program (KENPAVE) was utilised. This modified method is based on incorporating tire imprint instead of load over inflation pressure ratio and utilizing a more realistic representative value rather than tire inflation pressure for uniform tire-pavement contact stresses. It was found that critical tensile stain at the bottom of HMA is underestimated, and accordingly fatigue life is greatly overestimated when using conventional method. In addition, based on the results of modified layered linear elastic method, new generation of wide-base tires (Michelin445/50R22.5, Michelin455/55R22.5) reduce vertical contact stress and pavement damage, since they provide wider area of contact and require lower inflation pressure. On the other hand, older generation of wide-base tire (Goodyear425/65R22.5) was considered more detrimental to the pavement in terms of bottom-up fatigue cracking.

Key words: Tire-pavement footprint area, contact stresses, wide-base tire, layered linear elastic program.

INTRODUCTION

The current standard approach of pavement design simply assumes a stationary vertical axisymmetric contact pressure, equal to tire inflation pressure, uniformly distributed over a full circular area (load over tire inflation pressure $\frac{T_L}{T_{IP}}$). However, in order to correctly estimate pavement responses and accurately address the load-related distresses in pavements, it is important to capture the exact magnitude and distribution of contact stresses between moving pneumatic tires and pavement (De Beer et al., 1996; Weissman, 1999) and to incorporate the realistic tire footprint area (Park, 2008). The necessity of using measured non-uniform contact stresses and tire footprint area to study pavement responses have been suggested by Al-Qadi and Wang (2009), Luo and Prozzi (2007), Machemehl et al. (2005), Novak et al. (2003) and Park et al. (2005).

Due to the aforementioned drawbacks with the current method, if highway and transportation agencies seek to implement pavements that can sustain higher loads and last longer, the current procedure must be reviewed and revised to provide a more realistic modeling of tire-pavement contact stresses and to obtain accurate portrayal of tire-pavement interaction. On the other hand, the complexity involved in such studies, limits the usage

---

*Corresponding author. E-mail: d_moazami@mshdiau.ac.ir or d_moazzami@yahoo.com. Tel: (+60)172106770 or (+98)9121056881.

Abbreviations: HVS, Heavy vehicle simulator; **SIM,** stress-in-motion; **CSIR,** council for scientific and industrial research; **VRSPTA,** vehicle-road surface pressure transducer array; **CM,** conventional methods; **MM,** modified methods.

of this precise modeling in practical and routine pavement design procedure except for research purposes. So far, comprehensive effects of complex radial tire contact stresses have not been widely analyzed (Novak et al., 2003) and typically simplifying assumptions (for example, layered linear elastic theory) and/or limited number of variables (for example, vertical contact stresses, unique and constant tread pattern, constant speed, free rolling condition without steering and braking maneuvers to name but a few) have been incorporated for predicting pavement responses. These simplifying assumptions are due to the importance of fast computation in common pavement design procedure. In this study, the main focus was on tire-pavement footprint and the advantage of modeling a more realistic contact (stress and area) in the current layered linear elastic programs. Alternatively, finite element modeling may be used where a more rigorous analysis is desired. The two major research objectives of this study were to identify the effect of realistic footprint area on flexible pavement responses and to indicate the damaging effect caused by the first and the second generation of wide-base tires based on the modified layered linear elastic method.

Tire-pavement contact area studies by Luo and Prozzi (2007) showed that the conventional model resulted in a larger contact area ($\frac{T_L}{T_{IP}}$) relative to the footprint area, since it considers a full contact area between tire and the pavement. In addition, Al-Qadi and Wang (2009) also reported that both circular and equivalent rectangular contact areas (usually used in finite element modelling) overestimated the net contact area. Furthermore, a wealth of information already exists to prove that generally, the measured contact stresses are greater than inflation pressure used in conventional design method (De Beer et al., 2002; Novak et al., 2003; Park et al., 2008). Since increase in tire load has been so prevalent (De Beer et al., 1997; Huhtala et al., 1989; Mulungye et al., 2007; Weissman, 1999), this increase decreases the accuracy of traditional assumption for pavement response studies (Pezo et al., 1989). Therefore, in this research a simple but acceptable method, for predicting pavement responses in the existing layered elastic programs, was utilised. In this method, realistic tire-pavement contact area is used to calculate equivalent uniform vertical contact stress. Park (2008) and Park et al. (2005) first established the guidelines of the modified layered elastic method used in this study and recommended the application of this approximate approach in common pavement design analysis because of its simplicity and reliability.

The major difference between conventional and modified methods can be explained as follows: In the modified method, measured tire contact area is used to determine equivalent uniform vertical pressure, while in the con-ventional method contact area (load over inflation pressure) with tire inflation pressure is used. Therefore, in the modified method (the desired method in this study), tire footprint area plays a significant role and should be determined precisely. In this study, tire imprint properties for the two new generation of wide-base tires were obtained from the data provided by Michelin tire company (Michelin, 2005) and the estimated footprint area for (Goodyear425/65R22.5) was obtained from a regression model presented by Fernando et al. (2006) and Park, 2008) for this tire. KENPAVE layered elastic software developed by Huang (2004) was used to calculate pavement responses for a typical pavement structure with thin HMA layer, both in conventional and modified methods (CM and MM).

BACKGROUND OF TIRE IMPRINT STUDIES

Methods to obtain tire imprint

Different methods have been used so far to capture tires imprints. In a study by Marshek et al. (1985), the eight inked tires were statically loaded over a piece of paper with a load frame. The inked prints were then read by a digitizing camera and the obtained data were stored by the data acquisition system. In this study, tire-pavement contact areas were measured by digitizing database in Grinnell Imaging System. Following the experiment, (Pezo et al., 1989) conducted a further study on four statically loaded tires to capture the imprint of these inked tires on a white paper covered a steel plate. A transparent grid paper was then placed on the print to count the shaded squares in order to calculate the contact areas. A regression model was also developed to correlate the actual footprint area with traditional contact area (load over inflation pressure). (De Beer et al., 1996). captured tire footprints obtained under static loading at different tire load and inflation pressure for used 425/65 R22.5 R160AZ and new 425/65 R22.5 R164BZ wide-base tires. The Council for Scientific and Industrial Research (CSIR) in South Africa, first developed a vehicle-road surface pressure transducer array (VRSPTA) between 1992 and 1993 (De Beer, 1994) and during years, it has extensively improved and has been widely exploited. The recent completely developed and well-known version (until August 2010) of Stress-In-Motion (SIM) MK IV system which is able to measure 3D dynamic contact stresses and tire imprints can be referenced by De Beer and Fischer (2002). In a study by Fernando et al. (2006), blackboard paint was applied on the surface of the tested tire. It was then lowered to a white grid paper placed on top of a steel plate and loaded through the Heavy Vehicle Simulator (HVS) in SIM MK IV system. Researchers scanned and calculated the tire imprints using an image processing computer program. A number of regression models were developed to determine relationships between realistic tire contact area, tire load and tire inflation pressure for the different

Table 1. Footprint area properties for new generation of wide-base tires.

Tire type	Single axle load (KN)	Tire inflation pressure (KPa)	Footprint length (mm)	Footprint width (mm)	Realistic contact area (mm²)
445/50R22.5 X One® XDA®	75.6	725	201	376	47600
455/55R22.5 X One® XDA-HT™ Plus	75.6	690	227	385	51800

Table 2. Estimated contact area for an old generation of wide-base tire.

Tire type	Single axle load (KN)	Tire inflation pressure (KPa)	Regression equation	Realistic contact area (mm²)
GOODYEAR425/65R22.5	75.6	790	$(A = 53.64 + 0.0055 \times T_L - 0.2915 \times T_{IP})*$	43140

*, in this equation, Tire load is in lbs, Tire inflation Pressure is in Psi, and Area is in square inch.

tires tested in this project. As mentioned previously, the regression model for 425/65R22.5 tire which had been developed by Fernando et al. (2006) and Park (2008) was used in this research, and imprint data for the other two studied tires had been provided by the Michelin tire company (Michelin, 2005).

Dimensions of tire footprint area

Over the loading combinations of 11R24.5 radial tire in a study by Machemehl et al., (2005), the width of the contact area almost remained constant at approximately 200 mm, while the length of the contact area was changed from 240 mm to approximately 340 mm. In this study, the tire footprint area from (SIM) MK IV was divided to 232 (13 columns×19 rows) tangent circles (r=8.5mm) for non-uniform contact stress modeling in CIRCLY software approximation method. 204 (12 columns×17 rows) elements were used for the same purpose in the study by Prozzi and Luo (2005). Luo and Prozzi (2007) suggested the use of minimum 180 and maximum 247 small circular contact stresses, according to tire load and inflation pressure, to simulate single tire imprint in (SIM) MK IV system for use in CIRCLY software which deals with circular loading. Weissman (1999) also stated that the width of the contact area was a tire property, independent of the applied load, and that the imprint width had been dictated by the tire structure. This concurs with the (De Beer, et al., 1996) study on wide-base tires in which the tire width remained constant for all tests. Generally, the lateral dimension is more than 375 mm for wide-base tires which cause the contact area to become larger in the transverse direction than in the longitudinal, contrary to what is typically observed for conventional dual tires (De Beer et al., 1996; Kim et al., 2005. This difference can be seen in Table 1. The dimensions of footprint area for 445/50R22.5 and 455/55R22.5 tires and the total footprint area for 425/65R22.5 tire are presented in Tables 1 and 2.

CONTACT STRESSES (VERTICAL, HORIZONTAL) AND DISTRIBUTION

Although vertical, longitudinal and transverse contact stresses exist under a loaded tire, a number of factors result in considering only vertical contact stresses in many pavement studies. These factors include:

1. Applied wheel load can be used to verify vertical contact stress, while there is no equilibrium control on the two measured horizontal contact stresses (Machemehl et al., 2005).
2. The accuracy of measured vertical contact stresses are far better since they are established by direct equilibrium (Weissman, 1999).
3. Measuring horizontal contact stresses on real flexible pavements is very difficult unless on rigid surfaces instead (Tielking and Roberts, 1987).
4. Many researchers have not used horizontal contact stresses to be able to compare the result with traditional model (Machemehl et al., 2005; Weissman, 1999).
5. Horizontal contact stresses are very small relative to vertical contact stresses (De Beer et al., 1996; Machemehl et al., 2005; Prozzi and Luo, 2005; Yoo et al., 2006). For instance, Siddharthan et al. (2002) reported that considering horizontal contact stresses did not significantly influence any of the pavement responses. Al-Qadi et al. (2005) and Siddharthan et al. (2002), also reported that the longitudinal and transverse contact stresses were approximately 12 and 16% of the tire-induced vertical contact stresses. In a study done by De Beer et al. (1996), on used and new wide-base tire 425/65 R22.5, in average, the ratio of 10:1.5:1.0 was obtained between maximum vertical, transverse and longitudinal contact stresses in free-rolling condition. The ratio of the maximum vertical contact stress to the lateral and longitudinal stress was 10:1.6:0.8 for Michelin 425/65R22.5 wide-base tire (Siddharthan et al., 1998).

Therefore, vertical contact stress component has the

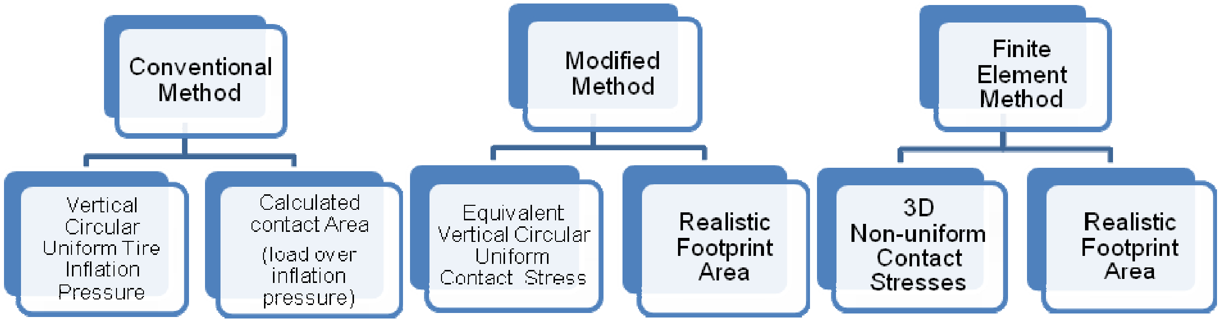

Figure 1. Conventional, modified and finite element methods of pavement design.

Table 3. Tire-pavement contact areas and contact pressures used in both analyses.

Tire type	Single axle load (KN)	Tire inflation pressure[1] (KPa)	Conventional contact area (mm^2)	Realistic contact area[3] (mm^2)	Equivalent contact pressure[4] (KPa)
445/50R22.5 X One® XDA®	75.6	725	52138	47600	794
455/55R22.5 X One® XDA-HT™ Plus	75.6	690	54783	51800	730
GOODYEAR 425/65R22.5	75.6	790	47848	43140	876

[1] Used in the CM (Conventional Method) analysis, [2] Used in the CM analysis and calculated by dividing the tire load by the tire inflation pressure, [3] Used in the MM (Modified Method) analysis, and [4] Used in the MM analysis and calculated by dividing the tire load by the realistic contact area.

dominant effect on induced horizontal strains at the bottom of HMA layer as well as induced vertical strain at the top of the subgrade which are the desirable responses in most pavement studies (Hu et et al., 2008; Luo and Prozzi, 2007; Prozzi and Luo, 2005). However, Luo and Prozzi (2007) reported that, the effect of horizontal contact stresses on the horizontal strains in the asphalt layer should not be overlooked especially for pavements with a thin asphalt layer.

LAYERED ELASTIC AND MODIFIED LAYERED ELASTIC ANALYSES

A large number of elastic and viscoelastic multilayer programs used in pavement analysis and design (for example, ELSYM5, CHEVPC, BISAR, WESLEA, etc.) use uniform vertical contact stress (equal to tire inflation pressure) over a full circular contact area (load over inflation pressure). The symmetric property with the distribution of tire inflation pressure over a full circular contact area in the conventional tire model results in less computing requirements and allows for fast computation speed, therefore this model has gained wide popularity in pavement studies. On the other hand, modified layered elastic method, used in this paper, has the superiority of considering realistic contact area, and incorporating more realistic contact pressure over the conventional method of pavement design. Figure 1 compares conventional, modified and finite element methods of pavement design.

As indicated in Figure 1, in modified layered elastic method footprint area is incorporated. However, the simplifying assumption in this method is due to uniform circular contact stress distribution but with higher value than tire inflation pressure (Table 3). Studies by De Beer et al. (1997) and Myers et al. (1999) showed that tire contact stresses are greatly influenced by the structural characteristics and design of truck tires, even more than tire load, inflation pressure etc. For instance, the second generation of wide-base tires (445,455) produce more uniform stress

(Michelin 445/50R22.5 X One® XDA®) (Michelin 455/55R22.5 X One® XDA-HT™ Plus) (GOODYEAR 425/65R22.5)

Figure 2. Shape comparison between new and old generation of wide-base tires.

Table 4. Layer material properties for pavement structure.

Material	Thickness (mm)	Modulus (MPa)
Dense asphalt pavement	40	3500
A-1-b base course	250	500
A-2-4 Subbase	200	250
A-6 Subgrade	infinite	75

distribution than the older generation of wide-base (385 and 425) single tires as well as conventional dual size (Al-Qadi and Wang, 2009). Therefore, the modified method used in this study seems rational especially for 445/50R22.5 and 455/55R22.5 tires. The modified method is used to model the average tire-pavement contact stresses more easily than finite element modeling and more precisely than conventional tire inflation method.

TIRE IMPRINT DATA SOURCE

The three studied tires in this research included new generation (Michelin445/50R22.5 and Michelin455/55R22.5) as well as old generation (Goodyear425/65R22.5) of wide-base single tires which have become more popular these days. Figure 2 compares these tires.

Tires imprints properties in this study are summarized in Tables 1 and 2. Table 3 shows tire-pavement contact areas and contact pressures used in both conventional and modified methods (CM, MM). Since the relation between loading and pavement damages are not linear, but exponential; therefore the differences between average contact stresses in CM and MM methods are of high significance (Table 3).

PAVEMENT STRUCTURE

The layer and material property data for the typical pavement structure with thin HMA layer were borrowed from previous studies (Luo and Prozzi, 2007; Prozzi and Luo, 2005). Each layer in Table 4 was assumed to be homogenous, isotropic and linearly elastic with a Poisson ratio of 0.35. In addition, any two neighbor layers were assumed to be full bonded. Various asphalt thicknesses were investigated by the authors and critical tensile strains at the bottom of HMA layer were calculated for each configuration. The results indicated that 40 mm thickness is the optimal value of asphalt thickness for the proposed loading, inflation pressure and material properties. This optimal value of asphalt thickness corresponded to a minimum absolute value of tensile strain. However, these results are not presented here since the details are beyond the scope of this paper.

CRITICAL DESIRED STRAINS

Critical tensile strain at the bottom of asphalt layer, and maximum vertical compressive strain at the top of subgrade in the middle of the contact patch for all three studied tires based on CM and MM are shown in Table 5. In this table, the sign convention to present tensile strains

Table 5. Critical pavement responses based on CM and MM analyses.

Tire type	Critical strains $(\times10^{-6})$ -CM analysis		Critical strains $(\times10^{-6})$ -MM analysis	
	Bottom of HMA	Top of subgrade	Bottom of HMA	Top of subgrade
445/50 R22.5	-153	431	-178	432
455/55R22.5	-141	429	-155	429
425/65R22.5	-177	430	-207	434

is negative.

In Table 5, significant difference up to 17% for tensile strains at the bottom of 40 mm thickness asphalt layer is obtained between CM and MM analyses. These differences indicate that tensile stain at the bottom of HMA is underestimated when using conventional method.

No significant difference was found between CM and MM methods for compressive strain at the top of the subgrade, since the differences in contact stress distribution are significant near the pavement surface and diminish by the depth. Therefore, conventional method is still reasonable to estimate the vertical compressive strain at the top of subgrade (subgrade rutting indicator).

Generally, the first generation of wide-base tires require higher inflation pressure with the increase in load. These tires need a high inflation pressure of 790 to 890 kPa in order to carry a normal 151 kN tandem axle load (Table 3). However, the new designed wide-base tire (455/55R22.5) can carry the same load at a tire inflation pressure of 690kPa. In other words, 455/55R22.5 can operate at higher load and lower inflation pressure in comparison with the first generation of wide-base tires. Consequently, lower inflation pressure in 455/55R22.5 tire does not cause any reduction in the contact area and any increase in the contact pressure. Furthermore, 455/55R22.5 tire size provides wider width and lower aspect ratio (Figure 2). Therefore, can reduce contact stress and pavement traditional fatigue further. On the other hand, first generation of wide-base tires (385 and 425), need higher inflation pressures and have smaller area of contact, so it is considered to be more detrimental in terms of bottom-up fatigue cracking. Based on the modified layered analyses proposed in this study, for the same axle load (and other same parameters); 455/55R22.5 tire induced the least tensile strain at the bottom of asphalt layer, and 445/50R22.5 resulted in smaller tensile strain than 425/65R22.5.

PREDICTION OF PAVEMENT FATIGUE LIFE (BOTTOM-UP FATIGUE CRACKS)

Fatigue cracking and rutting, which are two major flexible pavement distresses, were investigated in this research. However, since the axle load has the dominant effect on vertical compressive strain at the top of the subgrade and for the three studied tires in this research the tire load was the same, differences between predicted rutting lives were minor. Therefore, the rutting life is not discussed here.

Asphalt Institute fatigue cracking model is one of the most well-known methods. This model relates the allowable number of load repetitions leading to fatigue cracking to the tensile strain at the bottom of the asphalt layer and to the asphalt modulus.

The Asphalt Institute equation for fatigue is given by Huang (2004):

$$N_f=0.0796(\varepsilon_{AC})^{-3.291}(E_{AC})^{-0.854} \quad (1)$$

where, N_f = allowable number of load repetitions to cause fatigue cracking, ε_{AC} = tensile strain at the bottom of the asphalt layer, and ε_{AC} = the modulus of the asphalt layer (Psi).

As it can be seen from Figure3, the differences between fatigue lives in CM and MM methods are even more (up to 68%). Consequently, fatigue life is greatly overestimated for wide-base tires when using conventional method. To compare the bottom-up fatigue cracking induced by these wide-base tires based on modified layered elastic method, the damage ratio for fatigue failure mechanism was calculated as follows:

$$DR_i=\frac{N_{NG}}{N_{OG}} \quad (2)$$

where, DR_i = damage ratio between the old and new generation of wide-base tires, N_{NG} = number of cycles to failure for wide-base 455/55R22.5 and 445/50R22.5 tires, and N_{OG} = number of cycles to failure for wide-base 425/65R22.5 tire.

Based on modified layered elastic method, damage ratio of 2.58 was obtained between 455/55R22.5 and 425/65R22.5. Moreover, damage ratio was 1.65 between 445/50R22.5 and 425/65R22.5 tires. These ratios indicate that for equal normal loading, and thin asphalt layer, wide-base 425/65R22.5 is 2.58 and 1.65 times

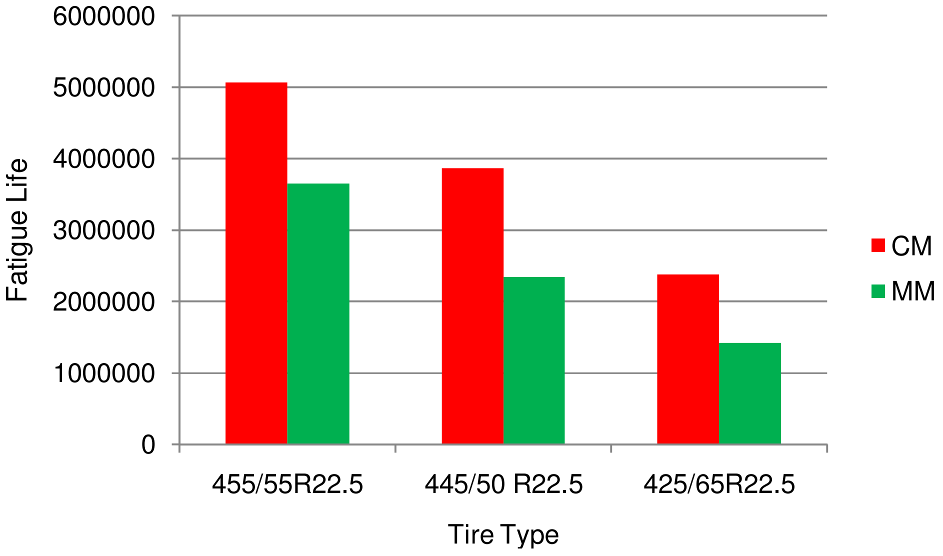

Figure 3. Predicted fatigue life based on CM and MM methods.

more damaging than 455/55R22.5 and 445/50R22.5, respectively in terms of bottom-up fatigue cracking.

Conclusion

Conventional contact model with vertical circular uniform inflation pressure and with full circular tire-pavement contact area $\left(\frac{T_L}{T_P}\right)$ are still used by most of the guidelines because of the simplicity which is required in common pavement design procedure. In this paper, the mechanistic part of the conventional method was further improved in order to predict more precise responses. The modified method has the superiority of considering realistic contact area, and incorporating more realistic contact pressure over the conventional method of pavement design.

The two major research objectives of this study were to identify the effect of footprint area on flexible pavement responses and to indicate the damaging effect caused by the first and the second generation of wide-base tires based on the modified layered elastic method. Critical tensile strain at the bottom of asphalt layer was used to calculate fatigue life of a typical four-layer pavement structure with thin HMA layer. It was found that, significant difference up to 17% between tensile strains at the bottom of 40 mm asphalt layer thickness exists between CM and MM analyses. This difference was even more (up to 68%) for the predicted fatigue lives. These differences indicated that tensile stain at the bottom of HMA is underestimated, and accordingly, fatigue life is greatly overestimated when using conventional method.

No significant difference was found between CM and MM methods for compressive strain at the top of the subgrade, since the differences in contact stress distribution are significant near the pavement surface and diminish by the depth. Therefore, conventional method is still reasonable to estimate the vertical compressive strain at the top of subgrade (subgrade rutting indicator).

Second generation of wide-base tires provide wider width and lower aspect ratio. Therefore, reduce contact stresses and pavement damage, this is especially true for 455/55R22.5 tire which is even wider than 445/50R22.5. On the other hand, first generation of wide-base tires (385 and 425), need higher inflation pressures and have smaller area of contact, so considered to be more detrimental to the pavements in terms of bottom-up fatigue cracking.

REFERENCES

Al-Qadi I, Wang H (2009). Evaluation of Pavement Damage Due to New Tire Designs. Report No. FHWA-ICT-09-048, Illinois Center for Transportation.

Al-Qadi I, Yoo P, Elseifi M, Janajreh I (2005). Effects of Tire Configurations on Pavement Damage. J. Assoc. Asphalt Paving Technol., 74(1): 921-961.

De Beer M (1994). Measurement of Tyre/Pavement Interface Stresses Under Moving Wheel Loads. Research Report DPVT 224, Pavement Engineering Technology, Division of Roads and Transport Technology, Council for Scientific and Industrial Research.

De Beer M, Fischer C (2002). Tire Contact Stress Measurements with the Stress-In-Motion (SIM) Mk IV System for the Texas Transportation Institute Contract Report No. CR-2002/82. Division of Roads and Transport Technology, Council for Scientific and Industrial Research, Pretoria, South Africa.

De Beer M, Fisher C, Jooste F (1997). Determination of pneumatic tyre/pavement interface contact stresses under moving loads and some effects on pavements with thin asphalt surfacing layers. Paper presented at the Proceedings of Eighth International Conference on Asphalt Pavements University of Washington, Seattle, Washington

De Beer M, Fisher C, Jooste F (2002). Evaluation of non-uniform tyre contact stresses on thin asphalt pavements. Paper presented at the Proceedings of the 9th International Conference on Asphalt Pavements, Copenhagen, Denmark.

De Beer M, Groenendijk J, Fischer C (1996). Three dimensional contact stresses under the LINTRACK wide base single tyres, measured with the Vehicle-Road Surface Pressure Transducer Array (VRSPTA) system in South Africa. Contract Report CR-96/056,Division of Roads and Transport Technology, Council of Scientific and Industrial Research.

Fernando E, Musani D, Park D, Wenting L (2006). Evaluation of Effects of Tire Size and Inflation Pressure on Tire Contact Stresses and Pavement Response. Research Report No.FHWA/TX-06/0-4361-1,Texas Transportation Institute.

Hu X, Sun L, Hu S, Walubita LF (2008). A Simple and Effective Laboratory Test Device for Measuring Tire-Pavement Contact Pressure. Journal of Testing and Evaluation. Am. Soc. Test. Mater. (ASTM), 36(4): 1-7.

Huang Y (2004). Pavement Analysis and Design: Prentice Hall: Englewood Cliffs, N.J.

Huhtala M, Pihlajamaki J, Pienimaki M (1989). Effects of tires and tire pressures on road pavements. Transp. Res. Rec., 1227: 107–114.

Kim D, Salgado R, Altschaeffl A (2005). Effects of supersingle tire loadings on pavements. J. Transp. Eng., 131(10): 732-743.

Luo R, Prozzi J (2007). Effect of Measured Three-Dimensional Tire—Pavement Contact Stress on Pavement Response at Asphalt Surface. Transportation Research Record: J. Transp. Res. Board, 203: 115-127.

Machemehl R, Wang F, Prozzi J (2005). Analytical study of effects of truck tire pressure on pavements with measured tire-pavement contact stress data. Transportation Research Record: J. Transp. Res. Board, 1919: 111-119.

Marshek KM, Hudson WR, ConnellRB, Chen HH, Saraf CL (1985). Experimental Investigation of Truck Tire Inflation Pressure on Pavement–Tire Contact Area and Pressure Distribution. Research Report 386-1, Center for Transportation Research, University of Texas at Austin.

Michelin (2005). Michelin® Truck Tire Service Manual.

Mulungye R, Owende,P, Mellon K (2007). Finite element modelling of flexible pavements on soft soil subgrades. Mater. Des., 28(3), 739-756.

Myers LA, Roque R, Ruth BE, Drakos C (1999). Measurement of Contact Stresses for Different Truck Tire Types To Evaluate Their Influence on Near-Surface Cracking and Rutting. Transp. Res. Rec., 1655: 175-184.

Novak M, Birgisson B, Roque R (2003). Near-surface stress states in flexible pavements using measured radial tire contact stresses and ADINA.. Comput. Struct., 81: 859-870.

Park D (2008). Prediction of pavement fatigue and rutting life using different tire types. KSCE J. Civil Eng., 12(5): 297-303.

Park D, Fernando E, Leidy J (2005). Evaluation of predicted pavement response with measured tire contact stresses. Transportation Research Record: J. Transp. Res. Board, 1919: 160-170.

Park D, Martin A, Jeong J, Lee S (2008). Effects of Tire Inflation Pressure and Load on Predicted Pavement Strains. Baltic J. Road Bridge Eng., 3(4): 181-186.

Pezo R, Marshek K, Hudson W (1989). Truck Tire Pavement Contact Pressure Distribution Characteristics for the Bias Goodyear 18-22.5, the Radial Mechelin 275/80R/24.5, the Radial Michelin 255/70R/22.5, and the Radial Goodyear 11R24.5 Tires: Research Report 1190-2F, University of Texas at Austin, Center for Transportation Research.

Prozzi J, Luo R (2005). Quantification of the joint effect of wheel load and tire inflation pressure on pavement response. Transportation Research Record: J. Transp. Res. Board, 1919: 134-141.

Siddharthan R, Yao J, Sebaaly P (1998). Pavement strain from moving dynamic 3 D load distribution. J. Transp. Eng., 124(6): 557-566.

Siddharthan R, Krishnamenon N, El-Mously M, Sebaaly P (2002). Investigation of tire contact stress distributions on pavement response. J. Transp. Eng., 128(2): 136-144.

Tielking JT, Roberts FL (1987). Tire contact pressure and its effect on pavement strain. J. Transp. Eng., 113(1): 56-71.

Weissman S (1999). Influence of tire-pavement contact stress distribution on development of distress mechanisms in pavements. Transportation Research Record. J. Transp. Res. Board, 1655: 161-167.

Yoo P, Al-Qadi I, Elseifi M, Janajreh I (2006). Flexible pavement responses to different loading amplitudes considering layer interface condition and lateral shear forces. Int. J. Pave. Eng., 7(1): 73-86.