Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 4(4):203-211
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Evaluation of Truck Tire Types on Near-Surface Pavement Response Based on Finite Element Analysis

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Abstract: The effects of truck tire types on near-surface pavement responses were evaluated via finite element anyalysis. First, three truck radial tires (11R22.5, 425/65R22.5, and 445/50R22.5) were modeled based on the tire geometries and specifications from the tire manufactures. Accordingly, tire-pavement interaction models were developed. These models were then verified by comparing predicted contact stresses with measured ones to make sure models can be used for further evaluation purpose. The results indicated that the super single (425/65R22.5) tire produced greater contact stress and more damage to the pavement in terms of top-down cracking and instability rutting, while new generation wide-based tire (445/50R22.50) induced approximately the same damage as the standard dual assembly tested (11R22.5).

***Key words**: ADINA; Contact stress; Instability rutting; Tire; Top-down cracking.*

Background

During past decades, new technologies were applied to the tire industry to increase the efficiency and more wide-base or super-single tires were introduced to replace the conventional dual-tire system. Compared to the conventional dual-tire system, the wide-base tire assembly decreases the vehicle weight by 400-577 kg (allowing more cargo weight), increases the fuel economy by 2%-5%, and lowers tire repair and replacement costs [1, 2]. Although the economical benefits of wide-base tire to trucking industry sound pretty attractive, the relatively more damage to pavement caused by wide-base tire over dual tires arouse big concerns among pavement engineers as well as tire engineers and has become a hot research topic over years.

Back to the early 1960s, Zube and Forsyth [3] performed an experiment to compare the vertical deflections and transverse strains of a flexible pavement surface due to wide-base tires and dual wheels. Their results indicated that pavement deflection was equivalent for 27 kN carried on a single tire or 40 kN carried on a dual pair. Christson *et al*. [4] conducted an experimental measurement of asphalt layer interface strains and surface deflections under different axle and tire configurations and gave similar results. Their studies showed that pavement damage in terms of measured strains caused by the wide-base tire could be theoretically 7 to 10 times worse than a dual pair for an equal load. This was also theoretically confirmed later by Treybig [5]. Eisenmann *et al*. [6] reported that the measured strain under wide-base tires were 50% greater than those under dual tires carrying the same load, and this would increase pavement fatigue damage by as much as a factor of 2.5.

Considering that more potential pavement damage might be caused by wide-base tires than dual tires, the Federal Highway Administration (FHWA) initiated a study in 1989 to assess the impact of wide-base tires, specifically the 425/65R22.5, on conventional flexible pavement damage by using accelerated pavement testing (APT) at the Turner-Fairbanks Research Center [7]. This study found that measured pavement strain and stress significantly increased under the single wide-base tires, and both the fatigue and rutting life of the pavement decreased dramatically.

Almost at the same time, Sebaaly [8] also evaluated the effects of tire configurations on the responses of flexible and rigid pavements using pavement instrumentation. Four tire types were considered in their study: the duals 11R22.5 and 245/75R22.5 and the wide-base 385/R65R22.5 and 425/65R22.5. Results of the study showed that tire type has almost no effect on the rigid pavement. For the flexible pavement, they concluded that the damage caused by wide-base tire was always greater than those caused by dual tires, but the relative damage was much lower than that was reported by FHWA. Other studies found the similar conclusion by using computer models [9, 10].

However, Joseph Ponniah [11] pointed out that past studies might have overstated the adverse effects of wide-base tires on pavement damages due to following reasons:

- Unbalanced loads between tires of a dual set due to unequal tire pressures, uneven tire wear, and pavement crown. Pavement deterioration increases as loads on two dual tires become more unbalanced.
- Wander effect. The effect of wander is considered beneficial to pavement deterioration because the repetitive loads are reduced particularly for single tires as the load is distributed over wider areas of pavement surface. Wander is expected to have a smaller beneficial effect on dual tires because the reduction in the number repetitive loadings is expected to be marginal due to the potential overlapping of the dual tire load distribution [12].
- Dynamic loadings caused by surface roughness. Pavement damage from dynamic loadings is typically localized and is approximately 2 to 4 times more severe than the damage due to

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Note: Submitted August 27, 2010; Revised November 30, 2010; Accepted January 7, 2011.

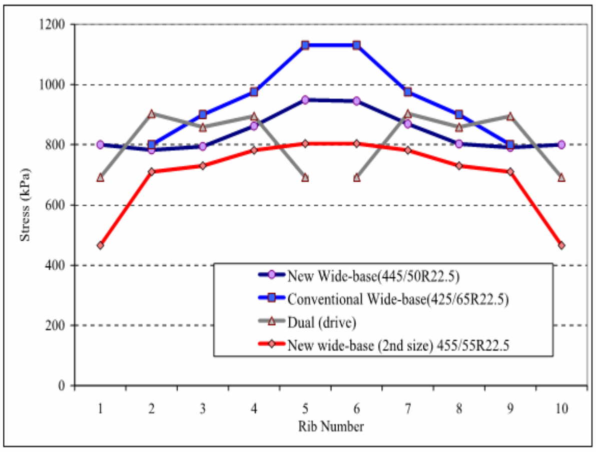


Fig. 1. Contact Stress Distributions for Different Tire Size [13].

static loading. It is commonly believed that wide-base tires having only two sidewalls are expected to absorb more of the dynamic loading than a pair of dual tires with four sidewalls.

From the perspective of mechanical model, most analyses have the following limitations that might also overestimate the effects of wide-base tires on pavement damages:

- Loading condition was assumed to be uniform, vertical, and circular. Actually, the distributions of contact stress between tire and pavement are extremely non-uniform and three-dimensional. The contact area under truck tire load is closer to rectangular than circular.
- Using power-law damage relationship like fourth power to evaluate pavement fatigue damage based on measured strain is questionable. For thin pavement, using high power to evaluate fatigue damage sounds reasonable since tire-pavement contact stress has great effects on the tensile strain at the bottom of an asphalt concrete (AC) layer. For a thick AC layer, tensile strain at AC bottom will be affected more by the total load than by the contact stress. Therefore, using high power might not be appropriate.

Due to above concerns plus introduction of new generation wide-base (NGWB) tire (455 and 445), several studies were conducted to re-evaluate the effects of new generation wide-base tire on pavement damages. The NGWB tire uses a new crown design crown architecture design that allows for lower aspect ratio geometry. Compared to conventional wide-base tires (385 and 425), the NGWB tires are 15% to 18% wider and have less average contact stress and more uniform stress distributions, as shown in Fig. 1 [13].

Al-Qadi *et al.* [14] conducted a study using both finite-element (FE) analysis and instrumented field test sections at the Virginia Smart Road on two NGWB tires, the 445/50R22.5 and 455/55R22.5. Fatigue cracking, top-down cracking, and rutting failure mechanisms were evaluated. They found that the 455/55R22.5 induced approximately the same pavement response or damage as the standard dual assembly tested (275/80R22.5). The other wide-base tire tested (445/50R22.5) was found to slightly increase the induced damage. Later, Priest *et al.* [15] also got similar results.

Although numerous computer models have been conducted to study the effects of tire types on pavement fatigue and general rutting, to date few models have been developed to assess effects of tire types on near-surface pavement response, neither do they consider the real interaction between tire and pavement. In addition, most of numerical models only applied uniform, vertical, and circular contact stresses to the pavement. In fact, tire-pavement contact stress is non-uniform and three-dimensional. And the horizontal shear contact stress might play a key role in understanding the mechanism of top-down cracking and instability rutting.

Objectives

The primary objective of this study is to investigate how truck tire types affect the near-surface pavement response based on two-dimensional (2-D) finite element (FE) analysis. The objective involved pursuit of the following tasks:

1. Develop 2-D FE-based tire models using tire geometries and structure information provided by tire manufacturers.
2. Develop 2-D FE-based tire-pavement interaction models.
3. Investigate effects of truck tire types on tire-pavement contact stress, top-down cracking, and instability rutting based on developed 2-D tire-pavement interaction models.

Scope

The research conducted in this study focused on developing 2-D tire-pavement interaction model and its effects on near-surface pavement response. The tire-pavement interaction model was only limited to tire contact stresses distributions. Other interaction situations such as noise would not be considered in the study. The study was restricted to radial truck tire and static loading condition. Materials were modeled as linear elastic which seems appropriate for behavior under a single load application, i.e., no wear or permanent shape change.

Tire Nomenclature

Given the interdisciplinary nature of this work, some key tire nomenclature and sign conventions used throughout the text are presented herein. Tire sign convention used is based on the Society of Automotive Engineering (SAE) standards, which define tire longitudinal axis as vehicle traveling direction and the lateral or transverse axis as perpendicular to travel.

The tire modeled was a modern radial tire, which consists of numerous parts, as shown in Fig. 2 [16]. The main components and their functions are described as follows:

Sidewall — made of rubber must withstand flexing and weathering and provide protection for the ply.

Belts — steel cord belt plies provide strength, stabilize the tread, and protect the air chamber from punctures.

Radial Ply — the radial ply, together with the belt plies, withstands the loads of the tire under operating pressure. The plies must transmit all load, driving, braking, and steering forces between the wheel and the tire tread.

Tread — made of rubber and provides the interface between the

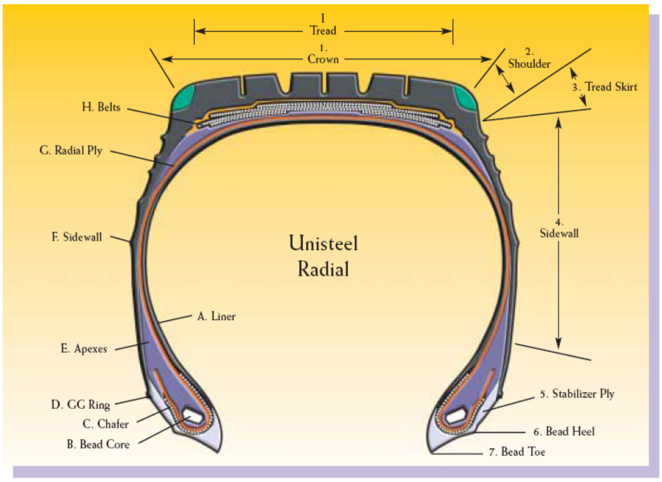


Fig. 2. Components of a Unisteel Radial Tire (After Goodyear 2004).

tire and the road. Its primary purpose is to provide traction and wear.

Shoulder — transition area between the crown and tread skirt.

Tread Skirt — intersection of tread and sidewall.

Crown — area of the tire that contacts the road surface.

Finite Element Analysis

Introduction of ADINA Program

The multi-purpose finite element program ADINA version 8.3 [17] was used to model 2-D tire-pavement interaction in this study. The capability of the ADINA program for 2-D finite element analysis, its versatility in modeling material behavior under load and temperature effects, and its capability in modeling the contact condition between tire and pavement make it an appropriate program to model complicated tire-pavement interaction.

Governing Equation

For static analysis, the governing equation for finite element analysis is given by:

$$[K][u] = [F] \tag{1}$$

where, $[K]$ is the stiffness matrix; $[u]$ is the vector of displacements at the nodal points of the mesh; and $[F]$ is the corresponding vector of forces and/or moments.

Contact Analysis

Tire-pavement interaction is a contact issue. Contact in ADINA is modeled using contact groups. Each contact group is composed of one or more contact surfaces. Contact pairs are then defined between contact surfaces. A contact pair consists of target and contactor. It is recommended that the stiffer surface be the target surface and the contactor surface should not penetrate into target surface. In this work, the tire surface was modeled as the contactor surface while the pavement surface was set as the target surface.

Contact Algorithms

One of the most important areas of the tire-pavement contact analysis is to determine the state of stress and strain under contact loading. ADINA offers three contact algorithms (1) constraint function method, (2) Lagrange multiplier (segment) method, and (3) rigid target method. The constraint function algorithm works better in most cases and should normally be selected. The Lagrange multiplier algorithm may work well in some cases involving friction, while the rigid method is a significantly simplified contact algorithm intended primarily for metal forming applications. Therefore, the constraint function method was selected in the present work and introduced as follows.

In constraint function algorithm, constraint functions are used for no-penetration and frictional contact condition. The normal constrain function is given by:

$$w(g,\lambda) = \frac{g+\lambda}{2} - \sqrt{(\frac{g-\lambda}{2})^2 - \varepsilon_N} \tag{2}$$

where, g is gap, and λ is the normal contact force, and ε_N is a small user-defined parameter.

The frictional constraint function $v(\dot{u},\tau)$ is defined by:

$$\tau + v - \frac{2}{\pi}\arctan(\frac{\dot{u} - v}{\varepsilon_T}) = 0 \tag{3}$$

where, $\dot{u}$ is sliding velocity, and ε_T is a small parameter that can provide some "elasticity" to the Coulomb friction law. τ is a nondimentional friction variable given by:

$$\tau = \frac{F_T}{\mu\lambda} \tag{4}$$

where, F_T is a tangential force, and μ is coefficient of friction.

2-D Modeling of Tire-Pavement Interaction

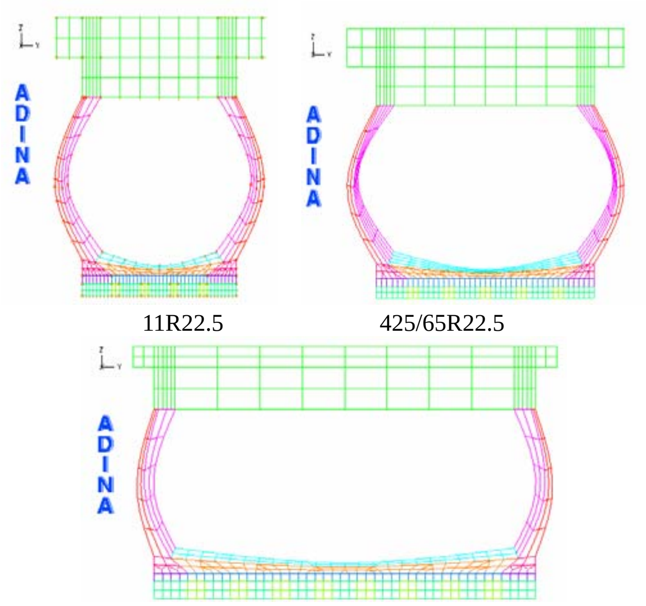
Mesh of Tire Model

To compare the effects of tire types on pavement response, three tires were modeled: dual tire 11R22.5, super single tire 425/65R22.5, and NGWB 445/50R22.5. Modeling a truck tire is really a challenge job due to its structural and material complexity. Typically, a radial tire mainly consists of the following parts: ply, belts, tread, and sidewall, as shown previously in Fig. 2. Tire materials are basically composite and rubber compounds vary through tire structure. However, exact material properties and actual structural make-up of these tires used by industry are not available to general public and thus make tire model extremely difficult. Fortunately, some basic response data regarding the behavior of typical radial truck tires and their structural make-up provided by Smithers Scientific Services along with previous work done by Myers *et al.* [18] make the development of two-dimensional tire model possible.

A proper tire model should catch both geometrical characters and structural behaviors. The structural behavior of radial truck tires is

Table 1. Material Properties for Tire Models.

	11R22.5		425/65R22.5		445/50R22.5	
Tire Parts	Modulus (MPa)	Possion Ratio, V	Modulus (MPa)	Possion Ratio, V	Modulus (MPa)	Possion Ratio, V
Rim	6.89E+9	0.1	6.89E+9	0.1	6.89E+9	0.1
Radial Ply	1.38E+3	0.4	1.38E+3	0.3	2.07E+3	0.3
Belt	3.45E+7	0.4	3.45E+6	0.2	6.89E+5	0.2
Sidewall	3.45E+0	0.495	3.45E+0	0.495	1.15E+1	0.495
Skirt Tread	1.15E+1	0.495	1.15E+1	0.495	1.15E+1	0.495
Shoulder	1.15E+1	0.495	1.15E+1	0.495	1.15E+1	0.495
Tread	1.15E+1	0.495	1.15E+1	0.495	1.15E+1	0.495
Grove	9.80E-6	0.499	9.80E-06	0.499	9.80E-06	0.499



11R22.5 425/65R22.5

455/50R22.5

Fig. 3. Developed 2-D Finite Element Tire Models.

governed by a low stiff wall structure and a high stiff tread structure resulting from the steel reinforcement embedded in tread [19]. Given the cross-section view in Fig. 2 and tire specifications, the 2-D finite element models for these three tires are developed as shown in Fig. 3. All models are meshed with 2-D solid plane strain elements. Different colors represent different element groups with corresponding stiffness. The rim is made of alloy and modeled as rigid body with very high stiffness. Ply and belts can be modeled as reinforcement. Sidewall, tread skirt, shoulder, and tread are made of rubber with different stiffness. All materials are treated as isotropic elastic material. The determination of tire material properties is based on the procedure developed by Myers [18] through adjusting the tire material properties to match the measured radius of curvature of the tire tread. Also, the material properties of previous tire models developed by other scholars [20-22] are taken as a reference. Finally, the material properties for these three tires are presented in Table 1.

Development of Axle-tire-pavement Contact Model

Table 2. Material Properties and Layer Thickness of the Pavement.

Pavement Layer	Modulus (MPa)	Poisson's Ratio	Thickness (mm)
Asphalt Concrete (AC)	3,000	0.40	200
Base	276	0.35	300
Subgrade	138	0.35	1,250

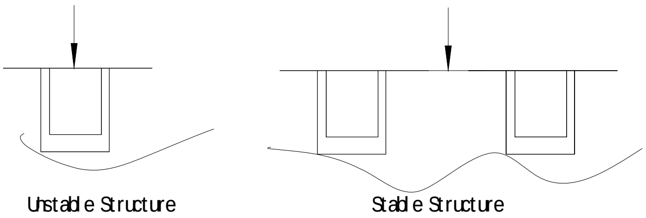


Fig. 4. Axle-Tire-Pavement Interactions.

To study effects of truck tire types on near-surface pavement stress response, the tire models need to be placed on a real pavement system. A typical three-layer pavement system, namely AC, base, and subgrade, was used in the analysis and its material properties and physical size was given in Table 2. As stated earlier, most studies didn't consider axle-tire-pavement interaction when they did comparison analysis between dual tire and wide-base tire. Actually, axle-tire-pavement interaction can't be captured using only surface stress (i.e., measured stress). To capture the rutting characteristics of pavement surface, an axle has to be used to link tires together, otherwise the tire will be unstable on unlevel surface, as shown in Fig. 4. Therefore, a comprehensive axle-tire-pavement finite element model was developed using ADINA, which can capture not only the loading characteristics, but also tire geometry and pavement surface conditions as well. The axle-tire-pavement interaction was modeled with three types of tires, i.e., dual tire 11R22.5, super single tire 425/65R22.5, and new generation wide-base tire 445/50R22.5. The whole meshes of these three models were presented in Fig(s). 5 to 7. And contact surfaces were defined in each model to model the contact conditions between tire and AC surface, which was shown in Fig. 8.

Element Selection

All 2-D solid elements were modeled as 9-node plane strain elements, with two translational degrees of freedom per node, as shown in Fig. 9. This type of node configuration has been shown to give a high level of accuracy in combination with an acceptable computing time demand. All elements are treated as isoparametric element.

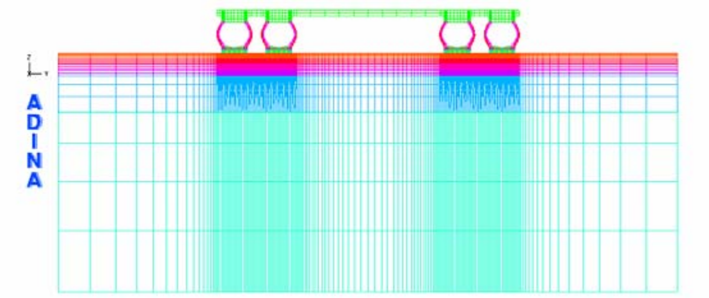


Fig. 5. 2-D Axle-tire-pavement Contact Model for Dual Tire 11R22.5.

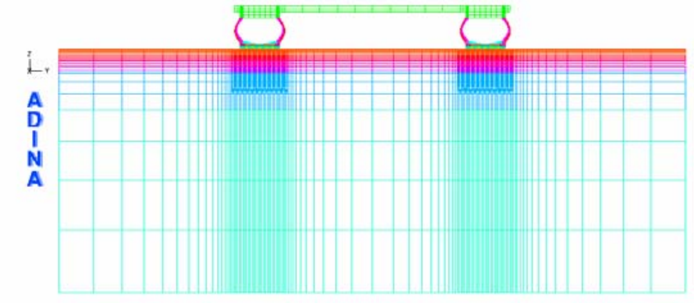


Fig. 6. 2-D Axle-tire-pavement Contact Model for Super Single 425/65R22.5.

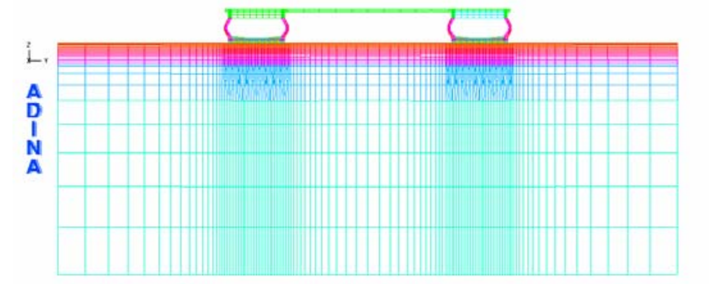


Fig. 7. 2-D Axle-tire-pavement Contact Model for NGWB 445/50R22.5.

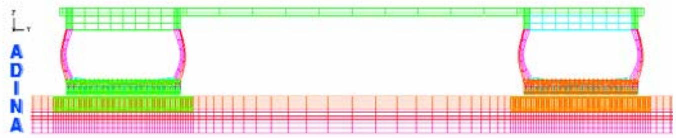


Fig. 8. Contact Surfaces between Tire and Pavement Surface.

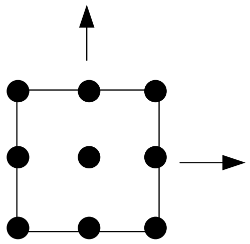


Fig. 9. 9-node Biquadratic Elements.

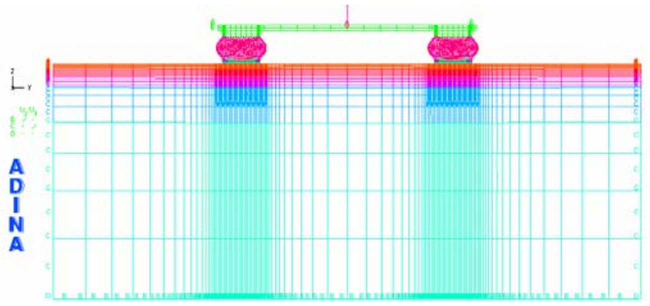


Fig. 10. Loading and Boundary Conditions.

Loading and Boundary Conditions

The tire-pavement contact model can be simulated by two steps. First, the inflation pressure is applied on the inner surface of the tire model and different pressure levels can be set to satisfy the requirements of the analysis. Second, a vertical load is applied on the rim axle under the given inflation pressure and the load can be gradually loaded under assigned time steps. The detail loading conditions are shown in Fig. 10. The boundary conditions for static analysis are also shown in Fig. 10. It can be observed that the bottom of the pavement is fixed at the Z translation, while sides of the pavement and rim axle are restricted with the Y translation.

Model Verification

In order to further verify developed tire-pavement contact models, a comparison was made between predicted contact stresses and measured contact stresses. Predicted contact stresses were obtained at the nodes of the pavement surface under the tire, and measured stresses were provided by Smithers Scientific Services, Michelin [23], and literature references [13, 14, 24, 25]. Figs. 11 and 12 show comparisons of contact stresses for Dual 11R22.5 between measured and predicted at the same load (20 kN) and inflation level (690 kPa), which clearly indicate that predicted vertical and horizontal shear contact stresses are similar to those measured under the real tire, except for some variation in magnitude. The variation might be caused by different loading conditions (FE model was running under static load, while the measurement was conducted under moving steel bed); tread groves (FE model didn't consider longitudinal grove); and element mesh. The overall errors are within 20%. Unfortunately, there are no detail measured contact stresses for both super single 425/65R22.5 tire and NGWB 445/50R22.5 tire, except for measured maximum contact stresses under each rib, as shown in Fig. 13 and Fig. 14, respectively. Both figures show that predicted maximum contact stresses agree well with the measured ones. The detail distributions of predicted contact stresses for both wide-base 425/65R22.5 and 445/50R22.5 are given in Fig(s). 15 and 16. It is noted that the transverse contact stresses show the some asymmetric distribution under each rib, either compression or tension, and the smallest shear stress is found at the center of each rib. And Poisson's effect is dominant over pneumatic effect. Those characteristics also agree well with previous studies [14, 19]. The most important thing is the model's ability to capture the patterns of both vertical contact stress and horizontal shear contact stress distributions.

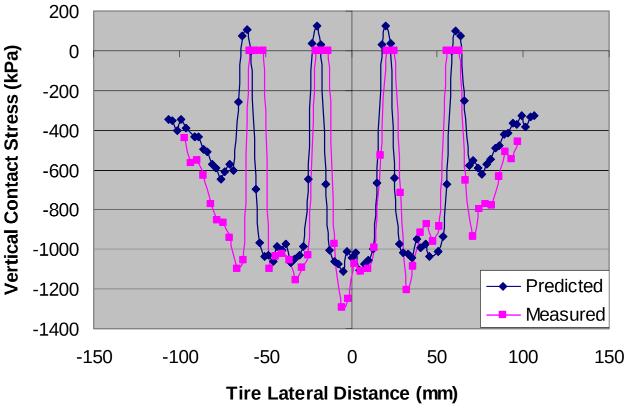


Fig. 11. Comparison of Vertical Contact Stress for Dual 11R22.5 (20 kN; 690 kPa).

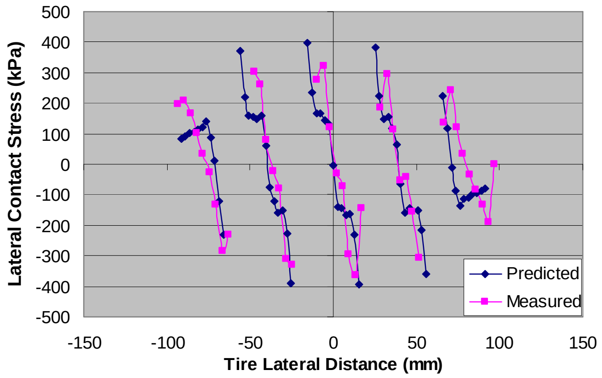


Fig. 12. Comparison of Lateral Contact Stress for Dual 11R22.5 (20 kN; 690 kPa).

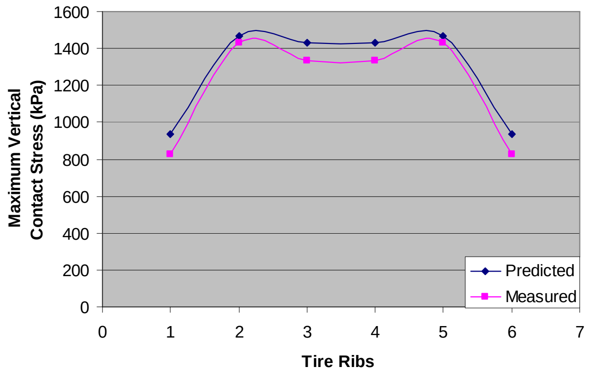


Fig. 13. Comparison of Vertical Contact Stress for Super Single 425/65R22.5 (40 kN; 790 kPa).

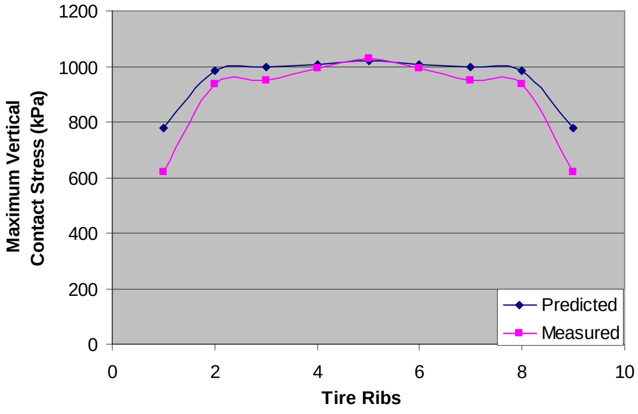


Fig. 14. Comparison of Vertical Contact Stress for NGWB 445/50R22.5 (40 kN; 690 kPa).

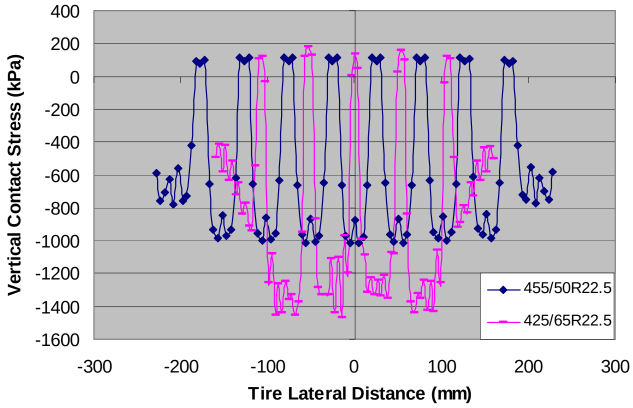


Fig. 15. Predicted Vertical Contact Stress for Wide-base Tires.

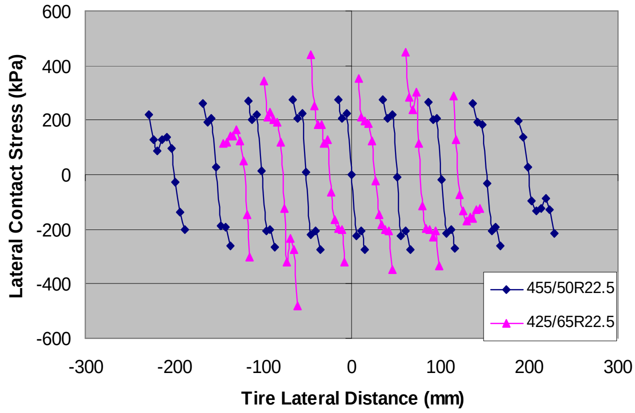


Fig. 16. Predicted Transverse Contact Stress for Wide-base Tires.

Evaluate Effects of Tire Types on Near-surface Stress Distributions

Contact Stress Distributions

Comparisons of contact stress distributions among different tires at manufacturer recommended inflation pressures (11R22.5: 690 kPa; 425/65R22.5: 790 kPa; and 445/50R22.5: 690 kPa) under the same load level of 40 kN (20 kN for single 11R22.5) are presented in Figs. 17 to 18. Here, the reason why using manufacturers recommended inflation pressure rather than using the same inflation pressure is that it would better reflect field conditions that how different truck inflation pressure rather than using the same inflation pressure is that it would better reflect field conditions that how different truck tires cause different pavement responses. As shown in Fig. 17, the super single 425/65R22.5 produces the highest maximum vertical contact stress, while dual 11R22.5 and NGWB 445/50R22.5 have very close

Table 3. Statistic Results of the Comparisons.

	11R22.5		425/65R22.5		445/50R22.5	
	Vertical Contact Stress (kPa)	Lateral Contact Stress (kPa)	Vertical Contact Stress (kPa)	Lateral Contact Stress (psi)	Vertical Contact Stress (kPa)	Lateral Contact Stress (kPa)
Maximum	-1109	396	-1468	479	-1013	276
Tire/Dual	1.00	1.00	1.32	1.21	0.91	0.70

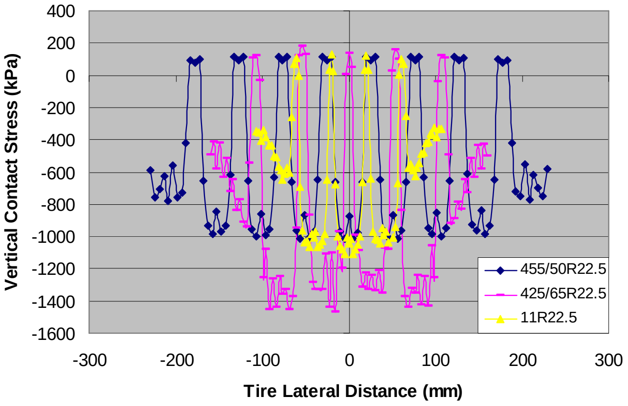


Fig. 17. Comparisons of Vertical Contact Stress among Different Tires.

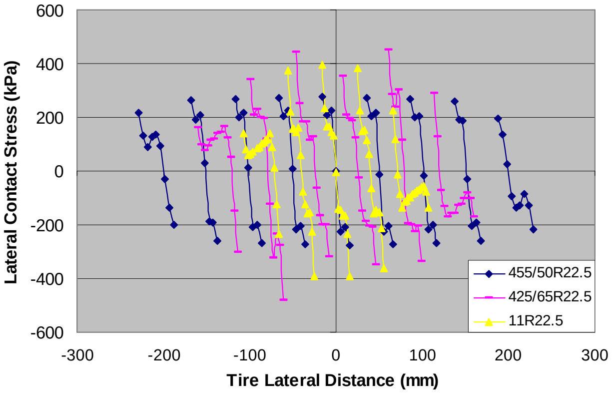


Fig. 18. Comparisons of Vertical Contact Stress among Different Tires.

maximum vertical contact stress. This makes sense since the NGWB tire is 15 percent to 18 percent wider than conventional wide-base tires (385 and 425) and thus has more average contact area, which makes it much comparable to that of dual tire assembly. Accordingly, the super single 425/65R22.5 also produces much higher transverse contact stresses than both dual 11R22.5 and NGWB 445/50R22.5 do. This characteristic of contact stress distribution will greatly affect the near-surface stress distribution. Table 3 gives the statistic results of the comparisons.

Near-surface Stress Distributions

Studies by authors showed that shear-induced principal tensile stress near the tire edge at AC surface has much higher magnitude than bending stress at AC surface, which is more likely responsible for top-down cracking. So the studies focused on the distributions of principal tensile stress along the AC surface. Fig. 19 shows the comparisons of principal tensile stresses distributions along the AC surface among different types of tires. As expected, super single 425/65R22.5 produces much higher peak SIGMA-1 than both dual 11R22.5 and NGWB 445/50R22.5 do.

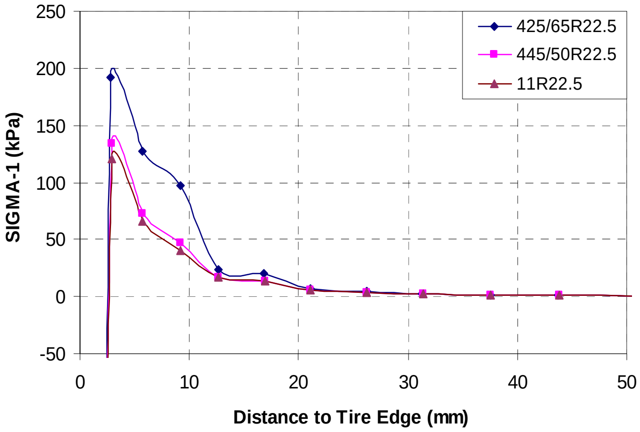


Fig. 19. Comparisons of Principal Tensile Stresses among Tires.

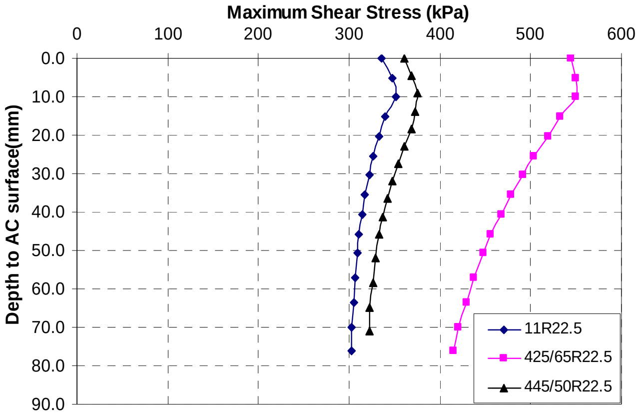


Fig. 20. Comparisons of Maximum Shear Stresses among Tires.

The maximum shear stress along the top AC layer was believed to be responsible for instability rutting. Studies by Drakos [26] and Novak *et al.* [27] showed that critical locations for maximum shear stress were along the longitudinal edges of the tire. The distributions of maximum shear stress along the top 50-mm AC layer at tire edges are given in Fig. 20. As shown in Fig. 20, the shear stress increases initially with depth, reaching the maximum value at a depth of approximate 10 mm, after which it decreases from the peak value. Again, the super single 425/65R22.5 tire generated much higher maximum shear stress than both dual 11R22.5 and NGWB 445/50R22.5 tires, which indicated that the super single

425/65R22.5 might cause more rutting than both dual 11R22.5 and NGWB 445/50R22.5 tires.

Summary

The effects of truck tire types on pavement response were evaluated based on finite element anyalysis. Some key points were summarized as follows:

- The developed 2-D tire-pavement finite element contact model can successfully capture patterns of both vertical contact stress and horizontal (lateral/transversal) shear contact stress distributions for all tires, which indicate that the model can be used for evaluation purpose.
- Based on developed 2-D models, under the same axle load (40 kN for wide-based tires and 20 kN for dual tire), the super single 425/65R22.5 tire generated the highest contact stress while dual 11R22.5 and NGWB 445/50R22.5 tires had very close contact stress at their recommendation inflation levels (690 kPa for 11R22.5 and 445/50R22.5, 790 kPa for 425/65R22.5).
- Evaluation of truck tire types on near-surface stress states indicated that super single 425/65R22.5 tire produced much higher peak principal tensile stress (SIGMA-1) than both dual 11R22.5 and NGWB 445/50R22.5 tires do. So did maximum shear stress. This indicated that super single tire might cause more damage to near-surface pavement than both dual tire and NGWB tire.

Acknowledgment

The authors acknowledge the support of the Florida Department of Transportation and FHWA in the ongoing study of top-down cracking.

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