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Jaime Hernandez
Marquette University, jaime.hernandez@marquette.edu

Imad L. Al-Qadi
University of Illinois - Urbana-Champaign

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Jaime A. Hernandez
Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA
Imad L. Al-Qadi
Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA

Abstract
The interaction between deformable tires and pavements was studied using finite-element modeling and a semicoupled approach. Three finite-element models were used: (1) a hyperelastic tire rolling on an infinitely rigid surface; (2) a three-dimensional pavement model; and (3) a hyperelastic tire rolling on a deformable viscoelastic body. The tire and pavement models have been successfully compared with experimental measurements. Tire interaction with a rigid surface provided contact stresses to excite the pavement model, and results of the pavement model defined the boundary conditions of the tire rolling on the deformable body. After that, the pavement loaded with the contact stresses

from the tire interacting with the deformable body was run. This study focuses on issues related to pavement damage (tire–pavement contact stresses and critical pavement responses) and lifecycle assessment (rolling resistance). Transverse contact stresses were the most affected by pavement deformation, which translated into impact on the maximum vertical strain and the maximum shear strain in the asphalt concrete layer. The tire moving on a deformable body showed that the thin pavement created a higher rolling resistance force than thick pavements. In addition, dissipation-based and deflection-based approaches for calculating pavement contribution to rolling resistance were equivalent. Finally, for the range of values considered, changes in tire inflation pressure affected the rolling resistance force more than changes in applied load.

Introduction

Advancement of tire–pavement interaction models not only improve structural design of flexible pavement, but also the lifecycle assessment of pavement infrastructure. Having an appropriate representation of tire–pavement contact stresses provides accurate critical pavement responses, which results in better prediction of pavement damage. In addition, by coupling tire and pavement, rolling resistance predictions generate a better estimation of fuel consumption and greenhouse gas emissions.

As a result of computational constraints, most of the research on tire–pavement interaction modeling has included simplifications, which depended on the purpose of the model. For instance, assuming the tire as infinitely rigid can be used to model tire–soil contact. On the other hand, the tire structure can be simplified to study the rolling phenomenon on a rigid surface (Shoop et al. 2002). A three-dimensional (3D) model was developed to study tire–snow interaction assuming the tire as rigid or deformable (shell elements) and snow as deformable characterized by Drucker-Prager. The model was validated using experimental measurements of contact forces (Shoop et al. 2006).

Other pavement research assumed that pavement structures are not infinitely rigid. Wang and Roque coupled tire and pavement in a single model and computed pavement responses. However, their analysis was static and material properties of both tire and pavement were assumed linear elastic (Wang and Roque 2011). An improvement to this model considered the tire as hyperlastic and the asphalt concrete (AC) as elastoviscoplastic, but tire loading was assumed static (Kim et al. 2012). In 2011, Al-Qadi and Wang used a decoupled approach to model tire–pavement interaction. In the decoupled approach, the tire is modeled independently and used on a rigid surface to predict 3D contact stresses, which were used as input for a 3D pavement model, thus predicting pavement responses (Al-Qadi and Wang 2011). Even though the tire model considered various materials, the rubber was assumed linear elastic.

The theoretical and numerical background for the Arbitrary Lagrangian-Eulerian (ALE) approach applied to tire–pavement interaction has been studied (Nackenhorst 2004); however, it has not been extensively applied. Wollny and Kaliske used ALE methodology on a pavement model with inelastic materials. The pavement was loaded with contact stresses from a steady-state rolling tire contacting a rigid surface (i.e., decoupled approach) (Wollny and Kaliske 2013). Similarly, the decoupled approach was also used by Zopf et al. (2015), but the effect of the tire on the pavement was represented by a set of nodal forces equal to the reaction forces of a tire rolling on a rigid surface.

The main contribution of this study lies in integrating advanced 3D tire and pavement models to study critical pavement responses and rolling resistance. The tire model considers hyperelastic rubber, material distribution in the cross section, accurate geometry, and validation with experimental measurements. On the other hand, the pavement model included variables that are usually omitted in the conventional analysis of flexible pavement such as dynamic analysis, linear viscoelastic AC, stresses dependent granular materials, and moving load.

Finite-Element Model

The finite-element (FE) analysis sequence, which will be detailed in the next section, consisted of three models: (1) a hyperelastic tire contacting a rigid surface; (2) a pavement model; and (3) a hyperelastic tire contacting a viscoelastic deformable body.

Model I: Hyperelastic Tire on Rigid Surface

The tire model comprised various advanced features. First, detailed dimensions of the tire and its cross section were measured along with the distribution of material properties and the location, orientation, and cross-sectional area of the reinforcement. Rubber components were considered hyperelastic with the behavior given by the Mooney-Rivlin model and the constants provided by the tire manufacturer. The reinforcement was assumed linear elastic with elastic modulus determined through laboratory testing [ASTM D882 (ASTM 2012)].

Cylindrical, hybrid, rebar, and Cartesian elements were used in the tire model. Cylindrical elements accurately cover longer arc length with less amount of finite elements (Danielson and Noor 1997; Kennedy 2003). The hybrid elements are ideal for modeling rubber's incompressibility; rebar elements model the embedded reinforcement without using homogenization (Helnwein et al. 1993); and Cartesian full-integration elements provide accurate contact stresses in the tire–pavement contact region (*ABAQUS*). The size and distribution of finite elements in the tire model were given by the coarsest mesh having strain energy with a difference of no more than 5% with respect to a very fine mesh. The tire model was validated using experimental measurements of contact area, deflection, and contact stresses (Hernandez and Al-Qadi 2015).

ALE technique used by the steady-state rolling analysis capability of *ABAQUS* was used to determine the three-dimensional contact stresses. The model described in this section has been used to predict 3D contact stresses not only at free rolling, but also at braking and traction (Hernandez and Al-Qadi 2015).

Model II: Pavement Model

Two structures were part of the numerical analysis matrix: thin and thick pavement. The thickness of the AC layer and the base for the thin road were 100.0 and 200.0 mm, respectively. For the thick pavement, the thickness of the AC and the base were 350.0 and 300.0 mm, respectively. The depth of both models was 4,500.0 mm, but the length and the width changed for each structure. Three types of finite elements composed the pavement model: full integration, reduced integration, and infinite elements. Full-integration elements were assigned to the AC layer, while reduced-integration elements were used for the base and subgrade. Infinite elements defined the boundary of the pavement model in the three orthogonal directions. The model dimensions, element types, and finite-element sizes were determined based on a mesh sensitivity analysis. In the mesh sensitivity analysis, critical pavement responses, such as tensile strains at the bottom of the AC and shear strains and maximum vertical strain in each layer, were monitored as the mesh changed. The final mesh configuration provided the closest pavement responses to a semianalytical results obtained from an axisymmetric solution, using the largest element size.

The material properties of each layer represented a wide range of road structures. Regarding the AC, the *Long-Term pavement performance data release* 26 (FHWA 2012) was analyzed to select dynamic modulus test results from more than 1,000 data sets and characterize AC as linear viscoelastic. The instantaneous modulus of the AC was 32,891.5 MPa. The base of the thin pavement was considered nonlinear anisotropic, and the corresponding constants were retrieved from a database of 114 materials. The material parameters of the base layer are $k_1 = 1235.5\ \mathrm{MPa}$, $k_2 = 0.5486$, $k_3 = -0.2801$, $k_4 = 401.7\ \mathrm{MPa}$, $k_5 = 1.4456$, $k_6 = -1.8752$, $k_7 = 466.4\ \mathrm{MPa}$, $k_8 = 0.7004$, and $k_9 = -0.8057$ (Tutumluer 2008). The base in the thick pavement had an elastic modulus of 300 MPa. On the other hand, the subgrade was modeled using the Drucker-Prager model in both thin and thick structures. The angle of friction was 28°, the ratio of the flow stress in triaxial tension to the flow stress in triaxial compression was 0.85, the dilation angle was 31°, and the yield stress was 77 kPa (Arnold 2004). The elastic part of the subgrade had an elastic modulus of 65.0 MPa. Other features of the pavement model included friction interaction between layers and nonuniform temperature distribution in AC. The pavement was loaded with the contact stresses obtained from the hyperelastic tire model moving on an approximately 1,000-mm-long wheelpath. The methodology used in the development of the pavement model has been successfully compared with experimental measurements (Wang and Al-Qadi 2009; Hernandez et al. 2016).

Model III: Hyperelastic Tire on Viscoelastic Deformable Body

The same material properties and geometry as in Model I (hyperelastic tire on rigid surface) were used for a tire rolling on a deformable viscoelastic body. However, the tire mesh consisted of Cartesian full-integration elements uniformly distributed along the circumference spanning an arc of 2°. Using the Lagrangian formulation, the tire was rolled over the viscoelastic body with a length of 3,600 mm, a width of 600 mm, and a thickness of 100 mm. The length allowed the tire to have a full revolution over the deformable body. On the other hand, the thickness and width along with the spring supports provided surface deformation similar to the one of the full pavement model. The viscoelastic deformable body utilized to simplify the pavement structure was supported by foundation elements in the three orthogonal directions perpendicular to each face. The constants of the foundation elements were obtained from 100-mm-deep stresses and deflections in the pavement model. Each element in the deformable body was cubic with 20-mm edges.

Analysis Sequence

The full analysis consists of four steps, each step comprising a finite-element run of one of the models presented in the previous sections, as shown in Fig. 1. In Step 1, Model I was used to determine the 3D contact stresses between the hyperelastic tire and rigid surface at free rolling. The tire was subjected to a load PP and a tire inflation pressure S. Step 2 entails the dynamic analysis of the pavement model (Model II) subjected to the 3D moving contact stresses from Step 1. Stresses and deflections from Model II allowed the calculation of the foundation elements constants to be used in the following step.

After the foundations constants were obtained, Step 3 was performed by analyzing the tire rolling on the viscoelastic deformable body (Model III). In order to guarantee free rolling, the moment at the tire's axis was kept at zero. Finally, in Step 4, Model II was run once more using the 3D contact stresses obtained in Step 3. Tire speed was equal for each step of the analysis.

The analysis described allows for the study of two main phenomena: the effect of pavement flexibility on pavement responses under the same load and tire inflation pressure and rolling resistance (and by extension to fuel consumption and greenhouse gas emissions). Both thin and thick pavement types were analyzed under high and low speeds ($V1 = 8\ \text{km/h}$ for urban streets and $V3 = 115\ \text{km/h}$ interstate highways) and temperatures ($T1 = -12°\text{C}$ as winter temperature and $Ts = 45°\text{C}$ as summer temperature) for typical half-axle load and tire-inflation pressure of $P3 = 44.4\ \text{kN}$ and $S3 = 758\ \text{kPa}$, respectively. In addition, the effect of load and tire-inflation pressure were evaluated for the thick pavement only using $P2 = 35.6\ \text{kN}$ and $S1 = 552\ \text{kPa}$ for the four combinations of temperature and speed mentioned previously. A summary of the variables considered is presented in Table 1.

Table 1. Values of Load, Tire Inflation Pressure, Speed, and Temperature

Load (kN)	Pressure (kPa)	Speed (km/hkm/h)	Temperature (°C)	Pavement type
$P2 = 35.6$	$S1 = 552$	$V1 = 8$	$T1 = -12$	Thick
$P3 = 44.4$	$S3 = 758$	$V3 = 115$	$T3 = 45$	Thin

Three-Dimensional Contact Stresses

Figs. 2–4 show the variation of contact stresses in the three directions along a central rib when the applied load was $P = 44.4\ \text{kN}$, the tire-inflation pressure was $S = 758\ \text{kPa}$, and the considered temperatures and speeds (Table 1). The plots show not only the effect of speed and temperature, but also include the contact stresses for the rigid surface. Temperature and pavement type cannot be considered in Model I, but the contact stresses for rigid surface were included in the plots for thick and thin pavements for reference purposes.

For the vertical contact stresses (σ_z), whose variation with contact length at a specific location across the tire is presented in Fig. 2, the resultant force was monitored and kept constant so a fair comparison could be made between the pavement responses in Steps 2 and 4. The magnitude of σ_z was redistributed in the contact patch between tire and the pavement. The redistribution translated into increment in contact length and/or increment of vertical contact stresses at the center of each rib.

For the transverse contact stresses (σ_y), the deformation of the contacted surface greatly affected not only the magnitude, but also the shape of the variation along the contact patch (Fig. 3). If surface was infinitely rigid, σ_y would have a positive and negative peak at the front and the back of the tire; however, if the surface was deformable, the transverse contact stresses would show a single curvature, and the maximum magnitude would be located around the center of the contact length. As previously mentioned, vertical contact stresses were higher at the edge contact point between the tire's ribs and the deformable pavement. Consequently, the upper limit for the resultant in-plane shear stresses (i.e., product of friction coefficient and contact pressure) is higher for the deformable body. In addition, assuming the surface as rigid or deformable greatly affects the restriction to motion of the contact points between the tire and the pavement, which influences the magnitude of the transverse contact stresses (Clark 1971). A symmetric behavior of σ_y across one rib was also noticed. If the surface was infinitely rigid, speed would not modify σ_y, but some influence would be observed when the surface was deformable.

Finally, the longitudinal contact stresses (σ_x) were higher on the rare part of the contact length if the surface was rigid as seen in Fig. 4. If the surface was deformable, the contact stresses on the front would be higher. In addition, speed would have a significant effect on σ_x if the surface on which the tire was rolling was infinitely rigid. Once this surface deformed, neither temperature nor speed greatly affected the longitudinal contact stresses.

The longitudinal and transverse contact stresses are orthogonal components of the resultant in-plane contact shear. Based on the analysis performed, it is evident that the surface deformation upon which the tire is rolling has a relevant effect on the orientation of the in-plane contact stresses. This change in orientation resulted in modifications in distribution and magnitude of σ_x and σ_y. The effect of these alterations on pavement responses and rolling phenomenon will be expanded in the following sections. In general, in the case of the deformable surface, both speed and temperature slightly affected the magnitude, but not the shape of the variation of the contact stresses, and no significant difference was observed on the contact stresses of thin and thick pavements.

Pavement Responses

To evaluate the effect of pavement flexibility on pavement responses, critical strains from Model II in Steps 2 and 4 were compared (Fig. 1). The only difference between the pavement models in the two steps is the input of the 3D contact stresses: the contact stresses came from a tire contacting a rigid surface in Step 2, while the tire contacted a deformable body in Step 4. The critical pavement responses considered have been linked to typical pavement distresses. Maximum tensile strain at the bottom of the AC in the longitudinal and transverse direction ($\epsilon_{11,ac}$ and $\epsilon_{33,ac}$, respectively) has been associated with bottom-up fatigue cracking. Maximum vertical strain in the AC, base, and subgrade ($\epsilon_{22,ac}$, $\epsilon_{22,bs}$, and $\epsilon_{22,sg}$, respectively) has been related to permanent deformation in the pavement structure. Finally, maximum vertical shear strain in the AC, base, and subgrade ($\epsilon_{23,ac}$, $\epsilon_{23,bs}$, and ϵ23,sgϵ23,sg, respectively) and transverse surface strain (ϵ_{sf}) have been associated with near-surface cracking (in the case of the AC layer) and shear flow (permanent deformation) of the pavement layers.

Tables 2–5 present the critical pavement responses for the considered pavement structures and loading cases (Fig. 5 shows a figure version of Table 2). In these tables, the combinations of temperature and speed are given in the first column (Table 1). Table 2 focuses on thin pavement subjected to a load of 44.4 kN and a tire inflation pressure of 758 kPa ($S3$ and $P3$ according to Table 1). In this case, the difference was less than 4.0% in all responses except for $\epsilon_{23,ac}$ at the highest pavement temperature and speed. The vertical shear strain in the AC predicted in Step 2 was lower than in Step 4 by 6.4%. In addition, slightly higher differences were observed for the higher speed. For the thick pavements subjected to the same loading conditions ($S3$ and $P3$), the highest differences were no longer seen on the maximum shear strain but on the maximum vertical strain in the AC layer. The largest difference corresponded to the Case $T3V3$, and it was lower for the contact stresses coming from a deformable body by 10.6%. Conversely, for the lowest pavement temperature and tire speed, the rigid surface underestimated $\epsilon_{22,ac}$ by 9.8%.

Table 2. Pavement Responses for Thin Pavement, 44.4 kN, and 758 kPa

Case	Assumption	$\epsilon_{11,ac}$	$\epsilon_{33,ac}$	$\epsilon_{33,sf}$	$\epsilon_{23,ac}$	$\epsilon_{23,bs}$	$\epsilon_{23,sg}$	$\epsilon_{22,ac}$	$\epsilon_{22,bs}$	$\epsilon_{22,sg}$
$T1\ V1$	Rigid surface	53.4	85.4	15.6	25.5	94.6	86.6	105.8	693.5	288.8
	Deformable body	53.2	87.1	15.6	25.1	94.3	86.5	106.7	694.5	288.3
	Difference (%)	0.4	-2.0	0.0	1.6	0.3	0.1	-0.9	-0.1	0.2
$T1\ V3$	Rigid surface	71.6	55.1	27.6	26.1	106.1	0.0	69.8	1,627	0.0
	Deformable body	71.4	56.4	27.3	25.6	106.1	0.0	70.5	1,626.7	0.0
	Difference (%)	0.3	-2.4	1.1	1.9	0.0	-	-1.0	0.0	-
$T3\ V1$	Rigid surface	471.8	413.1	123.7	175	513.8	401.1	499.6	1,822.5	1205.2
	Deformable body	474.4	424.7	123.7	175	514.5	403.4	507.3	1,826.7	1209.4
	Difference (%)	-0.6	-2.8	0.0	0.0	-0.1	-0.6	-1.5	-0.2	-0.3
$T3\ V3$	Rigid surface	101.9	122.6	71.5	62.7	189.9	0.0	141.6	2,137.9	0.0
	Deformable body	99.4	127.0	70.6	66.7	188.8	0.0	142.5	2,137.4	0.0
	Difference (%)	2.5	-3.6	1.3	-6.4	0.6	-	-0.6	0.0	-

Table 3. Pavement Responses for Thick Pavement, 44.4 kN, and 758 kPa

Case	Assumption	$\epsilon_{11,ac}$	$\epsilon_{33,ac}$	$\epsilon_{23,50\mathrm{mm}}$	$\epsilon_{23,bs}$	$\epsilon_{23,sg}$	$\epsilon_{22,ac}$	$\epsilon_{22,bs}$	$\epsilon_{22,sg}$
$T1\ V1$	Rigid surface	12.4	11.2	16.5	2.3	11	12.3	18.1	39.8
	Deformable body	12.3	11.2	16.0	2.3	11.0	13.5	18	39.8
	Difference (%)	0.8	0.0	3.3	0.0	0.0	-9.8	0.6	0.0
$T1\ V3$	Rigid surface	9.9	7.9	16.0	6.8	0.0	16.1	61.2	0.9
	Deformable body	9.8	7.8	16.2	6.7	0.0	16.6	60.9	0.9
	Difference (%)	1.0	1.3	-1.2	1.5	-	-3.1	0.5	0.0
$T3\ V1$	Rigid surface	49.1	49.9	122.6	14.9	30.7	153.3	67.7	112.2
	Deformable body	49.0	49.8	125.5	14.8	30.7	150.1	67.6	112.2
	Difference (%)	0.2	0.2	-2.4	0.7	0.0	2.1	0.1	0.0
$T3\ V3$	Rigid surface	21.6	17.6	70.7	12.5	0.0	87.9	136	0.6
	Deformable body	21.3	17.5	71.0	12.3	0.0	78.6	134.6	0.6
	Difference (%)	1.4	0.6	-0.4	1.6	-	10.6	1.0	0.0

Table 4. Pavement Responses for Thick Pavement, 44.4 kN, and 552 kPa

Case	Assumption	$\epsilon_{11,ac}$	$\epsilon_{33,ac}$	$\epsilon_{23,50\mathrm{mm}}$	$\epsilon_{23,bs}$	$\epsilon_{23,sg}$	$\epsilon_{22,ac}$	$\epsilon_{22,bs}$	$\epsilon_{22,sg}$
$T1\ V1$	Rigid surface	12.4	11.2	9.5	2.3	11.0	12.3	18.1	39.8
	Deformable body	12.2	11.2	10.2	2.3	11.0	15.7	18.0	39.7
	Difference (%)	1.6	0.0	-7.7	0.0	0.0	-27.6	0.6	0.3
$T1\ V3$	Rigid surface	9.9	7.9	9.6	6.8	0.0	16.1	61.2	0.9
	Deformable body	9.7	7.8	10.2	6.7	0.0	19.4	60.9	0.9
	Difference (%)	2.0	1.3	-6.4	1.5	-	-20.5	0.5	0.0
$T3\ V1$	Rigid surface	49.1	49.9	62.4	14.9	30.7	154.3	67.7	112.2
	Deformable body	48.7	49.9	72.1	14.8	30.6	205.3	67.6	112.0
	Difference (%)	0.8	0.0	-15.5	0.7	0.3	-33.1	0.1	0.2

$T3\ V3$	Rigid surface	21.6	17.6	35.8	12.5	0.0	88.5	136.0	0.6
	Deformable body	20.9	17.6	40.0	12.5	0.0	112.4	132.4	0.6
	Difference (%)	3.2	0.0	-11.8	0.0	-	-27.0	2.6	0.0

Table 5. Pavement Responses for Thick Pavement, 36.5 kN, and 758 kPa

Case	Assumption	$\epsilon_{11,ac}$	$\epsilon_{33,ac}$	$\epsilon_{23,50}$mm	$\epsilon_{23,bs}$	$\epsilon_{23,sg}$	$\epsilon_{22,ac}$	$\epsilon_{22,bs}$	$\epsilon_{22,sg}$
$T1\ V1$	Rigid surface	10.1	9.3	7.6	1.9	8.9	12.7	14.7	32.3
	Deformable body	10.3	9.7	7.1	1.9	8.9	16.1	14.8	32.4
	Difference (%)	-2.0	-4.3	6.3	0.0	0.0	-28.6	-0.7	-0.3
$T1\ V3$	Rigid surface	8.2	6.6	7.7	5.6	0.0	15.2	50.1	0.7
	Deformable body	8.4	7.0	7.3	5.8	0.0	18.6	50.8	0.8
	Difference (%)	-2.4	-6.1	4.8	-3.6	-	-22.4	-1.4	-14.3
$T3\ V1$	Rigid surface	40.3	41.5	47.1	12.0	24.9	105.7	55.4	90.9
	Deformable body	41.1	43.6	42.2	12.4	25.1	150.0	50.2	91.8
	Difference (%)	-2.0	-5.1	9.9	-3.3	-0.8	-41.9	9.4	-1.0
$T3\ V3$	Rigid surface	18.0	14.8	27.6	10.5	0.0	69.1	113.3	0.5
	Deformable body	18.5	16.1	25.6	11.3	0.0	86.0	116.4	0.5
	Difference (%)	-2.8	-8.8	7.1	-7.6	-	-24.5	-2.7	0.0

The effect of rigid body assumption on critical pavement responses under different loading conditions was evaluated for thick pavement and the results are given in Tables 4 and 5. The critical pavement responses after reducing the tire inflation pressure from 758 to 552 kPa are provided in Table 4. The difference between rigid and deformable body was significant not only for the maximum vertical strain in the AC, but also for the shear strain 50 mm from the pavement surface ($\epsilon_{23,50\ \mathrm{mm}}$). The largest difference in $\epsilon_{22,ac}$ was 33.1% and was observed at the highest temperature and lowest speed (most compliant AC layer), while the smallest was 20.5% at the lowest temperature and highest speed (stiffest AC layer). Similar trend but smaller discrepancy was seen for $\epsilon_{23,50\ \mathrm{mm}}$, where the highest (15.5%) and smallest (6.4%) percentage difference was seen for $T3V1$ and $T1V3$, respectively. It should be also mentioned that the rigid surface assumption underestimated $\epsilon_{22,ac}$ and $\epsilon_{23,50\ \mathrm{mm}}$ in all combinations of temperatures and speeds.

Table 5 shows the critical pavement responses for a load of 35.6 kN and a tire-inflation pressure of 758 kPa. As for the effect of tire-inflation pressure, the largest differences were observed on the maximum vertical strain in the AC and the maximum shear strain 50-mm-deep in the pavement structure. However, when decreasing the load from 44.4 to 35.6 kN, $\epsilon_{23,50\ \mathrm{mm}}$ was larger for the rigid surface assumption than for deformable pavement. The case with the highest temperatures and lowest speed provided the largest difference in vertical strain and shear strain in the AC: 9.9 and 41.9%, respectively. The difference decreased as the stiffness of the AC layer was higher (i.e., lower temperature and higher speed) becoming 4.8% for $\epsilon_{23,50\ \mathrm{mm}}$ and 22.4% for $\epsilon_{22,ac}$.

As previously discussed, considering pavement flexibility in the calculation of contact stresses greatly increases transverse contact stresses and to a lesser degree the distribution of vertical contact stresses (the result from the vertical contact stresses was unmodified). Previous studies have demonstrated that the effect of in-plane contact stresses was localized on the regions close to pavement surface (Al-Qadi and Yoo 2007; Wang and Al-Qadi 2009), which agrees with the result presented in Tables 2–5. In addition, after changing the tire-inflation pressure to a lower value, the tire–pavement contact area increased with respect to the rigid surface calculation, which translated into modification in the shear strain close to the surface.

Rolling Resistance

Rolling Resistance Force

Fig. 6 shows the reaction force in the traveling direction at the tire's axis, or rolling resistance force (RR_f), for the four combinations of speed and temperature (Table 1). Four scenarios were studied: thick and thin pavements subjected to the highest load and tire inflation pressure (Thick $S3P3$ and Thin $S3P3$, respectively); a thick pavement at the highest load and lowest inflation pressure (Thick $S1P3$); and a thick pavement at the lowest load and highest tire inflation pressure (Thick $S3P2$).

If the pavement and loading condition were fixed, the highest RR_f was observed for the Case $T3V1$, which represented the most compliant pavement structure. In addition, temperature was more relevant than traveling speed when analyzing the rolling resistance force. Regarding pavement type, no difference was observed between thin and thick pavements as long as the temperature was low, regardless the value of V. In other words, the pavement type is irrelevant for RR_f as long as the AC layer is sufficiently stiff. On the other hand, when the temperature was high, thin pavement presented higher rolling resistance force than thick pavement, and the difference was higher for the low speed.

The effect of loading conditions was analyzed for thick pavement only because it is composed of a higher volume of viscoelastic material than thin pavement. Since viscoelastic material dissipates energy, the effect of tire–pavement interaction on rolling resistance is expected to be higher. The RR_f decreased as load decreased and increased as tire inflation pressure diminished. Reducing tire-inflation pressure was of greater significance than decreasing the load when analyzing the rolling resistance force.

Structure-Induced Rolling Resistance

Dissipation-induced and deflection-induced approaches have been used to calculate the contribution of pavement structure to rolling resistance [i.e., structure-induced rolling resistance (SRR)], and by extension to fuel consumption and greenhouse gas emissions. The dissipation-based SRR (SRR_{dis}) results from dividing the energy dissipated by the viscoelastic AC layer by the traveled distance (Pouget et al. 2012). On the other hand, the deflection-based SRR (SRR_{def}) is obtained by dividing the power of the stresses/forces applied by the tire by the speed (Chupin et al. 2013). Using analytical procedures, both methods proved equivalent (Louhghalam et al. 2014).

Model III was successfully used to verify the equivalency between dissipation-based and deflection-based rolling resistance. The external work performed by the reaction forces while the tire traverses the central 1,000 mm was calculated as the area enclosed by the load-deflection curve in each direction (W_x, W_y, and W_z along the x-direction, y-direction, and z-direction, respectively). Variation of the total external work ($W = W_x + W_y + W_z$) with time for both pavements, speeds, and temperatures shown in Fig. 7. For the low temperature, almost all the work was recovered after the tires passed the studied surface section and the slope was almost zero (i.e., no dissipation). For the high temperature, the slope in the W versus t plot was computed; when divided by the speed, the slope provided the deflection-induced rolling resistance (SRR_{def}).

Table 6 compares SRR_{dis} and SRR_{def}. In addition, for the deflection-induced *SRR*, the effect of the in-plane contact forces was determined by comparing SRR_{def} using the total external work and the work performed by the vertical forces only. The highest difference between SRR_{dis} and SRR_{def} was 1.62% for the thin pavement subjected to the highest temperature and speed, proving excellent agreement between the deflection-based and dissipation-based *SRR*. This agreement was not observed when comparing SRR_{dis} and SRR_{def} in the full pavement model (Model II). In addition, a minimal influence of the in-plane contact forces was observed, as the highest difference between considering or ignoring the contact forces in the x-direction and y-direction was 1.8% for the thick pavement when $V = 115\ \text{km/h}$ and $T = 113°\text{C}$.

Table 6. Comparison between Dissipation-Induced and Deflection-Induced SRR

Case	Slope ($\text{N} \cdot \text{mm/s}$)		SRR_{dis} (N)	SRR_{def} (N)		Difference (%)	
	Total	Vertical		Total	Vertical	Total	Vertical
Thick $S3P3T3V1$	14,447	14,312	6.570	6.501	6.440	1.05	1.98
Thick $S3P3T3V3$	38,182	37,518	1.202	1.195	1.174	0.58	2.31
Thin $S3P3T3V1$	49,584	49,380	22.323	22.313	22.221	0.05	0.46
Thin $S3P3T3V3$	102,304	101,435	3.255	3.203	3.175	1.62	2.46
Thick $S3P2T3V1$	10,346	10,300	4.669	4.656	4.635	0.29	0.73
Thick $S3P2T3V3$	28,954	28,679	0.914	0.906	0.898	0.83	1.77
Thick $S1P3T3V1$	12,419	12,092	5.548	5.589	5.441	−0.73−0.73	1.92
Thick $S1P3T3V3$	31,668	30,457	0.964	0.991	0.953	−2.81−2.81	1.13

As part of the deflection-induced SRR, it has been affirmed that the tire is always moving uphill. For the linear-elastic case, the tire would be at the bottom of the surface deflection and the SRR would be higher as the difference between the point of maximum deflection and the location of the resultant of the vertical forces is higher. This statement was verified based on the results of Model III.

For a fixed time, the deflections along each of the 31 paths across the traffic direction were obtained, and the location of the paths' maximum deflection (x_{max}) was calculated. In addition, the reaction force in the vertical direction (F_z) at all the nodes for the same instant of time was also obtained. The resulting variation of F_z along the x-coordinate was used to calculate the location of the resultant along each path. Fig. 8 presents the location of the maximum deflection and the vertical reaction force resultant at a fixed time and various temperatures and speeds. A clear trend is observed: as the degree of compliance of the AC increased, the average separation between x_{max} and F_z increased. For instance, for the thin pavement case, the least-viscoelastic case (i.e., $T1V3$ = fastest speed and lowest temperature as presented in Table 1) showed both locations as almost coincidental. After decreasing the speed to $V1$, x_{max} became 9.5 mm. On the other hand, when the temperature and speed were the highest, the average distance between the maximum deflection and the resultant was 18.4 mm.

Finally, the largest average separation between $x_{\max}$ and the resultant of F_z was observed for the most-compliant case (i.e., $T3V1$ = highest temperature and lowest speed) and its magnitude was 39.8 mm.

Conclusions

A semi-decoupled tire–pavement interaction modeling approach was introduced by using three finite-element models in a four-step procedure. The three models are (1) a hyperelastic tire in contact with a rigid surface; (2) a three-dimensional pavement model; and (3) a hyperelastic tire rolling on a deformable viscoelastic body. In the four-step procedure, the contact stresses of the tire interacting with a rigid surface were used as input in the pavement model. After applying dynamic analysis of the pavement subjected to a moving load, boundary conditions were obtained for the tire rolling on a viscoelastic deformable body. Finally, contact stresses from the interaction between deformable tire and pavement were used as input in the pavement model. The tire model was validated with measured contact area, tire deflection, and vertical contact stresses, and the pavement model has been successfully compared with measurements from instrumentation.

The flexibility of the surface contacted by the tire mainly affected the transverse contact stresses and, to a lesser degree, the distribution of the vertical contact stresses. Regarding critical pavement responses, the maximum vertical strain in the AC layer was the most affected when comparing pavement responses assuming rigid or deformable body. Furthermore, vertical shear strain in the AC was modified after changing the loading condition. Rolling resistance analysis was based on the tire rolling of a viscoelastic deformable body. The rolling resistance force was higher for thin pavement and was more affected by AC temperature than by tire speed. In addition, a change in tire inflation pressure from 758 to 552 kPa caused higher change in the rolling resistance force than modifying the load from 44.4 to 35.6 kN. The deflection approach showed that the influence of in-plane contact stresses on SRR is negligible. Finally, deflection and dissipation approaches provided excellent agreement when calculating pavement contribution to rolling resistance. However, the agreement vanished when the two approaches were applied to the full pavement model. This issue is currently being researched by the authors.

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Notation

The following symbols are used in this paper:

F_z	=	vertical reaction force along the traffic direction;
P	=	applied load;
S	=	tire-inflation pressure;
SSR	=	structure-induced rolling resistance;
SSR_{dis} and SSR_{dfl}	=	dissipation-based and deflection-based SSRSSR;
T	=	pavement temperature;
t	=	time;
V	=	tire speed;

W	=	total work performed by the reaction forces;
$W_{x,y,z}$	=	work performed by the reaction forces in the longitudinal, vertical, and transverse directions;
x, y, and z	=	longitudinal, transverse, and vertical direction, respectively;
x_{max}	=	location of the maximum deflection;
$\epsilon_{11,ac}$ and $\epsilon_{33,ac}$	=	maximum longitudinal and transverse tensile strain at the bottom of the AC, respectively;
$\epsilon_{22,ac}$, $\epsilon_{22,bs}$, and $\epsilon_{22,sg}$	=	maximum vertical strain in the AC, base, and subgrade, respectively;
$\epsilon_{23,50\text{ mm}}$	=	maximum shear strain 50 mm from the pavement surface;
$\epsilon_{23,ac}$, $\epsilon_{23,bs}$, and $\epsilon_{23,sg}$	=	maximum vertical shear strain in the AC, base, and subgrade, respectively; and
$\sigma_{x,y,z}$	=	longitudinal, transverse, and vertical contact stresses.

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