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Potential of three-dimensional footprint mold in investigating the effect of tractor tire contact volume changes on rolling resistance

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ABSTRACT

In the present study a method is developed to estimate the three-dimensional (3D) footprint of pneumatic agricultural tires based on molding the tire footprint by liquid plaster and converting these molds to three-dimensional models using a 3D scanner. A Goodyear 12.4–28, 6 ply tractor drive tire was operated on a clay loam soil in a soil bin under three vertical loads, using three inflation pressures and three soil moisture contents at a constant forward speed of 0.45 ms^{-1}. The results showed the rut depth and contact volume increased by increasing the vertical load and inflation pressure and soil moisture content. Contact volume was increased by increasing the vertical load, inflation pressure, and soil moisture content. A multiple regression model was presented with a coefficient of determination (R^2) of 0.88 to predict the contact volume based on vertical load, inflation pressure, and soil moisture content. Finally, a univariate regression model was presented to predict the rolling resistance based on the contact volume with a relatively high R^2 of 0.93. It was also found that in deformable surfaces, vertical penetration and soil contact volume are the main reasons for the increase in rolling resistance.

1. Introduction

The wheels of a vehicle must fulfill duties such as supporting the weight of the vehicle, cushioning the vehicle over the surface irregularities, providing sufficient traction for driving and braking, and providing adequate steering control and direction stability (Wong, 2001). Because of performing these actions properly and efficiently, pneumatic tires are widely used for road and off-road vehicles. Because these tires have a widespread application and since the tire is the only interface between the vehicle and the road, many scientific studies have been conducted on the interaction between the tire and the road surface (De Beer and Fisher, 2013). Soil compaction, rolling resistance, loss of energy, and wheel slip are critical parameters that are the result of soil and wheel contact (Taghavifar and Mardani, 2013). Studying tire-soil interaction in agricultural lands is important because vertical deformation of soil (as a deformable material) is sometimes larger than the tire deflection. Knowing that the power efficiency of pneumatic tires on concrete surfaces is about 90% and sometimes less than 50% in loose or sandy soils, it is necessary to pay a special attention to fuel consumption (Wulfsohn et al., 1988; Lohnen, 1999; Gill and Vanden Berg, 1968).

The rolling resistance contributes to the energy that is lost when the tire is rolling. The main reason for the energy loss is the continuous deflection of the tire and deformation of the ground surface. Various parameters affect the rolling resistance including tire inflation pressure, tire load, tire diameter, tire width, tire construction, tire tread, speed, surface adhesion, sliding, and relative micro-sliding between contact surfaces (Wong, 2001).

Various mathematical algorithms have been presented to predict tire contact area with the soil. Grečenko (1995) presented several formulae for predicting the off-road tire footprint area on the hard ground. Many researchers have attempted to express the super ellipse shape of the tire surface in contact with the soil (Hallonborg, 1996; Keller, 2005; Roşca et al., 2014), and finally achieved the best fit between model data and experimental values with super ellipse exponent (Eq. (1)) as $k = 3.5$ (Roşca et al., 2014); where k is the super ellipse exponent, a is the major axis of the super ellipse, b is the minor axis of the super ellipse, x is the distance along the driving direction (m), and y is the lateral distance at right angles to the driving direction.

$$\left(\frac{2x}{a}\right)^k + \left(\frac{2y}{b}\right)^k = 1 \quad (1)$$

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The use of image processing techniques to determine the shape of the contact area as well as the influence of various parameters on that were investigated in (Diserens, 2009; Diserens et al., 2011; Taghavifar and Mardani, 2013). In addition to the physical properties of the contact area, some researchers made an effort to find the relationship between the contact area and the rolling resistance and ultimately offered a model to optimize energy consumption. Taghavifar and Mardani (2013) investigated the effect of velocity, inflation pressure, and vertical load on the rolling resistance of a radial-ply tire, and found that the rolling resistance is a function of the contact area. Besides, they reported a significant increase in the rolling resistance results due to the increase in contact area. Low tire inflation pressure or high vertical load can lead to overloaded tires and, in soft ground, result in high sinkage (Hallonborg, 1996). Accordingly, due to tire sinkage in soft ground and the effect of tire-soil parameters on tire sinkage, it can be stated that contact volume is a better parameter than contact area for analyzing tire-soil interaction. To predict the three-dimensional (3D) tire footprint, many studies have been carried out with the use of the Finite Element Method (FEM). In some studies, FEM was used for the analysis of tire-soil interaction (González Cueto et al., 2016, 2013). Also a combination of FEM for modeling a tire and a deep soil layer, and the Discrete Element Method (DEM) for modeling the surface layer of soil have been employed (Nakashima and Oida, 2004; Michael et al., 2015). Botta et al. (2009) investigated the effect of the number of tractor passes on rut depth and compaction in two tillage systems. They used two tractors with different weights and two different tillage systems to quantify their interaction effect on soil cone index and rut depth. They found that tire sizes and the rut depth/tire width ratio are particularly important with respect to compaction for different numbers of passes. They also found that axle load, tire size, and soil water content are important parameters affecting the rut depth and soil compaction. In a field study, Mohsenimanesh and Ward (2010) estimated the 3D tire footprint using dynamic soil–tire contact pressures. They used six miniature pressure sensors, three on the lug face and three on the undertread region between two lugs. In this method, the maximum rut depth was assumed to coincide with the peak pressure, and the other points on the contact patch corresponded with varying pressure levels on a rolling wheel. Contact pressure was used as a mediator parameter to estimate the depth of tire penetration into the soil, and the rut depth was not measured directly. Pierzchała et al. (2016) measured the wheel ruts and volume of the displaced soil using the close-range photogrammetry. Photogrammetry is the science of making measurements from photographs, especially for recovering the exact positions of surface points. In this study, they used an aerial Image of wheel rutting. In order to calculate the volume of the displaced soil, they reconstructed the original terrain surface. Finally, they visually identified the surface that altered by the wheel rutting and clipped it from the surface model. The extraction trail model was compared with the pre-rutting terrain surface and using the software calculations, and thus the volume of soil deformation was obtained. Kenarsari et al. (2017) used the close-range digital photogrammetry to create 3D models of tractor tire footprints in the static and rolling condition of soil bin. They used the obtained models to estimate the tire footprint depth, area and volume. They also evaluated the accuracy of the results obtained from this method and concluded that photogrammetry is a relatively strong technique in modeling the complex soil deformations in both static and rolling conditions. Also they concluded that lighting conditions are important especially for the dark organic soil.

Review of the literature indicates that the 3D contact volume is an important parameter in a given terramechanic system. Vertical load, tire inflation pressure, soil moisture content, and tire design (including ply rating, aspect ratio, etc.) influence tire contact volume. In turn, tire contact volume influences tire rolling resistance and soil compaction. Hence, the aim of this study is to conduct a thorough study on this subject.

2. Materials and method

A soil bin in the laboratory of Iranian Agricultural Engineering Research Institute (AERI) was utilized for the experiments. The soil bin, which was 20 m long, 1.7 m wide, and 1.3 m deep, was filled with clay loam soil. Soil textural composition and some mechanical characteristics are shown in Table 1. The soil is an inorganic silty-clay soil with low plasticity, which classified as CL-ML according to the Unified Soil Classification System (USCS, ASTM D 2487–83) (ASTM D, 1985). A single wheel tester (SWT) with chassis dimensions of 3.10 m in length, 1.90 m in width, and 2.23 m in height was used for operating the tire in the soil bin (Fig. 1). To supply tire input torque, an 11 kW three-phase electric motor (model 160L4A; MOTOGEN Co., Tabriz, Iran) was applied. A gearbox with a reduction ratio of 1:104 was used to reduce the rotation velocity and increase the torque delivered to the tire. An AC motor speed controller (model LS600-2020; MAXTHERMO-GITTA Group Co., Zhonghe City, Taipei County 235, Taiwan) providing variable frequencies powered the electric motor, allowing the intended wheel rotational velocities to be attained. A torque transducer (Datum Electronics, PTO shaft torque and power system; Series 420 PTO system, East Cowes, United Kingdom) with the capacity of 1800 N m was installed between the electric motor and gearbox to measure torque, rotational velocity, and power delivery to the wheel. A hydraulic system with the output pressure of 1.5 MPa was used to apply a vertical load on the tire. To power the hydraulic system, a 2.2 kW three-phase electric motor (model 112M6; MOTOGEN Co., Tabriz, Iran) with a gearbox was used. A compression load cell (model CLP-30KNB; Tokyo Sokki Kenkyujo Co., Ltd, Tokyo, Japan) with a 30 kN capacity was calibrated and then placed between the hydraulic cylinder and frame to measure the vertical load on the tire. Also, a fifth wheel was mounted on the frame to measure forward velocity during the investigation using a digital encoder (model RS-58; RS Components Ltd., Corby, United Kingdom).

The experiments were conducted in the soil bin laboratory to investigate the effect of the tire-soil interface on contact area, contact volume, rut depth, the rolling resistance, and 3D footprint changes under different conditions of vertical load of 6, 9 and 12 kN, inflation pressure of 80, 120 and 160 kPa, and soil moisture content of 11.20, 14.86, and 18.68 %d.b, a factorial layout at four replications, and an approximate constant forward speed of 0.45 ms^{-1}. A summary of the experimental parameters and inflation pressure recommended by the tire manufacturer for every level of vertical load (Titan International I, 2017) are shown in Table 2. The utilized driven tire was a Goodyear 12.4–28, 6 ply. The SPSS version 23 statistical software (IBM, Armonk, New York) was used for the data analysis. Moreover a completely randomized experimental design was chosen with three replications.

Table 1
Textural composition and some mechanical characteristics of the experimental soil.

Characteristic		%
Textural composition	Clay	29
	Silt	33
	Sand	38
	Organic matter	1.7
	Organic carbon	0.6
Mechanical characteristics	Plastic limit (PL)	24
	Liquid limit (LL)	32
	Shrinkage limit (SL)	11