



# Relationships among the contact patch length and width, the tire deflection and the rolling resistance of a free-running wheel in a soil bin facility

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## Abstract

Qualitative and quantitative analysis of contact patch length-rolling resistance, contact patch width-rolling resistance and tire deflection-rolling resistance at different wheel load and inflation pressure levels is presented. The experiments were planned in a randomized block design and were conducted in the controlled conditions provided by a soil bin environment utilizing a well-equipped single wheel-tester of Urmia University, Iran. The image processing technique was used for determination of the contact patch length and contact patch width. Analysis of covariance was used to evaluate the correlations. The highest values of contact patch length and width and tire deflection occurred at the highest wheel load and lowest tire inflation pressure. Contact patch width is a polynomial (order 2) function of wheel load while there is a linear relationship between tire contact length and wheel load as well as between tire deflection and wheel load. Correlations were developed for the evaluation of contact patch length-rolling resistance, contact patch width-rolling resistance and tire deflection-rolling resistance. It is concluded that the variables studied have a significant effect on rolling resistance.

**Additional key words:** terramechanics; tractor; off-road vehicles; soil-wheel interaction.

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## Introduction

Wheel, in off-road traversing, is subjected to different forces and the condition of soil-wheel interactions plays a fundamental role in traversing quality. Tire parameters, as well as soil properties, are influential on steering, stability, traction, and braking of wheeled vehicles. Traction as a general term includes wheel thrust (gross traction), rolling resistance, and the subtraction of gross traction and rolling resistance (soil resistance for driving wheels) namely, net traction (drawbar pull). Free-running (free-rolling) wheel and driving wheel are separate terms. Regarding the tractive efficiency the slip level by driving wheel is considered, which indicates that the optimal soil contact surface (by 10% slip) increases with the traction requirement. Tire rolling resistance is expressed as a required force to keep tires rolling at a steady pace. It is also known that rolling resistance, as an important energy loss fac-

tor, has a momentous impact on vehicle fuel efficiency. Energy loss in agricultural tires because of inaccurate management has been reported in USA to be about 575 million liters diesel per year (Wulfsohn, 1987). Considering the abovementioned facts, investigating the effect of tire parameters on rolling resistance is a significant issue. Many attempts have been made to explore the rolling resistance analytically, empirically and semi-empirically. Analytical approach is difficult to be interpreted by a tractor driver who should have good mathematical knowledge on the issue. Semi-empirical equations are limited to the prediction of separate performances in driving and braking modes. However, the model of Shmulevich & Osetinsky (2003), which is perfectly adapted for traction and resistance forces in the field, has been successfully verified by the data reported in the literature (Osetinsky & Shmulevich, 2004; Battiato & Diserens, 2013) and by full-scale field experiments.

Rolling resistance was analytically calculated from the standpoint of soil mechanical strength while it was established based on the assumption that at the tire contact patch, wheel is a plate penetrating to a depth of soil equal to the rut depth or soil sinkage (Bekker, 1960). Taghavifar & Mardani (2013) in a previous study investigated the effect of velocity, tire inflation pressure, and wheel load on rolling resistance and found that the effect of forward velocity on rolling resistance is negligible. They also reported that the main contributing factors on rolling resistance are wheel load and tire inflation pressure. Many studies have been designed so far to measure experimentally the rolling resistance focusing on the effect of different variables such as wheel load, tire inflation pressure, speed, sinkage, etc. on rolling resistance (Çarman, 2002; Zoz & Grisso, 2003; Way & Kishimoto, 2004; Elwaleed *et al.*, 2006; Coutermarsh, 2007; Kurjenluoma *et al.*, 2009; Taghavifar & Mardani, 2013). Analytical models have also been developed for determination of rolling resistance (Bekker, 1960; Pope, 1971; Wong, 1984; Komandi, 1999). Coutermarsh (2007) in a fused analytical-experimental study presented data from rubber tire rolling resistance measurements at three depths (0.0508, 0.127, and 0.1778 m) on uniform-density dry sand at velocities from 2.1 up to 18 m/s and at load ranges from 4.53 to 10.26 kN. It was reported that in dry sand, the rolling resistance increases with velocity until a peak and then it starts to decrease. Kurjenluoma *et al.* (2009) investigated the correlation between rolling resistance and rut depth at different ranges of wheel load and tire inflation pressure and reported that owing to lower rolling resistance, flotation tires are recommended for run-off-road vehicles with field inflation pressure, *i.e.* low inflation pressure (not with road pressure, high inflation pressure) in soft soil. Elwaleed *et al.* (2006) explored the effect of tire inflation pressure on lugged tires using a single wheel-tester and reported that reduced inflation pressure led to the decrease of rolling resistance; however, more decrease than recommended value resulted in the increase of rolling resistance. Çarman (2002) also reported that rolling resistance has a polynomial increase with the increase of wheel load.

From the theoretical perspective, the following model could be presented. The simplest basis for the prediction of rolling resistance is to assume that the work done against the rolling resistance is the work performed to compact the soil by a plate. Bekker (1960) proposed the following for the required work to deform the soil:

$$W = bl \int_0^{z_0} pdz \quad [1]$$

where  $W$  is work,  $z$  is sinkage,  $z_0$  is the maximum sinkage,  $b$  is the width of plate,  $l$  is the length of plate,  $p$  is the pressure applied to the plate.

$$W = \frac{l(k_c + bk_\phi)}{n+1} \left[ \frac{W}{l(k_c + bk_\phi)} \right]^{\frac{(n+1)}{n}} \quad [2]$$

where  $k_c$  and  $k_\phi$  are soil moduli and  $n$  is soil sinkage exponent. Bekker (1960) assumed that the wheel was equivalent to a plate continuously being pressed into the soil to a depth equal to the depth of the rut produced by the wheel considering the following:

$$p = \left( \frac{k_c}{b} + k_\phi \right) z^n \quad [3]$$

The wheel is assumed to impose a uniform pressure on the soil which deforms uniformly over the contact area until the contact pressure is equal to the weight on the tire. Consider the work done by a towing wheel for a distance  $l$  against the rolling resistance  $R$ . In simple terms, this is equal to the work done in forming the rut as calculated for the plate, length  $l$ , width  $b$  pressed into the soil.

$$Rl = \frac{l(k_c + bk_\phi)}{n+1} \left[ \frac{W}{l(k_c + bk_\phi)} \right]^{\frac{(n+1)}{n}} \quad [4]$$

Therefore,

$$R = \frac{(k_c + bk_\phi)}{n+1} \left[ \frac{W}{l(k_c + bk_\phi)} \right]^{\frac{(n+1)}{n}} \quad [5]$$

Writing this in terms of the ground pressure  $p = W/bl$ , the rolling resistance is obtained as:

$$R = \frac{b}{(n+1) \left( \frac{k_c}{b} + k_\phi \right)^{\frac{1}{n}}} p^{\frac{(n+1)}{n}} \quad [6]$$

The main purpose of this work was to study the effect of both contact patch length and width as well as tire deflection on rolling resistance, particularly inside soil a bin facility controlled conditions utilizing a single wheel-tester. We aimed to assess several experiments in this regard to shed light on the role of the above mentioned factors on rolling resistance, outlining the following hypotheses: (i) contact patch geometry determines the size of contact at soil-tire interface and thus contributes to soil deformation area and rolling resistance; (ii) tire deflection can potentially be assumed as an index of rolling resistance.

## Material and methods

### General testing facility

A manufactured soil bin with 23 m of length, 2 m width and 1 m of depth (Mardani *et al.*, 2010) was used to provide controlled experiments. The general depiction of the soil bin system is presented in Fig. 1. The major components of the bin system were the carriage and a single wheel-tester mounted to the carriage. To pull the carriage, an electric drive system is used by a 3-phase 22 kW at 1457 rpm Motogen driver electric motor. The generated power of the electric motor is transmitted to the carriage by means of two chain systems on the bin sides. Carriage travel speed can be adjusted within 20 km/h by applying a LG (Life's Good) inverter reducing unit (variable frequency drive-Stravert iS5) located at the main control console close to the set-up facility.

Net traction is the vector sum of the four reaction forces, and the input torque can be determined by the difference among the four reaction forces multiplied by the distance between the links. Vertical movement of the tire in this design configuration is permitted while traversing. For measuring the horizontal force, vertical force, sinkage, and rotation of the test tire, the facility is equipped with various transducers. The data acquisition system is able to: receive the data, measure the signals in real time, display the information on a monitor screen and finally record the information on a storage medium in real time.

For the experiments, a 220/65R21 driving tire was utilized. The volume of the soil bin was assessed to be 46 m<sup>3</sup> and it was filled with clay loam soil in order to simulate the real farmlands condition of the testing place, Urmia, Iran. The soil constituents were 34.3% sand, 22.2% silt and 43.5% clay. Soil bulk density, moisture content, frictional angle and cone

index were 2.36 Mg/m<sup>3</sup>, 12%, 32°, and 700 kPa, respectively.

### Data collection

#### *Data collection of rolling resistance*

Fig. 1 shows that the soil bin facility included four S-type load cells, able to measure tension and compression loads with 500 kg capacity and 0.01 precision (enough reliability and measurement stability). The load cells were calibrated and then situated on four parallel arms acting as linkages between the wheel-tester and the carriage to quantify the longitudinal forces. Furthermore, one load cell measured the vertical force applied to the wheel. The longitudinal and vertical load cells were connected to a data acquisition system including digital indicators and one data logger. A laptop device was used for data acquisition system, monitoring and real-time control of the system.

#### *Data collection of contact length, width and tire deflection*

A new method based on the application of image processing was performed to calculate contact pressure. A white powder was poured at the soil-tire interface in each treatment and the images were taken simultaneously with a Panasonic Lumix DMC TZ25 camera at a constant distance, using a 4×4 cm index for calibration. The images were taken in a RGB environment where illumination is combined with color in a manner that any small change in color space could significantly change the color of image. Therefore, it is necessary to use a space where color and illumination are separated. Utilising component *s* (saturation) in HSV color space and *b* component in LAB space, a better separation of tire track and background was achieved. First, the components were normalized in the range between 0 and 1. For improving the separation, the gamma correction was applied as following.

$$x_1 = (s + v) \quad [7]$$

$$x_2 = x_1^\alpha \quad [8]$$

where  $\alpha=2$  was found to be the optimal value for separations. Furthermore, dilation was performed with structural elements and Otsu's method was applied to achieve the desired thresholding level and binary images were obtained (Otsu, 1975). To delete the noise effects on the images, we also used structural element closing. Subsequently, connected components which



**Figure 1.** General testing facility setup and its components.

had pixels lower than a definite level were removed and the connected region was filled. A sample of the taken and processed images is shown in Fig. 2. The contact pressure value was calculated as the wheel load at each treatment divided by contact area. The command `imdistline` was applied to all the processed images to determine the contact length and width on account of the corresponding pixels. Additionally, the pre-determined length of the calibration object (Fig. 2a, black square paper, 4×4 cm) was calculated by the `imdistline` for each of the treatment images. Knowing the calibrator dimensions, the contact length and width were quantified by image processing technique for each of the treatments. A digital inclinometer, situated on a connecting arm, was used for the on-the-go measurement of tire deflection under implemented treatments sending the real time data to the data acquisition system.

## Variables

Table 1 shows that the tire inflation pressure and wheel load included four and five levels, respectively, with three replicates. The effects of contact patch length, contact patch width and tire deflection on rolling resistance were analyzed by ANCOVA

(analysis of covariance). Tire inflation pressure and wheel load were set as independent variables, rolling resistance as dependent variable and contact patch length and width and tire deflection as covariates. The analyses were conducted at 1% probability level of significance using SPSS 19 software (IBM Corp, 2010).

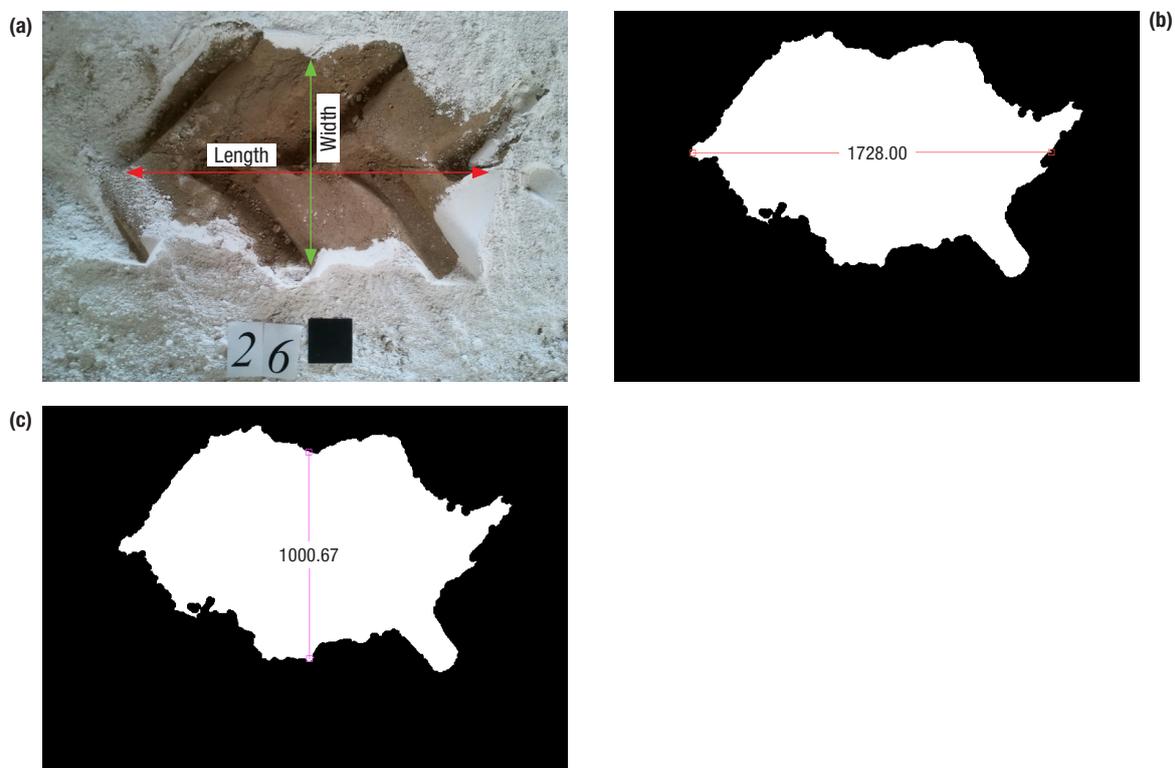
## Results and discussion

### Statistical results

ANCOVA results showed that the effect of contact area and contact length on rolling resistance was significant at the 5% probability level, wherein the effects of tire deflection, wheel load, tire inflation pressure and interaction of wheel load and tire inflation pressure on rolling resistance were all significant at the 1% probability level (Table 2).

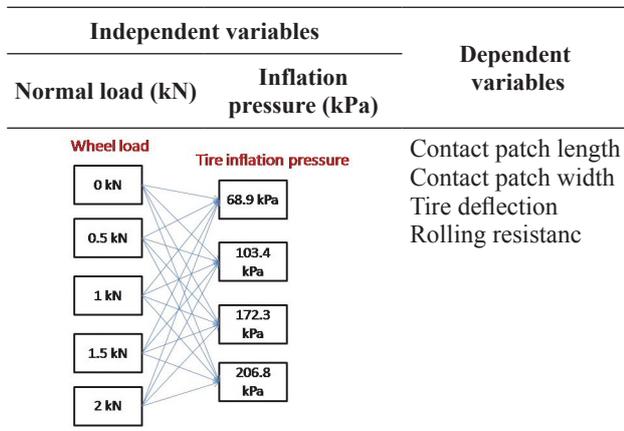
### Wheel load-tire deflection relationship

Deformable tire distorts when being under normal load and the magnitude of deflection depends on tire stiffness. Moreover, tire tread pattern, inflation pressure,



**Figure 2.** Sample of images taken from the experiment (wheel load of 2 kN and tire inflation pressure 68.9 kPa): (a) contact area at the soil-tire interface before implementation of image analysis showing the contact patch length and width and calibrator (black square, 4×4 cm); processed image including (b) the length and (c) width of contact in terms of pixels

**Table 1.** Summary of the experiment conducted. There were five levels of wheel load and four levels of inflation pressure with different configurations and combinations forming 20 treatments



**Table 2.** Analysis of co-variance for rolling resistance by contact patch length, contact patch width and tire deflection

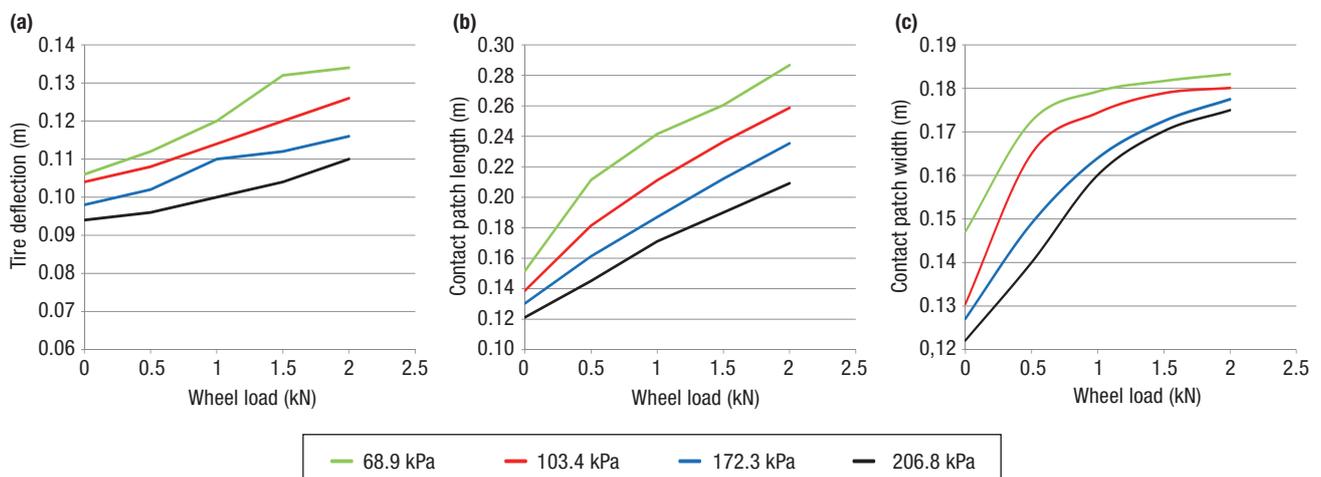
Source	Sum of squares	DOF	Mean squares	F-Value
Tire deflection	3.089	1	3.089	10.461**
Contact length	0.097	1	0.097	0.329*
Contact width	0.810	1	0.810	2.743*
Wheel load	244.273	4	61.068	206.795**
Inflation pressure	52.501	3	17.500	59.261**
Wheel load × Inflation pressure	385.521	12	32.127	108.791**
Error	5.020	17	0.295	
Total	56976.803	40		

DOF: degrees of freedom. \*\*, \*: significant at the 1% and 5% probability level, respectively.

ground strength (*i.e.* hard ground or soft ground), and high or low lugged tires are other beneficial factors contributing to tire deflection. Tire deflection was found to increase linearly with respect to wheel load in the range of the inflation pressures explored (Fig. 3a). It was noticed that the buffed tire led to a greater deflection than the unbuffed tire at all loads and inflation pressures studied. This may be attributed to the lower stiffness of the buffed tires caused due to the removal of the tread portion and smoothening of the side walls during the process of buffing. Yong *et al.* (1978) and Pandey & Tiwari (2006) also observed similar deflection characteristics for the buffed tires. Here, it is important to distinguish between the carcass stiffness  $k_c$  [kN/m] and the inflation pressure dependence stiffness  $\Delta K_p$  [kN/m·kPa]. Carcass stiffness is an intrinsic characteristic of the tire (Lines & Murphy, 1991) but the so called inflation pressure dependence stiffness is under the effect of the tire inflation pressure.

### Wheel load-contact patch length and contact patch width relationship

Contact patch length was found to have a linear relation with wheel load (Fig. 3b); however, contact patch width was found to be a polynomial (order 2) function of wheel load (Fig. 3c). This inconsistency may be attributed to the fact that the expansion of the contact area under the loading effect is greater in the longitudinal direction than in the lateral side. Furthermore, it was observed that both the contact patch length and width are lower at higher tire inflation pressures. This might also be due to the greater stiffness of the inflated tires caused by the tread portion and smoothening of the side walls. Hallonborg (1996), Sharma & Pandey (1996), Febo *et al.* (2000) and Keller (2005) reported similar effects of inflation pressure and normal load on contact patch determinations.



**Figure 3.** Tire deflection (a), contact patch length (b) and contact patch width (c) vs. load carried by wheel at various tire inflation pressures.

### Tire deflection-rolling resistance correlation

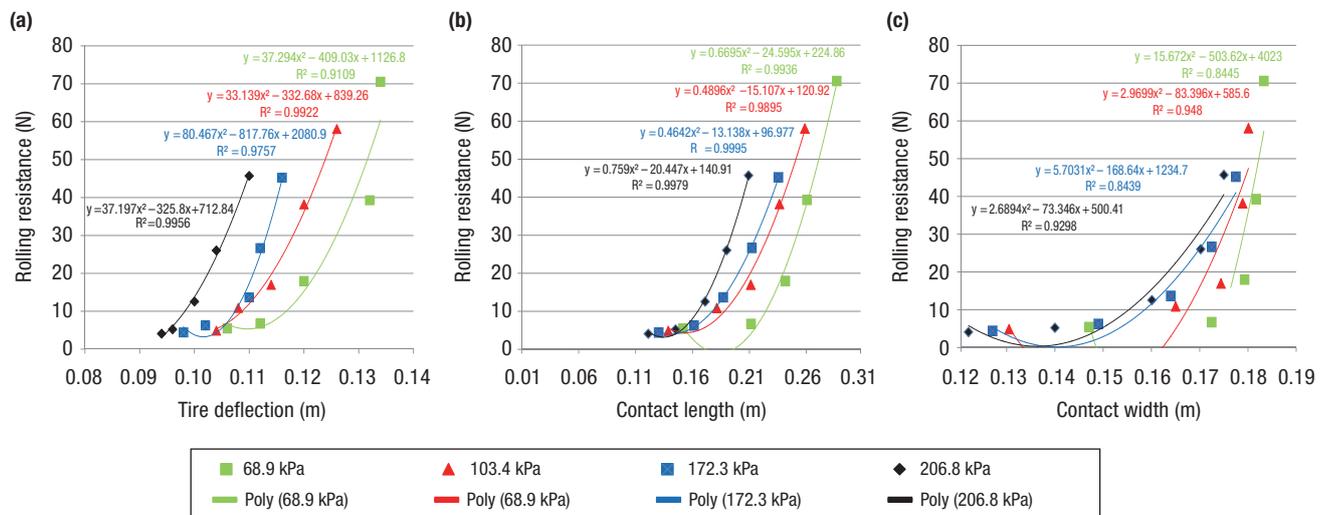
Rolling resistance is described as the parasitic energy dissipated by the constant deflections of traversing tire under acting load. This implies that tire deflection has a direct effect on rolling resistance. The converted energy is the summation of the required work to deform the rubber (elastic deformation) and the soil (plastic deformation) at soil-tire interface. Our experimental results under controlled conditions revealed that rolling resistance is a polynomial (order 2) function of tire deflection at the ranged tire inflation pressures conducted (Fig. 4a). We also noticed a steeping increase of rolling resistance when tire deflection increments.

### Contact patch length-rolling resistance and contact patch width-rolling resistance correlations

As shown in Figs. 4b and 4c, rolling resistance increases by both contact length and width, respectively. However, the rate of increase at higher contact lengths and widths for each inflation pressure treatments is higher when compared to lower ones. This might be attributed to the fact that at these conditions, a greater volumetric amount of soil profile is engaged with the tire and the elastic soil deformation, rut depth, increases and the amount of rolling resistance increases accordingly. This was also confirmed by Kurjenluoma *et al.* (2009), who observed that the correlations between contact patch

length and rolling resistance and also contact patch width and rolling resistance are nonlinear and can be better expressed by polynomial (order 2) relationships. Similar results were also obtained by us in a previous study of the correlations between the contact area and rolling resistance (Taghavifar & Mardani, 2013). These correlations can be attributed to the greater contact patch at soil-tire interface under various treatments, resulting in a greater area of soil deformation. Soil deformation in its turn leads to the increase of rolling resistance. Further studies are needed to include different soil properties and also various tire types for more generalization of the obtained results and trends.

In summary, rolling resistance is a very significant component of soil-wheel interaction in the Terramechanics' terminology. From the economic perspective, the reduction of rolling resistance has a great effect on the decrease of fuel consumption. Based on the obtained results, there are linear relationships between contact patch length and wheel load and also between tire deflection and wheel load. Unlike tire deflection and contact length, contact width may be better expressed by a polynomial function of the effect of various loadings. This might be attributed to the fact that the expansion of contact area under the loading effect is higher in the longitudinal direction than in the lateral side and also that there is more limitation in the expansion of tire at soil-tire interface in the lateral direction than in the longitudinal one. The results showed that rolling resistance increases with a polynomial function (order 2) with respect to tire deflection, contact length and contact width.



**Figure 4.** Correlation between (a) tire deflection, (b) contact patch length and (c) contact patch width and rolling resistance as affected by wheel load at different tire inflation pressures.

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