

## Prediction of Bias-Ply Tire Rolling Resistance Based on Section Width, Inflation Pressure and Vertical Load

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**Abstract:** This study was mainly conducted to predict rolling resistance (R) of bias-ply tire based on section width (b), inflation pressure (P) and vertical load (W). For this purpose, rolling resistance of four bias-ply tires with different section width was measured at three levels of inflation pressure and four levels of vertical load. Results of rolling resistance measurement for bias-ply tires No. 1, 2 and 3 were utilized to determine regression model and three-variable linear regression model  $R = 0.00932 b - 0.00124 P + 0.04003 W - 0.04556$  with  $R^2 = 0.97$  was obtained. Also, results of rolling resistance measurement for bias-ply tire No. 4 were used to verify model. The paired samples t-test results showed that the rolling resistance values predicted by model were statistically less than the rolling resistance values measured by test apparatus. To check the discrepancies between the rolling resistance values predicted by model with the rolling resistance values measured by test apparatus, RMSE and MRPD were calculated. The amounts of RMSE and MRPD were 0.036 kN and 16.3%, respectively. Rational amounts of RMSE and MRPD confirmed that the three-variable linear regression model may be used to predict rolling resistance of bias-ply tire based on section width, inflation pressure and vertical load. However, to calculate actual rolling resistance values or rolling resistance values measured by test apparatus ( $R_M$ ) based on rolling resistance values predicted by model ( $R_p$ ) the linear equation  $R_M = 1.135 R_p + 0.010$  with  $R^2 = 0.97$  can be strongly suggested.

**Key words:** Bias-ply tire • Rolling resistance • Prediction • Section width • Inflation pressure • Vertical load

### INTRODUCTION

The most important factor in tractor operation is traction performance. Obtained data from traction performance measurements indicates that gross traction and rolling resistance must be subtracted to achieve the net traction [1-3]:

$$NT = GT - R \quad (1)$$

where:

NT = Net traction, kN

GT = Gross traction, kN

R = Rolling resistance, kN

The rolling resistance of a vehicle is described as a force opposing horizontal motion on a deformable surface or on flexible tires. Also, rolling resistance can be considered as a rate of energy loss to the soil and/or tires.

It has been known in practice that the rolling resistance of a tire increase both with the vertical load on the tire and with the sinkage of the tire into the soil [4]. Rolling resistance consists of three components  $R_c$ ,  $R_b$  and  $R_f$  [3, 5]:

$$R = R_c + R_b + R_f \quad (2)$$

where:

$R_c$  = The rolling resistance component related to vertical soil compaction, kN

$R_b$  = The rolling resistance component related to horizontal soil displacement, kN

$R_f$  = The rolling resistance component related to flexing of the tire, kN

For vehicles operating on a hard surface,  $R_c$  constitutes the largest percentage of the rolling resistance force and this can be slightly reduced by increasing the

inflation pressure and the effective stiffness of the tire. In an off-road situation, however, the components  $R_b$  and  $R_c$  make up the largest proportion of the rolling resistance force [3, 5].

An extensive set of field tests of rolling resistance was performed by McKibben and Davidson [6] using tires of different sizes. They compared the rolling resistance of different towed pneumatic tires varying in overall unloaded diameter under three vertical loads and five different field and road surface conditions. Their results affirm that diameter is a prominent factor governing the rolling resistance of tires [7]. McKibben and Davidson [8] also demonstrated that the tire inflation pressure has a marked effect on rolling resistance, depending on the type of surface upon which the tire travels. On soft surfaces, a higher inflation pressure results in an increased rolling resistance force. On the other hand, larger inflation pressures reduce the rolling resistance of a tire traveling on surfaces which are more firm [3, 5]. A further factor which can influence the effort required to move tires on soil is the arrangement of two or more tires on a vehicle. Another set of experiments by McKibben and Davidson [9] indicated that a different result is caused by the placing of dual tires, side by side, or a tandem configuration in which one wheel follows the other. The investigators recommended that field machines should be designed such that transport tires follow one another and trailer tires be positioned in the same track as the towing tractor. In this way significant economy in rolling resistance energy could be realized [10].

As rolling resistance for a given tire size, inflation pressure and vertical load may be significantly different between bias-ply and radial-ply tires [1], this study was mainly conducted to predict rolling resistance ( $R$ ) of bias-ply tire based on section width ( $b$ ), inflation pressure ( $P$ ) and vertical load ( $W$ ).

## MATERIALS AND METHODS

**Tire Rolling Resistance Test Apparatus:** A three-wheel rolling resistance test apparatus was designed and constructed to measure rolling resistance of tires with different sizes at diverse levels of inflation pressure and vertical load. The three-wheel tester, linkages, weights, load cell and data logger are shown in Fig. 1.

**Experimental Procedure:** Rolling resistance of four bias-ply tires with different section width was measured at three levels of inflation pressure and four levels of vertical load. The section widths of four bias-ply tires are



Fig. 1: The tire rolling resistance test apparatus, linkages, weights, load cell and data logger

Table 1: Section width of the four bias-ply tires used in this study

Tire No.	Section width b (cm)
1	16.5
2	16.5
3	18.5
4	16.5

given in Table 1. Results of rolling resistance measurement for bias-ply tires No. 1, 2 and 3 (Tables 2, 3 and 4) were utilized to determine three-variable linear regression model and results of rolling resistance measurement for bias-ply tire No. 4 (Table 5) were used to verify model.

**Regression Model:** A typical three-variable linear regression model is shown in equation 3 [11-14]:

$$Y = C_0 + C_1X_1 + C_2X_2 + C_3X_3 \quad (3)$$

where:

$Y$  = Dependent variable, for example rolling resistance of bias-ply tire

$X_1, X_2, X_3$  = Independent variables, for example section width, inflation pressure and vertical load

$C_0, C_1, C_2, C_3$  = Regression coefficients

In order to predict rolling resistance of bias-ply tire from section width, inflation pressure and vertical load, a three-variable linear regression model was suggested and all the data were subjected to regression analysis using the Microsoft Excel 2007.

Table 2: Section width, inflation pressure, vertical load and rolling resistance (the mean of three replications) for bias-ply tire No. 1

Tire No.	Section width b (cm)	Inflation pressure P (psi)	Vertical load W (kN)	Rolling resistance R (kN)		
1	16.5	10	0.9996	0.1257		
			1.9992	0.1677		
			2.9988	0.2183		
		25	3.9984	0.2473		
			0.9996	0.1127		
			1.9992	0.1587		
		40	2.9988	0.1877		
			3.9984	0.2310		
			0.9996	0.0900		
					1.9992	0.1350
					2.9988	0.1770
					3.9984	0.1980

Table 3: Section width, inflation pressure, vertical load and rolling resistance (the mean of three replications) for bias-ply tire No. 2

Tire No.	Section width b (cm)	Inflation pressure P (psi)	Vertical load W (kN)	Rolling resistance R (kN)		
2	16.5	10	0.9996	0.1327		
			1.9992	0.1783		
			2.9988	0.2273		
		25	3.9984	0.2653		
			0.9996	0.1257		
			1.9992	0.1697		
		40	2.9988	0.2077		
			3.9984	0.2437		
			0.9996	0.1053		
					1.9992	0.1450
					2.9988	0.1943
					3.9984	0.2073

Table 4: Section width, inflation pressure, vertical load and rolling resistance (the mean of three replications) for bias-ply tire No. 3

Tire No.	Section width b (cm)	Inflation pressure P (psi)	Vertical load W (kN)	Rolling resistance R (kN)		
3	18.5	10	0.9996	0.1383		
			1.9992	0.1930		
			2.9988	0.2387		
		25	3.9984	0.2743		
			0.9996	0.1343		
			1.9992	0.1873		
		40	2.9988	0.2167		
			3.9984	0.2597		
			0.9996	0.1163		
					1.9992	0.1580
					2.9988	0.2043
					3.9984	0.2283

Table 5: Section width, inflation pressure, vertical load and rolling resistance (the mean of three replications) for bias-ply tire No. 4

Tire No.	Section width b (cm)	Inflation pressure P (psi)	Vertical load W (kN)	Rolling resistance R (kN)		
4	16.5	10	0.9996	0.1463		
			1.9992	0.2067		
			2.9988	0.2653		
		25	3.9984	0.2947		
			0.9996	0.1387		
			1.9992	0.2007		
		40	2.9988	0.2494		
			3.9984	0.2757		
			0.9996	0.1217		
					1.9992	0.1774
					2.9988	0.2164
					3.9984	0.2480

**Statistical Analysis:** A paired samples t-test was used to compare the rolling resistance values predicted by model with the rolling resistance values measured by test apparatus. Also, to check the discrepancies between the rolling resistance values predicted by model with the rolling resistance values measured by test apparatus, root mean squared error (RMSE) and mean relative percentage deviation (MRPD) were calculated using the equations 4 and 5, respectively [15-20]:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (R_{Mi} - R_{Pi})^2}{n}} \quad (4)$$

where:

RMSE = Root mean squared error, kN

$R_{Mi}$  = Rolling resistance measured by test apparatus, kN

$R_{Pi}$  = Rolling resistance predicted by model, kN

$$MRPD = \frac{100 \times \sum_{i=1}^n \frac{|R_{Mi} - R_{Pi}|}{R_{Mi}}}{n} \quad (5)$$

where:

MRPD = Mean relative percentage deviation, %

## RESULTS AND DISCUSSION

Three-variable linear regression model, p-value of independent variables and coefficient of determination ( $R^2$ ) of the model are shown in Table 6. In this model rolling resistance of bias-ply tire can be predicted as a function of section width (b), inflation pressure (P) and vertical load (W). The p-value of independent variables (b, P and W) and  $R^2$  of the model were 1.44E-06, 1.26E-11, 5.00E-25 and 0.97, respectively. Based on the statistical results, the three-variable linear regression model was initially accepted, which is given by equation 6:

$$R = 0.00932 b - 0.00124 P + 0.04003 W - 0.04556 \quad (6)$$

Rolling resistance of bias-ply tire No. 4 was then predicted at three levels of inflation pressure and four levels of vertical load using the three-variable linear regression model. The rolling resistance values predicted by model were compared with the rolling resistance values measured by test apparatus and are shown in Table 7.

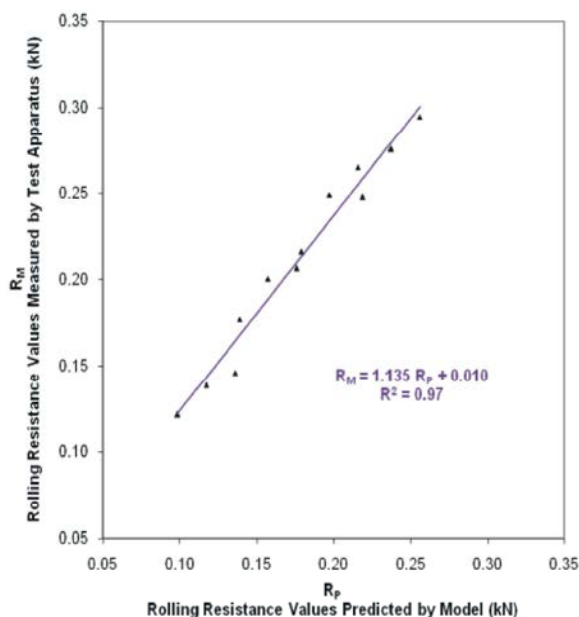


Fig. 2: Curve of rolling resistance values measured by test apparatus ( $R_M$ ) based on rolling resistance values predicted by model ( $R_p$ ) for bias-ply tire No. 4

The paired samples t-test results indicated that the rolling resistance values predicted by model were statistically less than the rolling resistance values measured by test apparatus. The average rolling resistance difference between two methods was -0.035 kN (95% confidence intervals for the difference in means: -0.042 kN and -0.027 kN; p-value = 1.0000). The standard deviation of the rolling resistance difference was 0.012 kN (Table 8). To check the discrepancies between the rolling resistance values predicted by model with the rolling resistance values measured by test apparatus, RMSE and MRPD were calculated. The amounts of RMSE and MRPD were 0.036 kN and 16.3%, respectively. Rational amounts of RMSE and MRPD confirmed that the three-variable linear regression model  $R = 0.00932 b - 0.00124 P + 0.04003 W - 0.04556$  with  $R^2 = 0.97$  may be used to predict rolling resistance of bias-ply tire based on section width, inflation pressure and vertical load. As it is indicated in Fig. 2, our attempts to relate rolling resistance values predicted by model ( $R_p$ ) to rolling resistance values measured by test apparatus ( $R_M$ ) using a linear equation resulted in very good agreements ( $R^2 = 0.97$ ) as equation 7:

$$R_M = 1.135 R_p + 0.010 \quad (7)$$

Table 6: Three-variable linear regression model, p-value of independent variables and coefficient of determination (R<sup>2</sup>)

Model	p-value			R <sup>2</sup>
	b	P	W	
R = 0.00932 b - 0.00124 P + 0.04003 W - 0.04556	1.44E-06	1.26E-11	5.00E-25	0.97

Table 7: Section width, inflation pressure, vertical load and rolling resistance (the mean of three replications) for bias-ply tire No. 4 used in evaluating the model

Section width b (cm)	Inflation pressure P (psi)	Vertical load W (kN)	Rolling resistance R (kN)	
			Measured by test apparatus	Predicted by model
16.5	10	0.9996	0.1463	0.1358
		1.9992	0.2067	0.1758
		2.9988	0.2653	0.2159
		3.9984	0.2947	0.2559
	25	0.9996	0.1387	0.1172
		1.9992	0.2007	0.1572
		2.9988	0.2494	0.1973
		3.9984	0.2757	0.2373
	40	0.9996	0.1217	0.0986
		1.9992	0.1774	0.1386
		2.9988	0.2164	0.1787
		3.9984	0.2480	0.2187

Table 8: Paired samples t-test analysis on comparing rolling resistance determination methods

Determination methods	Average difference (kN)	Standard deviation of difference (kN)	p-value	95% confidence intervals for the difference in means (kN)
Test apparatus vs. model	-0.035	0.012	1.0000	-0.042, -0.027

Therefore, actual or measured rolling resistance (R<sub>M</sub>) can be computed in two steps. At first step, predicted rolling resistance (R<sub>P</sub>) is calculated based on section width (b), inflation pressure (P) and vertical load (W) using the three-variable linear regression model. At second step, actual or measured rolling resistance (R<sub>M</sub>) is calculated based on predicted rolling resistance (R<sub>P</sub>) using the linear equation 7.

### CONCLUSIONS

It can be concluded that actual or measured rolling resistance (R<sub>M</sub>) of bias-ply tire can be computed in two steps. At first step, predicted rolling resistance (R<sub>P</sub>) is calculated based on section width (b), inflation pressure (P) and vertical load (W) using the three-variable linear regression model  $R = 0.00932 b - 0.00124 P + 0.04003 W - 0.04556$  with  $R^2 = 0.97$ . At second step, actual or measured rolling resistance (R<sub>M</sub>) is calculated based on predicted rolling resistance (R<sub>P</sub>) using the linear equation  $R_M = 1.135 R_P + 0.010$  with  $R^2 = 0.97$ .

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