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Prediction of Rolling Resistance for Bias-Ply Tire Based on Overall Unloaded Diameter, Inflation Pressure and Vertical Load

Mostafa Eslami, Majid Rashidi and Mohammad Gholami

Department of Agricultural Machinery,
Takestan Branch, Islamic Azad University, Takestan, Iran

Abstract: This study was mainly conducted to predict rolling resistance (R) of bias-ply tire based on overall unloaded diameter (d), inflation pressure (P) and vertical load (W). For this purpose, rolling resistance of four bias-ply tires with different overall unloaded diameter 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 = - 0.08711 + 0.00336 d - 0.00124 P + 0.04003 W with $R^2 = 0.98$ 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 0.0125 kN and 5.29%, 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 overall unloaded diameter, 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 $R_M = 1.135\, R_P - 0.023$ with $R^2 = 0.97$ can be strongly suggested.

Key words: Bias-ply tire · Rolling resistance · Prediction · Overall unloaded diameter · 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_t [3, 5]:

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

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

Corresponding Author: Dr. Majid Rashidi, Ph.D., Department of Agricultural Machinery, Takestan Branch, Islamic Azad University, Takestan, Iran.

For vehicles operating on a hard surface, R_t 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 overall unloaded diameter (d), 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.

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

Table 1: Overall unloaded diameter of the four bias-ply tires used in this study

Tire No.	Overall unloaded diameter d (cm)
1	57.0
2	59.0
3	64.0
4	67.0

Experimental Procedure: Rolling resistance of four bias-ply tires with different overall unloaded diameter was measured at three levels of inflation pressure and four levels of vertical load. The overall unloaded diameters of four bias-ply tires are 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	=	sIndependent variables, for example overall unloaded diameter, inflation pressure and vertical load
C_0, C_1, C_2, C_3	=	Regression coefficients

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

Tire No.	Overall unloaded diameter d (cm)	Inflation pressure P (psi)	Vertical load W (kN)	Rolling resistance R (kN)
1	57.0	10	0.9996	0.1257
			1.9992	0.1677
			2.9988	0.2183
			3.9984	0.2473
		25	0.9996	0.1127
			1.9992	0.1587
			2.9988	0.1877
			3.9984	0.2310
		40	0.9996	0.0900
			1.9992	0.1350
			2.9988	0.1770
			3.9984	0.1980

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

Tire No.	Overall unloaded diameter d (cm)	Inflation pressure P (psi)	Vertical load W (kN)	Rolling resistance R (kN)
2	59.0	10	0.9996	0.1327
			1.9992	0.1783
			2.9988	0.2273
			3.9984	0.2653
		25	0.9996	0.1257
			1.9992	0.1697
			2.9988	0.2077
			3.9984	0.2437
		40	0.9996	0.1053
			1.9992	0.1450
			2.9988	0.1943
			3.9984	0.2073

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

Tire No.	Overall unloaded diameter d (cm)	Inflation pressure P (psi)	Vertical load W (kN)	Rolling resistance R (kN)
3	64.0	10	0.9996	0.1383
			1.9992	0.1930
			2.9988	0.2387
			3.9984	0.2743
		25	0.9996	0.1343
			1.9992	0.1873
			2.9988	0.2167
			3.9984	0.2597
		40	0.9996	0.1163
			1.9992	0.1580
			2.9988	0.2043
			3.9984	0.2283

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

Tire No.	Overall unloaded diameter d (cm)	Inflation pressure P (psi)	Vertical load W (kN)	Rolling resistance R (kN)
4	67.0	10	0.9996	0.1463
			1.9992	0.2067
			2.9988	0.2653
			3.9984	0.2947
		25	0.9996	0.1387
			1.9992	0.2007
			2.9988	0.2494
			3.9984	0.2757
		40	0.9996	0.1217
			1.9992	0.1774
			2.9988	0.2164
			3.9984	0.2480

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

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 (RSME) 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 overall unloaded diameter (d), inflation pressure (P) and vertical load (W). The p-value of independent variables (d, P and W) and R^2 of the model were 5.34E-09, 1.56E-13, 2.42E-27 and 0.98, respectively. Based on the statistical results, the three-variable linear regression model was initially accepted, which is given by equation 6:

$$R = -0.08711 + 0.00336\, d - 0.00124\, P + 0.04003\, W \quad (6)$$

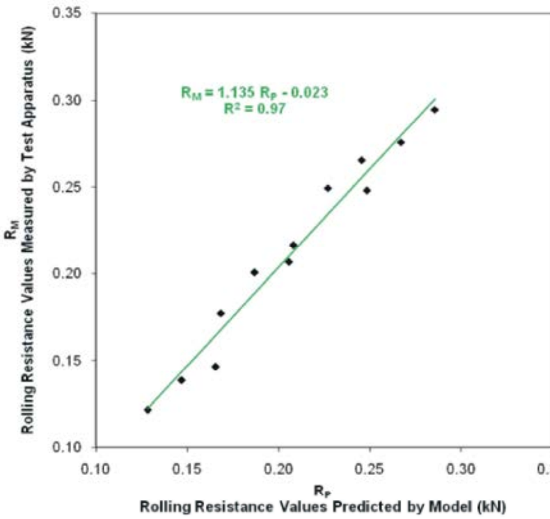

Fig. 2: Curve of rolling resistance values measured by test apparatus (R_M) based on rolling resistance values predicted by model (R_P) for bias-ply tire No. 4

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. 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 -0.005 kN (95% confidence intervals for the difference in means: -0.012 kN and 0.003 kN; p-value = 0.9003). 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 0.0125 kN and 5.29%, respectively. Rational amounts of RMSE and MRPD confirmed that the three-variable linear regression model $R = -0.08711 + 0.00336\, d - 0.00124\, P + 0.04003\, W$ with $R^2 = 0.98$ may be used to predict rolling resistance of bias-ply tire based on overall unloaded diameter, 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:

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

	p-value			
Model	d	P	W	R^2
R = - 0.08711 + 0.00336 d - 0.00124 P + 0.04003 W	5.34E-09	1.56E-13	2.42E-27	0.98

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

			Rolling resistance R (kN)	
Overall unloaded diameter d (cm)	Inflation pressure P (psi)	Vertical load W (kN)	Measured by test apparatus	Predicted by model
67.0	10	0.9996	0.1463	0.1656
		1.9992	0.2067	0.2056
		2.9988	0.2653	0.2456
		3.9984	0.2947	0.2856
	25	0.9996	0.1387	0.1470
		1.9992	0.2007	0.1870
		2.9988	0.2494	0.2270
		3.9984	0.2757	0.2670
	40	0.9996	0.1217	0.1284
		1.9992	0.1774	0.1684
		2.9988	0.2164	0.2084
		3.9984	0.2480	0.2484

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	-0.005	0.012	0.9003	-0.012, 0.003

$$R_M = 1.135\ R_P - 0.023 \quad (7)$$

Therefore, actual or measured rolling resistance (R_M) can be computed in two steps. At first step, predicted rolling resistance (R_P) is calculated based on overall unloaded diameter (d), inflation pressure (P) and vertical load (W) using the three-variable linear regression model. At second step, actual or measured rolling resistance (R_M) is calculated based on predicted rolling resistance (R_P) using the linear equation 7.

CONCLUSIONS

It can be concluded that actual or measured rolling resistance (R_M) of bias-ply tire can be computed in two steps. At first step, predicted rolling resistance (R_P) is calculated based on overall unloaded diameter (d), inflation pressure (P) and vertical load (W) using the three-variable linear regression model R = - 0.08711 + 0.00336 d - 0.00124 P + 0.04003 W with R^2 = 0.98. At second step, actual or measured rolling resistance (R_M) is calculated based on predicted rolling resistance (R_P) using the linear equation $R_M = 1.135\ R_P - 0.023$ with R^2 = 0.97.

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