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Prediction of Rolling Resistance for Radial-Ply Tire Based on Tire Size, Inflation Pressure and Vertical Load

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Abstract: The rolling resistance of a tire is described as a force opposing horizontal motion on a surface. As rolling resistance for a given tire size, inflation pressure and vertical load are may be different between radial-ply and bias-ply tires, this study was mainly conducted to predict rolling resistance (R) of radial-ply tire based on tire size, viz. section width (b) and/or overall unloaded diameter (d), inflation pressure (P) and vertical load (W). For this purpose, rolling resistance of four radial-ply tires with different section width and/or overall unloaded diameter were measured at three levels of inflation pressure and four levels of vertical load. Results of rolling resistance measurement for radial-ply tires No. 1, 2 and 3 were utilized to determine multiple-variable regression models and three-variable linear regression model R = - 0.17827 + 0.00465 d - 0.00168 P + 0.03161 W with R^2 = 0.976 was selected. Also, results of rolling resistance measurement for radial-ply tire No. 4 were used to verify selected 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 0.017 kN and 10.81%, respectively. Rational amounts of RMSE and MRPD confirmed that selected model may be used to predict rolling resistance of radial-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 $R_M = 1.011\ R_P + 0.013$ with $R^2 = 0.958$ can be robustly suggested.

Key words: Radial-ply tire · Rolling resistance · Overall unloaded diameter · Inflation pressure · Vertical load · Prediction

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

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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

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 radial-ply and bias-ply tires [1], this study was mainly conducted to predict rolling resistance (R) of radial-ply tire based on tire size, viz. section width (b) and/or 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.

Experimental Procedure: Rolling resistance of four radial-ply tires with different section width and/or overall unloaded diameter was measured at three levels of inflation pressure and four levels of vertical load. The dimensions of four radial-ply tires are given in Table 1. Results of rolling resistance measurement for radial-ply tires No. 1, 2 and 3 (Tables 2, 3 and 4) were utilized to determine multiple-variable regression models and results of rolling resistance measurement for radial-ply tire No. 4 (Table 5) were used to verify selected model.

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

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

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

Table 1: Dimensions of the four radial-ply tires used in this study

Tire No.	Section width b (cm)	Overall unloaded diameter d (cm)
1	17.5	52.0
2	18.5	55.0
3	18.5	57.0
4	20.5	58.0

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

Tire No.	Section width b (cm)	Overall unloaded diameter d (cm)	Inflation pressure P (psi)	Vertical load W (kN)	Rolling resistance R (kN)
1	17.5	52	10	0.9996	0.0633
				1.9992	0.1190
				2.9988	0.1363
				3.9984	0.1817
			25	0.9996	0.0540
				1.9992	0.0740
				2.9988	0.1193
				3.9984	0.1473
			40	0.9996	0.0403
				1.9992	0.0663
				2.9988	0.0927
				3.9984	0.1193

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

Tire No.	Section width b (cm)	Overall unloaded diameter d (cm)	Inflation pressure P (psi)	Vertical load W (kN)	Rolling resistance R (kN)
2	18.5	55.0	10	0.9996	0.0843
				1.9992	0.1323
				2.9988	0.1497
				3.9984	0.1957
			25	0.9996	0.0637
				1.9992	0.0990
				2.9988	0.1297
				3.9984	0.1583
			40	0.9996	0.0470
				1.9992	0.0763
				2.9988	0.0977
				3.9984	0.1307

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

Tire No.	Section width b (cm)	Overall unloaded diameter d (cm)	Inflation pressure P (psi)	Vertical load W (kN)	Rolling resistance R (kN)
3	18.5	57.0	10	0.9996	0.0920
				1.9992	0.1373
				2.9988	0.1650
				3.9984	0.2083
			25	0.9996	0.0853
				1.9992	0.1123
				2.9988	0.1393
				3.9984	0.1660
			40	0.9996	0.0493
				1.9992	0.0870
				2.9988	0.1130
				3.9984	0.1403

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

Tire No.	Section width b (cm)	Overall unloaded diameter d (cm)	Inflation pressure P (psi)	Vertical load W (kN)	Rolling resistance R (kN)
4	20.5	58.0	10	0.9996	0.1120
				1.9992	0.1623
				2.9988	0.1763
				3.9984	0.2313
			25	0.9996	0.3960
				1.9992	0.1360
				2.9988	0.1510
				3.9984	0.1813
			40	0.9996	0.0633
				1.9992	0.1123
				2.9988	0.1350
				3.9984	0.1603

Table 6: Seven multiple-variable regression models and their relations

Model No.	Model	Relation
1	$R = C_0 + C_1 b + C_2 d + C_3 P + C_4 W$	$R = -0.15284 - 0.00382 b + 0.00546 d - 0.00168 P + 0.03161 W$
2	$R = C_0 + C_1 b + C_2 P + C_3 W$	$R = -0.25109 + 0.01801 b - 0.00168 P + 0.03161 W$
3	$R = C_0 + C_1 d + C_2 P + C_3 W$	$R = -0.17827 + 0.00465 d - 0.00168 P + 0.03161 W$
4	$R = C_0 + C_1 (bd) + C_2 P + C_4 W$	$R = -0.07513 + 0.00015 (bd) - 0.00168 P + 0.03161 W$
5	$R = C_0 + C_1 (b/d) + C_2 P + C_3 W$	$R = 0.56079 - 1.45758 (b/d) - 0.00168 P + 0.03161 W$
6	$R = C_0 + C_1 (d/b) + C_2 P + C_3 W$	$R = -0.40256 + 0.15912 (d/b) - 0.00168 P + 0.03161 W$
7	$R = C_0 + C_1 (bd)^{0.5} + C_2 P + C_3 W$	$R = -0.22311 + 0.00950 (bd)^{0.5} - 0.00168 P + 0.03161 W$

Where:

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

$X_1, X_2, \ldots, X_n$ = Independent variables, for example section width, overall unloaded diameter, inflation pressure and vertical load

$C_0, C_1, C_2, \ldots, C_n$ = Regression coefficients

In order to predict rolling resistance of radial-ply tire from tire size, viz. section width and/or overall unloaded diameter, inflation pressure and vertical load, seven multiple-variable regression models were suggested and all the data were subjected to regression analysis using the Microsoft Excel 2007. All the multiple-variable regression models and their relations are shown in Table 6.

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, 16]:

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

Where:

RMSE = Root mean squared error, kN

R_{mi} = Rolling resistance measured by tire rolling resistance test apparatus, kN

R_{pi} = Rolling resistance predicted by multiple-variable linear regression 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

The p-value of independent variables and coefficient of determination (R^2) for the seven multiple-variable regression models are shown in Table 7. Among the seven models, model No. 3 had the highest R^2 value (0. 976). Moreover, this model totally had the lowest p-value of

Table 7: The p-value of independent variables and coefficient of determination (R^2) for the seven multiple-variable regression models

	p-value								
Model No.	b	d	bd	b/d	d/b	$(bd)^{0.5}$	P	W	R^2
1	0.548410	0.000671	---	---	---	---	1.37E-17	1.87E-24	0.976
2	9.28E-07	---	---	---	---	---	9.21E-16	1.14E-22	0.965
3	---	2.34E-09	---	---	---	---	4.86E-18	4.05E-25	0.976
4	---	---	1.13E-08	---	---	---	1.98E-17	1.81E-24	0.973
5	---	---	---	3.55E-06	---	---	2.87E-15	3.97E-22	0.962
6	---	---	---	---	3.58E-06	---	2.89E-15	4.00E-22	0.962
7	---	---	---	---	---	1.25E-08	2.17E-17	2.00E-24	0.973

Table 8: Overall unloaded diameter, inflation pressure, vertical load and rolling resistance (the mean of three replications) for radial-ply tire No. 4 used in evaluating model No. 3

			Rolling resistance R (kN)	
Overall unloaded diameter d (cm)	Inflation pressure P (psi)	Vertical load W (kN)	Measured by test apparatus	Predicted by model No. 3
58.0	10	0.9996	0.1120	0.1065
		1.9992	0.1623	0.1381
		2.9988	0.1763	0.1697
		3.9984	0.2313	0.2013
	25	0.9996	0.0990	0.0813
		1.9992	0.1360	0.1129
		2.9988	0.1510	0.1445
		3.9984	0.1813	0.1761
	40	0.9996	0.0633	0.0561
		1.9992	0.1123	0.0877
		2.9988	0.1350	0.1193
		3.9984	0.1603	0.1509

Table 9: 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 No. 3	-0.015	0.009	0.9999	-0.020, -0.009

independent variables among the seven models. Based on the statistical results model No. 3 was selected as the best model, which is given by equation 6:

$$R = - 0.17827 + 0.00465\ d - 0.00168\ P + 0.03161\ W \quad (6)$$

Rolling resistance of radial-ply tire No. 4 was then predicted at three levels of inflation pressure and four levels of vertical load using model No. 3. The rolling resistance values predicted by model No. 3 were compared with the rolling resistance values measured by test apparatus and are shown in Table 8. 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 -0.015 kN (95% confidence intervals for the difference in means: -0.020 kN and -0.009 kN; p-value = 0.9999). The standard deviation of the rolling resistance difference was 0.009 kN (Table 9). To check the discrepancies between the rolling resistance values predicted by model No. 3 with the rolling resistance values measured by test apparatus, RMSE and MRPD were calculated. The amounts of RMSE and MRPD were 0.017 kN and 10.81%, respectively. Rational amounts of RMSE and MRPD confirmed that the three-variable linear regression model $R = - 0.17827 + 0.00465\ d - 0.00168\ P + 0.03161\ W$ with $R^2 = 0.976$ may be used to predict rolling resistance of radial-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 No. 3 (R_P) to rolling resistance values measured by test apparatus (R_M) using a linear equation resulted in very good agreements ($R^2 = 0.958$) as equation 7:

$$R_M = 1.011\ R_P + 0.013 \quad (7)$$

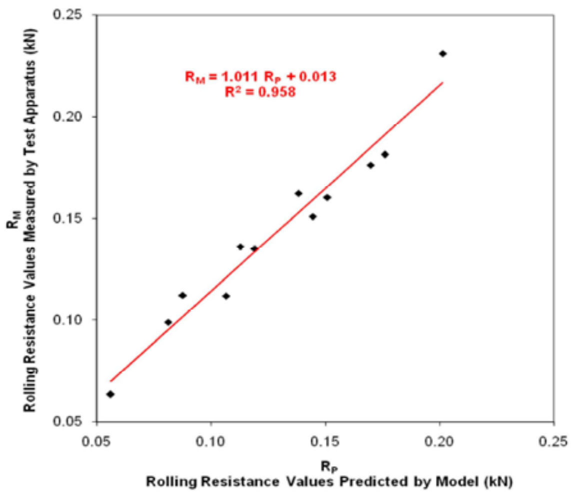

Fig. 2: Curve of rolling resistance values measured by test apparatus (RM) based on rolling resistance values predicted by model No. 3 (RP) for radial-ply tire No. 4

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 No. 3. 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 radial-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 $R = -0.17827 + 0.00465\,d - 0.00168\,P + 0.03161\,W$ with $R^2 = 0.976$. At second step, actual or measured rolling resistance (R_M) is calculated based on predicted rolling resistance (R_P) using the linear equation $R_M = 1.011\,R_P + 0.013$ with $R^2 = 0.958$.

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