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Modeling of Rolling Resistance for Bias-Ply Tire Based on Tire Dimensions, Inflation Pressure and Vertical Load

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Abstract: This study was conducted to model rolling resistance (R) of bias-ply tire based on tire dimensions, viz., section width (b) and overall unloaded diameter (d), inflation pressure (P) and vertical load (W). For this purpose, rolling resistance of three bias-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. In order to model rolling resistance based on dimensions, inflation pressure and vertical load, seven multiple-variable regression models were suggested and all the data were subjected to regression analysis. The statistical results of study revealed that the multiple-variable regression model R = - 0.09986 - 0.00985 b + 0.00639 d - 0.00124 P + 0.04003 W with R^2 = 0.9817 may be suggested to predict rolling resistance of bias-ply tire based on tire dimensions (section width and overall unloaded diameter), inflation pressure and vertical load for a limited range of tire sizes. However, experimental verification of this model is necessary before the model can be recommended for wider use.

Key words: Bias-ply tire · Rolling resistance · Dimensions · Inflation pressure · Vertical load · Modeling

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 net traction [1, 2, 3]:

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

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, viz., R_c, R_b and R_t [3, 5]:

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

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 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

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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 conducted to model rolling resistance of bias-ply tire based on tire dimensions, viz., section width (b) and 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 three bias-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 three bias-ply tires are given in Table 1. Also, results of rolling resistance measurement for bias-ply tires No. 1, 2 and 3 are given in Tables 2, 3 and 4, respectively.

Regression Model: A typical multiple-variable regression model is shown in equation 3 [11, 12, 13, 14]:

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

where:

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

To model rolling resistance based on dimensions, inflation pressure and vertical load, seven multiple-variable regression models were suggested.

Table 1: Dimensions of the three bias-ply tires used in this study

Tire No.	Section width b (cm)	Overall unloaded diameter d (cm)
1	16.5	57.0
2	16.5	59.0
3	18.5	64.0

Table 2: Section width, overall unloaded diameter, inflation pressure, vertical load and rolling resistance (the mean of three replications) for bias-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	16.5	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: Section width, overall unloaded diameter, inflation pressure, vertical load and rolling resistance (the mean of three replications) for bias-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	16.5	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: Section width, overall unloaded diameter, inflation pressure, vertical load and rolling resistance (the mean of three replications) for bias-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	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

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

RESULTS AND DISCUSSION

In order to model rolling resistance of bias-ply tire based tire dimensions (section width and 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 5.

In addition, the p-value of the independent variables and coefficient of determination (R^2) for the seven multiple-variable regression models are shown in Table 6. Among the seven models, model No. 1 had the highest R^2 value (0.9817). Moreover, this model totally had the lowest p-value of independent variables among the seven models. Based on the statistical results model No. 1 was selected as the best model, which is given by equation 4:

$$R = -0.09986 - 0.00985\,b + 0.00639\,d - 0.00124\,P + 0.04003\,W \quad (4)$$

In this model, rolling resistance of bias-ply tire can be predicted using multiple-variable regression of section width, overall unloaded diameter, inflation pressure and vertical load.

Table 5: Seven multiple-variable regression models and their relations

Model No.	Model	Relation
1	$R = C_0 + C_1 b + C_2 d + C_3 P + C_4 W$	$R = -0.09986 - 0.00985 b + 0.00639 d - 0.00124 P + 0.04003 W$
2	$R = C_0 + C_1 b + C_2 P + C_3 W$	$R = -0.04556 + 0.00932 b - 0.00124 P + 0.04003 W$
3	$R = C_0 + C_1 d + C_2 P + C_3 W$	$R = -0.08711 + 0.00336 d - 0.00124 P + 0.04003 W$
4	$R = C_0 + C_1 (bd) + C_2 P + C_4 W$	$R = 0.02472 + 0.00009 (bd) - 0.00124 P + 0.04003 W$
5	$R = C_0 + C_1 (b/d) + C_2 P + C_3 W$	$R = 0.14616 - 0.11094 (b/d) - 0.00124 P + 0.04003 W$
6	$R = C_0 + C_1 (d/b) + C_2 P + C_3 W$	$R = 0.08383 + 0.00875 (d/b) - 0.00124 P + 0.04003 W$
7	$R = C_0 + C_1 (bd)^{0.5} + C_2 P + C_3 W$	$R = -0.06807 + 0.00569 (bd)^{0.5} - 0.00124 P + 0.04003 W$

Table 6: 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	0.037849	0.000121	---	---	---	---	6.00E-14	1.84E-27	0.9817
2	1.44E-06	---	---	---	---	---	1.26E-11	5.00E-25	0.9702
3	---	5.34E-09	---	---	---	---	1.56E-13	2.42E-27	0.9789
4	---	---	1.02E-07	---	---	---	1.65E-12	4.08E-26	0.9747
5	---	---	---	0.816542	---	---	4.82E-08	3.63E-20	0.9379
6	---	---	---	---	0.821044	---	4.82E-08	3.64E-20	0.9379
7	---	---	---	---	---	8.85E-08	1.48E-12	3.56E-26	0.9749

CONCLUSIONS

It can be concluded that the multiple-variable regression model $R = -0.09986 - 0.00985\ b + 0.00639\ d - 0.00124\ P + 0.04003\ W$ with $R^2 = 0.9817$ may be suggested to predict rolling resistance of bias-ply tire based on tire dimensions (section width and overall unloaded diameter), inflation pressure and vertical load for a limited range of bias-ply tire sizes. However, experimental verification of this model is necessary before the model can be recommended for wider use.

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