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Prediction of Bias-Ply Tire Contact Area Based on Section Width, Overall Unloaded Diameter, Inflation Pressure and Vertical Load

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Abstract: Tire contact area is a key parameter and many equations have been developed based on it to evaluate the tractive performance of bias-ply and radial-ply tires. As contact areas for a given tire size, inflation pressure and vertical load are significantly different between bias-ply and radial-ply tires, this study was conducted to predict contact area (A) of bias-ply tire based on section width (b), overall unloaded diameter (d), inflation pressure (P) and vertical load (W). For this purpose, contact area of four 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. Results of contact area measurement for bias-ply tires No. 1, 2 and 3 were utilized to determine multiple-variable linear regression models and results of contact area measurement for bias-ply tire No. 4 were used to verify selected model. The paired samples t-test results indicated that the difference between the contact area values predicted by model and measured by test apparatus were not statistically significant and to predict contact area of bias-ply tire based on section width, overall unloaded diameter, inflation pressure and vertical load, the multiple-variable linear regression model A = 171.65 - 0.2280 b - 1.6818 d - 2108.6 P + 33.429 W with R^2 = 0.910 can be strongly recommended.

Key words: Bias-ply tire · Contact area · Prediction · Section width · Overall unloaded diameter · Inflation pressure · Vertical load

INTRODUCTION

In the case of tracked vehicles, the contact area between machine and ground surface is relatively constant for varying sinkage in the soil and is calculated as the length of track on hard ground times track width. However, a flexible tire has a smaller contact area on hard surface than it dose on soft ground. A rule of thumb which can be used for estimation of tire contact area is shown by equation 1 [1]:

$$A = bL \qquad (1)$$

where:
A = Contact area (m^2)
b = Section width (m)
L = Contact length (m)

Wong [2] and Bekker [3] gave an approximate method for calculating contact length as equation 2:

$$L = 2(d\delta - \delta^2)^{0.5} \qquad (2)$$

where:
d = Overall unloaded diameter (m)
δ = Deflection (m)

Contact area is a key parameter and many equations have been developed based on it to evaluate the tractive performance of bias-ply and radial-ply tires operating in cohesive-frictional soils. Gross traction, motion resistance, net traction and tractive efficiency are predicted as a function of soil strength, tire load, tire slip, tire size, tire deflection and tire contact area [1, 4].

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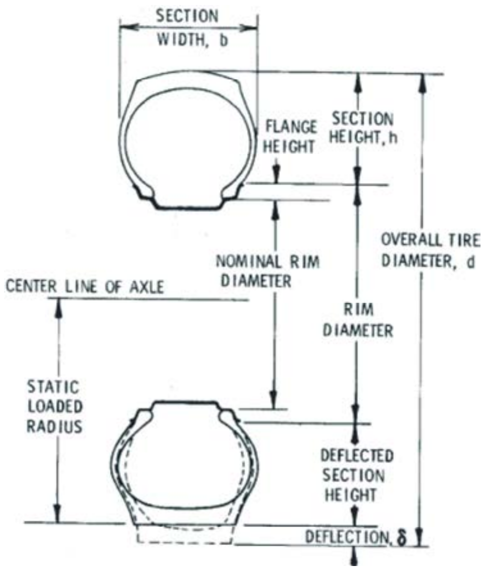

Fig. 1: Tire dimensions, adapted from Brixius [4]

Fig. 1 shows the tire dimensions (b, d and δ) used. The tire dimensions can be obtained from tire data book or by measuring the tire [4]. The section width (b) is the first number in a tire size designation (i.e., nominally 18.4 inches for an 18.4-38 tire). The overall unloaded diameter (d) can be obtained from the tire data handbooks available from off-road tire manufacturers. The tire deflection (δ) on a hard surface is equal to d/2 minus the measured static loaded radius. The static loaded radius for the tire's rated load and inflation pressure is also standard tire data from the tire data handbooks. It can also be obtained by measuring the tire [4, 5].

As contact area for a given tire size, inflation pressure and vertical load are significantly different between bias-ply and radial-ply tires, this study was conducted to predict contact area (A) of bias-ply tire based on section width (b), overall unloaded diameter (d), inflation pressure (P) and vertical load (W).

MATERIALS AND METHODS

Tire Contact Area Measurement Apparatus: A tire contact area measurement apparatus (Fig. 2) was designed and constructed to measure contact area of tires with different sizes at diverse levels of inflation pressure and vertical load. The contact area measurement system (Fig. 3) consisted of tekscan sensor (Fig. 4), tekscan USB handle and computer equipped with I-Scan software (Fig. 5).

Fig. 2: Tire contact area measurement apparatus

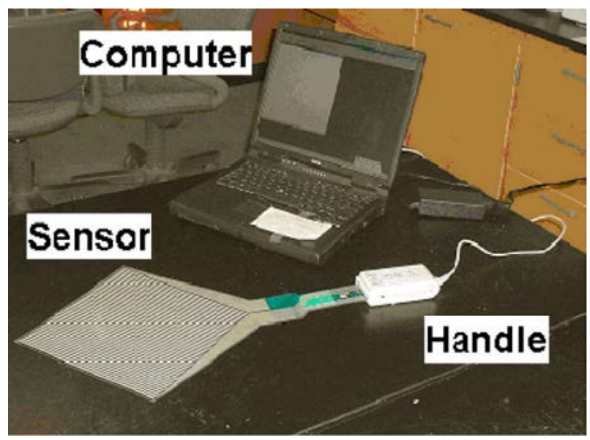

Fig. 3: Contact area measurement system, i.e. tekscan sensor, tekscan USB handle and computer equipped with I-Scan software, adapted from Anderson [6]

Experimental Procedure: Contact area of four bias-ply tires with different dimensions was measured at three levels of inflation pressure and four levels of vertical load. The dimensions of four bias-ply tires are given in Table 1. Results of contact area measurement for bias-ply tires No. 1, 2 and 3 (Tables 2, 3 and 4) were utilized to determine multiple-variable linear regression models and results of contact area measurement for bias-ply tire No. 4 (Table 5) were used to verify selected model.

Regression Model: A typical multiple-variable linear regression model is shown in equation 3:

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

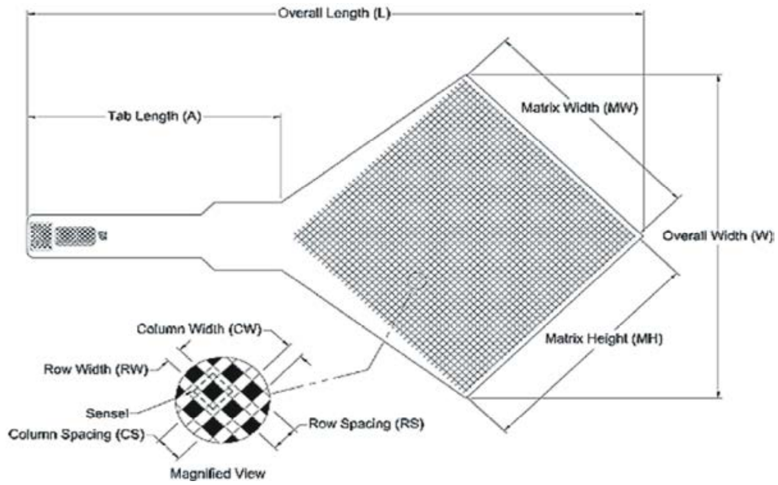

Fig. 4: Tekscan sensor, adapted from Tekscan [7]

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

Tire No.	Section width b (cm)	Overall unloaded diameter d (cm)
1	5.00	33.00
2	6.00	35.56
3	16.5	33.00
4	15.0	50.00

Table 2: Section width, overall unloaded diameter, inflation pressure, vertical load and contact area (three replications) for bias-ply tire No. 1

					Contact area A (cm^2)		
Tire No.	Section width b (cm)	Overall unloaded diameter d (cm)	Inflation pressure P (MPa)	Vertical load W (kN)	R_1	R_2	R_3
1	5.00	33.00	0.025	1.67	120.1	118.9	119.6
				2.02	129.8	129.6	129.9
				2.42	139.7	139.6	140.1
				2.92	158.0	159.3	160.1
			0.030	1.67	109.9	108.6	109.9
				2.02	119.9	119.5	120.5
				2.42	132.7	133.0	132.4
				2.92	150.6	150.4	150.0
			0.035	1.67	100.8	100.9	100.8
				2.02	108.8	106.9	107.1
				2.42	125.6	125.0	125.6
				2.92	133.0	134.8	134.9

Table 3: Section width, overall unloaded diameter, inflation pressure, vertical load and contact area (three replications) for bias-ply tire No. 2

					Contact area A (cm^2)		
Tire No.	Section width b (cm)	Overall unloaded diameter d (cm)	Inflation pressure P (MPa)	Vertical load W (kN)	R_1	R_2	R_3
2	6.00	35.56	0.025	1.67	118.4	118.0	119.0
				2.02	126.0	126.7	126.0
				2.42	133.0	133.8	134.0
				2.92	153.9	153.3	153.7
			0.030	1.67	105.7	105.7	106.0
				2.02	112.8	113.5	113.0
				2.42	121.7	123.0	126.0
				2.92	137.0	136.1	136.7
			0.035	1.67	104.1	105.0	105.0
				2.02	111.0	110.9	111.0
				2.42	118.0	117.0	117.5
				2.92	127.0	128.2	129.0

Table 4: Section width, overall unloaded diameter, inflation pressure, vertical load and contact area (three replications) for bias-ply tire No. 3

Tire No.	Section width b (cm)	Overall unloaded diameter d (cm)	Inflation pressure P (MPa)	Vertical load W (kN)	Contact area A (cm^2)		
					R_1	R_2	R_3
3	16.5	33.00	0.025	1.67	101.5	102.2	101.0
				2.02	128.0	127.8	126.0
				2.42	152.5	154.0	154.5
				2.92	165.8	166.0	165.9
			0.030	1.67	94.60	94.00	94.80
				2.02	114.9	115.5	115.6
				2.42	135.4	136.0	135.4
				2.92	151.5	151.7	152.0
			0.035	1.67	91.00	89.90	90.90
				2.02	100.0	101.1	100.5
				2.42	117.9	118.0	117.5
				2.92	139.9	140.2	140.0

Table 5: Section width, overall unloaded diameter, inflation pressure, vertical load and contact area (three replications) for bias-ply tire No. 4

Tire No.	Section width b (cm)	Overall unloaded diameter d (cm)	Inflation pressure P (MPa)	Vertical load W (kN)	Contact area A (cm^2)		
					R_1	R_2	R_3
4	15.0	50.00	0.025	1.67	77.80	78.00	77.40
				2.02	94.00	93.00	94.00
				2.42	103.7	103.6	103.7
				2.92	123.0	123.7	124.0
			0.030	1.67	70.10	69.00	69.90
				2.02	86.80	86.60	85.00
				2.42	102.0	101.5	101.7
				2.92	113.3	112.7	113.5
			0.035	1.67	66.00	66.00	65.90
				2.02	80.00	80.20	80.10
				2.42	100.1	99.90	99.80
				2.92	109.9	109.8	110.0

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

Model No.	Model	Relation
1	$A = C_0 + C_1\, b + C_2\, d + C_3\, P + C_4\, W$	$A = 171.65 - 0.2280\, b - 1.6818\, d - 2108.6\, P + 33.429\, W$
2	$A = C_0 + C_1\, b + C_2\, P + C_3\, W$	$A = 113.18 - 0.0601 b - 2108.6\, P + 33.429\, W$
3	$A = C_0 + C_1\, d + C_2\, P + C_3\, W$	$A = 155.24 - 1.2587\, d - 2108.6\, P + 33.429\, W$
4	$A = C_0 + C_1\, (bd) + C_2\, P + C_4\, W$	$A = 113.33 - 0.0023\, (bd) - 2108.6\, P + 33.429\, W$
5	$A = C_0 + C_1\, (b/d) + C_2\, P + C_3\, W$	$A = 112.38 - 29.959\, (b/d) - 1934.8\, P + 33.429\, W$
6	$A = C_0 + C_1\, (d/b) + C_2\, P + C_3\, W$	$A = 92.840 - 2.4547\, (d/b) - 1953.7\, P + 33.429\, W$
7	$A = C_0 + C_1\, (bd)^{0.5} + C_2\, P + C_3\, W$	$A = 114.31 - 0.0994\, (bd)^{0.5} - 2108.6\, P + 33.429\, W$

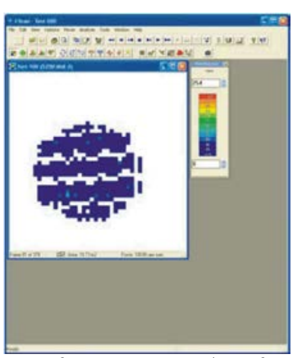

Fig. 5: I-Scan software screenshot for tire contact area measurement

where:

Y = Dependent variable, for example contact area 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

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

Statistical Analysis: A paired samples t-test and the mean difference confidence interval approach were used to compare the contact area values predicted by selected model with the contact area values measured by test apparatus. The Bland-Altman approach [8] was also used to plot the agreement between the contact area values measured by test apparatus with the contact area values predicted by selected model. The statistical analyses were also performed using Microsoft Excel 2007.

RESULTS AND DISCUSSION

The p-value of independent variables and coefficient of determination (R^2) for the seven multiple-variable linear regression models are shown in Table 7. Among the seven models, model No. 1 had the highest R^2 value (0.910). 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:

$$A = 171.65 - 0.2280\, b - 1.6818\, d - 2108.6\, P + 33.429\, W \quad (4)$$

Contact area of bias-ply tire No. 4 was then predicted at three levels of inflation pressure and four levels of vertical load using the multiple-variable linear regression model No. 1. The contact area values predicted by model No. 1 were compared with the contact area values measured by test apparatus and are shown in Table 8. A plot of the contact area values predicted by model No. 1 and the contact area values measured by test apparatus with the line of equality (1.0: 1.0) is shown in Fig. 6. Also, a paired samples t-test and the mean difference interval approach were used to compare the contact area values predicted by model No. 1 with the contact area values measured by test apparatus. The Bland-Altman approach [8] was also used to plot the agreement between the contact area values measured by test apparatus with the contact area values predicted by model No. 1. The average contact area difference between two methods was 0.04 cm^2 (95% confidence intervals for the difference in means: -5.23 cm^2 and 5.31 cm^2; P = 0.9875). The standard deviation of the contact area difference was 8.29 cm^2 (Table 9). The paired samples t-test results showed that the contact area values

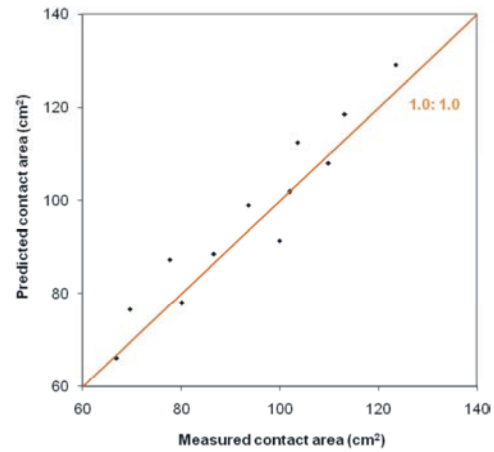

Fig. 6: Measured contact area using test apparatus and predicted contact area using model No. 1 for bias-ply tire No. 4 with the line of equality (1.0: 1.0)

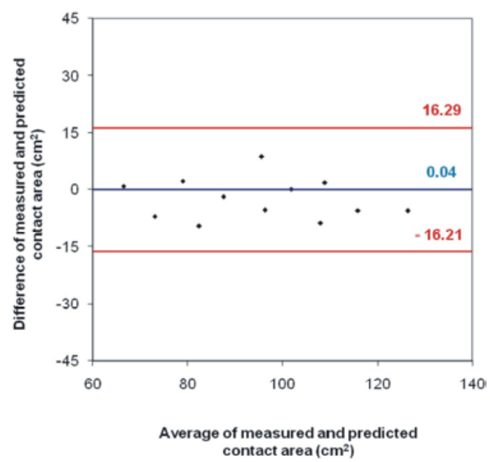

Fig. 7: Bland-Altman plot for the comparison of measured contact area using test apparatus and predicted contact area using model No. 1 for bias-ply tire No. 4; the outer lines indicate the 95% limits of agreement (-16.21, 16.29) and the center line shows the average difference (0.04)

predicted by model No. 1 were not significantly different than the contact area values measured by test apparatus. The contact area difference values between two methods were normally distributed and 95% of these differences were expected to lie between μ-1.96σ and μ+1.96σ, known as 95% limits of agreement [9-13]. The 95% limits of agreement for comparison of the contact area values determined by test apparatus and model No. 1 was calculated at -16.21 cm^2 and 16.29 cm^2 (Fig. 7). Thus, the contact area values predicted by model No. 1 for bias-ply tire No. 4 may be 16.21 cm^2 lower or 16.29 cm^2 higher than

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

	p-value								
Model No.	b	d	bd	b/d	d/b	$(bd)^{0.5}$	P	W	R^2
1	0.056375	0.001319	---	---	---	---	1.02E-28	3.80E-50	0.910
2	0.591696	---	---	---	---	---	2.09E-27	1.29E-48	0.901
3	---	0.008025	---	---	---	---	2.03E-28	6.56E-50	0.907
4	---	---	0.510470	---	---	---	1.99E-27	1.21E-48	0.901
5	---	---	---	4.01E-06	---	---	1.79E-12	2.88E-36	0.808
6	---	---	---	---	1.43E-06	---	6.89E-13	1.32E-36	0.812
7	---	---	---	---	---	0.433478	1.87E-27	1.12E-48	0.901

Table 8: Section width, overall unloaded diameter, inflation pressure, vertical load and contact area for bias-ply tire No. 4 used in evaluating model No. 1

				Contact area A (cm^2)			
Section width b (cm)	Overall unloaded diameter d (cm)	Inflation pressure P (MPa)	Vertical load W (kN)	Measured by test apparatus	Predicted by model No. 1	Average of measured and predicted contact area (cm^2)	Difference of measured and predicted contact area (cm^2)
15	50	0.025	1.67	77.73	87.18	82.45	-9.45
			2.02	93.66	99.01	96.34	-5.35
			2.42	103.7	112.4	108.0	-8.73
			2.92	123.6	129.1	126.3	-5.54
		0.030	1.67	69.66	76.64	73.15	-6.98
			2.02	86.66	88.47	87.57	-1.81
			2.42	102.0	101.8	101.9	0.16
			2.92	113.2	118.6	115.9	-5.40
		0.035	1.67	66.96	66.09	66.53	0.87
			2.02	80.10	77.93	79.01	2.17
			2.42	99.33	91.30	95.61	8.63
			2.92	109.9	108.0	109.0	1.89

Table 9: Paired samples t-test analyses on comparing contact area determination methods

Determination methods	Average difference (cm^2)	Standard deviation of difference (cm^2)	p-value	95% confidence intervals for the difference in means (cm^2)
Test apparatus vs. model No. 1	0.04	8.29	0.9875	-5.23, 5.31

the contact area values measured by test apparatus for this tire. The average percentage difference for the contact area values predicted by model No. 1 and measured by test apparatus was 5.2%.

CONCLUSION

It can be concluded that the multiple-variable linear regression model A = 171.65 - 0.2280 b - 1.6818 d - 2108.6 P + 33.429 W with R^2 = 0.910 can be strongly suggested to predict contact area of bias-ply tire based on section width, overall unloaded diameter, inflation pressure and vertical load.

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