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Modeling of Contact Area for Radial-Ply Tire Based on Tire Size, Inflation Pressure and Vertical Load

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Abstract: This study was conducted to predict contact area (A) of radial-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 radial-ply tires with different section width and/or overall unloaded diameter were measured at five levels of inflation pressure and five levels of vertical load. Results of contact area measurement for radial-ply tires No. 1, 2 and 3 were utilized to determine multiple-variable linear regression models and results of contact area measurement for radial-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 radial-ply tire based on section width, overall unloaded diameter, inflation pressure and vertical load, the multiple-variable linear regression model $A = - 25.33 - 1.848\ b + 1.001\ d - 4.088\ P + 20.65\ W$ with $R^2 = 0.981$ can be strongly recommended.

Key words: Radial-ply tire · Contact area · Modeling · Tire size · 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]:

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

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:

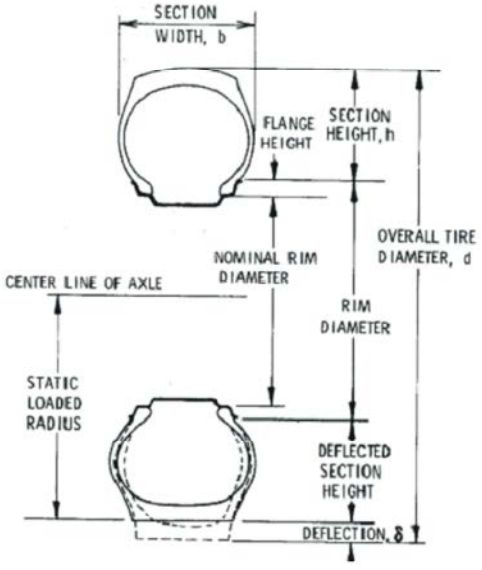

Fig. 1: Tire dimensions, adapted from Brixius [4]

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

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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 radial-ply and bias-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].

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. 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 radial-ply and bias-ply tires, this study was conducted to predict contact area (A) of radial-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).

Experimental Procedure: Contact area of four radial-ply tires with different dimensions was measured at five levels of inflation pressure and five levels of vertical load. The dimensions of four radial-ply tires are given in Table 1. Results of contact area measurement for radial-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 radial-ply tire No. 4 (Table 5) were used to verify selected model.

Fig. 2: Tire contact area measurement apparatus

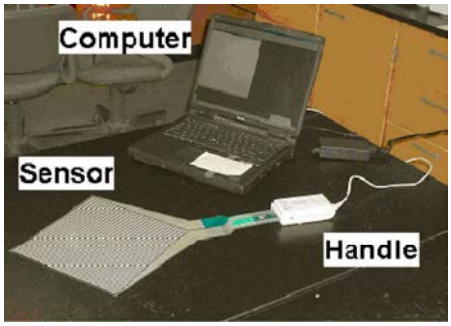

Fig. 3: Contact area measurement system, i.e. tekscan sensor, tekscan USB handle and computer equipped with I-Scan software, adapted from Anderson [6]

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

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

where:
Y = Dependent variable, for example contact area 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 contact area of radial-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.

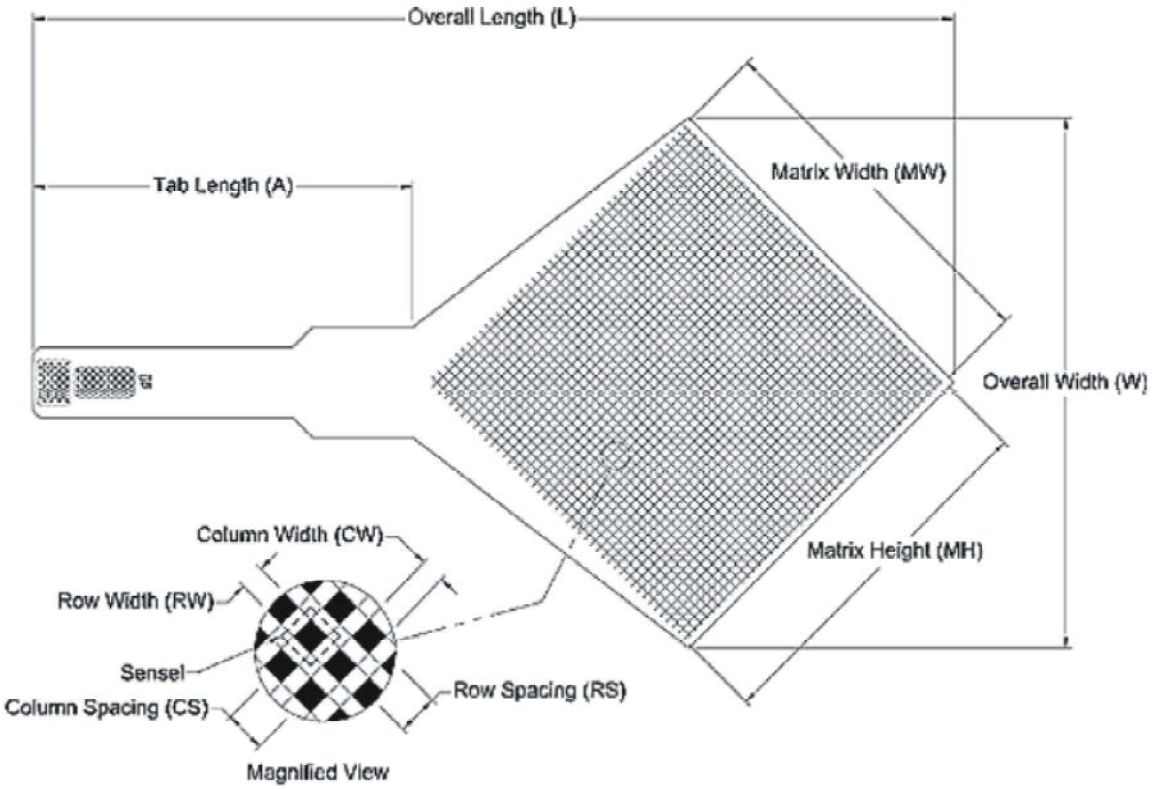

Fig. 4: Tekscan sensor, adapted from Tekscan [7]

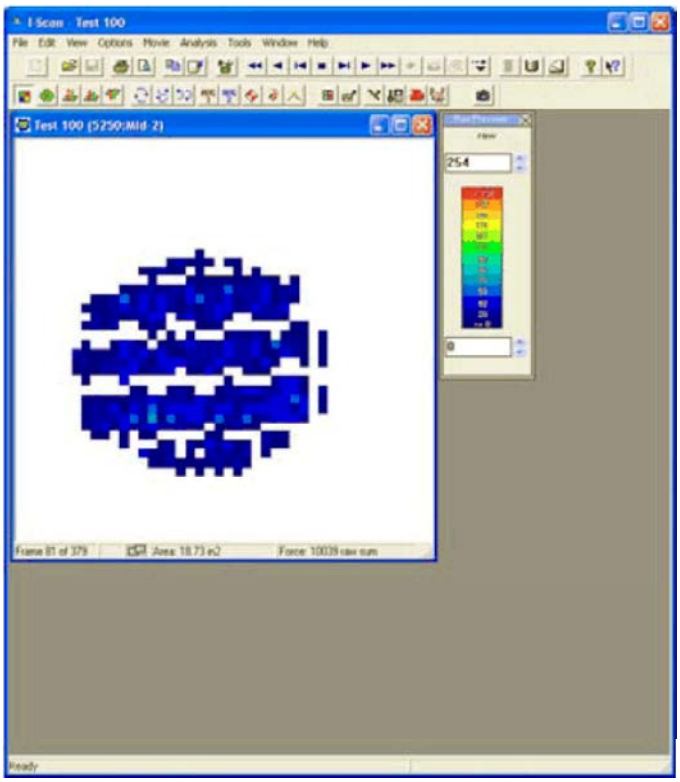

Fig. 5: I-Scan software screenshot for tire contact area measurement

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

Tire No.	Section width b (mm)	Overall unloaded diameter d (mm)
1	165	535
2	185	580
3	185	610
4	216	650

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

Tire No.	Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressure P (psi)	Vertical load W (kN)	Contact area A (cm^2)
1	165	535	30	5.8720	199.00
				7.8290	239.50
				9.7870	289.28
				11.744	320.46
				13.701	350.56
			32	5.8720	192.35
				7.8290	235.48
				9.7870	285.00
				11.744	314.40
				13.701	345.29
			34	5.8720	192.82
				7.8290	234.40
				9.7870	275.85
				11.744	303.74
				13.701	338.84
			36	5.8720	182.95
				7.8290	230.60
				9.7870	283.52
				11.744	294.40
				13.701	326.76
			38	5.8720	176.30
				7.8290	223.52
				9.7870	261.41
				11.744	295.17
				13.701	321.59

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

Tire No.	Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressure P (psi)	Vertical load W (kN)	Contact area A (cm^2)
2	185	580	30	5.8720	203.40
				7.8290	258.74
				9.7870	297.77
				11.744	334.70
				13.701	370.57
			32	5.8720	201.29
				7.8290	259.58
				9.7870	292.98
				11.744	337.58
				13.701	360.28
			34	5.8720	187.88
				7.8290	236.56
				9.7870	274.48
				11.744	309.20
				13.701	359.91
			36	5.8720	179.00
				7.8290	233.23
				9.7870	262.28
				11.744	299.61
				13.701	349.78
			38	5.8720	180.03
				7.8290	220.39
				9.7870	263.85
				11.744	307.11
				13.701	335.40

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

Tire No.	Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressure P (psi)	Vertical load W (kN)	Contact area A (cm^2)
3	185	610	30	5.8720	235.21
				7.8290	290.22
				9.7870	325.01
				11.744	369.97
				13.701	412.36
			32	5.8720	223.98
				7.8290	271.25
				9.7870	323.72
				11.744	352.14
				13.701	394.65
			34	5.8720	212.66
				7.8290	267.26
				9.7870	306.92
				11.744	360.16
				13.701	411.12
			36	5.8720	209.09
				7.8290	245.45
				9.7870	299.34
				11.744	344.69
				13.701	376.00
			38	5.8720	201.54
				7.8290	238.78
				9.7870	305.00
				11.744	326.80
				13.701	363.26

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

Tire No.	Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressure P (psi)	Vertical load W (kN)	Contact area A (cm^2)
4	216	650	30	5.8720	218.30
				7.8290	273.77
				9.7870	324.80
				11.744	340.09
				13.701	382.72
			32	5.8720	210.11
				7.8290	244.76
				9.7870	305.04
				11.744	348.18
				13.701	375.53
			34	5.8720	200.37
				7.8290	252.11
				9.7870	297.63
				11.744	333.44
				13.701	372.78
			36	5.8720	187.36
				7.8290	244.51
				9.7870	282.51
				11.744	330.99
				13.701	370.06
			38	5.8720	200.98
				7.8290	239.19
				9.7870	275.91
				11.744	323.08
				13.701	345.73

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

Model No.	Model	Relation
1	$A = C_0 + C_1 b + C_2 d + C_3 P + C_4 W$	$A = - 25.33 - 1.848 b + 1.001 d - 4.088 P + 20.65 W$
2	$A = C_0 + C_1 b + C_2 P + C_3 W$	$A = 14.72 + 1.156 b - 4.088 P + 20.65 W$
3	$A = C_0 + C_1 d + C_2 P + C_3 W$	$A = - 56.62 + 0.483 d - 4.088 P + 20.65 W$
4	$A = C_0 + C_1 (bd) + C_2 P + C_4 W$	$A = 91.08 + 0.001 (bd) - 4.088 P + 20.65 W$
5	$A = C_0 + C_1 (b/d) + C_2 P + C_3 W$	$A = 690.8 - 1515 (b/d) - 4.088 P + 20.65 W$
6	$A = C_0 + C_1 (d/b) + C_2 P + C_3 W$	$A = - 260.7 + 149.3 (d/b) - 4.088 P + 20.65 W$
7	$A = C_0 + C_1 (bd)^{0.5} + C_2 P + C_3 W$	$A = - 32.08 + 0.790 (bd)^{0.5} - 4.088 P + 20.65 W$

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 (0.981). 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:

$$A = - 25.33 - 1.848 b + 1.001 d - 4.088 P + 20.65 W \quad (4)$$

Contact area of radial-ply tire No. 4 was then predicted at five levels of inflation pressure and five 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

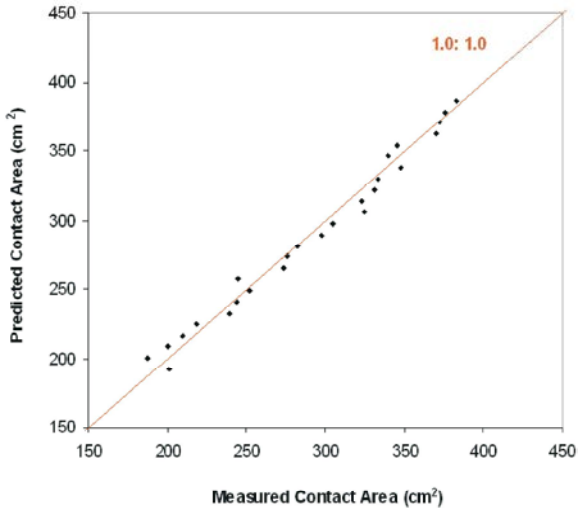

Fig. 6: Measured contact area using test apparatus and predicted contact area using model No. 1 for radial-ply tire No. 4 with the line of equality (1.0: 1.0)

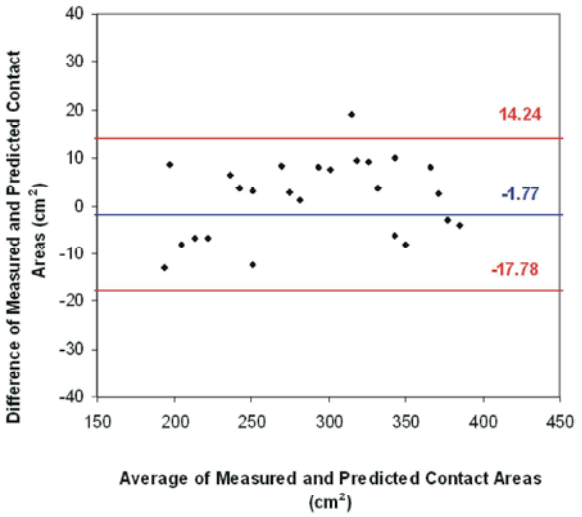

Fig. 7: Bland-Altman plot for the comparison of measured contact area using test apparatus and predicted contact area using model No. 1 for radial-ply tire No. 4; the outer lines indicate the 95% limits of agreement (-17.78, 14.24) and the center line shows the average difference (-1.77)

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	1.89E-09	4.93E-19	---	---	---	---	7.86E-18	2.18E-60	0.981
2	3.62E-08	---	---	---	---	---	7.57E-09	2.76E-44	0.941
3	---	6.60E-18	---	---	---	---	2.85E-13	1.92E-53	0.968
4	---	---	6.50E-13	---	---	---	8.20E-11	1.07E-48	0.956
5	---	---	---	9.75E-07	---	---	2.51E-08	5.52E-43	0.935
6	---	---	---	---	5.95E-07	---	2.11E-08	3.53E-43	0.936
7	---	---	---	---	---	1.19E-12	1.08E-10	1.90E-48	0.956

Table 8: Section width, overall unloaded diameter, inflation pressure, vertical load and contact area for radial-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 (Psi)	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)
216	650	30	5.8720	218.30	224.94	221.62	-6.64
			7.8290	273.77	265.35	269.56	8.42
			9.7870	324.80	305.79	315.29	19.01
			11.744	340.09	346.20	343.14	-6.11
			13.701	382.72	386.61	384.67	-3.89
		32	5.8720	210.11	216.76	213.44	-6.65
			7.8290	244.76	257.17	250.97	-12.41
			9.7870	305.04	297.61	301.32	7.43
			11.744	348.18	338.02	343.10	10.16
			13.701	375.53	378.44	376.98	-2.91
		34	5.8720	200.37	208.59	204.48	-8.22
			7.8290	252.11	249.00	250.55	3.11
			9.7870	297.63	289.43	293.53	8.20
			11.744	333.44	329.85	331.64	3.59
			13.701	372.78	370.26	371.52	2.52
		36	5.8720	187.36	200.41	193.88	-13.05
			7.8290	244.51	240.82	242.67	3.69
			9.7870	282.51	281.26	281.88	1.25
			11.744	330.99	321.67	326.33	9.32
			13.701	370.06	362.08	366.07	7.98
		38	5.8720	200.98	192.23	196.61	8.75
			7.8290	239.19	232.65	235.92	6.54
			9.7870	275.91	273.08	274.49	2.83
			11.744	323.08	313.49	318.29	9.59
			13.701	345.73	353.91	349.82	-8.18

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	-1.77	8.17	0.2883	-5.15, 1.61

between two methods was -1.77 cm^2 (95% confidence intervals for the difference in means: -5.15 cm^2 and 1.60 cm^2; P = 0.2883). The standard deviation of the contact area difference was 8.17 cm^2 (Table 9). The paired samples t-test results showed that the contact area values 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-1.96ó and μ+1.96ó, known as 95% limits of agreement [9-14]. The 95% limits of agreement for comparison of the contact area values determined by test apparatus and model No. 1 was calculated at -17.78 cm^2 and 14.24 cm^2 (Fig. 7). Thus, the contact area values predicted by model No. 1 for radial-ply tire No. 4 may be 17.78 cm^2 lower or 14.24 cm^2 higher than

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 2.65%.

CONCLUSION

It can be concluded that the multiple-variable linear regression model A = - 25.33 - 1.848 b + 1.001 d - 4.088 P + 20.65 W with R^2 = 0.981 can be strongly suggested to predict contact area of radial-ply tire based on section width, overall unloaded diameter, inflation pressure and vertical load.

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