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

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Abstract: This study was conducted to model contact area (A) of radial-ply tire based on tire dimensions, viz., section width (b) and overall unloaded diameter (d) of tire, tire inflation pressure (P) and vertical load on tire (W). For this purpose, contact area of three 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. In order to model contact area based on dimensions, inflation pressure and vertical load, seven multiple-variable linear regression models were suggested and all the data were subjected to regression analysis. The statistical results of study indicated 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 may be suggested to predict contact area of radial-ply tire based on tire dimensions, tire inflation pressure and vertical load on tire for a limited range of radial-ply tire sizes. However, experimental verification of this model is necessary before the model can be recommended for wider use.

Key words: Radial-ply tire · Contact area · Dimensions · Inflation pressure · Vertical load · Modeling

INTRODUCTION

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]:

$$A = bL \tag{1}$$

where:

A = Tire Contact area (m^2)
b = Section width of tire (m)
L = Contact length of tire (m)

McKyes [1] gave an approximate method for estimating contact length of tire on hard and soft surfaces (Fig. 1) as given below in equations 2 and 3, respectively:

$$L = \frac{d}{4} \quad \text{(On a hard surface)} \tag{2}$$

$$L = \frac{d}{2} \quad \text{(On a soft surface)} \tag{3}$$

where:

d = Overall unloaded diameter of tire (m)

Moreover, Wong [2] and Bekker [3] gave an approximate method for calculating contact length of tire as given below in equation 4:

$$L = 2(d\delta - \delta^2)^{0.5} \tag{4}$$

where:

δ = Tire deflection (m)

Tire contact area is a key parameter and many equations have been developed based on tire contact area 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 [4]. Fig. 2 shows the tire dimensions (b, d and δ) used.

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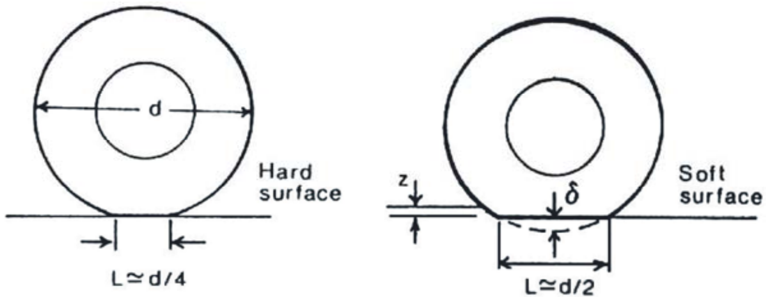

Fig. 1: Contact lengths of tires on hard and soft surfaces, adapted from McKyes [1]

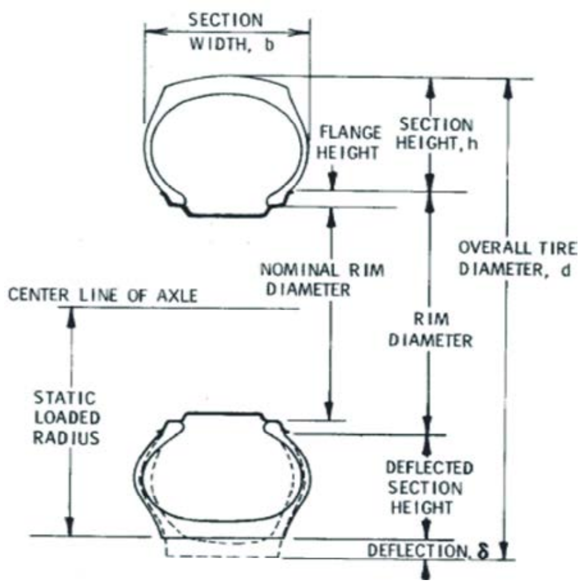

Fig. 2: Tire dimensions, adapted from Brixius [4]

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 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, tire inflation pressure and vertical load on tire are significantly different between radial-ply and bias-ply tires, this study was conducted to model contact area (A) of radial-ply tire based on tire dimensions, viz., section width (b) and overall unloaded diameter (d) of tire, tire inflation pressure (P) and vertical load on tire (W) using linear regression models.

Fig. 3: Tire contact area measurement apparatus

MATERIALS AND METHODS

Tire Contact Area Measurement Apparatus: A tire contact area measurement apparatus (Fig. 3) 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. 4) consisted of tekscan sensor (Fig. 5), tekscan USB handle and computer equipped with I-Scan software (Fig. 6).

Experimental Procedure: Contact area of three radial-ply tires with different dimensions was measured at five levels of inflation pressure and five levels of vertical load. The dimensions of three radial-ply tires are given in Table 1.

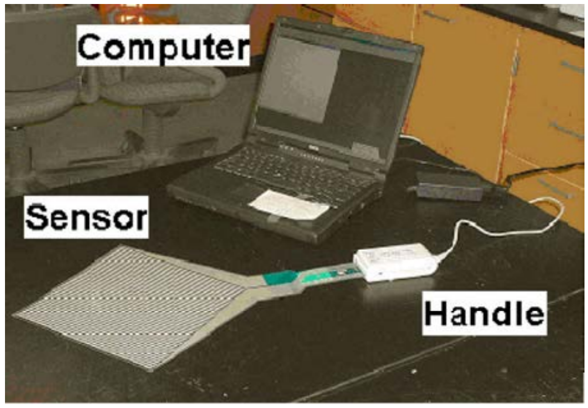

Fig. 4: Contact area measurement system, i.e. tekscan sensor, tekscan USB handle and computer equipped with I-Scan software, adapted from Anderson [6]

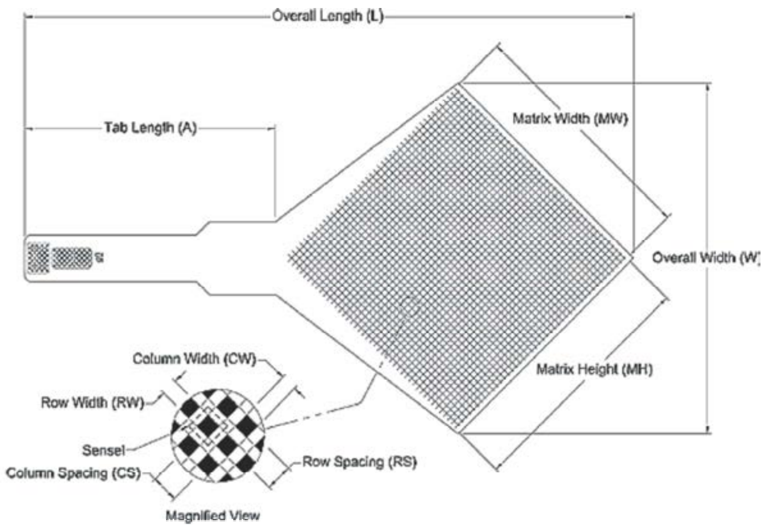

Fig. 5: Tekscan sensor, adapted from Tekscan [7]

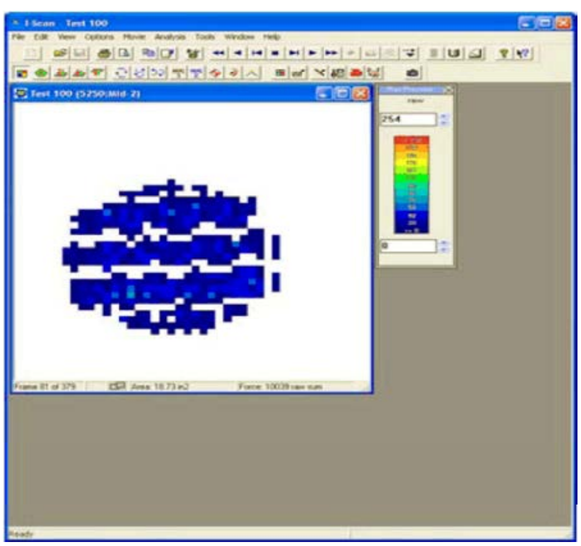

Fig. 6: I-Scan software screenshot for tire contact area measurement

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

Tire No.	Tire size designation	Section width b (mm)	Overall unloaded diameter d (mm)
1	R13-165/65	165	535
2	R14-185/65	185	580
3	R15-185/65	185	610

Results of contact area measurement for radial-ply tires No. 1, 2 and 3 are given in Tables 2, 3 and 4, respectively.

Regression Model: A typical multiple-variable linear regression model is shown in equation 5 [8-12]:

$$Y = C_0 + C_1X_1 + C_2X_2 + \ldots + C_nX_n \quad (5)$$

where:

Y = Dependent variable, for example contact area of radial-ply tire

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

Tire No.	Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressure P (kPa)	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 (three replications) for radial-ply tire No. 2

Tire No.	Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressure P (kPa)	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 (three replications) for radial-ply tire No. 3

Tire No.	Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressure P (kPa)	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: 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	$A = C_0 + C_1 (bd)^{0.5} + C_2 P + C_3 W$	$A = -32.08 + 0.790 (bd)^{0.5} - 4.088 P + 20.65 W$

$X_1, X_2, \ldots, X_n$ = 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 contact area based on dimensions, inflation pressure and vertical load, seven multiple-variable linear regression models were suggested.

RESULT AND DISCUSSION

In order to model contact area of radial-ply tire based tire dimensions (section width and overall unloaded diameter of tire), tire inflation pressure and vertical load on tire, 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 5.

In addition, the p-value of the independent variables and coefficient of determination (R^2) for the seven multiple-variable linear regression models are shown in Table 6.

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 6:

$$A = -25.33 - 1.848 b + 1.001 d - 4.088 P + 20.65 W \quad (6)$$

Table 6: 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

In this model, contact area of radial-ply tire can be predicted using multiple-variable linear regression of section width, overall unloaded diameter, inflation pressure and vertical load [13-15].

CONCLUSIONS

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 $R^2 = 0.981$ may be suggested to predict contact area of radial-ply tire based on tire dimensions, tire inflation pressure and vertical load on tire for a limited range of radial-ply tire sizes. However, experimental verification of this model is necessary before the model can be recommended for wider use.

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