American-Eurasian J. Agric. & Environ. Sci., 14 (9): 843-850, 2014
ISSN 1818-6769

DOI: 10.5829/idosi.aejaes.2014.14.09.12397

Modeling of Contact Length of Bias-ply Tire Based on Tire Dimensions, Inflation Pressure, Vertical Load and Rotational Speed

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Abstract: This study was conducted to model contact length (L) of bias-ply tire based on tire dimensions, viz. section width (b) and overall unloaded diameter (d), inflation pressure (P), vertical load (W) and rotational speed (N). For this reason, contact length of three bias-ply tires with different section width and overall unloaded diameter were measured at three levels of inflation pressure, four levels of vertical load and six levels of rotational speed. In order to model contact length 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 five-variable linear regression model L = 36.20 - 2.533 b + 0.719 d - 0.647 P + 0.185 W + 0.006 N with $R^2 = 0.944$ may be suggested to predict contact length of bias-ply tire based on section width, overall unloaded diameter, inflation pressure, vertical load and rotational speed 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.

Key words: Bias-ply tire · Contact length · Dimensions · Inflation pressure · Vertical load · Rotational speed · 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]:

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

Where:

A = Contact area of tire (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:

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

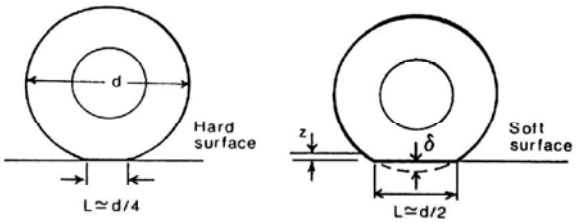

Fig. 1: Contact lengths of tires on hard and soft surfaces, adapted from McKyes [1]

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

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:

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

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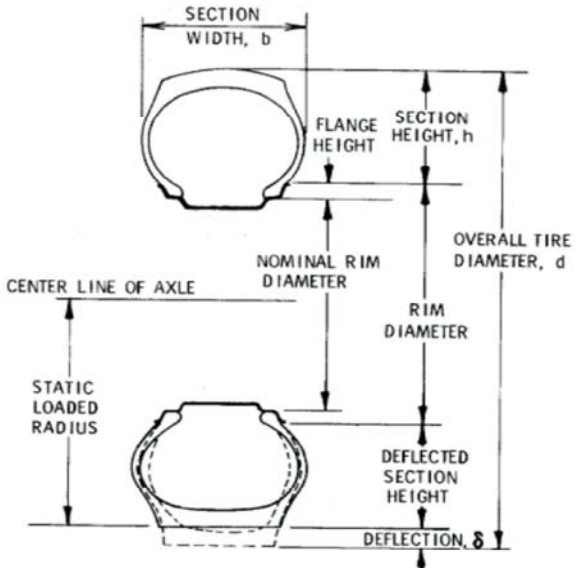

Fig. 2: Tire dimensions, adapted from Brixius [4]

Where:

δ = Deflection of tire (m)

Tire contact length is a key parameter and many equations have been developed based on tire contact length 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 length [4]. Fig. 2 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. 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 length for a given tire dimensions, inflation pressure, vertical load and rotational speed may significantly be different between radial-ply and bias-ply tires, this study was conducted to model contact length (L) of bias-ply tire based on tire dimensions, *viz*. section width (b) and overall unloaded diameter (d), inflation pressure (P), vertical load (W) and rotational speed (N) using linear regression models.

MATERIALS AND METHODS

Tire Contact Length Test Apparatus: A tire contact length test apparatus was designed and constructed to measure contact length of tires with different sizes at diverse levels of inflation pressure, vertical load and rotational speed (Fig. 3).

Experimental Procedure: For this purpose, contact length of three bias-ply tires with different section width and overall unloaded diameter were measured at three levels of inflation pressure, four levels of vertical load and six levels of rotational speed. The dimensions of three bias-ply tires are given in Table 1. Results of contact length 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 linear regression model is shown in equation 5 [6-11]:

$$Y = C_0 + C_1X_1 + C_2X_2 + C_3X_3 \ldots + C_nX_n \quad (5)$$

Where:

- Y = Dependent variable, for example contact length of bias-ply tire
- X_1, X_2, X_3, …, X_n = Independent variables, for example section width, overall unloaded diameter, inflation pressure, vertical load and rotational speed
- C_0, C_1, C_2, C_3, …, C_n = Regression coefficients

To model contact length based on dimensions, inflation pressure, vertical load and rotational speed, seven multiple-variable linear regression models were suggested.

Fig. 3: Tire contact length measurement apparatus

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

Tire No.	Section width b (mm)	Overall unloaded diameter d (mm)
1	142	596
2	152	654
3	165	676

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

Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressurez (psi)	Vertical load W (kg)	Rotational speed N (rev/min)	Contact length L (mm)		
					L_1	L_2	L_3
142	596	30	100	0	106	105	106
				600	102	102	102
				700	106	105	106
				800	108	107	108
				900	110	111	110
				1000	113	114	113
			150	0	117	118	117
				600	112	112	113
				700	116	116	116
				800	117	118	117
				900	119	119	119
				1000	123	122	122
			200	0	126	125	126
				600	122	123	122
				700	125	125	126
				800	126	127	127
				900	130	131	130
				1000	131	132	132
			250	0	136	135	135
				600	131	131	131
				700	135	136	135
				800	136	136	137
				900	138	139	138
				1000	139	140	140
		35	100	0	103	104	103
				600	100	101	100
				700	103	102	103
				800	105	105	105
				900	107	107	107
				1000	110	111	110
			150	0	112	113	112
				600	108	107	108
				700	111	111	112
				800	114	114	115
				900	116	115	116
				1000	119	120	119
			200	0	122	121	122
				600	119	118	119
				700	121	122	122
				800	124	124	124
				900	127	127	127
				1000	128	129	129
			250	0	133	132	133
				600	129	128	129
				700	131	132	132
				800	135	134	134
				900	135	135	135
				1000	137	136	137

Table 2: Continue

Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressurez (psi)	Vertical load W (kg)	Rotational speed N (rev/min)	Contact length L (mm) L_1	L_2	L_3
		40	100	0	100	101	100
				600	97	98	97
				700	100	101	100
				800	103	104	103
				900	105	105	104
				1000	106	107	107
			150	0	110	111	110
				600	105	105	105
				700	109	108	109
				800	112	113	112
				900	113	114	114
				1000	115	116	116
			200	0	119	120	119
				600	115	115	115
				700	119	120	119
				800	120	121	121
				900	123	122	123
				1000	125	126	125
			250	0	128	129	128
				600	124	124	125
				700	128	127	128
				800	130	131	130
				900	131	132	132
				1000	134	134	134

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

Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressurez (psi)	Vertical load W (kg)	Rotational speed N (rev/min)	Contact length L (mm) L_1	L_2	L_3
152	654	30	100	0	120	120	121
				600	116	115	116
				700	120	121	120
				800	121	122	122
				900	125	125	125
				1000	128	128	128
			150	0	130	131	130
				600	125	125	125
				700	128	129	129
				800	132	132	133
				900	135	136	135
				1000	138	138	139
			200	0	144	145	145
				600	140	141	140
				700	145	145	146
				800	147	146	147
				900	149	149	150
				1000	152	152	153
			250	0	153	153	153
				600	149	150	149
				700	152	152	152
				800	154	154	155
				900	157	158	157
				1000	159	159	160

Table 3: Continue

Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressurez (psi)	Vertical load W (kg)	Rotational speed N (rev/min)	Contact length L (mm)		
					L_1	L_2	L_3
		35	100	0	118	118	118
				600	115	114	115
				700	119	119	120
				800	122	121	122
				900	125	125	126
				1000	128	128	128
			150	0	128	128	128
				600	124	124	124
				700	128	128	128
				800	130	129	130
				900	133	133	133
				1000	136	137	136
			200	0	140	141	140
				600	135	135	136
				700	139	140	139
				800	142	142	143
				900	144	144	144
				1000	147	147	146
			250	0	149	149	150
				600	145	145	145
				700	148	147	148
				800	150	151	151
				900	154	154	154
				1000	156	157	157
		40	100	0	115	115	116
				600	111	111	111
				700	115	115	116
				800	118	118	119
				900	120	121	121
				1000	123	123	124
			150	0	124	125	124
				600	120	120	120
				700	124	123	124
				800	127	127	127
				900	129	130	130
				1000	132	132	133
			200	0	133	134	133
				600	130	129	130
				700	133	134	134
				800	137	137	137
				900	139	140	140
				1000	142	143	143
			250	0	143	144	143
				600	139	140	140
				700	144	144	144
				800	147	147	147
				900	149	150	149
				1000	152	151	152

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

Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressurez (psi)	Vertical load W (kg)	Rotational speed N (rev/min)	Contact length L (mm) L_1	L_2	L_3
165	676	30	100	0	108	107	107
				600	103	103	103
				700	106	106	105
				800	108	108	108
				900	111	112	111
				1000	114	114	113
			150	0	117	117	118
				600	114	114	113
				700	117	117	117
				800	119	118	119
				900	121	121	122
				1000	123	123	123
			200	0	124	124	123
				600	120	120	121
				700	124	123	124
				800	125	125	126
				900	127	127	127
				1000	130	130	131
			250	0	132	132	131
				600	129	129	129
				700	131	132	131
				800	133	132	133
				900	134	134	133
				1000	135	136	136
		35	100	0	104	104	105
				600	100	100	100
				700	103	103	104
				800	105	105	105
				900	105	106	106
				1000	107	108	108
			150	0	112	111	112
				600	109	109	109
				700	112	111	112
				800	114	114	115
				900	115	115	115
				1000	117	117	118
			200	0	122	122	122
				600	118	117	118
				700	122	122	123
				800	125	125	125
				900	126	127	127
				1000	130	130	131
			250	0	130	131	130
				600	125	126	125
				700	129	130	129
				800	132	132	132
				900	134	134	135
				1000	136	137	136

Table 4: Continue

Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressurez (psi)	Vertical load W (kg)	Rotational speed N (rev/min)	Contact length L (mm)		
					L_1	L_2	L_3
		40	100	0	102	102	102
				600	99	98	99
				700	101	100	101
				800	104	104	104
				900	106	105	106
				1000	108	108	109
			150	0	112	111	112
				600	108	108	109
				700	112	112	112
				800	114	115	114
				900	115	115	115
				1000	116	117	117
			200	0	117	118	117
				600	113	112	113
				700	116	116	117
				800	118	118	118
				900	120	120	121
				1000	122	123	123
			250	0	124	125	124
				600	120	120	120
				700	125	124	124
				800	127	127	127
				900	128	129	129
				1000	132	132	133

RESULTS AND DISCUSSION

In order to model contact length of bias-ply tire based tire dimensions, *viz*. section width and overall unloaded diameter, inflation pressure, vertical load and rotational speed, 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 (0.944). 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:

$$L = 36.20 - 2.533\ b + 0.719\ d - 0.647\ P + 0.185\ W + 0.006\ N \quad (6)$$

In this model, contact length of bias-ply tire can be predicted using multiple-variable linear regression of section width, overall unloaded diameter, inflation pressure, vertical load and rotational speed.

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

Model No.	Model	Relation
1	$L = C_0 + C_1\ b + C_2\ d + C_3\ P + C_4\ W + C_5\ N$	$L = 36.20 - 2.533\ b + 0.719\ d - 0.647\ P + 0.185\ W + 0.006\ N$
2	$L = C_0 + C_1\ b + C_2\ P + C_3\ W + C_4\ N$	$L = 124.8 - 0.094\ b - 0.647\ P + 0.185\ W + 0.006\ N$
3	$L = C_0 + C_1\ d + C_2\ P + C_3\ W + C_4\ N$	$L = 78.05 + 0.050\ d - 0.647\ P + 0.185\ W + 0.006\ N$
4	$L = C_0 + C_1\ (bd) + C_2\ P + C_3\ W + C_4\ N$	$L = 109.0 + 0.00001\ bd - 0.647\ P + 0.185\ W + 0.006\ N$
5	$L = C_0 + C_1\ (b/d) + C_2\ P + C_3\ W + C_4\ N$	$L = 459.9 - 1466.7\ (b/d) - 0.647\ P + 0.185\ W + 0.006\ N$
6	$L = C_0 + C_1\ (d/b) + C_2\ P + C_3\ W + C_4\ N$	$L = -241.5 + 83.81\ (d/b) - 0.647\ P + 0.185\ W + 0.006\ N$
7	$L = C_0 + C_1\ (bd)^{0.5} + C_2\ P + C_3\ W + C_4\ N$	$L = 104.9 + 0.017\ (bd)^{0.5} - 0.647\ P + 0.185\ W + 0.006\ N$

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	N	R^2
1	8.1E-265	5.9E-269	---	---	---	---	3.27E-72	0	9.74E-42	0.944
2	0.008512	---	---	---	---	---	1.41E-14	5.0E-129	3.18E-08	0.621
3	---	3.46E-07	---	---	---	---	5.92E-15	1.6E-131	2.00E-08	0.632
4	---	---	0.646472	---	---	---	1.90E-14	3.7E-128	3.73E-08	0.617
5	---	---	---	5.5E-156	---	---	3.44E-37	6.1E-238	1.02E-20	0.873
6	---	---	---	---	3.4E-160	---	3.81E-38	2.2E-241	2.91E-21	0.876
7	---	---	---	---	---	0.360440	1.84E-14	3.1E-128	3.68E-08	0.617

CONCLUSIONS

It can be concluded that the multiple-variable linear regression model L = 36.20 - 2.533 b + 0.719 d - 0.647 P + 0.185 W + 0.006 N with R^2 = 0.944 may be suggested to predict contact length of bias-ply tire based on tire dimensions, *viz*. section width and overall unloaded diameter, inflation pressure, vertical load and rotational speed 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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