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Modeling of Radial-Ply Tire Deflection Based on Section Width, Overall Unloaded Diameter, Inflation Pressure, Vertical Load and Rotational Speed

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Abstract: This study was conducted to model deflection (δ) of radial-ply tire based on section width (b), overall unloaded diameter (d), inflation pressure (P), vertical load (W) and rotational speed (N). For this purpose, deflection of three radial-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 deflection based on section width, overall unloaded diameter, inflation pressure, vertical load and rotational speed, a five-variable linear regression model was suggested and all the data were subjected to regression analysis. The statistical results of study indicated that the five-variable linear regression model $\delta = 178.12 + 0.3354\ b - 0.3800\ d - 0.3788\ P + 0.0651\ W - 0.0019\ N$ with $R^2 = 0.9777$ may be suggested to predict deflection of radial-ply tire based on section width, overall unloaded diameter, inflation pressure, vertical load and rotational speed for a limited range of radial-ply tire sizes.

Key words: Radial-ply tire · Deflection · Section width · Overall unloaded diameter · Inflation pressure · Vertical load · Rotational speed · Modeling

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

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

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

Where:

d = Overall unloaded diameter of tire (m)
δ = Deflection of tire (m)

Tire deflection is a key parameter and many equations have been developed based on tire deflection 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 and tire deflection [4].

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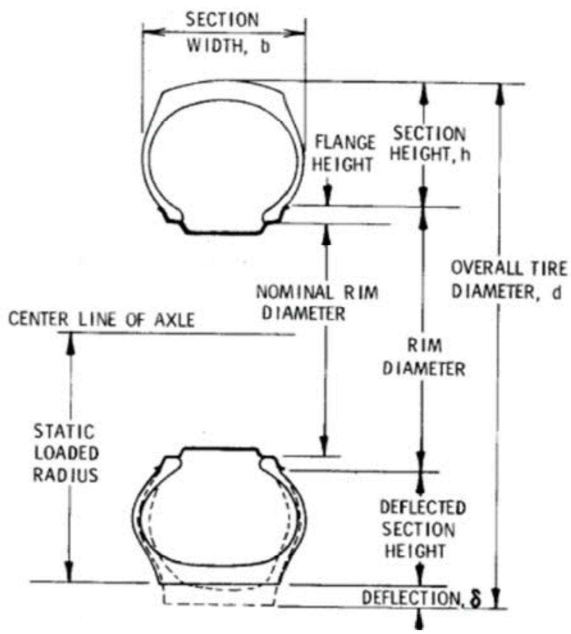

Fig. 1: Tire dimensions, adapted from Brixius [4]

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. 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 deflections for a given tire size, inflation pressure, vertical load and rotational speed may significantly be different between bias-ply and radial-ply tires, this study was conducted to model deflection (δ) of radial-ply tire based on section width (b), overall unloaded diameter (d), inflation pressure (P), vertical load (W) and rotational speed (N) using a linear regression model.

MATERIALS AND METHODS

Tire Deflection Test Apparatus: A tire deflection test apparatus was designed and constructed to measure deflection of tires with different sizes at diverse levels of inflation pressure, vertical load and rotational speed (Fig. 2).

Fig. 2: Tire deflection test apparatus

Experimental Procedure: For this purpose, deflection of three radial-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 section width and overall unloaded diameter of three radial-ply tires are given in Table 1. Results of deflection measurement for radial-ply tires No. 1, 2 and 3 are given in Tables 2, 3 and 4, respectively.

Regression Model: A typical five-variable linear regression model is shown in equation 3 [6-9]:

$$Y = C_0 + C_1X_1 + C_2X_2 + C_3X_3 + C_4X_4 + C_5X_5 \quad (3)$$

Where:

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

X_1, X_2, X_3, X_4, X_5 = 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_4, C_5 = Regression coefficients

Table 1: Section width and overall unloaded diameter of three radial-ply tires used in this study

Tire No.	Section width b (mm)	Overall unloaded diameter d (mm)
1	175	578
2	195	582
3	185	605

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

Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressure P (kPa)	Vertical load W (kN)	Rotational speed N (rev/min)	Deflection δ (mm) δ_1	δ_2	δ_3
175	578	30	100	0	9.500	9.500	9.250
				600	8.750	8.750	8.500
				700	8.500	8.500	8.250
				800	8.250	8.250	8.000
				900	8.000	8.000	7.500
				1000	7.500	7.500	7.250
			150	0	14.50	14.50	14.25
				600	13.25	13.25	13.00
				700	13.00	13.00	12.75
				800	12.75	12.75	12.50
				900	12.50	12.50	12.25
				1000	12.25	12.25	12.25
			200	0	18.50	18.50	18.25
				600	17.50	17.50	17.25
				700	17.25	17.25	17.25
				800	17.00	17.00	16.75
				900	16.75	16.75	16.50
				1000	16.50	16.50	16.50
			250	0	22.00	22.00	21.75
				600	20.75	20.75	20.50
				700	20.50	20.50	20.25
				800	20.25	20.25	20.00
				900	20.00	20.00	19.75
				1000	19.75	19.75	19.75
		35	100	0	11.25	11.25	11.00
				600	9.750	9.750	10.00
				700	9.750	9.500	9.750
				800	9.500	9.250	9.250
				900	9.250	9.250	9.250
				1000	8.750	8.750	9.000
			150	0	14.25	14.25	14.50
				600	13.25	13.25	13.50
				700	13.00	13.00	13.25
				800	12.75	12.50	12.75
				900	12.50	12.25	12.50
				1000	12.25	12.25	12.25
			200	0	18.50	18.75	18.50
				600	17.50	17.75	17.50
				700	17.50	17.50	17.25
				800	17.25	17.25	17.00
				900	17.00	17.00	17.00
				1000	16.25	16.50	16.25
			250	0	21.25	21.00	21.25
				600	20.25	20.00	20.25
				700	20.00	20.00	20.00
				800	19.75	19.75	19.50
				900	19.50	19.50	19.25
				1000	19.25	19.25	19.25

Table 2: Continue

Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressure P (kPa)	Vertical load W (kN)	Rotational speed N (rev/min)	Deflection δ (mm) δ_1	δ_2	δ_3
		40	100	0	8.250	8.500	8.250
				600	7.250	7.500	7.250
				700	6.750	7.000	6.750
				800	6.750	6.750	6.750
				900	6.500	6.500	6.750
				1000	6.250	6.250	6.000
			150	0	11.75	11.75	12.00
				600	10.75	10.75	11.00
				700	11.00	10.50	10.75
				800	10.75	10.75	10.50
				900	10.25	10.50	10.25
				1000	10.00	10.25	10.00
			200	0	15.25	15.00	15.25
				600	14.25	14.00	14.25
				700	14.00	13.75	14.00
				800	13.75	13.25	13.75
				900	13.50	13.25	13.50
				1000	13.25	13.00	13.25
			250	0	19.00	18.75	19.00
				600	18.00	17.75	18.00
				700	17.75	17.50	17.75
				800	17.25	17.00	17.50
				900	17.25	17.00	17.25
				1000	16.75	16.50	16.75

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

Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressure P (kPa)	Vertical load W (kN)	Rotational speed N (rev/min)	Deflection δ (mm) δ_1	δ_2	δ_3
195	582	30	100	0	17.75	17.75	17.50
				600	17.00	17.00	16.75
				700	16.75	16.75	16.50
				800	16.50	16.50	16.25
				900	16.25	16.25	16.00
				1000	16.00	16.00	16.00
			150	0	21.00	21.00	20.75
				600	20.25	20.25	20.00
				700	20.00	20.00	19.75
				800	19.75	19.75	19.50
				900	19.50	19.50	19.25
				1000	19.25	19.25	19.00
			200	0	24.50	24.50	24.00
				600	23.50	23.50	23.25
				700	23.25	23.25	23.00
				800	23.00	23.00	22.75
				900	22.75	22.75	22.50
				1000	22.50	22.50	22.50
			250	0	27.00	27.00	26.75
				600	26.25	26.25	26.00
				700	26.00	26.00	25.75
				800	25.75	25.75	25.50
				900	25.50	25.50	25.25
				1000	25.25	25.25	25.00

Table 3: Continue

Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressure P (kPa)	Vertical load W (kN)	Rotational speed N (rev/min)	Deflection δ (mm) δ_1	δ_2	δ_3
		35	100	0	14.75	14.75	14.50
				600	14.00	14.00	13.75
				700	13.75	13.75	13.50
				800	13.50	13.50	13.25
				900	13.25	13.25	13.00
				1000	13.00	13.00	12.75
			150	0	18.25	18.25	18.50
				600	17.50	17.50	17.75
				700	17.25	17.25	17.50
				800	17.00	17.00	17.25
				900	16.75	16.75	17.00
				1000	16.50	16.50	16.50
			200	0	21.50	21.50	21.25
				600	20.75	20.75	20.50
				700	20.50	20.50	20.25
				800	20.25	20.25	20.00
				900	20.00	20.00	19.75
				1000	19.75	19.75	19.50
			250	0	25.25	25.25	25.00
				600	24.50	24.50	24.25
				700	24.25	24.25	24.00
				800	24.00	24.00	23.75
				900	23.75	23.75	23.50
				1000	23.50	23.50	23.25
		40	100	0	14.50	14.50	14.25
				600	13.75	13.75	13.50
				700	13.50	13.50	13.25
				800	13.25	13.25	13.00
				900	13.00	13.00	12.75
				1000	12.75	12.75	12.75
			150	0	17.50	17.50	17.25
				600	16.75	16.75	16.50
				700	16.50	16.50	16.25
				800	16.25	16.25	16.00
				900	16.00	16.00	15.75
				1000	15.75	15.75	15.50
			200	0	19.75	19.75	19.50
				600	19.00	19.00	18.75
				700	18.75	18.75	18.50
				800	18.50	18.50	18.25
				900	18.25	18.25	18.00
				1000	18.00	18.00	17.75
			250	0	22.25	22.25	22.00
				600	21.50	21.50	21.25
				700	21.25	21.25	21.00
				800	21.00	21.00	20.75
				900	20.75	20.75	20.50
				1000	20.50	20.50	20.50

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

Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressure P (kPa)	Vertical load W (kN)	Rotational speed N (rev/min)	Deflection δ (mm) δ_1	δ_2	δ_3
185	605	30	100	0	5.500	5.500	5.250
				600	4.750	4.750	4.500
				700	4.500	4.500	4.250
				800	4.250	4.250	4.000
				900	4.000	4.000	3.750
				1000	3.750	3.750	3.500
			150	0	9.500	9.500	9.250
				600	8.250	8.250	8.000
				700	8.000	8.000	7.750
				800	7.750	7.750	7.500
				900	7.500	7.500	7.250
				1000	7.250	7.250	7.000
			200	0	12.50	12.50	12.25
				600	11.25	11.25	11.00
				700	11.00	11.00	10.75
				800	10.75	10.75	10.50
				900	10.50	10.50	10.25
				1000	10.25	10.25	10.50
			250	0	17.25	17.25	17.00
				600	16.00	16.00	15.75
				700	15.75	15.75	15.50
				800	15.50	15.50	15.25
				900	15.25	15.25	15.00
				1000	15.00	15.00	14.75
		35	100	0	3.000	3.000	2.750
				600	2.000	2.000	1.750
				700	1.750	1.750	1.500
				800	1.500	1.500	1.250
				900	1.250	1.250	1.000
				1000	1.000	1.000	1.000
			150	0	7.250	7.250	7.000
				600	6.500	6.500	6.250
				700	6.250	6.250	6.000
				800	6.000	6.000	5.750
				900	5.750	5.750	5.500
				1000	5.500	5.500	5.250
			200	0	8.750	8.750	8.500
				600	7.500	7.500	7.250
				700	7.250	7.250	7.000
				800	7.000	7.000	6.750
				900	6.750	6.750	6.500
				1000	6.500	6.500	6.250
			250	0	13.25	13.25	13.00
				600	12.25	12.25	12.25
				700	12.00	12.00	11.75
				800	11.75	11.75	11.75
				900	11.75	11.50	11.50
				1000	11.50	11.25	11.25
		40	100	0	2.750	2.750	2.500
				600	1.750	1.750	1.500
				700	1.500	1.500	1.250
				800	1.250	1.250	1.000
				900	1.000	1.000	0.750
				1000	0.750	1.000	0.750

Table 4: Continue

Section width b (mm)	Overall unloaded diameter d (mm)	Inflation pressure P (kPa)	Vertical load W (kN)	Rotational speed N (rev/min)	Deflection δ (mm) δ_1	δ_2	δ_3
			150	0	5.000	5.000	4.750
				600	3.750	3.750	3.500
				700	3.500	3.500	3.250
				800	3.250	3.250	3.000
				900	3.000	3.000	2.750
				1000	2.750	2.750	2.500
			200	0	8.000	8.000	7.750
				600	7.000	7.000	6.750
				700	6.750	6.750	6.500
				800	6.500	6.500	6.250
				900	6.250	6.250	6.000
				1000	6.000	6.000	6.750
			250	0	9.250	9.250	9.000
				600	8.000	8.000	7.750
				700	7.750	7.750	7.500
				800	7.500	7.500	7.250
				900	7.250	7.250	7.000
				1000	7.000	7.000	6.750

To model deflection based on section width, overall unloaded diameter, inflation pressure, vertical load and rotational speed, a five-variable linear regression model was suggested.

RESULTS AND DISCUSSION

In order to model deflection of radial-ply tire based on section width, overall unloaded diameter, inflation pressure, vertical load and rotational speed, a five-variable linear regression model was suggested and all the data were subjected to regression analysis using the Microsoft Excel 2007. The five-variable linear regression model, p-value of independent variables and coefficient of determination (R^2) of the model are shown in Table 5. As it is shown in Table 5, this model has a high R^2 value at 0.9777, indicating good agreement of the experimental data. In addition, the p-value of independent variables (b, d, P, W and N) is as follows: 5.3E-308, 0, 2.7E-180, 0 and 5.22E-51, respectively. Thus, based on the statistical results, this model is initially accepted, which is given by equation 4:

$$\delta = 178.12 + 0.3354\ b - 0.3800\ d - 0.3788\ P + 0.0651\ W - 0.0019\ N \quad (4)$$

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

Table 5: Five-variable linear regression model, p-value of independent variables and coefficient of determination (R^2)

Model	p-value b	d	P	W	N	R^2
$\delta = 178.12 + 0.3354\ b - 0.3800\ d - 0.3788\ P + 0.0651\ W - 0.0019\ N$	5.3E-308	0	2.7E-180	0	5.22E-51	0.9777

CONCLUSIONS

It can be concluded that the five-variable linear regression model $\delta = 178.12 + 0.3354\ b - 0.3800\ d - 0.3788\ P + 0.0651\ W - 0.0019\ N$ with $R^2 = 0.9777$ may be suggested to predict deflection of radial-ply tire based on section width, overall unloaded diameter, inflation pressure, vertical load and rotational speed for a limited range of radial-ply tire sizes.

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