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Ranjeet Kumar
Assistant professor, RMD College of Agriculture and Research Station, Ambikapur, Chhattisgarh, India

KP Pandey
Ret. Professors, IIT Kharagpur, West Bengal, India

DK Gupta
Assoc. Professor, RMD CARS, Ambikapur, Chhattisgarh, India

VK Tewari
Research Scholar, IIT Kharagpur, West Bengal, India

Satya prakash
Scientist, CIAE, Bhopal, Madhya Pradesh, India

Sanjeev Kumar
Research Scholars, IIT Kharagpur, West Bengal, India

Correspondence
Ranjeet Kumar
Assistant professor, RMD College of Agriculture and Research Station, Ambikapur, Chhattisgarh, India

Deflection characteristics for radial-ply tractor tyres

Ranjeet Kumar, KP Pandey, DK Gupta, VK Tewari, Satya Prakash and Sanjeev Kumar

Abstract
The deflection characteristics of four radial-ply tyres (12.4 R 28, 13.6 R 28, 14.9 R 28 and 16.9 R 28) were studied on a hard surface. The normal load on the test tyres was varied from 4.91 to 19.13 kN and inflation pressure from 41 to 207 kPa. Based on the test observations, empirical model was developed to predict deflection of the radial-ply tyres. This model was validated and was found to perform well. The developed deflection model was used to determine the possible combinations of normal load and inflation pressure to achieve the desired deflection of 20, 24 and 28 per cent for each test tyre.

Keywords: Deflection, radial-ply tractor tyres

Introduction

The best single indicator of a tyre‘s ability to perform satisfactorily and deliver normal service life is tyre deflection. When a tyre is over deflected as a result of over load and under inflation or a combination of these, service life will be reduced. The over deflected tyre bulges excessively at ground contact making it more subject to puncture damage. This requires that the recommended inflation pressure is maintained in all tyres and that the tyres are not subjected to load more than the recommended load. It is, therefore, essential to study the deflection characteristics of a tyre with a view to arrive at optimum combinations of load and inflation pressure for evaluating its traction performance.

The tyre deflection characteristics have extensively been reviewed and presented as follows

2. Materials and methods

The experimental facilities for deflection test included a tyre test carriage (single wheel tester), an electronic plate-form balance and deflection measuring device. The tyre test carriage could accommodate the various sizes of the tyres and could be raised and lowered using a hydraulic cylinder. The vertical deflection of the tyre was measured with displacement transducer and recorded by a Data Acquisition System (DAS). The four different sizes of test tyres (12.4R28, 13.6R28, 14.9R28 and 16.9R28) were selected for the study. The tyre aspect ratio varied from 0.812 to 0.860 and b/d ratio from 0.25 to 0.31.

1. Hydraulic cylinder, 2. Displacement transducer, 3. Base plate, 4. Side rail

Fig 1: Test set-up for tyre vertical deflection measurement

The tyre with a given inflation pressure was loaded to the desired vertical load with the dead weights on a single wheel tester. The tyre was slowly brought down and allowed to rest on the hard surface and the transducer output was recorded for deflection measurement. The transducer was calibrated before conducting the tests. First, initial reading was recorded in a Data Acquisition System (DAS) for a zero position of the displacement. Then using gauge blocks with dimensions corresponding to the displacement, the final output was measured in the DAS. The difference between initial and final readings of the DAS indicated the deflection. The per cent deflection was calculated using the following formula.

$$\text{Tyre deflection, per cent} = \frac{\text{Vertical tyre deflection, } (\delta)}{(\text{Tyre section height } (h) - \text{Flange height})} \times 100$$

3. Research plan

The objective of this study was to obtain vertical tyre deflection and contact area characteristics of radial ply tyres at various normal loads and inflation pressure. In order to accomplish the objective four sizes of radial ply tyres were tested at seven different inflation pressures and six different normal loads on hard surface.

Independent parameters:			
Tyre (radial-ply)	4	T_1-12.4 R 28 (321mm × 711mm) T_2-13.6 R 28 (358mm × 711mm) T_3-14.9 R 28 (405mm × 711mm) T_4-16.9 R 28 (452mm × 711mm)	
Inflation pressure, kPa (psi)	7	41(6), 69 (10), 97 (14), 124 (18), 152 (22), 179 (26), 207 (30)	
Normal load, kN (kgf)	6	4.905 (500), 6.377 (650), 7.848 (800), 9.32 (950), 10.791 (1100), 12.263 (1250)	- for T_1
	6	6.377 (650), 7.848 (800), 9.32 (950), 10.791 (1100), 12.263 (1250), 13.734 (1400)	- for T_2
	6	7.848 (800), 9.81 (1000), 11.772 (1200), 13.734 (1400), 15.696 (1600), 17.658 (1800)	- for T_3
	6	9.32 (950), 11.282 (1150), 13.244 (1350), 15.206 (1550), 17.168 (1750), 19.13 (1950)	- for T_4
Supporting surface	1	Hard surface	
Replication	3		
Dependent parameters:			
Vertical tyre deflection, mm			

4. Results

Calibration of displacement transducer

The displacement transducer was calibrated for measurement of vertical tyre deflection. In order to calibrate the displacement transducer the change in output voltage was recoded with respect to change in deflection. The calibration curve (Fig. 2) shows a linear relationship between output voltage and deflection. The calibration equation was fed to the data acquisition system for real time measurement of vertical tyre deflection.

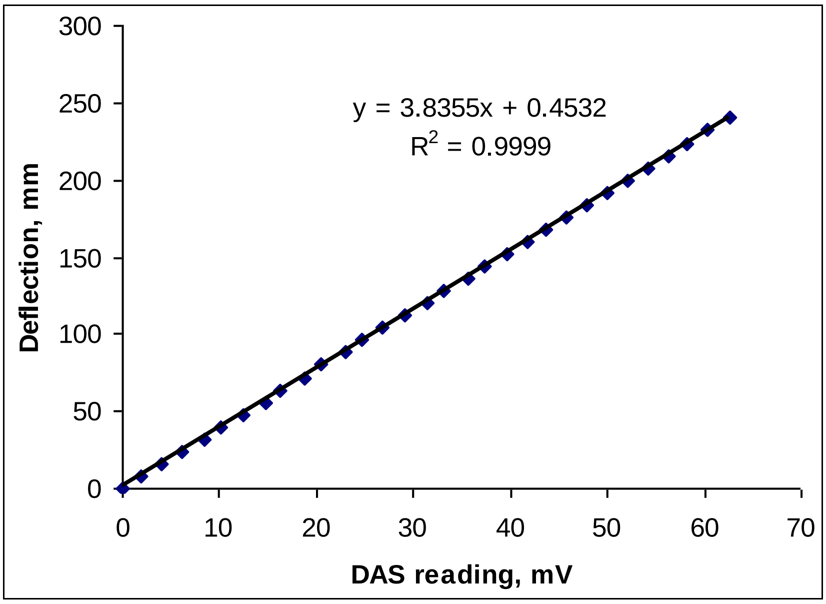


Fig 2: Calibration of displacement transducer for tyre vertical deflection

Effect of normal load and inflation pressure on tyre deflection

The relationship between inflation pressure and tyre deflection ratio at different normal loads is shown in Fig. 3 and that between normal load and tyre deflection ratio at different inflation pressure in Fig.4.

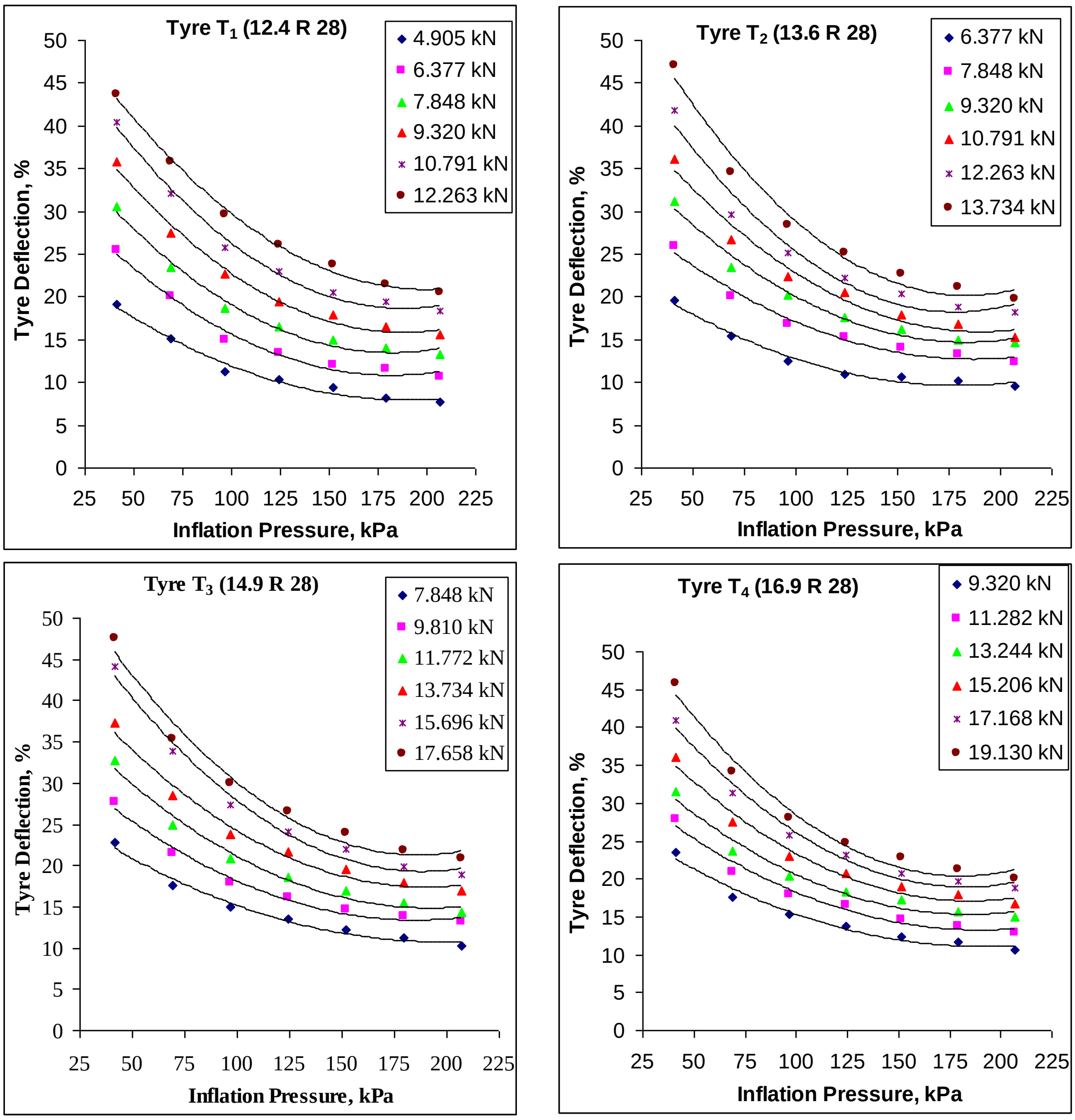
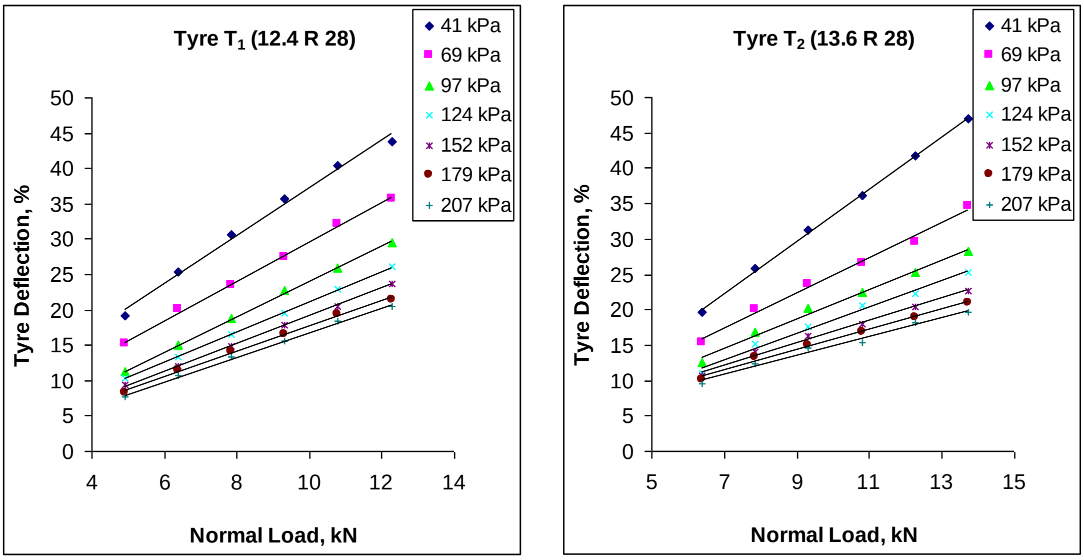


Fig 3: Relationship between inflation pressure and tyre deflection at different normal loads for test tyres

The general trend shows that tyre deflection decreased non-linearly with increase in inflation pressure from 41 to 207 kPa, while it increased linearly with increase in normal load for different test tyres. A similar trend was also observed by Abeel (1976), Fujimoto (1977), Yong *et al*. (1978), Plackett (1983), Sharma and Pandey (1996) and Tiwari (2006). It is also noticed that the rate of increase of deflection with normal load is higher at lower values of inflation pressure than at higher ones. This may be due to the fact that carcass stiffness is not a constant value but changes with inflation pressure. This finding is supported by Karafaith and Nawatzki (1978). He suggested that tyre carcass stiffness is influenced by its inflation pressure and it reduces with inflation pressure.



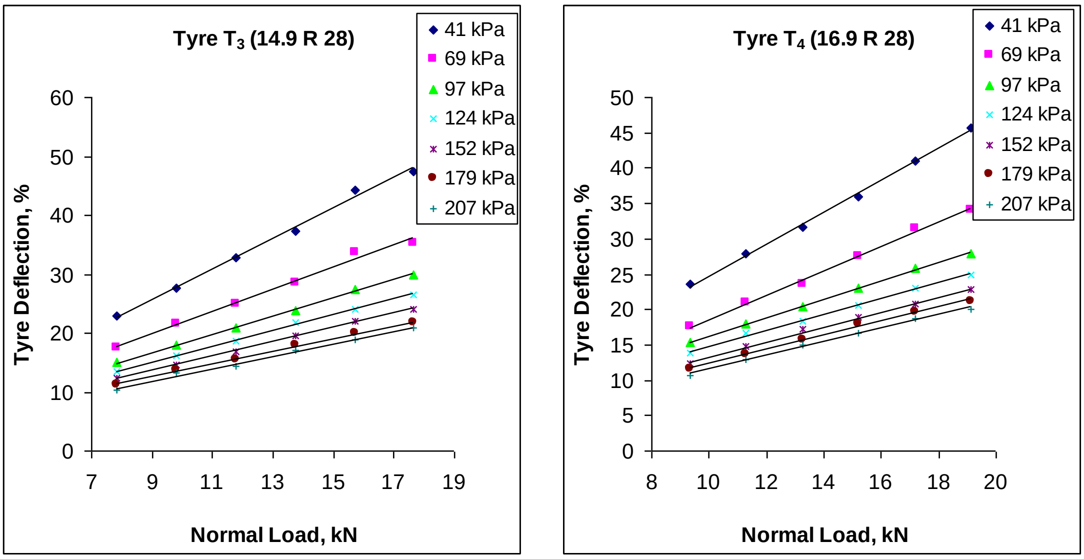


Fig 4: Relationship between normal load and tyre deflection at different inflation pressures for test tyres

The relationship between tyre deflection ratio and inflation pressure is represented by

$$\frac{\delta}{h} = C_1 \times pi^2 + C_2 \times pi + C_3$$

and that between tyre deflection ratio and normal load by

$$\frac{\delta}{h} = C_4 \times W + C_5$$

where, $\frac{\delta}{h}$ = deflection ratio, percent;
p_i = inflation pressure, kPa;
W = normal load, kN; and
C_1 to C_5 = constants.

It is clear from the curves that due to higher stiffness, the larger tyres yielded smaller deflection compared to smaller tyres at the same inflation pressure and normal load.

Deflection models

The deflection of agricultural tyres depends on their normal load, air inflation pressure and b/d ratio. The experimental data were analyzed to develop two deflection models based on regression analysis approach and dimensional analysis approach to predict deflection of agricultural tyres at different inflation pressures and normal loads.

Regression analysis approach

A second degree-regression equation was found to best fit the experimental data as given below.

$$\frac{\delta}{h} = C_1 + C_2 \times W + C_3 \times pi + C_4 \times \frac{b}{d} + C_5 \times W \times pi + C_6 \times W \times \frac{b}{d} + C_7 \times pi \times \frac{b}{d} + C_8 \times (pi)^2 + C_9 \times \left(\frac{b}{d}\right)^2$$

where, $\frac{\delta}{h}$ = deflection ratio, per cent;
$\frac{b}{d}$ = width to diameter ratio of tyre,
p_i = inflation pressure, MPa;
W = normal load, kN; and
C_1 to C_9 = regression coefficients (Table 5.1).

Table 1: Coefficients of the developed deflection model based on regression approach

Constants	Coefficients	Std. Error
C_1	56.38	0.2058
C_2	7.64	0.0045
C_3	-445.05	0.2801
C_4	-255.42	1.5123
C_5	-8.92	0.0061
C_6	-16.74	0.0152
C_7	829.63	1.0348
C_8	839.25	0.4140
C_9	349.16	2.8011

R^2 = 0.98

A high value of R^2 shows that the experimental data fit the regression very well. This model was used to calculate the load-pressure combinations to get the desired level of 20, 24 and 28 per cent tyre deflection for each test tyre. These values are given in Table 2 and the same were adopted to study the traction performance of test tyres under different soil conditions.

Table 2: Inflation pressure required to achieve 20, 24 and 28 per cent deflection at different normal loads for the test tyres

Tyre	Load, kN (kgf)	Inflation pressure, kPa (psi) At tyre deflection, %		
		20	24	28
T_1 (12.4R28)	7.36 (750)	85 (12.3)	63 (9.1)	44 (6.4)
	9.32 (950)	121 (17.5)	92 (13.4)	71 (10.3)
	11.28 (1150)	171 (24.8)	126 (18.3)	99 (14.4)
T_2 (13.6R28)	9.32 (950)	94 (13.7)	70 (10.1)	50 (7.2)
	11.28 (1150)	127 (18.4)	97 (14)	74 (10.7)
	13.24 (1350)	171 (24.8)	125 (18.1)	98 (14.2)
T_3 (14.9R28)	11.28 (1150)	103 (14.9)	76 (11)	55 (8)
	13.73 (1400)	139 (20.2)	105 (15.3)	81 (11.8)
	16.19 (1650)	194 (28.2)	137 (19.8)	108 (15.6)
T_4 (16.9R28)	14.22 (1450)	115 (16.7)	87 (12.6)	66 (9.5)
	16.68 (1700)	145 (21)	111 (16.1)	87 (12.6)
	19.13 (1950)	175 (25.4)	134 (19.4)	108 (15.6)

Dimensional analysis approach

A mathematical relationship between tyre deflection and ground pressure was formulated using dimensional analysis approach as discussed in section 3.4.3. The experimental data of all the tyres were fitted to this model and the values of the constants C_1 and C_2 were determined. The generalized deflection model takes the following form,

$$\frac{\delta}{h} = C_1 \times \left[\frac{P_g}{W} (d \times b) \right]^{C_2}$$

where, δ/h = deflection ratio, per cent
b = width of the tyre, m;
d = diameter of the tyre, m;
W = normal load, kN;
P_g = $(p_i + p_c)$,
= ground pressure (W/A), kPa;
A = tyre-surface contact area, m^2 and
C_1 and C_2 = constants (Table 5.3).

This model can be used to determine the tyre deflection in terms of ground pressure and normal load for radial-ply tyres having b/d ratio in the test range of 0.25 to 0.31. The nonlinear regression summary statistics and the coefficients of the developed deflection model is given in Table 3.

Table 3: Nonlinear regression summary statistics for the deflection model based on dimensional analysis approach

Source	Sum of Squares	DF	Mean Square	F
Regression	75307.87	2	37653.9	45273*
Residual	297.71	138	2.157	
Total	75605.58	140		
			95 % Confidence Interval	
Parameter	Estimate	Std. Error	Lower	Upper
C_1	114.43	2.564	109.361	119.499
C_2	-1.07	0.016	-1.103	-1.039

* Significant at 5 per cent level R^2 0.97

The average ground pressure P_g for a specific tyre at given normal load and inflation pressure can be derived from the so called "generalized deflection chart," normally available from tyre manufacturers. However, P_g can also be determined using a model developed in the present study.

Validation and comparison of the developed model

The developed model based on regression analysis has 9 coefficients while that based on dimensional analysis has only 2 coefficients. Even though the coefficient of determination of the model based on dimensional analysis is lower, but it is more compact and handy. Therefore, this model is finally recommended to predict the deflection characteristics of the radial-ply tyres. The developed model was validated with the test data which were not included for developing the model of four test tyres. The predicted and the experimental deflection ratio were plotted against the dimensionless term. From the curve (Fig. 5) it can be found that the model predicts the deflection ratio very well. The statistical analysis for the validation and comparison of the developed model is shown in Table 4.

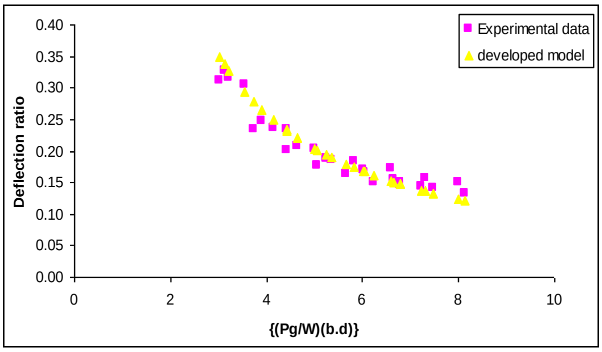


Fig 5: Comparison of the developed deflection model based on dimensional analysis approach with the test data

Table 4: Statistical analysis for model validation and comparison

Models	Mean		RMSE %	Model Effi.	Bias %	Deviation %	R^2
	Obs.	Sim.					
Developed	0.198	0.203	1.085	0.989	-2.2	-7.6 to 8.6	0.948

R^2 = Correlation coefficient, Obs. = Observed, Sim. = Simulated.

It was noticed from the analysis that the model based on dimensional analysis was suitable to predict deflection of agricultural tyres as this model gives a high value of coefficient of determination (0.948) with a per cent deviation of -7.6 to 8.6 %. The model efficiency of 0.989 indicates that the developed model was acceptable. The root mean square error (RMSE) of the developed model was 1.085 % and per cent bias was -2.2 also supported the acceptability of the developed model.

5. Conclusions

The test results showed that the tyre deflection increased non-linearly with decrease in inflation pressure from 207 to 41 kPa, while it increased linearly with increase in normal load for all the test tyres. It was also noticed that the rate of increase of deflection with normal load was higher at lower values of inflation pressure than at higher ones.

The following models were developed to predict deflection of the tyres on a hard surface

$$\frac{\delta}{h} = 114.43\left[\frac{P_g}{W}(d \times b)\right]^{-1.07}$$

where $\frac{\delta}{h}$ = deflection ratio, per cent;

b = width of the tyre, m;

d = diameter of the tyre, m;

W = normal load, kN; and

P_g = ground pressure (W/A), kPa.

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