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"Research Note"

Investigation and Evaluation of Rolling Resistance Prediction Models for Pneumatic Tires of Agricultural Vehicles

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Abstract- Wheel numeric and different versions of mobility numbers are important models for predicting the rolling resistance. In this study, data related to the rolling resistance of cross ply and radial ply tires were compared with the resultant values from several models. Also, the preciseness of models in rolling resistance prediction was evaluated. For this purpose F test and 1-1 line method ($p \geq 0.05$) were used. According to the results of the evaluation, *Cn* and *Bn* models overestimated the rolling resistance for both cross ply and radial ply tires, but the slope of these models did not show any significant difference compared to 1-1 lines. Results indicated that these models had better prediction if an adjusting coefficient could be applied. The *EMOB* model showed better results compared to *Cn* and *Bn* models for cross ply tires, whereas it did not have acceptable predictions for radial tires. The *N.I.A.E., FMOB* and *Dwyer* models did not act well for any tire type, even though the best fit line of the Dwyer model did not show any significant difference with the 1-1 line for cross ply tires.

KeyWords: Rolling resistance, Prediction models, Pneumatic tires, Radial tires, Cross-ply tires, Mobility number

INTRODUCTION

The most important factor in tractor operation is traction performance. Obtained data from traction performance measurements indicates that gross traction and rolling resistance must be subtracted to achieve net traction (7). Correct prediction of off-road vehicles performance widely depends on *tire-terrain* interaction models. One of the basic studies regarding the classification of rut characteristics is to propose the equations that can widely explain *pressure-sinkage* and *stress-shear displacement* relations (13, 19 and 20).

Rowland (14) proposed an expression for the mean maximum pressure beneath a pneumatic tire as:

$$P = \frac{W}{b^{0.85}} d^{1.5} \sqrt{\frac{\delta}{h}} \qquad (1)$$

Where W is tire load, b is tire width, d is tire diameter, δ is tire deflection and h is tire section height.

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Rolling resistance (some times referredo as motion resistance) is considered as a restrictive factor and consists of three components R_c, R_b and R_t, where R_c is the component related to vertical soil compaction, R_b horizontal soil displacement and R_t flexing of the tire. For vehicles operating on a hard surface, R_t constitutes the largest percentage of the motion resistance force, and this can be slightly reduced by increasing inflation pressure and the effective stiffness of the tire. In an off-road situation, however, the components R_b and R_c make up the largest proportion of the motion resistance force (12). Bernstein (2) attributed rolling resistance to the work of rut formation and Uffelmann (17) investigated rigid wheels operating at small sinkage and indicated the pressure beneath the wheel as P= 5.7c and sinkage Z as:

$$Z = \frac{w^2}{(5.7c)^2 b^2 d} \tag{2}$$

Rolling resistance was thus defined as:

$$Rl = A\int P dz \Rightarrow R = \frac{A}{l}\int_0^z 5.7c dz \Rightarrow R = b\left[\frac{w^2}{(5.7c)^2 b^2 d}\right](5.7c) = \frac{w^2}{5.7bcd} \tag{3}$$

Where c is soil cohesion and l is the length of contact area.

Bekker (1) proposed the following expression where k_c is a modulus of deformation due to the cohesive ingredient, k_φ a modulus of deformation due to the frictional ingredient, n the exponent of soil deformation, *b* the tire width and *l* the length of the contact area.

$$R_c = \frac{\left(w/l\right)^{\frac{n}{n+1}}}{(n+1)\left(k_c + b k_\varphi\right)^{\frac{1}{n}}} \tag{4}$$

By considering the curvature of a rigid wheel, Bekker also formulated an expression for its sinkage and compaction resistance component as (1):

$$R_c = \frac{\left(3w/\sqrt{d}\right)^{\frac{2n+2}{2n+1}}}{(3-n)^{\frac{2n+2}{2n+1}}(n+1)\left(k_c + b k_\varphi\right)^{\frac{1}{2n+1}}} \tag{5}$$

Bekker also developed an expression for predicting the motion resistance of pneumatic tires in which the inflation pressure of the tire is presented by p_i, and the carcass stiffness is expressed by p_c.

$$R_c = \frac{\left[b\left(P_i + P_c\right)\right]^{\frac{n+1}{n}}}{(n+1)\left(k_c + b\,k_\varphi\right)^{\frac{1}{n}}} \qquad (6)$$

By considering the soil normal (radial) and tangential (shear) stresses beneath a rigid wheel, Gee-Clough (6) included their effects into a semi-empirical theory for rigid wheels. His equation for motion resistance was equal to the Bekker equation multiplied by $(i+1)^{\frac{-n}{2n+1}}$ in which i is the wheel slip.

Wismer and Luth (18) proposed the following equation for rolling resistance, which was related to wheel numeric, c_n:

$$CRR = \left(\frac{1.2}{c_n}\right) + 0.04 \qquad c_n = \frac{Cbd}{W} \qquad (7)$$

Freitag (5), however, initiated a method based on dimensional analysis, by which the rolling resistance of pneumatic tires could be predicted. A predicting technique based on two dimensionless mobility numbers was proposed as:

$$\text{Clay mobility number} = \frac{Cbd}{W}\left(\frac{\delta}{h}\right)^{\frac{1}{2}} \qquad (8)$$

$$\text{Sand mobility number} = G(bd)^{\frac{3}{2}}\left(\frac{\delta}{h}\right) \qquad (9)$$

Freitag, therefore, used the cone index value (C) and the gradient of cone index (G) to characterize the soil, and the parameters of load (W), width (b), diameter (d), section height (h) and deflection (δ) to characterize the wheel.

Turnage (16) undertook further work to improve the relationships proposed by Freitag, and included an additional term ($\frac{1}{1+\frac{b}{2d}}$) to his equation.

$$M = \frac{Cbd}{W}\left(\frac{\delta}{h}\right)^{\frac{1}{2}}\left(\frac{1}{1+\frac{b}{2d}}\right) \qquad (10)$$

An examination of the mobility number method was also undertaken by Dwyer et al (4) and later by Gee-Clough et al (7). This work led to the proposal of the expression:

$$CRR = \frac{0.287}{M} + 0.049 \qquad (11)$$

Where the mobility number (M) was the mobility number proposed by Turnage (16).

McAllister (9) also used the mobility number of Turnage to propose improved relationships for the coefficient of rolling resistance, including the effect of tire construction:

for cross-ply tires $CRR = \frac{0.323}{M} + 0.054$ (12)

for radial-ply tires $CRR = \frac{0.321}{M} + 0.037$ (13)

Gee-Clough and Sommer (8), however, had doubts about the use of soil cone index to characterize soil mechanical properties and therefore used four forms of mobility number in their analysis, two of which were based on soil cohesion (c) and angle of soil internal friction (φ):

$$M_1 = EMOB = \frac{Cbd}{W}\left(\frac{\delta}{h}\right)^{\frac{1}{2}}\left(\frac{1}{1+\frac{b}{2d}}\right) \quad (14)$$

$$M_2 = B_n = AMOB = \frac{Cbd}{W}\left(\frac{\delta}{h}\right)^{\frac{1}{2}}\left(\frac{1+\frac{5}{h}}{1+\frac{3b}{d}}\right) \quad (15)$$

$$M_3 = CMOB = \frac{cbd}{W}\left(\frac{\delta}{h}\right)^{\frac{1}{2}}\left(\frac{1}{1+\frac{b}{2d}}\right) \quad (16)$$

$$M_4 = \varphi MOB = \frac{cbd}{W}\left(\frac{\delta}{h}\right)^{\frac{1}{2}}\left(\frac{1}{1+\frac{b}{2d}}\right)\varphi^n \quad (17)$$

Clark (3) proposed the following equation for the coefficient of rolling resistance:

$$CRR = \frac{C_1}{C_n} + C_2 \quad (18)$$

C_1 and C_2 are constant coefficients related to soil surface characteristics. C_1 and C_2 vary in the range of 0 -0.1 and 0-0.5, respectively.

The N.I.A.E. models were developed based on drawbar pull tests of farm tractors in the U.K. The difference among these models is initiated from transferring and distribution of weight between tractor axels(10, 11)

In these models, the coefficient of rolling resistance was proposed as:

$$CRR = \frac{0.2}{M} + 0.07 \quad (19)$$

Rowland (14) proposed the mobility number and coefficient of rolling resistance as:

$$N_R = \frac{\mathrm{CI} \times \mathrm{b}^{0.85} \times \mathrm{d}^{0.15}}{\mathrm{W}} \left(\frac{\delta}{\mathrm{h}}\right)^{0.5} \quad (20)$$

$$\mathrm{CRR} = 3 \times N_R^{-2.7} \quad (21)$$

The objectives of the present research were: (a) To compare the measured values of rolling resistances of cross ply and radial ply tires with the predicted values from several models and (b) to evaluate the preciseness of the rolling resistance perdition models.

MATERIALS AND METHODS

Measured values of this study have been obtained from the *National Institute of Agricultural Engineering (NIAE), Silsoe, Bedford*, through tests on 23 types of soil with different values of cone index (11). The measurements were done in two days in each field. The tires tested for each day are shown in Table 1. Having the tires and soil parameters, predicted values of rolling resistance for each tire were calculated according to each of the mentioned models under standard operating conditions. Results of calculations are shown in Tables 2and 3for eight types of tested tires.

Table 1. Tire dimensions

Day	Tire	Ply rating	Load (KN)	Inflation pressure (Kpa)	Diameter (m)	Width (m)	Section height (m)	W/d	Deflection %	EMOB/C
1	12.5-15	8	10	142	0.876	0.313	0.247	0.357	19.03	0.010480
1	12.5-15	8	20	284					21.26	0.005364
1	13.5-17.5	12	10	101					18.46	0.011830
1	13.5-17.5	12	20	303	0.948	0.343	0.260	0.362	17.50	0.005759
1	13.5-17.5	12	30	485					17.31	0.003819
1	12-18	Radial	20	202					24.40	0.007041
1	12-18	Radial	20	303	0.892	0.317	0.218	0.355	25.69	0.006112
1	12-18	Radial	20	404					22.02	0.005633
1	12-18	Radial	20	505					19.37	0.005270
2	12-18	Radial	10	101					26.83	0.012437
2	12-18	Radial	20	303	0.892	0.317	0.218	0.355	25.69	0.006112
2	12-18	Radial	32	505					26.15	0.003837
2	7.5-16	8	10	404	0.792	0.209	0.194	0.264	17.02	0.006031
2	7.5-16	8	13	456					19.07	0.004912
2	12-16	8	10	142	0.860	0.309	0. 228	0.359	21.27	0.010389
2	12-16	8	20	284					23.25	0.05431
2	12-18	10	10	142					22.51	0.011708
2	12-18	10	20	233	0.920	0.314	0.231	0.341	27.71	0.006495
2	12-18	10	25	375					24.68	0.004904
2	400-17.5	8	10	81					30.10	0.018316
2	400-17.5	8	20	203	0.854	0.391	0.206	0.458	30.83	0.009268
2	400-17.5	8	23	233					27.67	0.007635

Evaluation of prediction models was done separately for cross-ply and radial tires because of the different characteristics and treatments of these tires. For the evaluation of the models, F test and 1-1 line method at a 95% confidence level were utilized (15). Test data were considered as 1-1 line in this procedure. If the slope and intercept difference between the best fit line of the data and the 1-1 line is not significant, the model will have suitable ability in predicting rolling resistance. For this purpose a program was developed in the Macro section of Excel software. Figure 1 shows a sample of this program worksheet.

Table 2. Coefficients of rolling resistance for cross-ply tires at recommended loads and inflation pressures

	W	P	Bn	Cn	E	F	NIAE	Dwyer	T
400-17.5	10	81	0.124109	0.084276	0.080695	0.075722	0.08653	0.07272	0.079
400-17.5	20	203	0.208219	0.128551	0.106754	0.096927	0.10266	0.09587	0.094
400-17.5	23	233	0.233452	0.181834	0.118037	0.106109	0.10965	0.1059	0.103
12-18	10	142	0.122505	0.091178	0.087989	0.083035	0.09105	0.0792	0.083
12-18	20	233	0.205009	0.142356	0.115269	0.106338	0.10794	0.10344	0.1
12-18	25	375	0.246262	0.167945	0.135152	0.123322	0.12025	0.12111	0.134
12-16	10	142	0.132135	0.095364	0.093303	0.08647	0.09372	0.08303	0.079
12-16	20	284	0.224269	0.151269	0.127272	0.116113	0.11537	0.11411	0.11
7.5-16	10	404	0.168373	0.129316	0.119969	0.112273	0.11084	0.10761	0.125
7.5-16	13	456	0.206884	0.156111	0.135011	0.125568	0.12016	0.12098	0.145
13.5-17.5	10	101	0.11511	0.085467	0.087637	0.082484	0.09083	0.07889	0.09
13.5-17.5	20	303	0.19022	0.130934	0.123095	0.11251	0.11278	0.11039	0.116
13.5-17.5	30	485	0.26533	0.176401	0.158209	0.142245	0.13453	0.14159	0.15
12.5-15	10	142	0.12872	0.09392	0.093214	0.08727	0.09428	0.08384	0.086
12.5-15	20	284	0.21743	0.14784	0.1282	0.11695	0.11594	0.11493	0.107

Table 3. Coefficients of rolling resistance for radial-ply tires at recommended loads and Inflation pressures

	W	P	Bn	Cn	E	F	NIAE	Dwyer	T
12-18	**20**	**202**	**0.21252**	**0.144569**	**0.093167**	**0.084693**	**0.105**	**0.09922**	**0.074**
12-18	**20**	**303**	**0.21252**	**0.144569**	**0.101995**	**0.092188**	**0.1105**	**0.10711**	**0.094**
12-18	**20**	**404**	**0.21252**	**0.144569**	**0.107155**	**0.09657**	**0.11371**	**0.11172**	**0.101**
12-18	**20**	**505**	**0.21252**	**0.144569**	**0.112045**	**0.100722**	**0.11676**	**0.1161**	**0.111**
12-18	**10**	**101**	**0.12626**	**0.092285**	**0.068799**	**0.064002**	**0.08981**	**0.07743**	**0.064**
12-18	**20**	**303**	**0.21252**	**0.144569**	**0.101995**	**0.092188**	**0.1105**	**0.10711**	**0.095**
12-18	**32**	**505**	**0.31604**	**0.207311**	**0.140073**	**0.124521**	**0.13422**	**0.14116**	**0.147**

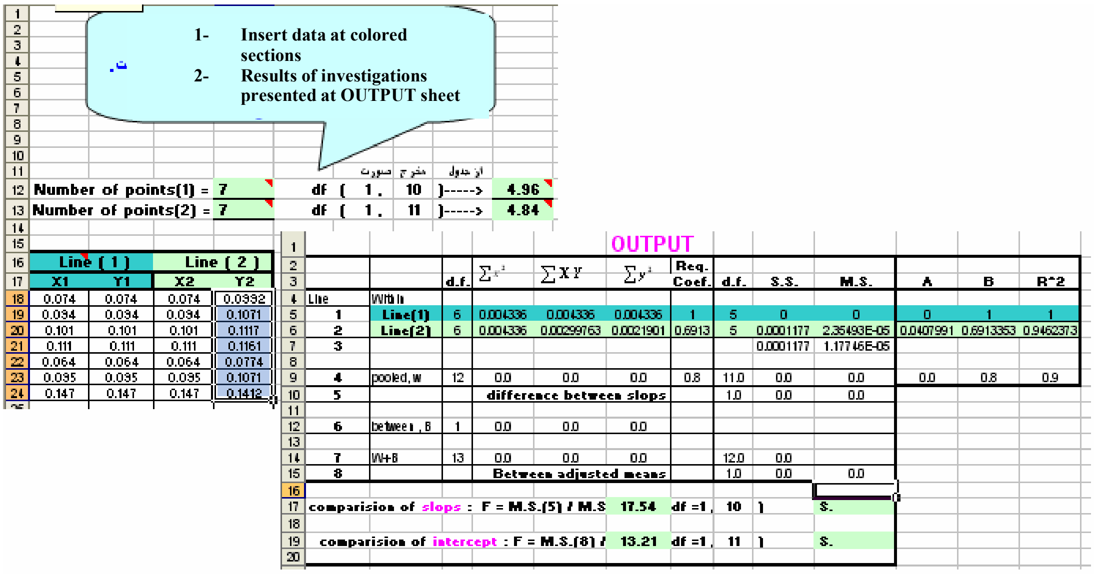

Fig1. Developed program of Excel software for evaluation of models based on F test and 1-1 line method

RESULTS AND DISCUSSION

According to the results of the F test, the best fit line of rolling resistance based on wheel numeric (*Cn*) had no significant difference with the 1-1 line of the test data for radial tires from the stand point of slope but intercepts of these lines were significantly different. According to this fact and the values of coefficient of rolling resistance (Table 3 and Fig 3), it is clear that this model (*Cn*) has overestimated the values of rolling resistance, whereas, considering the non significant difference of the lines' slope, prediction of rolling resistance could be improved by applying an adjusting coefficient to this model.

The slope of the best fit line of the rolling resistance coefficient based on *EMOB* for radial tires had significant difference with the 1-1 line, but the intercepts of the two lines did not differ significantly. According to the data, it is clear that this model has had a better estimation of rolling resistance coefficient for 12-18 tires with a 20kN load and high inflation pressures.

For the model of coefficient of rolling resistance based on Bn for radial tires, the situation is the same as the previous model but in this case values have been more overestimated. This model also enables us to predict rolling resistance correctly by applying a coefficient to the model.

Evaluation of the *FMOB* model had the same results as the preceding model, except that this model showed a better estimation for 12-18 tires with a 10kN load and low inflation pressures.

For cross-ply tires, Cn and Bn models performed the same as the radial tires. The evaluation of *EMOB* model had the same results as the two preceding models but values from this model (Table 2 and Fig. 2) were closer to the test results and the best fit line of this model was almost the same as the 1-1 line of test results.

The slope and intercept of best fit lines of rolling resistance coefficient for radial tires based on *Dwyer* and *N.I.A.E.* models had a significant difference with the 1-1 lines and did not predict rolling resistance suitably (Fig. 3).

The slope of best fit lines of *FMOB* and *N.I.A.E.* models for cross-ply tires was significantly different fromthe 1-1 line slope but there was not any significant difference between the lines of the models and the 1-1 line considering the intercept.

The best fit line of the *Dwyer* model had significant difference with the 1-1 line considering the slope and intercept ($p \geq 0.05$).

Finally, we may suggest EMOB and modified Cn models (by applying a reduction coefficient) for predicting the rolling resistance of cross-ply tires and radial tires, respectively.

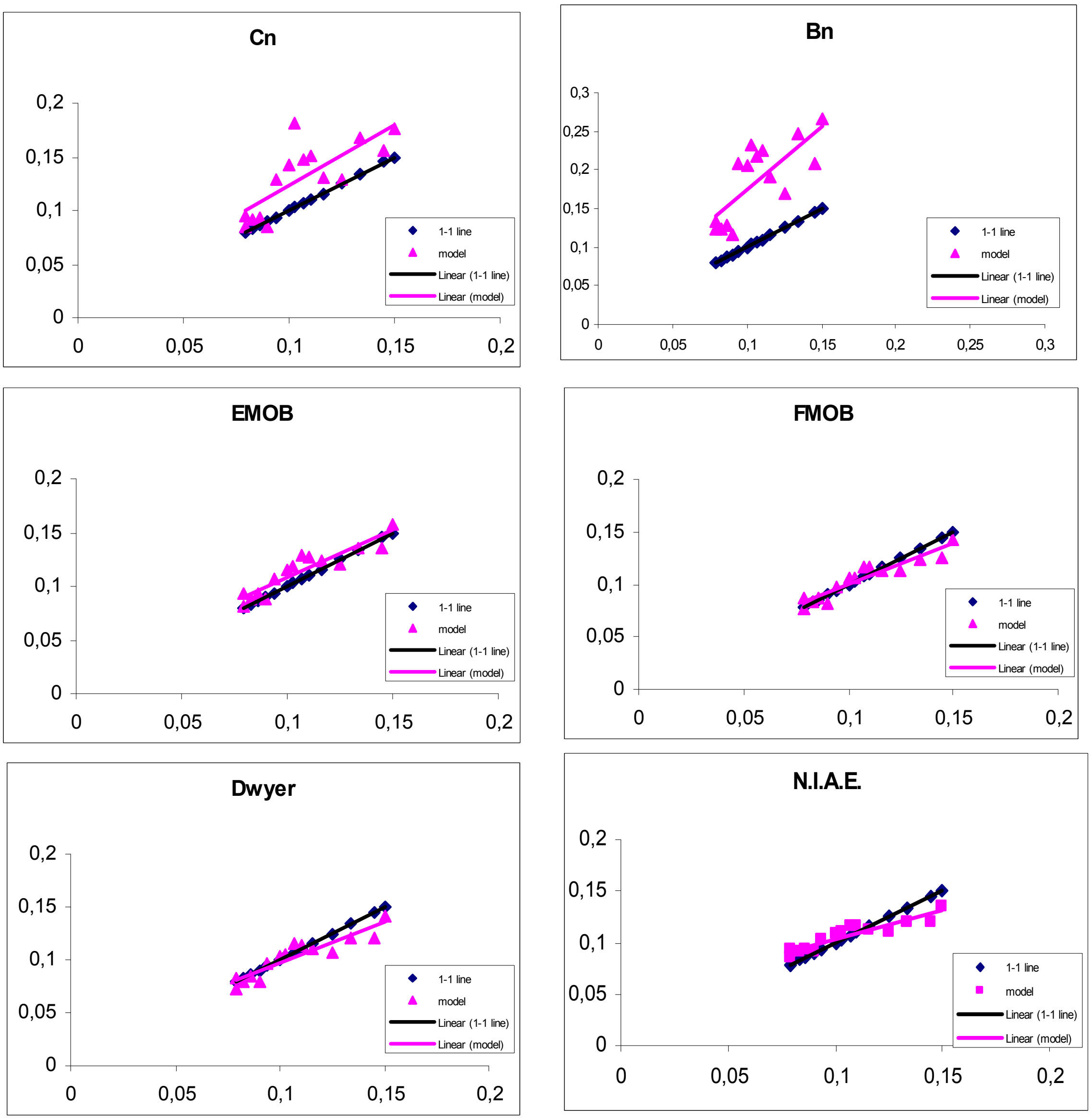

Fig 2. Comparison of best fit lines of prediction models of rolling resistance with 1-1 line of test data for cross-ply tires

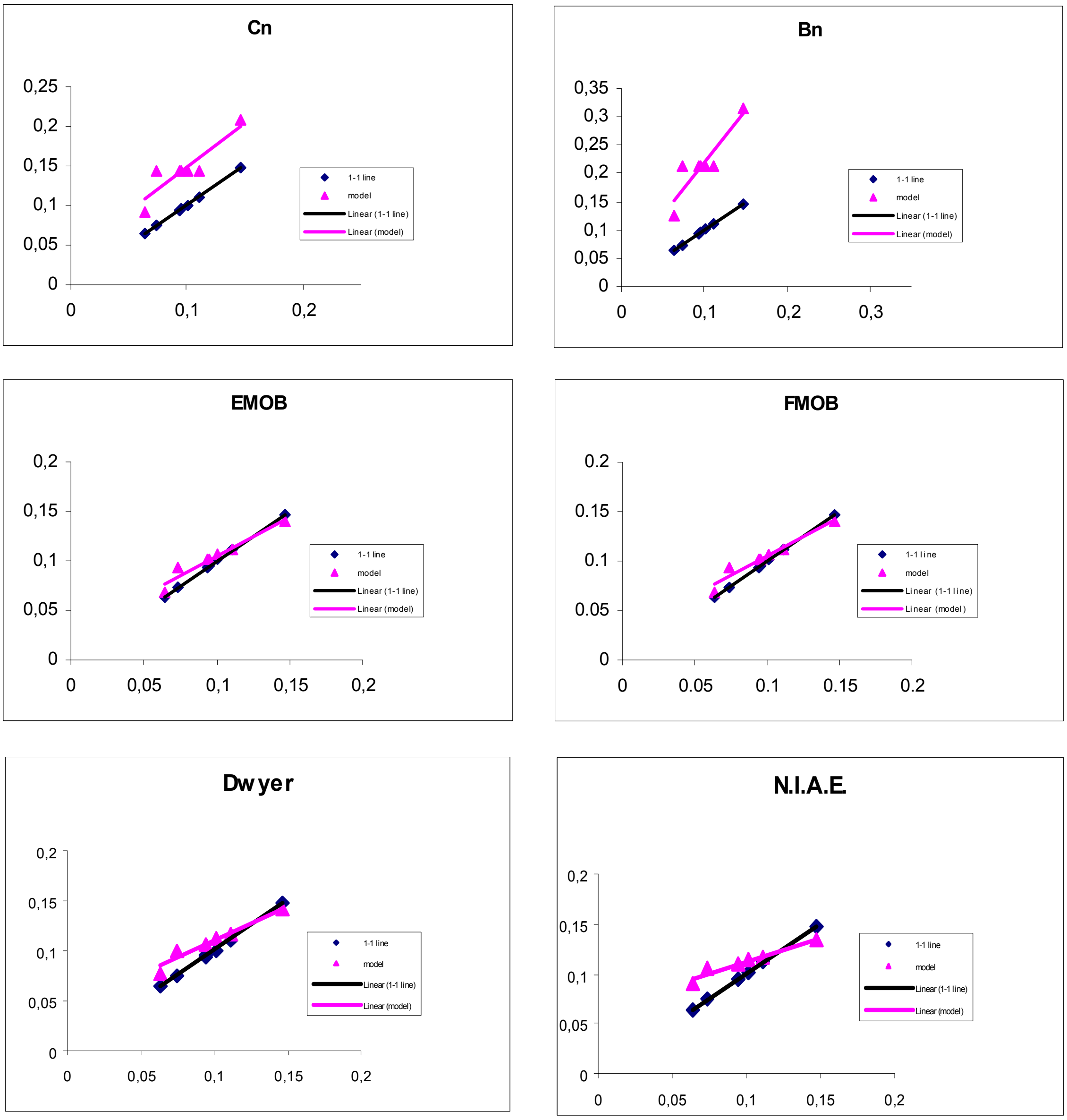

Fig 3. Comparison of best fit lines of prediction models of rolling resistance with 1-1 line of test data for radial- ply tires

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"مقاله کوتاه"

بررسی و ارزیابی مدل های پیشگویی مقاومت غلتشی تایرهای بادی ادوات کشاورزی

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چکیده- از جمله مدل های مهم برای پیشگویی نیروی مقاومت غلتشی تایرهای بادی عدد چرخ و ویرایش های مختلف عدد تحرک پذیری است. در این تحقیق داده های آزمایشی مربوط به مقاومت کششی تایرهای معمولی و رادیال با مقادیر بدست آمده توسط مدل های مختلف مورد مقایسه قرار گرفت و میزان دقت مدل ها در پیشگویی مقاومت غلتشی و برازش با داده های آزمایشی مورد ارزیابی قرار گرفت. بدین منظور از آزمون F با سطح احتمال ۹۵ درصد و روش خط یک به یک استفاده گردید. طبق نتایج حاصل از ارزیابی ها، مدل های C_n و B_n مقاومت غلتشی هر دو نوع تایر را بیشتر از مقادیر آزمایشی پیشگویی کردند ولی شیب خطوط برازش مربوط به داده های این دو مدل و خط یک به یک داده های آزمایشی از نظر شیب اختلاف معنی داری را نشان نداد. این امر نشان می دهد که با اعمال یک ضریب تصحیح، این دو مدل پیشگویی بهتری را ارایه خواهند نمود. مدل EMOB در مورد تایرهای رادیال پیشگویی مطلوبی را ارایه نکرد، در حالی که در مورد تایرهای معمولی این مدل نسبت به دو مدل C_n و B_n بهتر عمل نمود. مدل های N.I.A.E.، FMOB و Dwyer در مورد هر دو نوع تایر چندان مطلوب عمل نکردند. با این وجود خط برازش داده ها در مدل Dwyer برای تایرهای معمولی با خط یک به یک اختلاف معنی داری را نشان نداد.

واژه های کلیدی: مقاومت غلتشی، مدل های پیش بینی ، تایرهای بادی و رادیال، تایرهای لایه مورب و عدد تحرک پذیری

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