TRANSPORT PROBLEMS 2016 Volume 11 Issue 3
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2016.11.3.11

tire wear; wear modeling

Rosen IVANOV
University of Ruse
8, Studentska, 7017 Ruse, Bulgaria
Corresponding author. E-mail: rossen@uni-ruse.bg

TIRE WEAR MODELING

Summary. On the basis of a known relationship, an enhanced model for specific tire wear per kilometer has been developed. It is appropriate for practical use - for evaluation of the influence of different factors. Two types of experiments have been carried out with a testing device - one without sideslip, but with a known longitudinal slip, and the other one with the same longitudinal slip but also with a known sideslip. As a result, the coefficients of the proportion of the developed model have been evaluated. After the model validation, an analytical investigation concerning the influence of tire pressure, sideslip and longitudinal slip on the tire wear has been carried out. The results are presented graphically.

МОДЕЛИРОВАНИЕ ИЗНОСА ШИН

Аннотация. На основе известной зависимости разработана модель относительного износа шин в зависимости от пробега. Она подходящая для практического использования – оценки влияния разных факторов. Два типа эксперимента проведены с помощью испытательной установки – один без поперечного увода и с известным продольным скольжением, а другой с тем самым скольжением, но и с известным уводом. В результате получены коэффициенты пропорциональности модели. После проверки модели, проведено аналитическое исследование влияния давления в шине, увода и продольного скольжения на относительный износ шины. Приведены графические результаты.

1. INTRODUCTION

The tire wear is one significant factor for the price of vehicle supplies. The increase of tire life is an important problem.

There are 3 types of wear of pneumatic tires: abrasive, due to the tire material fatigue and due to the rolling with sideslip [8, 12, 15]. The part of each type of wear depends on the running conditions [5, 9 - 11, 15].

There are many investigations concerning the tire properties and the tire wear carried out by the different authors and research groups [1…17]. A team from the University of Ruse have worked on these problems for 20 years and they have a lot of research, including dissertations [1, 5, 7].

In the general case of motion, the main constructive characteristics of the vehicle, influencing the tire wear are the wheel camber α_o, the king-pin camber β, the caster angle γ, the toe-in δ_o and the steering geometry. The main running factors include the inflation pressure in the tire *p*, the speed *V*, the turning radius R, the tractive force F_T and the road surface. Studying the influence of these factors on tire wear requires the use of one general equation for wear.

The main goal of this paper is to present a model developed for the tire wear evaluation and a method for its practical use for estimating the influence of various constructive and running factors.

2. TIRE WEAR MODEL

It is appropriate to start from the well-known relation [8, 12] for abrasive and fatigue types of tire wear

$$I_a = \frac{3C_1}{(C_2 E)}\left[C_2 \mu_{TP} \frac{\sigma}{\sigma_o}\left(\frac{E}{\sigma}\right)^{1-\beta t}\right]^t \sigma \frac{S}{l}, \quad (1)$$

where σ is nominal specific pressure on the road surface; S - slip in contact area; C_1, C_2, βt - constants concerning road surface roughness; t, σ_o - parameters of the fatigue curve of material; l - contact area length ; E - module of elasticity of the material; μ_{TP} - friction coefficient.

The part in square brackets depends mostly on the properties of tire material [8, 12], and for the wear of one model of tires with constant physical properties of the tire material and the road surface, equation (1) can be written as

$$I_a = \left(3C_1 \sigma \frac{S}{C_2 E\, l}\right) k_M , \quad (2)$$

or in differential form

$$I_a = A_a \sigma t \frac{dS}{dl}, \quad (3)$$

where: $A_a = \frac{3C_1}{C_2 E} k_M$; $\frac{dS}{dl}$ is an elementary slip in contact area length; k_M - coefficient concerning the tire material.

The relation (3) shows, in a differential form, that the intensity of wear is proportional to the work of friction of the elementary tread element passing along the whole length of the contact area. If this work of friction is minimal in some conditions, the tire wear will also be minimal, independently of the value of k_M . Hence, on the basis of equation (3), the influence of the main constructive and running factors on the tire wear of concrete model tires and concrete type of road surface can be studied.

In some research [5, 8, 12] authors prove that the intensity of tire wear caused by the sideslip is also proportional to the normal load and sideslip. Analogically to (3), for this type of wear the equation will be

$$I_\delta = A_\delta \sigma \frac{dS_y}{dl}, \quad (4)$$

where: dS_y is the increasing of the slip, caused by the sideslip; A_δ - proportional coefficient (analog to A_a)

The slip appears at a point of tread if the tangential stresses τ exceed the grip limit

$$\tau = \varphi_y \sigma , \tag{5}$$

where: φ_y is the lateral grip coefficient and for that reason σ in 2.4 must be substituted with τ / φ_y.

The tangential stress can be expressed by the lateral force Y_k and the surface S_k of the contact area between the tire and the road [9]

$$\tau = \frac{Y_k}{S_k} = k_\delta \frac{\delta}{S_k} , \tag{6}$$

where: k_δ is sideslip coefficient; δ - sideslip angle.

Taking into account that $\sigma\, S_k = Z$ the last equation becomes

$$\tau = \sigma k_\delta \frac{\delta}{Z} , \tag{7}$$

where: Z is the normal reaction acting on the tire.

The sideslip when travelling all the length of the contact area, assuming δ is too small, is evaluated with the expression

$$S_y = \sin \delta l \approx \delta l \text{ and } dS_y = \delta dl . \tag{8}$$

The intensity of wear when all types of wear are present will be the sum of (3) and (4):

$$I = I_a + I_\delta = A_a \sigma \frac{dS}{dl} + \frac{A_\delta \sigma k_\delta \delta}{Z \varphi_y} \frac{dS_y}{dl} \tag{9}$$

The wear of a tread element along the whole length of the contact area I_l will be determined by integrating the expression of elementary wear (9)

$$I_l = \int_0^l I\, dl = \int_0^S A_a\, \sigma\, dS + \int_0^{Sy} A_\delta\, \sigma\, k_\delta\, \delta / (Z\, \varphi_y)\, dS . \tag{10}$$

The solution of the above equation is

$$I_l = A_a \sigma S_o + \frac{A_\delta \sigma k_\delta \delta^2}{Z \varphi_y} l , \tag{11}$$

where: S_o is the slip of each element of the tread when passing all the length of the contact area without a sideslip angle.

In the case of the steady-state motion on the hard road surface, the turning radius does not change at $p =$ *const*. For a definite distance, an element of tread will be an exact number in the contact area.

This gives the reason to accept that the specific wear I_o for 1 km distance will be proportional to I_l.

$$I_o = k_\Pi I_l = \left(A_a^{'} S_o + \frac{A_\delta^{'} k_\delta l \delta^2}{Z \varphi_y} \right) \sigma , \tag{12}$$

where: k_Π is proportional coefficient; $A_a^{'} = A_a k_\Pi$; $A_\delta^{'} = A_\delta k_\Pi$.

The nominal value of the specific pressure can be expressed by the normal reaction Z on the tire and the surface S_k of the contact area, and (12) will become

$$I_o = \left(A_a^{'} S_o + \frac{A_\delta^{'} k_\delta \, l \delta^2}{Z \varphi_y} \right) \frac{Z}{S_k} . \tag{13}$$

In real conditions of motion in the curve, it is necessary to modify the relation (13) because of different distances of the inner and outer wheel, the equal number of left and right turns, etc. In the case of straightforward motion, the quantities included in (13) and wear are equal for both tires. That way the equation (13) can be used directly for evaluating the influence of different factors on the tire wear.

For a practical use of (13) is necessary to have experimentally obtained data for S_K , *l*, k_δ , φ_y in function of normal load *Z*, inflation pressure in the tire *p*, and the wheel camber α_o. It will be better if there are regression models for them.

The big problem is connected with two coefficients of proportion $A_a^{'}$ and $A_\delta^{'}$, which take into consideration a lot of characteristics of tire material and tire structure. They can be very hard to calculate analytically.

We propose an experimental approach for the determination of the coefficients $A_a^{'}$ and $A_\delta^{'}$, which consists of two special experiments. As a result of the experiments, the specific wear I_o has to be measured. Let the values obtained from the experiments be I_{o1} and I_{o2}.

The first experiment has to be done at a straightforward motion with a known normal load Z of the wheel, known longitudinal slip S_o and without sideslip ($\delta = 0$). In these conditions, the second part of the equation (9) is equal to zero and the first coefficient can be evaluated from the I_{o1} obtained.

$$A_a^{'} = \frac{I_{o1} S_k}{S_o Z} . \tag{14}$$

During the second experiment in the same conditions but with known sideslip $\delta \neq 0$, the specific wear I_{o2} is measured. The first part of (13) has the same value and the difference is caused by the second part

$$I_{o2} - I_{o1} = \frac{A_\delta^{'} \; k_\delta \; l \; \delta^2}{\varphi_y \; S_k} . \tag{15}$$

After some transformation of (15), the second coefficient can be obtained as

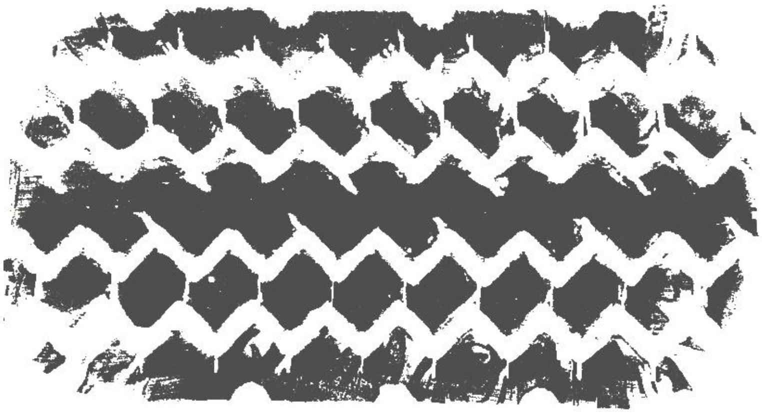
$$A_\delta^{'} = \frac{(I_{o2} - I_{o1}) \, \varphi_y \; S_k}{k_\delta \; l \;\; \delta^2} . \tag{16}$$

This way, making two special experiments, it is possible to obtain experimentally the coefficients of proportion needed for using the equation (9). It can be applied to analytically study the influence of different factors, as well as to optimize the working conditions of tires and comparative analysis of tire wear for different models of tires in the same running conditions.

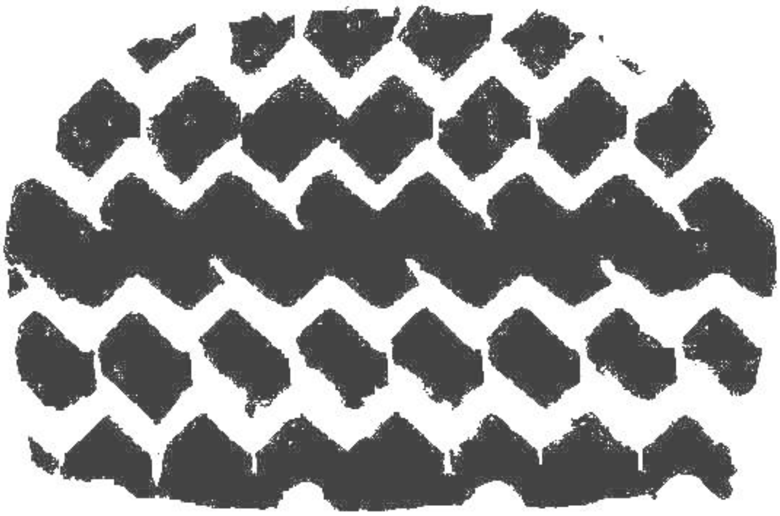
3. EXPERIMENTAL DETERMINATION OF THE COEFFICIENTS

An application of that method for experimental determination of the coefficients was realized, using a mobile testing device developed in the Department of Engines and Vehicles of the University of Ruse [8]. The tested tire was model DNEPROSHINA 11.00R20.

A fast and relative method [11] was used for tire wear measurement. Special indicators (rivets) were placed into the protector of the tire tested. The tire wear was estimated on the basis of losses of indicators weight. The footprints of the contact area of the tire were made on the paper sheets (Fig. 1).



a)



b)

Fig. 1. Examples of footprint of the contact area of the tire:

a - at p =0,2 *MPa*, Z =19,53 *kN* , α_o =0° ; b - at p =0,4 *MPa*, Z =19,53 *kN* и α_o =2°

Рис. 1. Пример отпечатков контакта шины с дорогой:

a - при p =0,2 *MPa*, Z =19,53 *kN* , α_o =0° ; b - при p =0,4 *MPa*, Z =19,53 *kN* и α_o =2°

As a result of previous research [1, 5], the regression models for the contact area S_K and length of the contact area l have been created. They are

$$S_K = 64{,}7731 + 44{,}9653 Z + 18{,}0000 \alpha_o - 48{,}8603\, pZ \text{ , } cm^2 \tag{17}$$

$$l = 104{,}0481 + 18{,}4752 Z + 10{,}6250 \alpha_o - 18{,}9444\, pZ \text{ , } mm \tag{18}$$

For the grip coefficient and the sideslip coefficient, values that were experimentally obtained for the same tire were used (Tab.1).

As a result of three experiments, the values of the coefficients $A_a^{'}$ and $A_\delta^{'}$ were evaluated by using relations (10) and (12). They were presented in Tabs. 2 and 3.

Table 1

Sideslip and lateral grip coefficients at different values of *Z* and *p*

Inflation pressure in the tire *p*, *MPa*	0,6		0,4		0,2	
Normal reaction acting on the tire *Z*, *kN*	6	12	6	12	6	12
Sideslip coefficient k_δ, *kN/rad*	37,0	61,7	34,0	56,0	31,0	50,3
Coefficient of lateral grip φ_y	0,62	0,60	0,61	0,59	0,60	0,58

Table 2

Values of the coefficient $A_a^{'}$, obtained in three experiments

Level of the factor in the experiment	***Registered slip*, %**	**$A_a^{'}$, $mg/kN10^{-6}$**
Z=12 *kN*, p=0,2 *MPa*, α_o=0°, δ=0°	4,95	9208,58
Z=12 *kN*, p=0,4 *MPa*, α_o=0°, δ=0°	3,9	9215,77
Z=12 *kN*, p=0,6 *MPa*, α_o=0°, δ=0°	3,4	9156,35

Table 3

Values of the coefficient $A_\delta^{'}$, obtained in three experiments

Level of the factors	**Obtained specific tire wear I_o, *mg/km***	**$A_\delta^{'}$**
Z =12 *kN*, p=0,6 *MPa*, α_o=0°, δ=2,8°, *slip* 41%	482,00	94158,37
Z =12 *kN*, p=0,2 *MPa*, α_o=0°, δ=2,8°, *slip* 20%	233,00	93936,87
Z =12 *kN*, p=0,6 *MPa*, α_o=0°, δ=2,8°, *slip* 3,4%	192,80	93224,73

It is obvious from Tabs. 2 and 3 that the variation of the values of the coefficients is very small – < 0,6% for $A_a^{'}$, and <1% for $A_\delta^{'}$, respectively. Hence, the method applied for the determination of the coefficient gives sustainable results.

4. ANALYTICAL STUDY

Using the values obtained for the two coefficients, models (17) and (18), and data from Tab. 1, an analytical investigation was carried out. Specific tire wear was evaluated by the equation (13) in cases of different values of normal reaction *Z*, inflation pressure *p*, sideslip δ and longitudinal slip.

The results presented on Figs. 2 to 7 show that the influence of the sideslip is nonlinear and stronger than that of the longitudinal slip. The sideslip is presented in the second part of equation (13) and it is at second power.

At the same time, the longitudinal slip is presented in the first part of (13) as *So* and generates a linear influence on tire wear—the curves on the figures are equidistant.

The sideslip has a stronger influence on tire wear at smaller values of the longitudinal slip. For example, at longitudinal slip 10%, the increase of sideslip from 0° to 5° causes an increase of the tire wear of 22 ÷ 766% at different levels of *Z* and *p*. At longitudinal slip 60%, the increase of sideslip from 0° to 5° causes an increase of the tire wear of 4 ÷ 128%.

Depending on the influence on tire wear, the other factors are arranged as follows—normal reaction on the wheel, inflation pressure and wheel camber at the end.

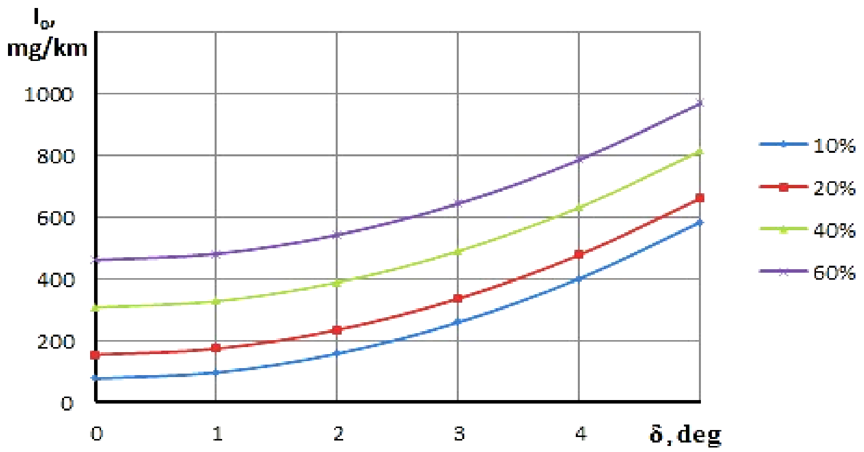


Fig. 2. Specific tire wear depending on the sideslip at p = 0,6 *MPa*, *Z* =12 *kN*, α_o = 0° and different values of longitudinal slip in %

Рис. 2. Относительный износ шин в зависимости от увода, при p = 0,6 *MPa*, *Z* =12 *kN*, α_o = 0° и разных значениях продольного скольжения в %

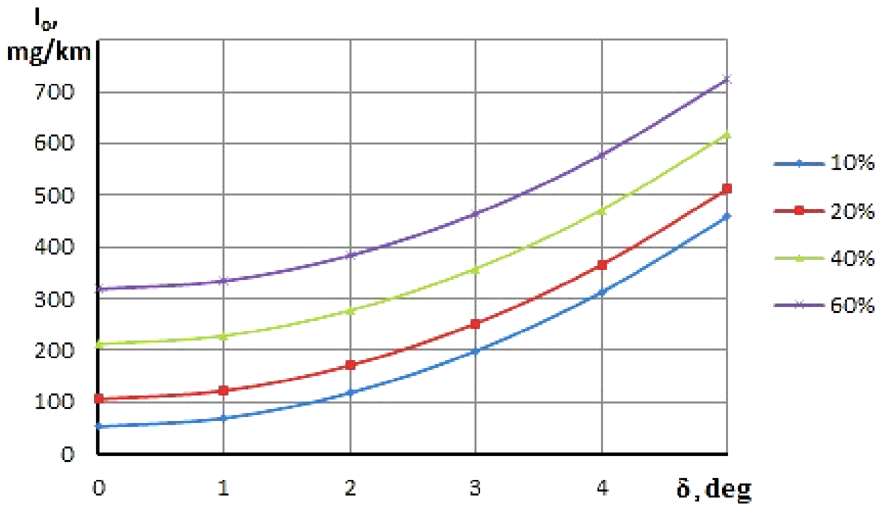


Fig. 3. Specific tire wear depending on the sideslip at p = 0,6 *MPa*, *Z* = 6 *kN*, α_o = 0° and different values of longitudinal slip in %

Рис. 3. Относительный износ шин в зависимости от увода, при p = 0,6 *MPa*, *Z* = 6 *kN*, α_o = 0° и разных значениях продольного скольжения в %

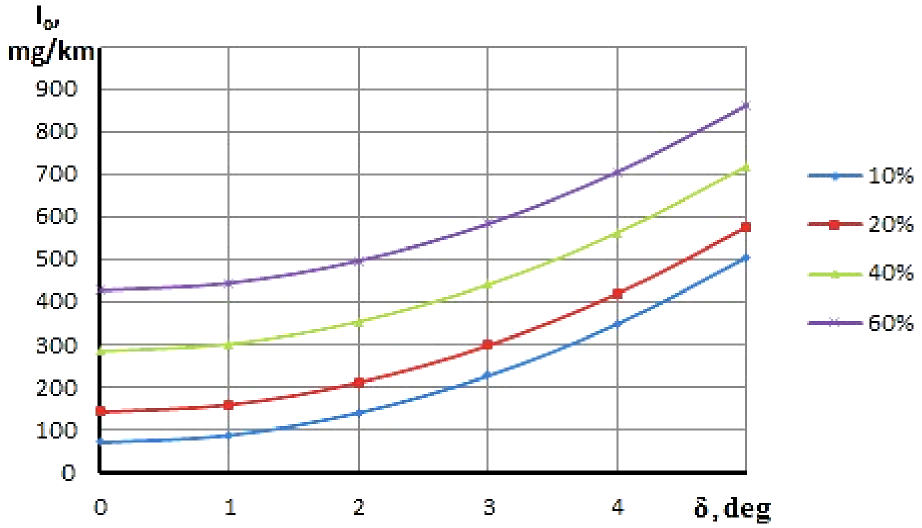


Fig. 4. Specific tire wear depending on the sideslip at p = 0,4 *MPa*, *Z* =12 *kN*, $\alpha_o = 0^{\circ}$ and different values of longitudinal slip in %

Рис. 4. Относительный износ шин в зависимости от увода, при p = 0,4 *MPa*, *Z* =12 *kN*, $\alpha_o = 0^{\circ}$ и разных значениях продольного скольжения в %

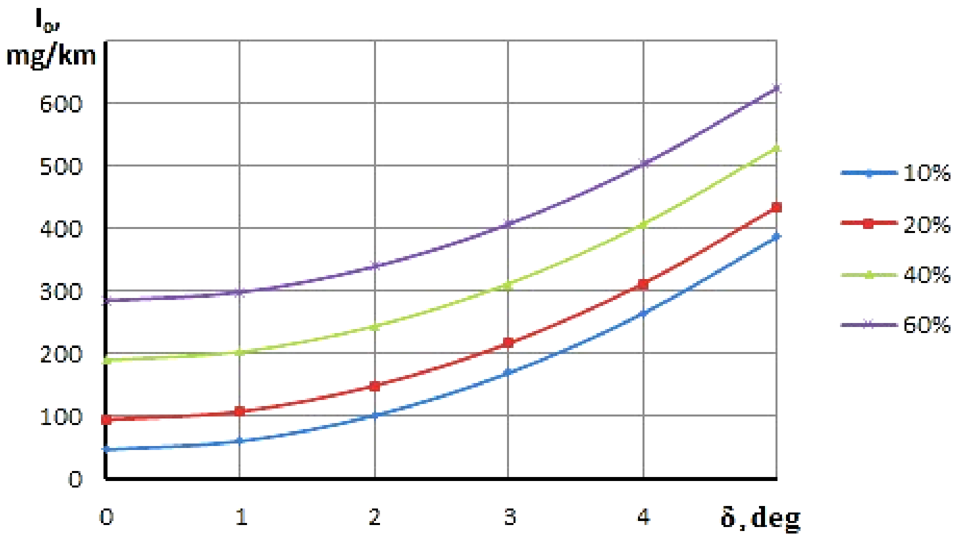


Fig. 5. Specific tire wear depending on the sideslip at p = 0,4 *MPa*, *Z* = 6 *kN*, $\alpha_o = 0^{\circ}$ and different values of longitudinal slip in %

Рис. 5. Относительный износ шин в зависимости от увода, при p = 0,4 *MPa*, *Z* = 6 *kN*, $\alpha_o = 0^{\circ}$ и разных значениях продольного скольжения в %

5. CONCLUSIONS

1. The results obtained show that the developed model (9) for the estimation of a specific tire wear can be used for the analysis of the influence of constructive and running factors in various conditions of motion. Its application needs some experimental data for the investigated model of tire—as contact area, sideslip and lateral grip coefficients concerning concrete running conditions.

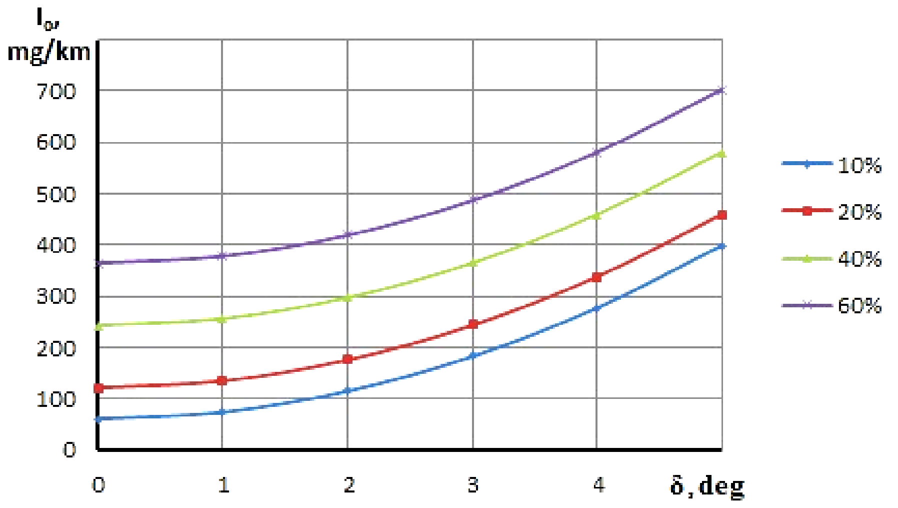


Fig. 6. Specific tire wear depending on the sideslip at p = 0,2 *MPa*, *Z* =12 *kN*, $\alpha_o = 0^{\circ}$ and different values of longitudinal slip in %

Рис. 6. Относительный износ шин в зависимости от увода, при p = 0,2 *MPa*, *Z* =12 *kN*, $\alpha_o = 0^{\circ}$ и разных значениях продольного скольжения в %

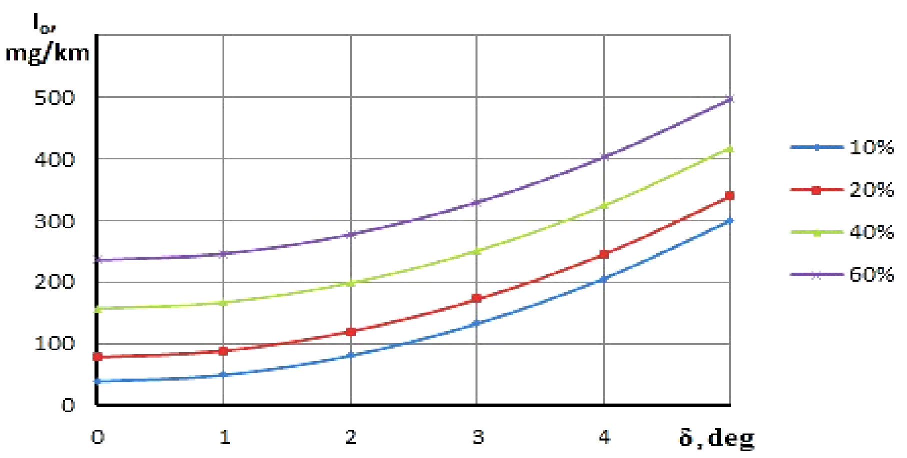


Fig. 7. Specific tire wear depending on the sideslip at p = 0,2*MPa*, *Z* = 6 *kN*, $\alpha_o = 0^{\circ}$ and different values of longitudinal slip in %

Рис. 7. Относительный износ шин в зависимости от увода, при p = 0,2*MPa*, *Z* = 6 *kN*, $\alpha_o = 0^{\circ}$ и разных значениях продольного скольжения в %

2. Two coefficients of proportion for the investigated tire can be evaluated on the basis of two special experiments made in the same conditions and longitudinal sleep—one without sideslip and the other with a known sideslip angle. Using that method, their values are obtained with good accuracy, which permits studying of the influence of various factors on tire wear.

References

1. Аврамов, Е. Изследване влиянието на характеристиките на гумите върху устойчивостта и безопасността на движение на двуосен товарен автомобил. Дисертация за ОНС „доктор“. Русе. 2014. 123 с. [In Bulgarian: Avramov, E. *Investigation on tire characteristics influence on stability and road safety of two axle lory*. PhD thesis. Ruse. University of Ruse. 2014. 123 p.]
2. Baranowski, P. & Bogusz, P. & Gotowicki, P. & Małachowski, J. Assessment of Mechanical Properties of Off-road Vehicle Tire. Coupons Testing and FE Model Development. *Acta mechanica et automatica*. 2012. Vol. 6. No. 2. P. 17-22.
3. Бродский, Г.И. и др. *Истирание резины.* Москва. Химия. 1975. 239 с. [In Russian: Brodskij, G. & et al. *Ruber wear*. Moscow. Chemestry. 1975. 239 p.]
4. Erdogan, G. *New Sensors and Estimation Systems for the Measurement of Tire-Road Friction Coefficient and Tire Slip Variables*. Dissertation submitted to the faculty of the graduate school of the University of Minnesota. 2009.
5. Георгиев, К. *Изследване износването на пневматични гуми на товарен автомобил*. Дисертация за ОНС „доктор“. Русе. 2014. 133 с. [In Bulgarian: Georgiev, K. *Investigation on the wear of a truck pneumatic tires*. PhD thesis. Ruse. University of Ruse. 2014. 133 p.]
6. Guang Tong & Xiaoxiong Jin. Study on the Simulation of Radial Tire Wear Characteristics. *WSEAS TRANSACTIONS on SYSTEMS*. 2012. Vol. 11. No. 8. E-ISSN: 2224-2678.
7. Ivanov, R. & Rusev, R. & Ilchev, P. A laboratory investigation of tyre sliding grip coefficient. *Research Journal" TRANSPORT"*. 2006. Vol. 21. No. 3. P. 172-181. ISSN 1648-4142.
8. Кнороз, В.И и др. *Шины и колеса*. Москва. Машиностроение. 1975. 184 с. [In Russian: Knoroz, V. & et al. *Tires and wheels*. Moscow. Mashinostroenie. 1975. 184 p.]
9. Pacejka, H. *Tire and Vehicle Dynamics*. SAE. Warrendale. 2007.
10. *The Pneumatic Tire*. National Highway Traffic Safety Administration. DOT HS810561. 2006. 707 p.
11. Троицкий, В.П. и др. Ускоренный способ оценки неравномерного износа шин. *Труды МАДИ.* 1982. С. 91-93. [In Russian: An accelerated method for evaluation tire wear irregulation. *MADI Proceedings.* 1982. P. 91-93].
12. Тройцкий, В.П. *Снижение износа шин управляемых колес обеспечением рационального соотношения углов и поворота при эксплутации легкового автомобиля в условиях города*. Канд. диссертация. Москва. 1983. [In Russian: Troizkij, V. *Decrease the tire wear of steering wheels trough ensure optimal correlation between steering angles of the wheels and turning radii during use a car in city conditions.* PhD thesis. Moscow. 1983].
13. Uil, R.T. *Tyre models for steady-state vehicle handling analysis*. Master's thesis, Eindhoven University of Technology. 2007.
14. Wang, H. & Al-Qadi, I. & Stanciulescu, I. Effect of Surface Friction on Tire-Pavement Contact Stresses during Vehicle Maneuvering. *Journal of Engineering Mechanics.* 2013. Vol. 140. No. 4. P. 1-8. DOI:10.1061/(ASCE)EM.1943-7889.0000691.
15. *Tyre wear: Causes and Consequences*. Available at: http://www.timloto.org/download/pdf_lesbrieven/steering/chapter3tyrewear.pdf
16. *Factors Affecting Treadwear.* Available at: http://www.goodyeartrucktires.com/pdf/resources/service-manual/Retread_S7_V.pdf
17. Steyn, W. & Haw, M. *The effect of road surfacing condition on tyre life.* Available at: http://researchspace.csir.co.za/dspace/handle/10204/1863

Received 17.02.2015; accepted in revised form 31.08.2016