EXPERIMENTAL RESEARCH ON TYRES IN TRANSIENT SIDESLIP CONDITIONS

WITOLD LUTY[1]

Warsaw University of Technology

Summary

The paper presents selected results of experimental research on motor truck tyres in transient sideslip conditions. The tests were carried out with the use of two test facilities: a quasi-static test stand and a trailer for dynamic tyre testing. Results of measurements of the lateral reaction transmitted by the tyre of a vehicle wheel have been presented here against the background of changes in the wheel motion conditions. During the tests, quick changes were forced in the tyre slip angle, with single pulse, stepwise, and oscillating inputs being applied. A method of observing and analysing the share of tyre relaxation in the process of transmission of the lateral reaction in transient tyre sideslip conditions has been presented. The measurement results obtained contribute to elucidation of the tyre relaxation issues. Simultaneously, they constitute a source of data that make it possible to verify a model of tyre-road interaction where tyre relaxation would be taken into account.

Keywords: tyre relaxation, experimental research on tyres, tyre sideslip

1. Introduction

The research on tyres in transient wheel motion conditions is a particularly difficult task. For the work of this kind to be properly done, special test facilities, research methods, methods of observation, and measurement result processing methods must be used. Results of the research provide a possibility of observing the tyre relaxation process and getting to know its nature. Simultaneously, they enable the researcher to verify the tyre relaxation model prepared in respect of both correctness of the mathematical description used and selection of model coefficients.

In most cases, tests on tyres in transient sideslip states are carried out with the use of stands for dynamic tests [2, 9, 13]. The test stands of this type offer real wheel motion conditions; however, they also impose limitations as regards the rates of changes in these conditions, which cause considerable difficulties in pursuing the cognitive objectives of the research carried out. In specific cases, it is advisable to use quasi-static test stands, where step changes in some wheel motion conditions, e.g. tyre sideslip angle or normal wheel load, can be simulated [6]. As an indirect method of researching into transient states of tyre sideslip, road vehicle tests may be carried out in dynamic conditions of motion [9].

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[1] Warsaw University of Technology, Faculty of Transport, ul. Koszykowa 75, 00-662 Warsaw, Poland, e-mail: wluty@wt.pw.edu.pl, tel. +48 22 234 81 13

In most cases, transient sideslip states are associated with the situation of quick changes in the tyre sideslip angle values. In reality, however, they may also take place in result of a change in any of the physical quantities that determine the value of the lateral reaction transmitted by the tyre in sideslip conditions. This may be explained with taking as an example the mathematical description of the model of tyre-road interaction. In practically every known model, the value of the lateral reaction F_y transmitted by the pneumatic tyre may be expressed as a product of two factors:

$$F_y = s_y \cdot k_\delta \tag{1}$$

where: F_y – lateral reaction acting on the tyre in the tyre-road contact patch;
s_y – tyre sideslip;
k_δ – coefficient of proportionality, which may also be referred to as coefficient of tyre resistance to sideslip in steady wheel motion conditions.

If the Dugoff, Fancher, and Segel's (DFS) model is taken as an example, these factors may be described as follows [1]:

$$s_y = tg\delta \tag{2}$$

and

$$k_\delta = \frac{c_y}{1 - s_x} \qquad \text{for } s_w \leq 0.5 \tag{3}$$

or

$$k_\delta = \frac{c_y}{1 - s_x}\left(\frac{4 \cdot s_w - 1}{4 \cdot s_w^2}\right) \qquad \text{for } s_w \geq 0.5 \tag{4}$$

where the following calculations must be additionally made:

$$s_w = \frac{\sqrt{c_x^2 \cdot s_x^2 + c_y^2 \cdot s_y{}^2}}{\mu \cdot F_z \cdot (1 - s_x)} \tag{5}$$

$$\mu = \mu_0 \cdot (1 - k \cdot v_{s\delta}) \tag{6}$$

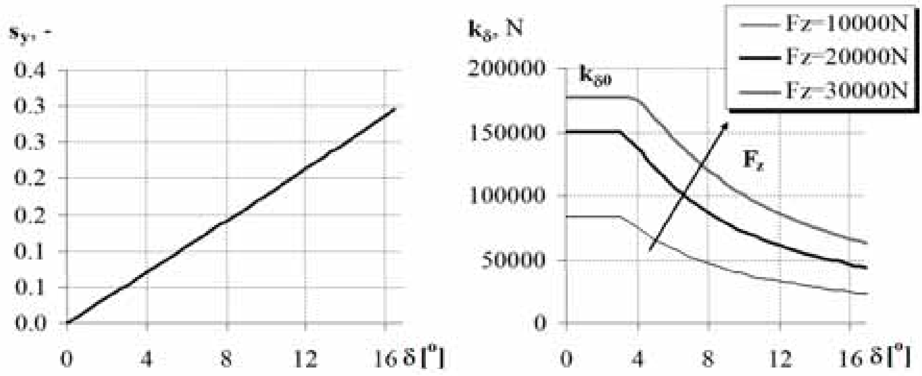
$$v_{s\delta} = v_x \cdot \sqrt{s_x^2 + s_y^2} \tag{7}$$

In the expressions above, the following notation has been used:
δ – tyre sideslip angle;
c_x – coefficient of longitudinal slip stiffness of the tyre;
c_y – coefficient of lateral slip stiffness of the tyre;
s_x – longitudinal tyre slip;
s_y – lateral tyre slip;
μ_O – coefficient of friction between tyre tread rubber and road surface;
k – coefficient of influence of the slip velocity on the coefficient of friction between tyre tread rubber and road surface;

$v_{s\delta}$ – tyre slip velocity relative to road;
v_x – longitudinal velocity of the wheel centre relative to road;
F_z – normal wheel load (normal reaction acting on the wheel in the tyre-road contact patch).

The coefficients s_y and k_δ change with increasing tyre sideslip angle as shown in Fig. 1a, and this translates into a characteristic of the tyre resistance to sideslip, according to equation (1). The graph presented as an example shows that the value of the lateral reaction F_y transmitted by the tyre in the steady sideslip state depends not only on the value of tyre sideslip s_y but also on the instantaneous value of the coefficient k_δ of tyre resistance to sideslip. This coefficient assumes the value of the coefficient c_y of lateral tyre slip stiffness only at low values of the tyre sideslip angle.

a) Changes in the values of coefficients s_y and k_d as functions of the tyre sideslip angle



b) Characteristics of the pneumatic tyre resistance to sideslip

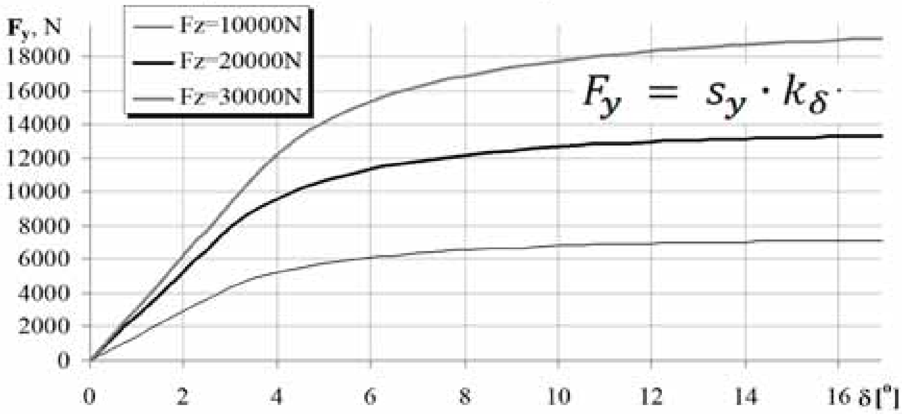


Fig. 1 a) Changes in the lateral tyre slip s_y and coefficient of tyre resistance to sideslip k_δ as functions of the tyre sideslip angle δ; b) Characteristics of the pneumatic tyre resistance to sideslip, determined for different values of normal wheel load F_z

In this connection, changes in the wheel motion conditions, inevitably accompanied by the appearance of transient tyre sideslip conditions, include changes not only in the tyre sideslip angle but also in the coefficient of tyre resistance to sideslip k_δ. According to equations (3) to (7), the latter may considerably vary with changes in other wheel motion conditions, such as:

- longitudinal tyre slip s_x, e.g. in the case of violent applying and releasing of wheel brakes;
- lateral tyre slip s_y, e.g. in the case of rapid turns or action of strong and violent gusts of side wind;
- coefficient of friction between tyre tread rubber and road surface μ, e.g. when the vehicle is driven on a road surface with different properties, which affect the adhesion of vehicle wheels to the road surface;
- normal wheel load F_z, e.g. when the vehicle is driven on a road with rough surface.

When the tyre-road interaction model was prepared with tyre relaxation being taken into account, experimental tests of a pneumatic tyre were carried out in transient sideslip conditions. During the experiments, the tyre behaviour was observed in different cases of changes in the wheel motion conditions, practicable at laboratory tests carried out with the use of the research equipment available; the research equipment used included the following test facilities built at the Military Institute of Technology:

- test stand for quasi-static tyre testing [4];
- dynamometric trailer for dynamic tyre testing, with a drum test stand [5].

The tests were carried out for different variants of forced changes in the wheel motion conditions with the wheel being rolled with sideslip. The findings presented here include results of pneumatic tyre testing in the conditions of changes in the tyre sideslip angle, where the changes were induced as follows:

- by step changes in the sideslip angle value in quasi-static tyre motion conditions;
- by oscillatory changes in the sideslip angle value when the wheel was rolled straight-on in dynamic conditions;
- by oscillatory changes in the sideslip angle around a preset constant value of this angle.

2. Tyre test results

Paradoxically, the tyre relaxation process can be easily simulated and observed during tests in quasi-static wheel motion conditions [6]. When a wheel with a tyre is pressed against the raceway of a test stand with a preset tyre sideslip angle δ and the vehicle rolling process begins, the lateral reaction F_y transmitted by the tyre increases in a way typical for the tyre relaxation process (Fig. 2).

In quasi-static test conditions, the lateral reaction F_y for each of the preset tyre sideslip angles δ increases until it reaches a value achievable for the tyre in the steady wheel motion conditions. The curve representing the process of changes in the value of the lateral reaction F_y as a function of the distance travelled or the time elapsed may be referred to as a tyre relaxation characteristic. The tyre relaxation characteristics shown in Fig. 2 are typical for a first-order inertial element [8]. In practice, the tyre relaxation characteristics determined in quasi-static conditions make it possible to select a value of "tyre relaxation length" L_n. The tyre relaxation length is an important coefficient in the tyre relaxation model. At a specific wheel rolling velocity v_x, its value determines the relaxation time, according to the following equation [6]:

$$t_n = \frac{L_n}{v_x} \tag{8}$$

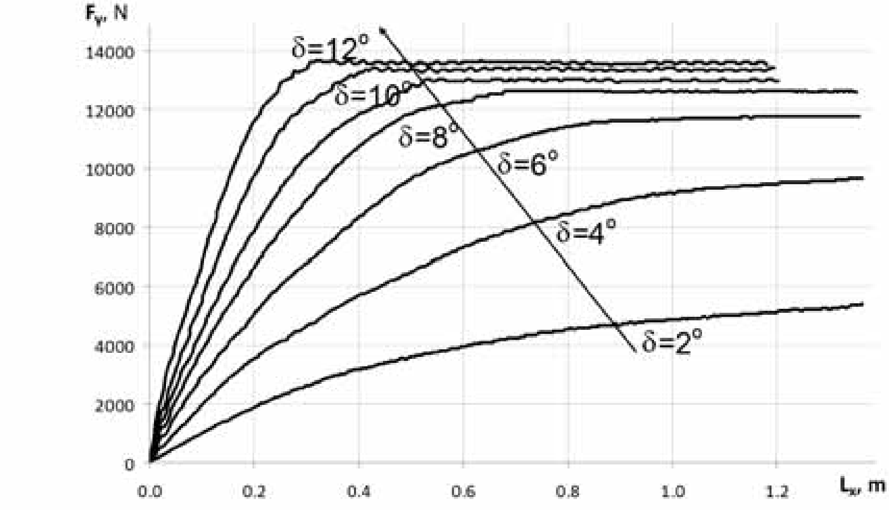


Fig. 2. Tyre relaxation characteristics determined in quasi-static wheel motion conditions (for tyres of a medium-capacity motor truck, at normal wheel load of F_z = 20 000 N)

The tyre relaxation characteristics presented in Fig. 1 cannot be observed in dynamic wheel motion conditions. When a wheel is rolled with a high velocity, it is impossible to apply a step change in the tyre sideslip angle value, even if the wheel turning angle is controlled by a machine. The maximum rate of changing the wheel turning angle, i.e. the rate of applying a specific value of the tyre sideslip angle, is limited by the power capacity of the wheel steering mechanism and resistance of the inertia of the wheel being turned. The example of the measurement results presented in Fig. 3a shows that even a step change in the voltage signal that controls the hydraulic system to turn the dynamometric trailer wheel does not result in a step change in the tyre sideslip angle. In consequence, the rate of changes in the value of the lateral reaction F_y transmitted by the tyre under tests is markedly reduced (Fig. 3a). Changes in the value of the lateral reaction F_y follow changes in the tyre sideslip angle δ. However, when the time histories of these physical quantities are analysed, the question whether any relationship occurs between the said quantities and the tyre relaxation process is not only hard to be unequivocally answered but also difficult to be generally examined. Nevertheless, the effects of tyre relaxation may even be observed in the wheel motion conditions as described above. Such effects can be seen in Fig. 3b. If the curves representing the measured values of the lateral reaction F_y vs. the tyre sideslip angle δ applied are superimposed onto each other then it can be seen that changes in the lateral reaction value follow changes in the tyre sideslip angle with a clearly visible lag, forming a left-handed loop. This lag is chiefly caused by tyre relaxation. It results in a difference between the values of the measured lateral reaction F_y and the value of the reaction F_{yu} that can be transmitted by the tyre in steady wheel motion conditions. The expected values of the latter force have also been marked in Fig. 3b. Making use of

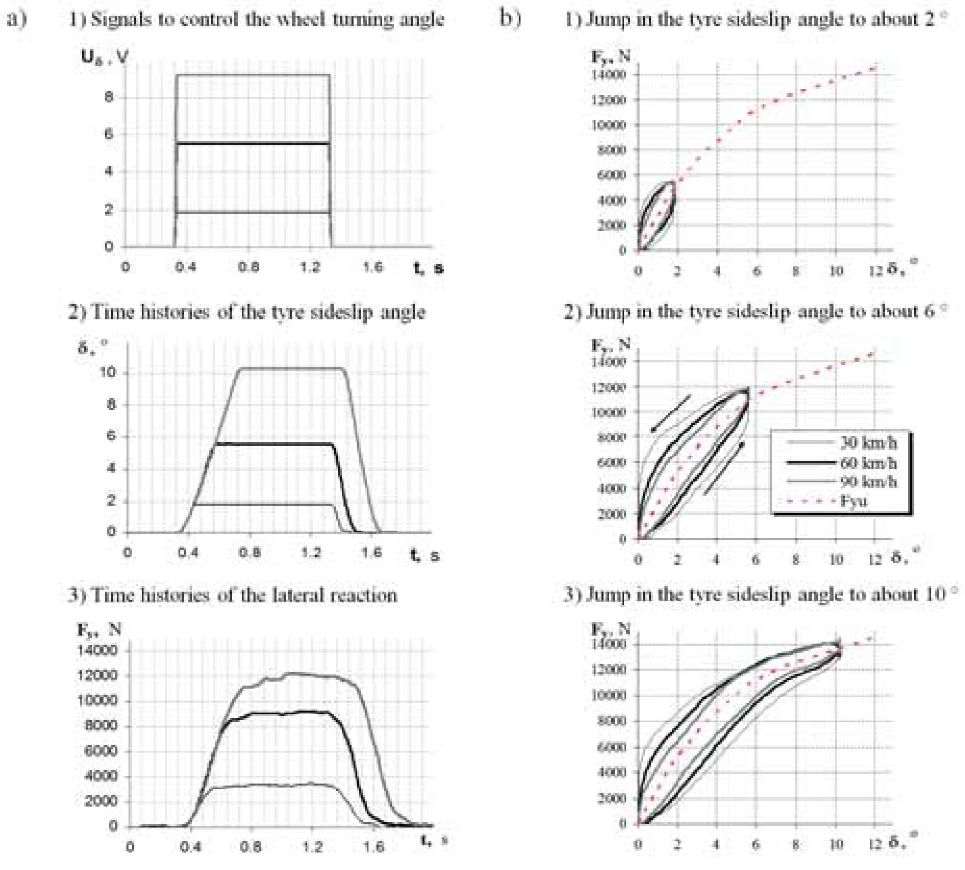


Fig. 3. Results of pneumatic tyre testing in the conditions of dynamic change in the tyre sideslip angle: a) example of control signals with measured values of the tyre sideslip angle δ and the lateral reaction Fy transmitted by the tyre (v = 30 km/h); b) measured values of the lateral reaction Fy for different values of the inputted tyre sideslip angle δ and wheel rolling velocity vx

the principles of analysing the properties of dynamic systems based on the Lissajous curves, one can state that the width of the hysteresis loop having been formed is in this case a measure of the phase shift of changes in the lateral reaction F_y in relation to the inputted changes in the value of the tyre sideslip angle δ [7].

The hysteresis loop width decreases with increasing rate of the tyre reaction to changes in the wheel motion, i.e. to changes in the tyre sideslip angle δ. Fig. 3b shows the decrease in the hysteresis loop width with increasing wheel rolling velocity and with increasing tyre sideslip angle. This indicates that the share of tyre relaxation in the process of transmission of the lateral reaction by the tyre of a wheel being rolled with sideslip markedly decreases with increasing wheel rolling velocity and tyre sideslip angle.

The tyre relaxation process also takes place in other cases of changes in the tyre sideslip angle in dynamic conditions. At the next stage of the research work, the inputs used to force changes in the wheel motion conditions had the form of oscillations in the tyre sideslip angle δ around the position of the wheel being rolled straight-on (with no sideslip, Fig. 4a) and around a preset initial constant value δ_u of this angle (Fig. 4b).

In the case of the wheel being rolled straight-on, a growth in the amplitude at constant oscillation frequency leads to quicker changes in the tyre sideslip angle δ. In consequence, the width of the observed hysteresis loops in the graph $F_y = f(\delta)$ markedly increases. Simultaneously, as it is in the previous case, the width of the hysteresis loops considerably decreases with increasing wheel rolling velocity v_x (Fig. 4a). Oscillations in the tyre sideslip angle δ around a preset initial constant value δ_u of this angle also result in the creation of a typical hysteresis loop in the graph $F_y = f(\delta)$ (Fig. 4b). In this case, it can be seen that the hysteresis loop becomes markedly narrower with a growth in the preset initial constant value δ_u of the tyre sideslip angle. Thus, this research stage has also proved that if a wheel is rolled with sideslip then the share of tyre relaxation in the process of transmission of the lateral reaction by the tyre markedly declines with growing wheel rolling velocity and tyre sideslip angle.

The tyre behaviour presented herein is confirmed by results of other author's research work as well as by literature sources [6, 8, 3]. The share of tyre relaxation in the process of transmission of the lateral reaction by a tyre depends on the actual value of the tyre relaxation time t_n in each specific test instance. This time decreases with increasing wheel rolling velocity and with decreasing tyre relaxation length L_n, according to equation (8). In turn, the tyre relaxation length L_n decreases with increasing tyre sideslip angle.

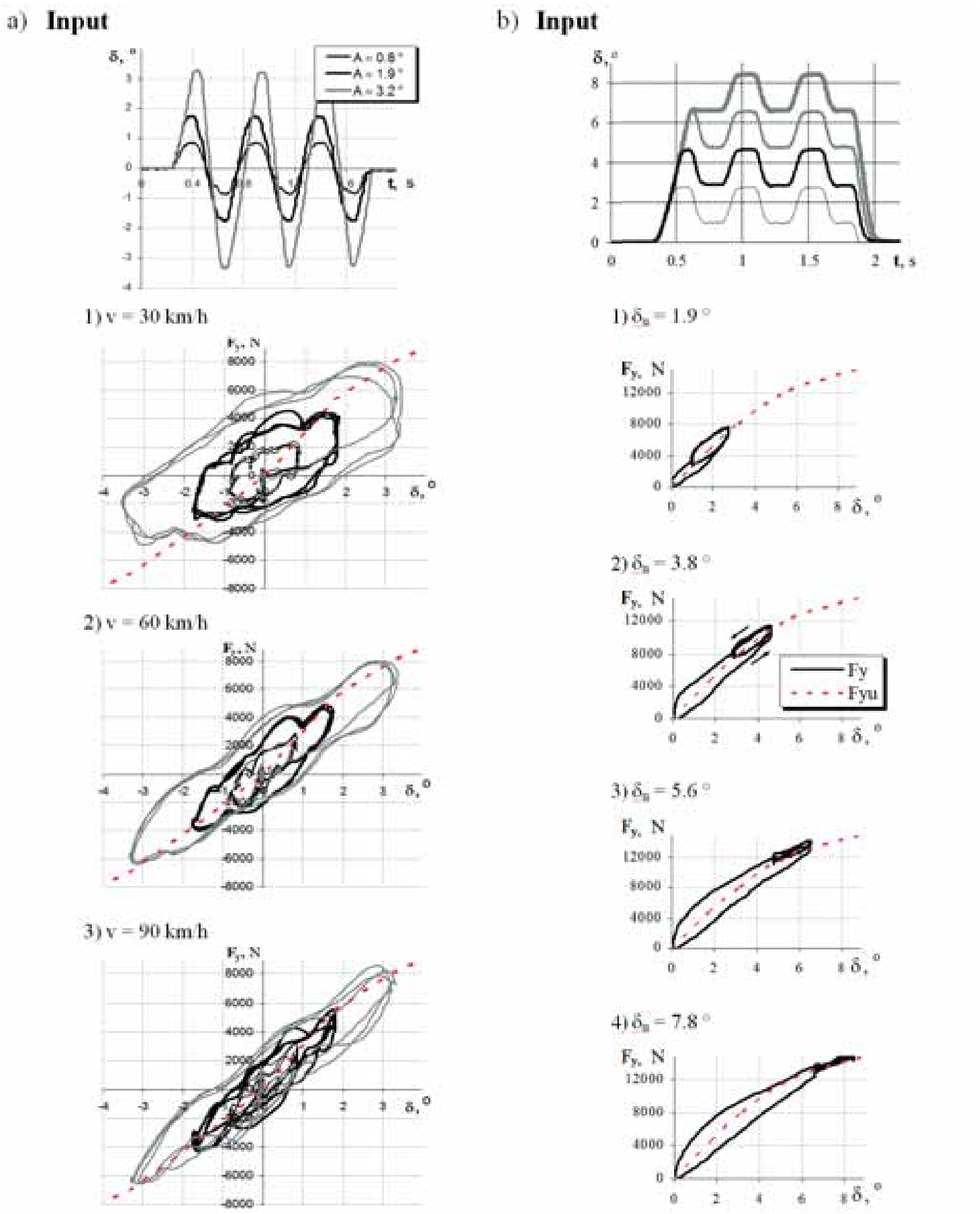


Fig. 4. Tyre relaxation in the conditions of oscillatory changes in the tyre sideslip angle: a) oscillations in the tyre sideslip angle δ around its zero value, with different amplitudes (f = 2 Hz); b) oscillations in the tyre sideslip angle δ around a preset initial constant value δ_u of this angle (f = 2 Hz, A = 1°, v_x = 60 km/h)

3. Recapitulation

Taking the presented results of experimental research as an example, methods of simulating in laboratory conditions the transient tyre sideslip states by changing the tyre sideslip angle have been demonstrated. Results of the observation and evaluation of the share of tyre relaxation in the process of transmission of lateral reaction by the tyre of a wheel being rolled with sideslip have been shown. The tyre relaxation process may be observed in quasi-static conditions by analysing the growing value of the lateral reaction transmitted by the tyre as a function of the distance travelled or the time elapsed. For the tyre relaxation process to be investigated in dynamic conditions, the domain in which the measurement results are observed must be changed. It has been shown that an analysis of changes in the lateral reaction values as a function of the input applied (i.e. changes in the tyre sideslip angle in this case) offers a possibility of observing and assessing in qualitative terms the share of tyre relaxation in the process of transmission of lateral reaction by the vehicle wheel. It has also been shown that in dynamic conditions, the said share of tyre relaxation may vary depending on vehicle rolling velocity, tyre sideslip angle, and rate of changes in this angle. The research results presented provide a basis for the preparation of a mathematical description of the tyre relaxation phenomenon or for quantitative and qualitative verification of a tyre relaxation model where the dependences shown would be taken into account.

References

[1] DUGOFF, H.; FANCHER, P. S.; SEGEL, L.: *An analysis of tire traction properties and their influence on vehicle dynamic performance.* SAE Transactions 700377, Vol. 79.

[2] LEE, S.; HEYDINGER, G. J.; GUENTHER, D. A.: *The application of pulse input techniques to the study of tire lateral force and self-aligning moment dynamics in the frequency domain*. SAE Paper 950317, 1995.

[3] LOEB, J. S.; GUENTHER, D. A.; Chen, H. H. F.; Ellis, J. R.: *Lateral stiffness, cornering stiffness and relaxation length of the pneumatic tire.* SAE Paper 900129, 1990.

[4] LUTY, W.; PROCHOWSKI, L.; SZURKOWSKI, Z.: *Stanowisko do badań ogumienia dużego rozmiaru (Large-size tyre testing stand).* 7th International Symposium of Institute of Motor Vehicles, Warszawa-Rynia, 8–10 Dec. 1999.

[5] LUTY, W.; WYSOCKI, T.: *Przyczepa dynamometryczna do badań dynamicznych ogumienia* (*Dynamometric trailer for dynamic testing of tyres*). 7th International Symposium of Institute of Motor Vehicles, Warszawa-Rynia, 8–10 Dec. 1999.

[6] LUTY, W.: *Wyznaczanie parametrów modelu nabiegania ogumienia na podstawie wyników badań eksperymentalnych* (*Determination of tire relaxation model parameters based on experimental research results*). Postępy Nauki i Techniki No. 14, 2012.

[7] SYDENHAM, P. D.: *Podręcznik metrologii* (*Handbook of Measurement Science* – translated into Polish). Wydawnictwa Komunikacji i Łączności, Warszawa 1990.

[8] RILL, G.: *First order tire dynamics.* 3rd European Conference on Computational Mechanics Solids, Structures and Coupled Problems in Engineering, Lisbon, Portugal, 5–8 June 2006, University of Applied Sciences Regensburg.

[9] SAR, H.; REŃSKI, A.: *Simulation of non-steady-state curvilinear vehicle motion*. Journal of KONES Powertrain and Transport, Vol. 16, No. 3/2009.

[10] SCHMID, I.; TOMASKE, W.: *Tire testing facility for simulation of transient operating conditions.* ATZ 1/ 1984.

[11] TAKAHASHI, T.; PACEJKA, H. B.: *Cornering on uneven roads.* Supplement to Vehicle System Dynamics, Vol. 17 (1988).

[12] WILLUMEIT, H. P.; BÖHM, F.: *Wheel vibration and transient tire forces.* Vehicle System Dynamics, Vol. 24 (1995), pp. 525–550.

[13] ZANTEN, A.; ERHARDT, R.; LUTZ, A.: *Measurement and simulation of transients in longitudinal and lateral tire forces.* SAE Paper 900210, 1990.