AN ANALYSIS OF TIRE RELAXATION PROCESS DURING DYNAMIC CHANGES OF CORNERING ANGLE

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Abstract

The work presents results of laboratory experimental research of a truck tire in dynamic motion conditions. Researches were performed using dynamometric trailer and dual drum facility for tire dynamics testing. The research object was a new structure truck, tubeless tire (275/70R22.5) with steel cord included also in carcass and belt. Tested tired wheel was rolling over steel drum surface with different speed. A wheel cornering angle was forces with different increase and similar decrease rate. The control system of hydraulic wheel turning mechanism was controlled by the voltage signals generated by software, through the D/A converter card. Values of cornering angle and also lateral reaction force transmitted by tested wheel were measured during tests performing. Changes of lateral reaction force values, transmitted by a tired wheel depending on forced wheel cornering angle were observed. Tire behaviour in the conditions of wheel cornering angle variations at different wheel rolling speed is presented. An influence of tire relaxation on values of transmitted lateral reaction force, during forcing of wheel cornering angle, is presented. As a result, there are presented differences in transient tire behaviour during forcing of wheel cornering angle with different increase rate and at different wheel rolling speed. A scope of wheel motion conditions are indicated, where tire relaxation can be important in case of modelling its interaction with the ground in the aspect of vehicle driving safety and comfort. Lateral reaction force value, transmitted by a wheel, the tire relaxation phenomenon becomes less significant when the rolling speed increases, the cornering angle value increases and when the rate of the wheel cornering angle variation rate decreases. It has been also shown that the relaxation phenomenon occurs both when cornering angle increases or decreases.

Keywords: *pneumatic tire, tire relaxation, tire cornering stiffness*

1. Introduction

Tire properties can affect the vehicle driving safety and comfort. Also the behaviour of a vehicle in a curvilinear motion significantly depends on tire characteristics, especially on the lateral reaction forces, transmitted by a tired wheel in particular driving conditions. Tired wheel ability to transfer a lateral reaction force makes the main stream of interest of the scientific and research circles in the world. Experimental research is continuously performed in order to define the characteristics of new structure tires. At the same time, the works on improvement the modelling of interaction between a tire and road surface are carried out in order to increase the reliability of vehicle simulation tests and also the improvement of driving simulator behaviour.

In recent years, the interest has been focused on the tire characteristics that determine its behaviour during a dynamic change of wheel motion conditions. In the curvilinear vehicle motion, a dynamic variation of driving wheel motion conditions leads to a phenomenon called a relaxation. The relaxation, as unstable state of tire-road interaction, occurs, for example, in case of a fast cornering angle change. In such conditions, the change of a lateral reaction force value up to value, related to new motion condition requires a certain distance to drive by wheel. Tire relaxation can be the most easily observed in the laboratory conditions. There are many tire relaxation testing methods [1,2,3]. The most of them are dynamic test methods. Within a scope of the author’s work, a new own tire relaxation testing method during wheel cornering using a quasistatic tire testing facility were developed [4, 5]. Advantage of a quasistatic method is a possibility of setting a cornering angle step of a tested wheel before the wheel starts rolling. When the wheel starts rolling on the facility carrier surface, there is actually an effect of sudden, step wheel cornering angle change. So there is a case of extremely fast increase of the cornering angle to a settled value. A course of the wheel relaxation characteristics, created in that way, does not depend on cornering angle increase speed rate. Such conditions are close to perfect from the point of view of performing observation a relaxation phenomenon and defining relaxation parameters. It cannot be achieved in any dynamic tire testing facilities.

A typical course of lateral reaction force F_y changes, transmitted by a wheel tire in quasistatic testing conditions are presented on figure 1. Presented curve of tired wheel relaxation is a course of a function known as IPG-TIRE model [6]. This model is described with the following equation, of typical inertial element:

$$F_y(t) = F_y - t_n \cdot \dot{F}_y(t)\,, \tag{1}$$

where:
F_y - lateral reaction force transferred by a wheel in steady state motion conditions,
$F_y(t)$ - temporary value of lateral reaction force, transmitted by a wheel, during its relaxation process,
$\dot{F}_y(t)$ - derivative of lateral reaction force increase/decrease function F_y,
t_n- relaxation time coefficient.

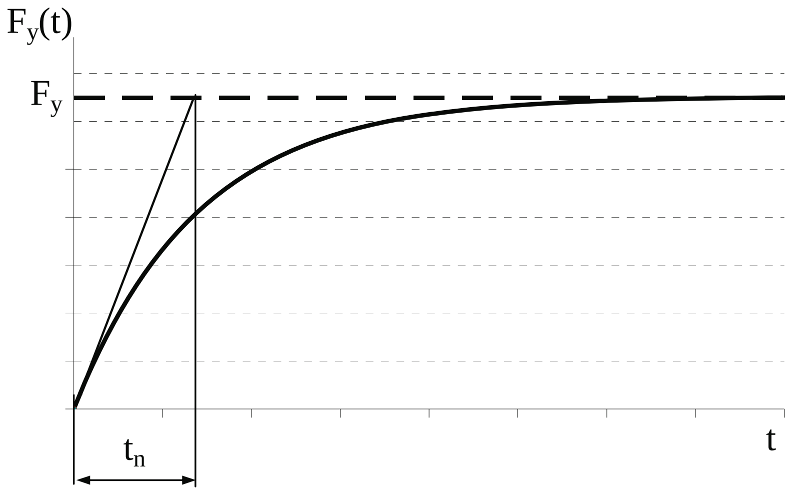


Fig. 1. A relaxation curve of tired wheel as an effect of cornering angle step input – interpretation of IPG-TIRE equation coefficients

The relaxation time t_n is actually a time constant, which characterizes a rate of lateral reaction force value $F_y(t)$ increase, until its is settled on a value level F_y, which the wheel transfers in a steady state cornering (Fig. 1). A modified form of the formula is often used in the experimental and simulation research, replacing a relaxation time with following expression:

$$t_n = \frac{L_n}{v_k}\,, \tag{2}$$

in that case the IPG–TIRE formula gets the following form:

$$F_y(t) = F_y - \frac{L_n}{v_k} \cdot \dot{F}_y(t), \tag{3}$$

where: L_n- relaxation length,
v_k – wheel centre speed.

Obtained form of IPG – TIRE equation is more advantageous because it depends on the wheel speed v_k and a constant parameter called the relaxation length L_n, which interpretation is analogical to the relaxation time t_n. It is also known that the relaxation length value L_n is characteristic of a tire type and wheel motion conditions [4].

The Figure 2 presents the measurement results of the lateral reaction force F_y, transmitted by tired wheel, increasing due to a step change of the cornering angle in quasistatic conditions. Successively set values of cornering angle result in the increase of lateral reaction force value F_y transmitted by a wheel but also make changes in the rate of reaction force increase. The figure also shows the functions that approximate relaxation curves obtained as the measurement result. As it is noticeable, the IPG-TIRE model in the quasistatic conditions, often used for a description of a tired wheel relaxation process, gives satisfactory approximation results.

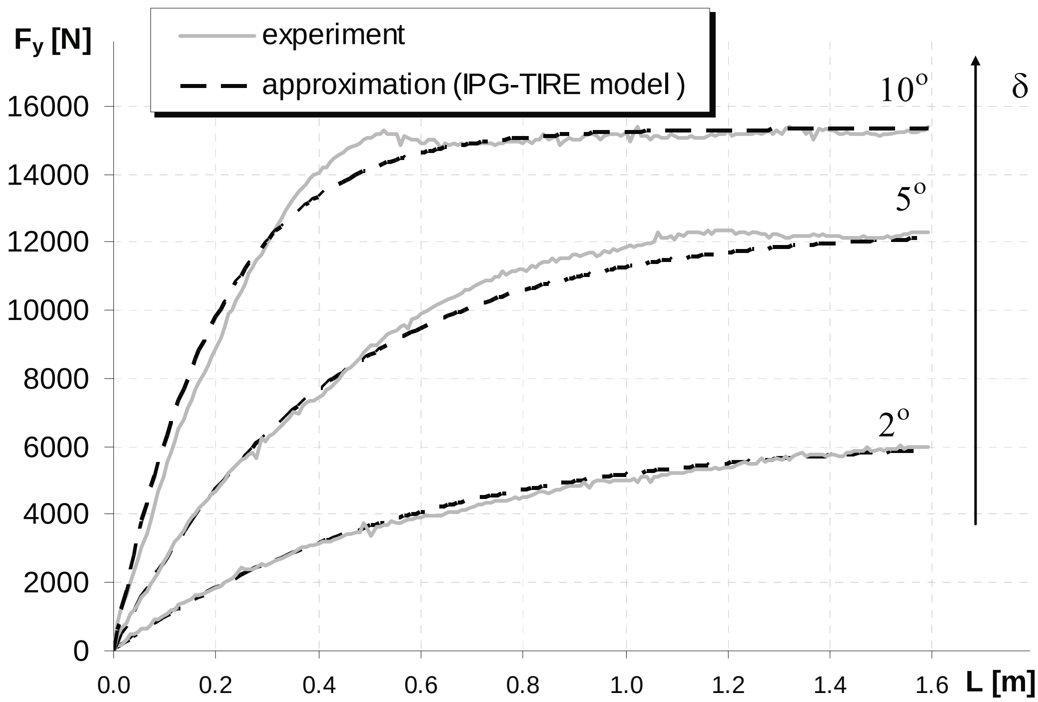


Fig. 2. Variations of lateral reaction force value F_y, transmitted by a tired wheel after forcing of cornering angle δ step change, in function of rolling distance L (all-steel 275/70R22.5 tire, normal load F_z=20000N)

The results of the tire tests in the quasistatic conditions allow to define the tire relaxation parameters (in that case the relaxation length L_n). The values of the relaxation length L_n, determined for a tested tire in a wide range of wheel motion conditions variations, are presented on Figure 3. As it is noticeable, a relaxation length L_n depends on a value of a set cornering angle value and also on normal wheel load value F_z.

Presented examples of experimental tire research results were achieved in the quasistatic conditions, so at a low wheel rolling speed and step change of the cornering angle value. However, a question should be answered: how the relaxation phenomenon affects the courses of changes of lateral reaction force values F_y, transmitted by a wheel in the dynamic conditions, when a wheel is rolling in the operational scope of speed and the speed rate of motion condition changes is limited.

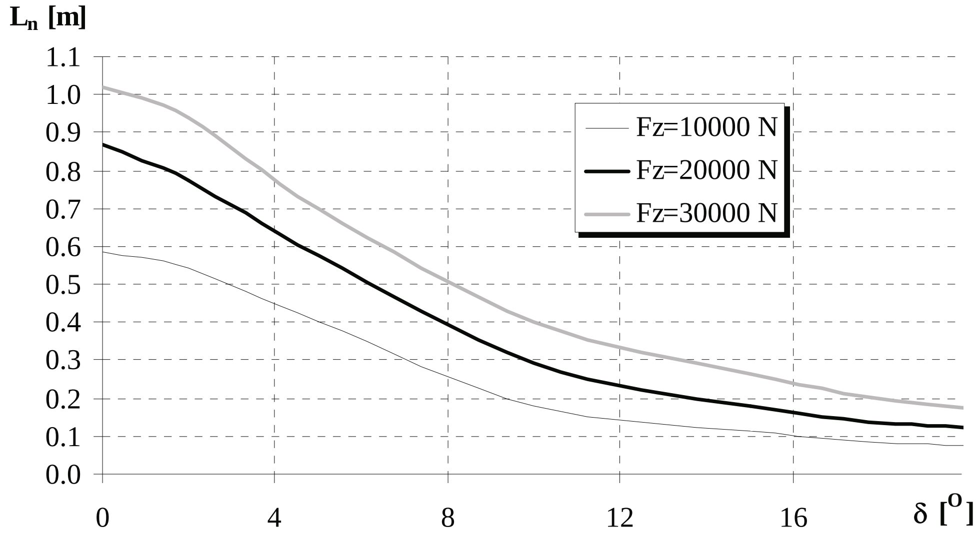


Fig. 3. Variations of the relaxation length value L_n, after forcing a cornering angle step δ(all-steel 275/70R22.5 tire, normal load F_z=20000N)

Basing on the quasistatic research results and the IPG-TIRE formula (equation 3) one can expect that the tire relaxation will proceed in a way which depends on a wheel rolling speed. At a steady value of the relaxation length L_n faster changes of the lateral reaction force values F_y can occur at a higher wheel rolling speed *v*. You can also expect that changes of the lateral reaction force values F_y occur quicker in the scope of higher cornering angle values δ, where the relaxation length is shorter (Fig. 3).

It should be noticed that tire relaxation occurs during any changes of the wheel motion conditions, leading to a change of transmitted lateral reaction force value F_y. So you can expect that in the traffic conditions tire relaxation can be a result of:

- dynamic change of the cornering angle value (as a result of a sudden turn of the driving wheels, impulsive action of the lateral force resulting from a side wind blow or changes of road side slope or unevenness),
- dynamic braking during cornering, which leads to a decrease of lateral reaction forces transmitted by car wheels,
- dynamic change of normal wheel load F_z (e.g. when crossing a road unevenness).

In that case the analysis was focused on changes of interaction between a tire and road surface in unsteady conditions of side cornering, caused by changes of the cornering angle values during wheel rolling. The author is especially interested in answers to the following questions:

- How the speed rate of cornering angle changes affects the course of relaxation?
- Is the course of relaxation similar during the increase and decrease of the cornering angle value?
- Does the wheel cornering angle value affects the relaxation process?
- In what range of wheel rolling speeds the tire relaxation significantly affects the value of a lateral reaction force transmitted by a wheel?

In order to answer the questions above, the experimental research of a truck tire in dynamic conditions has been performed.

2. Research object, conditions and method

As the research object it was a truck wheel equipped with all-steel 275R22.5 size tire. The tire data are presented in Table 1.

Tab. 1. Basic data of the research object

Tire size	Carcass construction	Layer structure description			
		Body		Band	
		Material	Number of layers	Material	Number of layers
275/70R22.5 all-steel	Radial	steel	1	steel	4

The tests were performed in the following conditions:

- normal wheel load – F_z*=20000N*,
- wheel cornering angle changes rate – defined by a cornering angle increase time *(t=0.4, 0.8, 1.2s)* to a settled value δ,
- settled turn angle values – $\delta = 4, 8^O$,
- wheel rolling speed – *v=30, 60, 90 km/h*,
- tire air inflation pressure – *650kPa*.

A dynamometric trailer was used in the dynamic tests. Its wheels are rolled on a surface of the steel drums of double-drum facility (Fig. 4) [7].

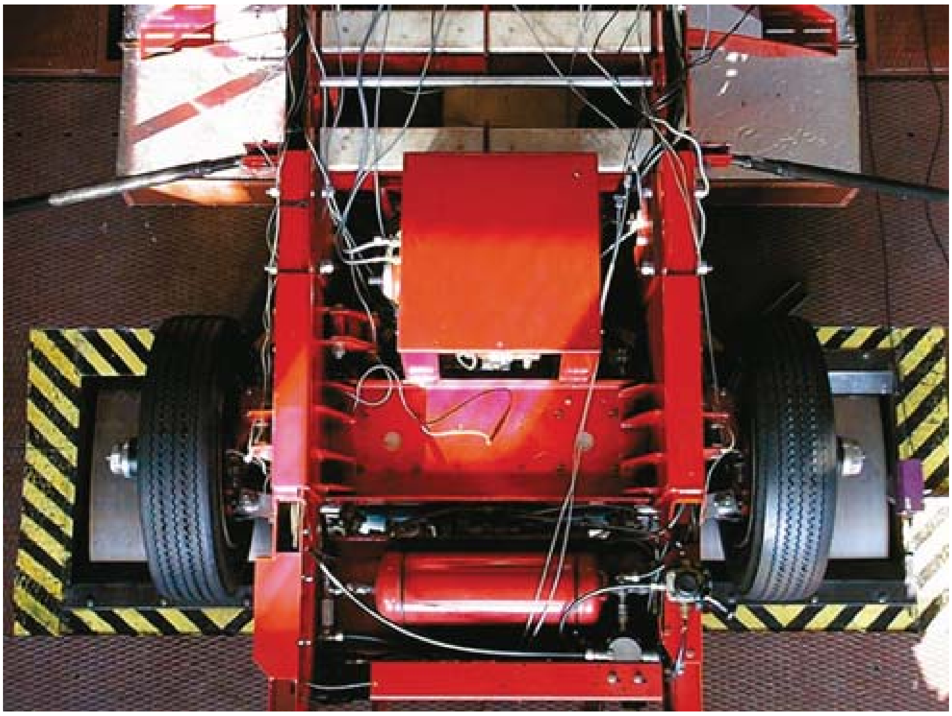


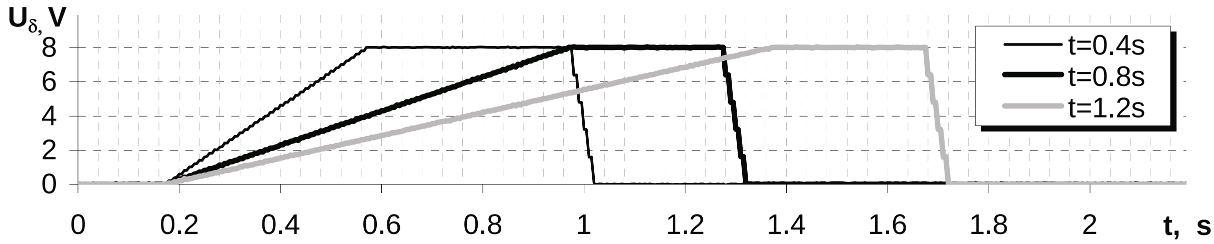
Fig. 4. A dynamometric trailer during the tire tests at the double-drum facility – top view

The values of reaction forces transmitted by a wheel are measured by means of the measurement system installed in the driving axle suspension of the trailer. The trailer systems are controlled by the machine. The control system of the wheel turning mechanism can be controlled by the voltage signals generated from the D/A converter card (Fig. 5).

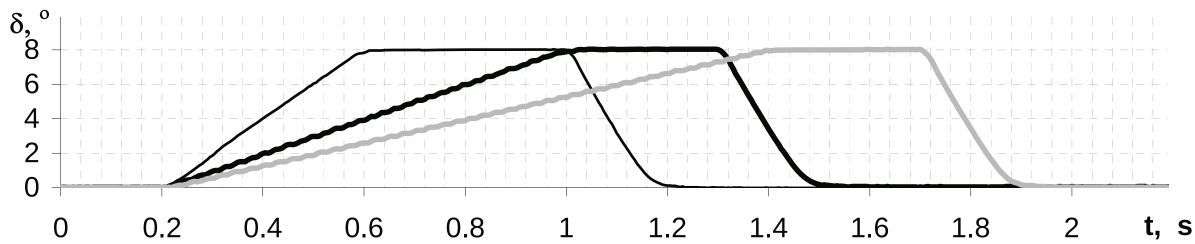
In that case it makes a significant feature of the trailer, making allowed the execution of planned tests. The machine control of a tested wheel turning allows obtaining repeatable test conditions, especially within a scope of variation rate and setting value of a wheel cornering angle δ. Generation and transmission of the courses of the voltage signal, controlling the wheel turning, is provided by specially developed software.

Fig. 5. A view of the Keithley P500 station cooperating with a microcomputer – the panel of software which allows to control the trailer systems, rolling speed and normal load of the trailer wheels

a) the voltage signal controlling the wheel turning system



b) changes of tested wheel cornering angle



c) changes of lateral reaction force values F_y, transmitted by a tested wheel

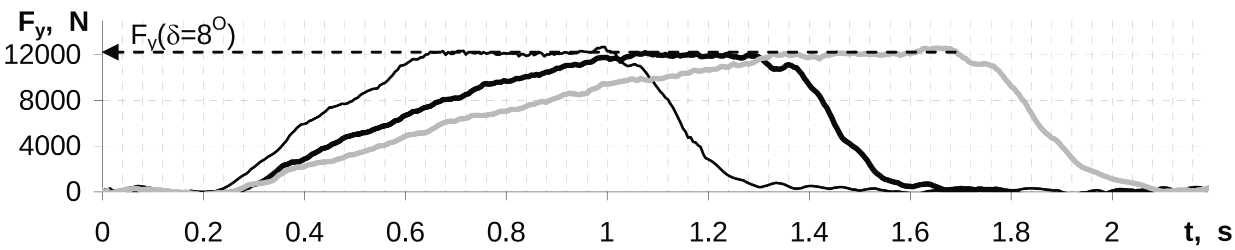


Fig. 6. Specification of measurements results, acquired during forcing a wheel turn up to cornering angle of $\delta=8^O$ (a turn made with different angle increase and similar angle decrease speed rate)

The same software allows to control the wheel rolling speed as well as to control the values of a normal load of a tested wheel. Examples of the courses of the voltage changing, controlling the wheel turn angle (cornering angle δ) and measured values of physical parameters are presented on Figure 6. As you can see, a various rate of the cornering angle increase up to 8^o results in adequate changes of lateral reaction force F_y increase rate. However, a wheel cornering angle decrease rate, to straight rolling direction was every time comparable (app. 0.3 s). At the same time, the lateral reaction force values F_y acquired after a short-time stabilization of the wheel cornering angle value δ were defined as points $F_y(\delta)$ of the tire cornering resistance characteristics in steady-state motion conditions (Fig. 6c).

3. Test results

In order to carry out the analysis of tire relaxation process, set courses of the lateral reaction force value changes F_y were compared, depending on the cornering angle values δ, on the background of tire cornering resistance characteristics points, measured in steady-state motion conditions (Fig.7, Fig. 8).

Specified measurement results show that during the wheel cornering angle increase δ the values of transmitted lateral reaction force F_y are lower and during the cornering angle decrease these values are higher than ones that are transferred by wheel in steady-state motion conditions. At the same time it is noticeable that, in the same wheel rolling speed *v*, changes in cornering angle increase rate results in differences between lateral reaction force values F_y transmitted by a wheel (Fig. 7). Differences between the lateral reaction force values are clearly seen at a low wheel rolling speed $v=30km/h$ (Fig. 7a). At that speed, the lateral reaction value F_y measured during cornering angle increase δ in the successively increasing periods of time from $t=0.4$ to *1.2s* are more and more higher and closer to the values, acquired in steady-state motion conditions (Fig. 7a).

Differences between the lateral reaction force values F_y, transmitted by a wheel during faster and faster cornering angle increase, get lower and lower as the wheel rolling speed *v* is higher. At speed $v=90$ *km/h* only the fastest cornering angle increase δ (t=0.4) results in significant reduction of transmitted lateral reaction force values F_y , in the relaxation process (Fig. 7c). During the cornering angle decrease δ at the same wheel rolling speed, the lateral reaction force decrease rate F_y is comparable (Fig. 7). The Figure 8 shows that at the same rate of the wheel cornering angle value changes δ, the increase of the wheel rolling speed *v* significantly increases the variation rate (increase and decrease) of the lateral reaction force value F_y and brings them closer to the ones that can be acquired in steady-state cornering conditions.

Concluded behaviour of a tired wheel is in accordance with previously defined expectations. In case of a tire relaxation length L_n, steady for a particular normal wheel load value F_z, increase of the transmitted lateral reaction force value variation rate F_y with the increase of the wheel rolling speed *v* or with the decrease of the cornering angle value variation rate is justified. That tire behaviour is accordance with description of equation 3.

Basing on presented results, it can be noticed that loop thickness ΔF_y, defined as a difference of the lateral reaction values measured for the same cornering angle value δ, during its increase and decrease, is lower not only with the higher wheel rolling speed *v* and with lower cornering angle variations rate δ (Fig. 7, 8). The loop is gets thicker, as a result of getting the lateral reaction force value F_y closer to the value of that reaction measured in steady-state cornering conditions, also with the increase of the wheel cornering angle δ (Fig. 7 and 8). Such behaviour can be also justified by using the presented results of the tire tests in the quasistatic conditions. The values of the relaxation length L_n, presented on Figure 3, that decrease with the increase of a cornering angle, can justify the limitation of the relaxation importance also in a scope of the higher cornering angle values also in the dynamic conditions.

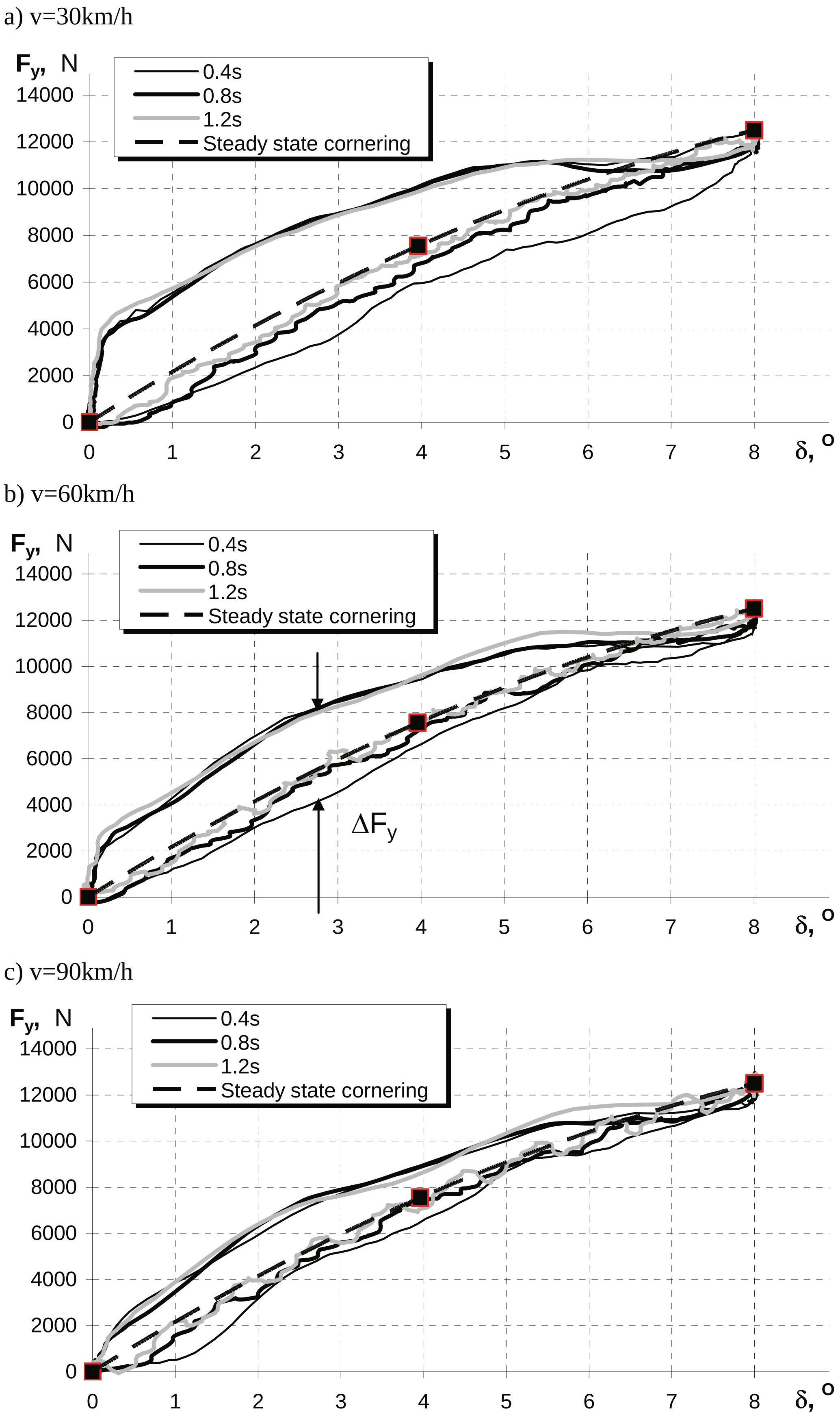
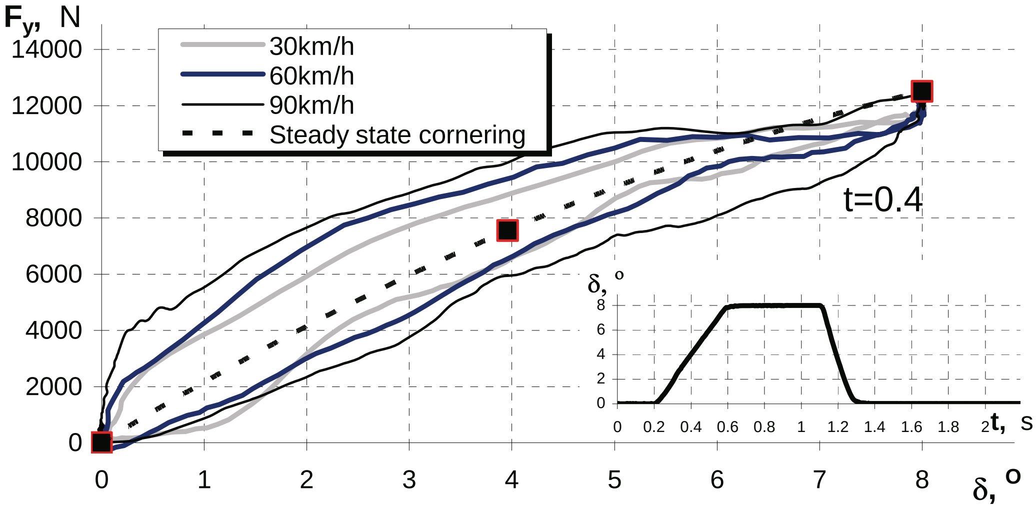
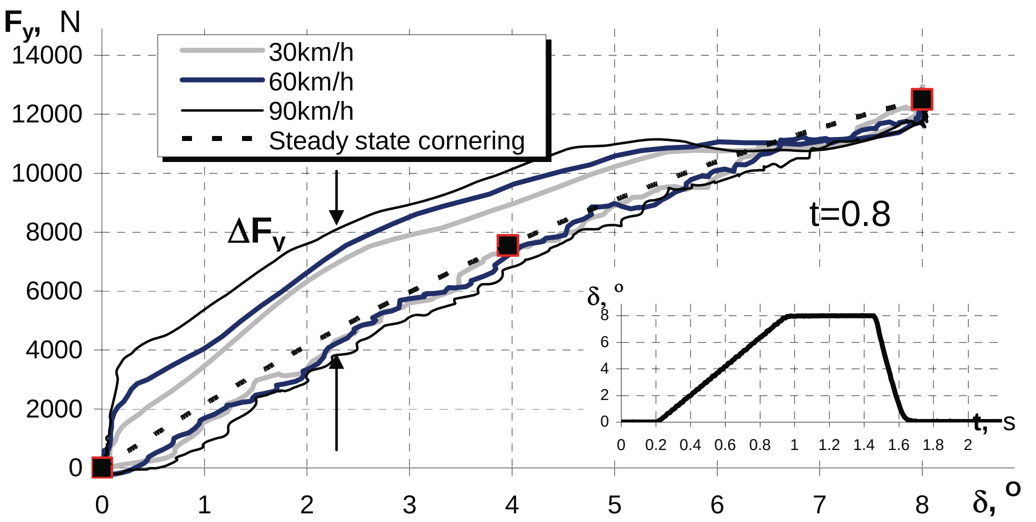


Fig. 7. Specification of measurement results acquired during a dynamic change of cornering angle value up to $\delta=8^O$ (influence of the cornering angle increase speed rate δ at similar wheel rolling speed v)

a) time of cornering angle increase t = 0.4s



b) time of cornering angle increase t = 0.8s



c) time of cornering angle increase t = 1.2s

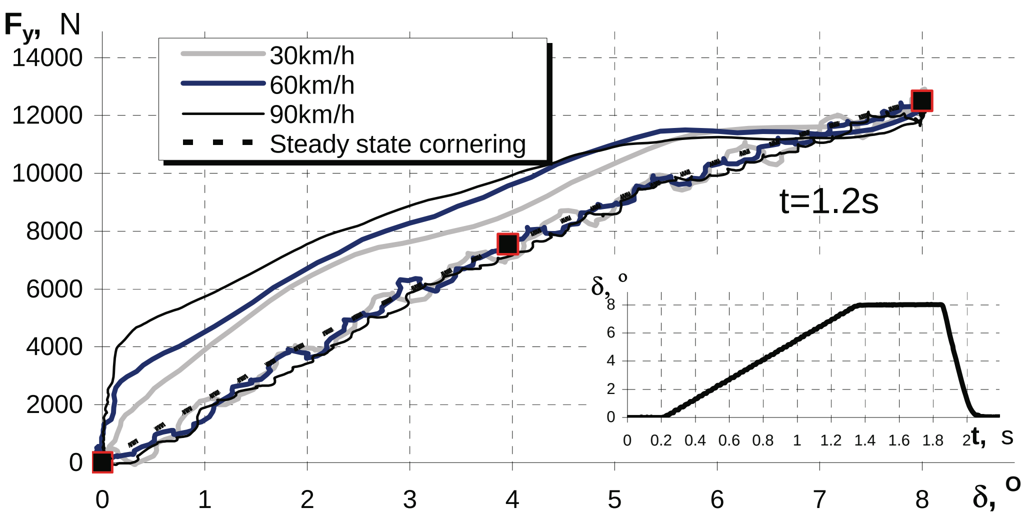


Fig. 8. Specification of measurement results acquired during dynamic change of cornering angle value up to $\delta=8^{O}$ (influence of the wheel rolling speed v at a similar cornering angle increase speed rate $\dot{\delta}$)

4. Summary

Presented research results make a part of a wide research programme of new structure tires. It has been shown that tire characteristics in unsteady wheel motion conditions, defined during the quasistatic tests are also reflected in dynamic conditions, close to the real wheel motion conditions. It has been demonstrated that a high cornering angle variation rate changes the significant values of the lateral reaction force transferred in the wheel relaxation process. However, from the point of view of a the lateral reaction force value, transmitted by a wheel, the tire relaxation phenomenon becomes less significant when the rolling speed increases, the cornering angle value increases and when the rate of the wheel cornering angle variation rate decreases. It has been also shown that the relaxation phenomenon occurs both when cornering angle increases or decreases.

In this wok only the process of increase and decrease of the lateral reaction value transferred by a wheel during the relaxation process, as a result of a single change of the wheel cornering angle value has been analyzed. Other tire behaviours in unsteady motion conditions are also interesting. First of all they are variations of lateral reaction force values and phase shift as a result of sinusoidal cornering angle variations or fast change of the normal wheel load value, e.g. when crossing over road unevenness. Such research has been carried out and the results will make a subject of other publications.

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