Article citation info:
PARCZEWSKI K. Effect of tyre inflation preassure on the vehicle dynamics during braking manouvre. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2013; 15 (2): 134–139.

Krzysztof PARCZEWSKI

EFFECT OF TYRE INFLATION PREASSURE ON THE VEHICLE DYNAMICS DURING BRAKING MANOUVRE

WPŁYW CIŚNIENIA W OGUMIENIU NA DYNAMIKĘ RUCHU POJAZDU PODCZAS MANEWRU HAMOWANIA*

The paper presents the problem of reducing the impact of inflation pressure on the tires, and the weight distribution of the vehicle on the road. The results presented in this publication are based on the research bench and passenger vehicle equipped with anti-lock braking system. Bench testing was conducted stiffness of tires and road tests, performing maneuvers based on ISO standards, braking in the straight patch of road and of the twisting road.

Keywords*: vehicle dynamics, tyre, vehicle testing, braking, wheel sideslip angle, vehicle stability.*

W publikacji przedstawiono zagadnienie wpływu obniżenia ciśnienia w oponie na charakterystykę opon, rozkład nacisków i zachowanie się pojazdu na drodze. Wyniki prezentowane w publikacji oparto na badaniach stanowiskowych i drogowych samochodu osobowego wyposażonego w układ zapobiegający blokowaniu kół. Przeprowadzono badania stanowiskowe sztywności opon oraz badania drogowe, polegające na wykonywaniu manewrów opartych na normach ISO: hamowania na prostoliniowym odcinku oraz na łuku drogi.

Słowa kluczowe*: dynamika ruchu, opony, badania pojazdu, hamowanie pojazdu, kąty znoszenia kół, stabilność pojazdu.*

1. Introduction

During the vehicle motion for the transmission of power from the vehicle are the responsibility of the state of the tire and the road surface. The forces transmitted to the road depend on the parameters of the vehicle and its movement. The uneven tire pressure changes the stiffness of the tires both radial and longitudinal and transverse, as well as changing wheel rolling and load resistance provided by the vehicle to the ground. It should also be noted that the phenomenon of the contact patch with the road affect the stability and controllability of the vehicle. Analysis of these phenomena has been carried out and the static conditions - when measured as a tire and vehicle motion conditions on the test track.

2. The tire inflation pressure characteristics

The study of the influence of tire inflation pressure on their characteristics dealt with especially in laboratories engaged in researching tires. The first comprehensive work on the tires was presented by S. Clark and others [4]. One of the most important laboratories studying tire center in Delft (TNO Automotive - Netherlands). The center of this is related to HB Pacejka dealing with modeling of tires. Published several works related to the study and modeling of tires, including tire cooperation model was established with the road, known as MF (magic formula) [11]. The issue of inflation pressure in the tire shown in the literature [3, 10, 15]. Similar tires studies were conducted in different laboratories, including lab CRREL (U.S. Army Cold Regions Research and Engineering Laboratory in Anchorage) [8].

Posted in literature results allow to conclude that the reduction in tire inflation pressure reduces directional and angular stiffness of tires. To the relation of directional and angular tire stiffness where substituted individual forces and moments from the model MF, the index *nom* refers to the tire stiffness in the nominal inflation pressure.

Radial stiffness was determined from the formula [3]:

$$C_{Fz} = \left.\frac{dF_z}{d\rho_z}\right|_{\rho_z=0} = (1 + q_{CFz3} \cdot dp_i) \cdot C_{Fz,nom} \tag{1}$$

where ρ_z – radial deflection of tires, q_{CFzi} – MF tire model parameter, $C_{Fz,nom}$ – radial stiffness at nominal inflation pressure in the tires, dp_i – coefficient of pressure change, where p_i is the real pressure and p_{i0} is the nominal pressure.

$$dp_i = (p_i - p_{i0}) / p_{i0} \tag{2}$$

Longitudinal stiffness was determined from the following formula [3] assuming a constant loading force F_z:

$$C_{Fx} = \left.\frac{\partial F_{xW}}{\partial d_x}\right|_{d_x=0} \tag{3}$$

$$C_{Fx} = C_{Fx,nom} \cdot (1 + q_{CFx3} \cdot dp_i + q_{CFx4} \cdot dp_i^2) \tag{4}$$

where: d_z – longitudinal deflection of the tire, q_{CFxi} – MF tire model parameters, $C_{Fx,nom}$ –longitudinal stiffness of the tire at nominal inflation pressure.

Lateral stiffness was determined as above [3] assuming a constant loading force F_z:

$$C_{Fy} = \left.\frac{\partial F_{yW}}{\partial d_y}\right|_{d_y=0} \tag{5}$$

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

$$C_{Fy} = C_{Fy,nom} \cdot (1 + q_{CFy3} \cdot dp_i) \tag{6}$$

where: d_y – lateral deflection of the tire, q_{CFyi} – MF tire model parameters, $C_{Fy,nom}$ – lateral stiffness of the tire at nominal inflation pressure.

Tire torsional stiffness was determined as above [3] assuming a constant loading force F_z:

$$C_{Mz} = \left.\frac{\partial M_{zW}}{\partial \psi}\right|_{\psi=0} \tag{7}$$

$$C_{Mz} = C_{Mz,nom} \cdot (1 + q_{CMz1} \cdot dp_i) \tag{8}$$

where y – angular deflection of the tire, q_{CMi} – MF tire model parameters, $C_{Mt,nom}$ – torsional tire stiffness at nominal inflation pressure.

As can be seen in all relationships there is an additional factor $(1+q_{MFi} \cdot dp_i)$, which is the product of the inflation pressure change coefficient dp_i and MF tire model parameter q_{MFi} except longitudinal stiffness in the case where the additional element is described in a quadratic function.

Similarly, reduction the inflation pressure in the tire increases the rolling resistance. In the literature [8] was described, the empirical relationship shown below:

$$\mu_r = \frac{K}{1000} \cdot \left(5.1 + \frac{5.5 \cdot 10^5 + 90 \cdot F_z}{p} + \frac{1100 + 0.0388 \cdot F_z}{p} \cdot v_x^2 \right) \tag{9}$$

where: K – coefficient depending on the tire construction (0.8 for radial tires, 1.0 for diagonal tires), v_x - tire longitudinal velocity [m/s], p – inflation pressure [MPa].

Dissipated power to overcome the rolling resistance will be so dependent on the pressure in the following way:

$$\begin{aligned} P &= F_r \cdot v_x = -\mu_r \cdot v_x \cdot F_z = \\ &= \frac{-K \cdot v_x}{1000} \cdot \left(5.1 + \frac{5.5 \cdot 10^5 + 90 \cdot F_z}{p} + \frac{1100 + 0.0388 \cdot F_z}{p} \cdot v_x^2 \right) \cdot F_z \end{aligned} \tag{10}$$

where: P – power lost in overcoming rolling resistance, F_r – rolling resistance force.

3. Investigation of tire characteristics

The tire stiffness test for stationary conditions was carried out in the Laboratory of Vehicles, University of Bielsko-Biala. For the measurement was selected tires of size 155/60R14 with nominal inflation pressure 0.22 MPa. The tire was placed on the moveable base during tests. Vertical force was exerted on the axis of the wheel (in the case of measuring the radial stiffness, the force is changed from 0 to a maximum of ~ 50% higher than the static load), and in other cases (measured in longitudinal and lateral stiffness) tires were tested at two values of the loading force. Tire deflection measurement was performed using an optical displacement meter. Tangential force was applied to the moveable base, on which was a wheel. Measurements were carried out at different values of tires inflation pressure of minimum 0.06 to 0.3 MPa. Force measurements were carried out using strain gauges.

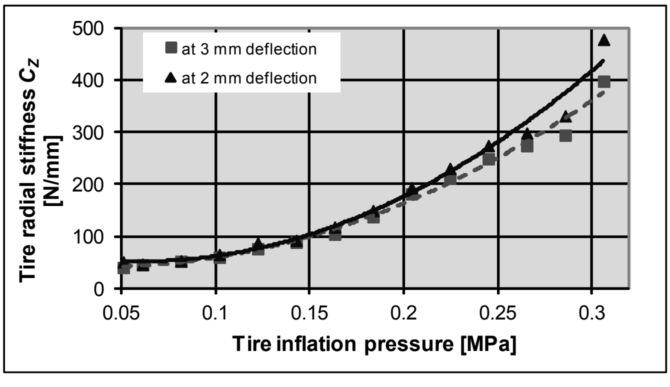

Fig. 1. The changes of tire radial stiffness C_Z as a function of inflation pressure to deflection 2 and 3 mm (own research)

The research obtained the radial, longitudinal and lateral stiffness characteristics as a function of the tire inflation pressure and the tire model parameters q_{MFi} (Figure 1-3).

The measurements suggest that the radial stiffness increases with increasing pressure and the nominal inflation pressure (~ 0.22 MPa) stiffness is C_z =~ 200 N/mm. The parameter model MF, $q_{CFz3} = -0.550$ for the pressure $p = 0.1$ MPa.

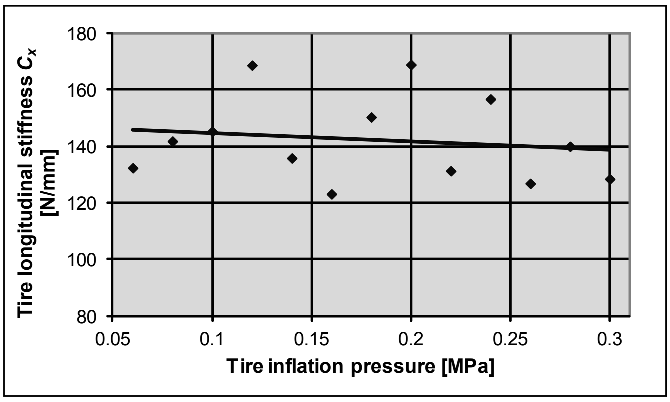

Fig. 2. The changes of tire longitudinal stiffness C_X as a function of inflation pressure (own research)

The measurements suggest that the change in the longitudinal stiffness of the tire to a slightly dependent on the inflation pressure in the tire, and its value is maintained at a constant level with a slight decline C_X = ~ 145 N/mm. The parameter model MF, $q_{CFx2} = 0.035$ for the pressure $p = 0.1$ MPa.

Lateral stiffness of the tire in the inflation pressure range of 0.22 to 0.27 MPa is the highest and is about 105 to 115 N/mm. The parameter model MF, $q_{CFy3} = -0.427$ for the pressure $p = 0.1$ MPa.

Tire stiffness parameters affect both the behavior of the vehicle at the overcoming rough roads and during turning maneuvers. In addition, the radial stiffness of the tire influence on the deflection of the suspension (as shown in the following part).

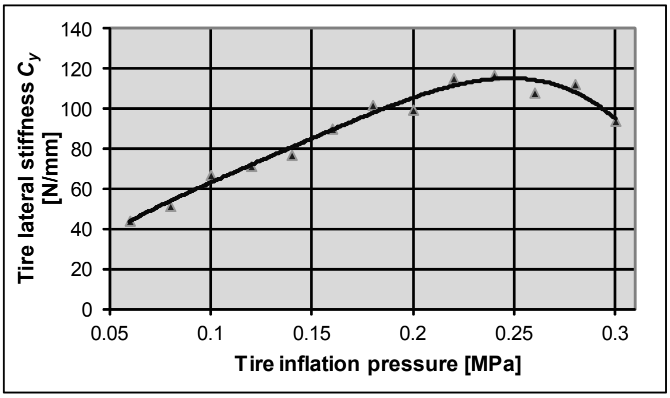

Fig. 3. The changes of tire lateral stiffness C_Y as a function of inflation pressure (own research)

Figure 4 shows the percentage change in reaction force volume of the suspension (in a quasi-static conditions) depending on the tire inflation pressure and the load operate to the wheel.

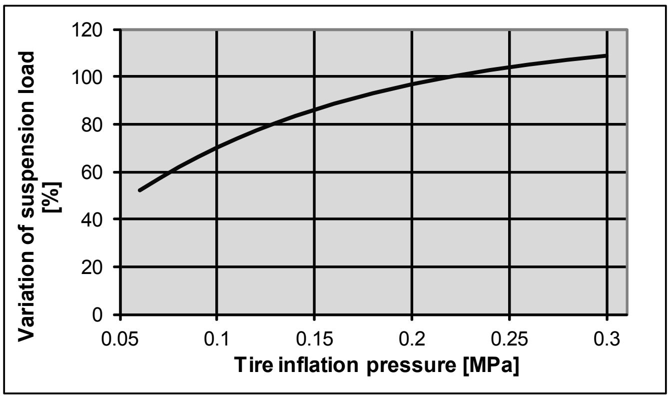

Fig. 4. The percentage changes of suspension load F_Z as effect of tire inflation pressure

At low inflation pressures, lower by 0.1 MPa from the nominal pressure, the reaction force in the suspension is reduced by ~ 30%, the increase in tire pressure of 0.1 MPa above the nominal pressure, increases the reaction force of ~ 10%.

4. The behavior of tire inflation pressure affect on vehicle motion

4.1. Assumptions for the road test

Vehicle Division of University of Bielsko-Biala, led the research vehicle based on ISO standards [13, 14]. For comparisons of selected two trials: braking on straight and curvilinear section of road. In both studies the impact of the driver on the test results is relatively small and the tire impact is clearly noticeable. The force on the brake pedal was large enough to activate the ABS system [5, 7].

For safety reasons, the test was performed on clean dry asphalt. For testing uses several types of sensors: pressure sensors mounted in the brake system, the force sensor on the brake pedal, sensors to measure the longitudinal and transverse velocity, acceleration sensors allowing to measure in the 3 direction, sensors to measure the angular velocity of the car body, sensors to measure the angle of rotation and torque on the steering wheel [12, 13]. Vehicle weight was due to its own weight, driver and measuring equipment.

During braking, the wheels normal forces are changing with deceleration. This changes the limits of adhesion forces and as a result of the launch of anti-lock braking system (ABS) and reduction of braking forces generated by individual wheels brakes. Load of each wheel was determined by measuring the center of gravity position, and the longitudinal and lateral forces arising from the motion conditions. In determining the normal forces on individual wheels does not include the impact of the stabilizer. Based on the measured pressure in the brake system and the brakes set of geometrical parameters for braking force at individual wheels.

Presents the results of two tests – test vehicle braking maneuver performing at a straight and at the curvilinear section of the road.

4.2. Braking test of the straight section of road

The first test was carried out on a straight section of road. The driver continued straight direction. After obtaining the appropriate speed pressed for the brake pedal. Braking force was so large that it has launched the ABS system.

Braking test on straight section of road shows (Fig. 6) that the reduced inflation pressure in one of the car wheels, equipped with ABS,

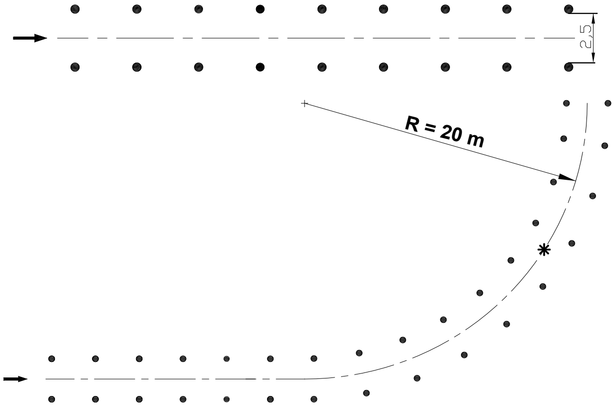

Fig. 5. Vehicle trajectories of individual tests: a) braking of the straight section of road,b) braking of the curvilinear section of road

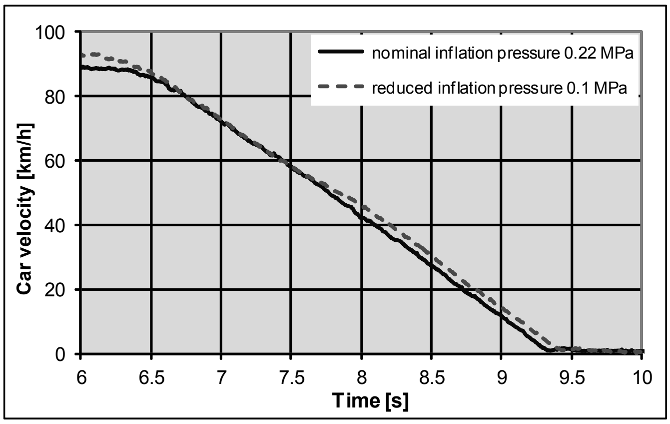

Fig. 6. The change of the vehicle velocity during brake test on a straight section of the road (the inflation pressure in the right front tire was nominal and reduced)

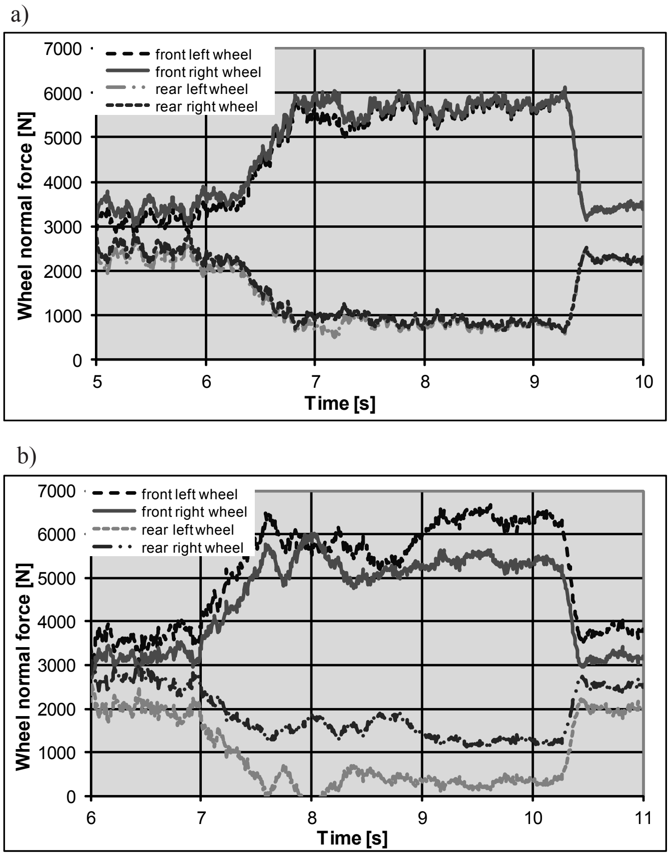

Fig. 7. Wheel load of the vehicle during test to brake on a straight section of the road (the inflation pressure in the right front tire was nominal (a) and reduced (b))

will result in a smaller change in velocity and an increase in vehicle stopping distance. It should be noted that braking test was carried out on a clean, dry road, with a relatively high adhesion. If the test performed in worse terms of grip, speed reduction would be smaller and the difference of stopping distances would increase.

The diagram shows the difference of normal forces on individual wheels acting on road during deceleration (Fig. 7). Reduction of the inflation pressure in one of the wheels to change the distribution of loads and affects their activities of the ABS - as shown in the diagrams in the pressure at brake circuits of individual wheels.

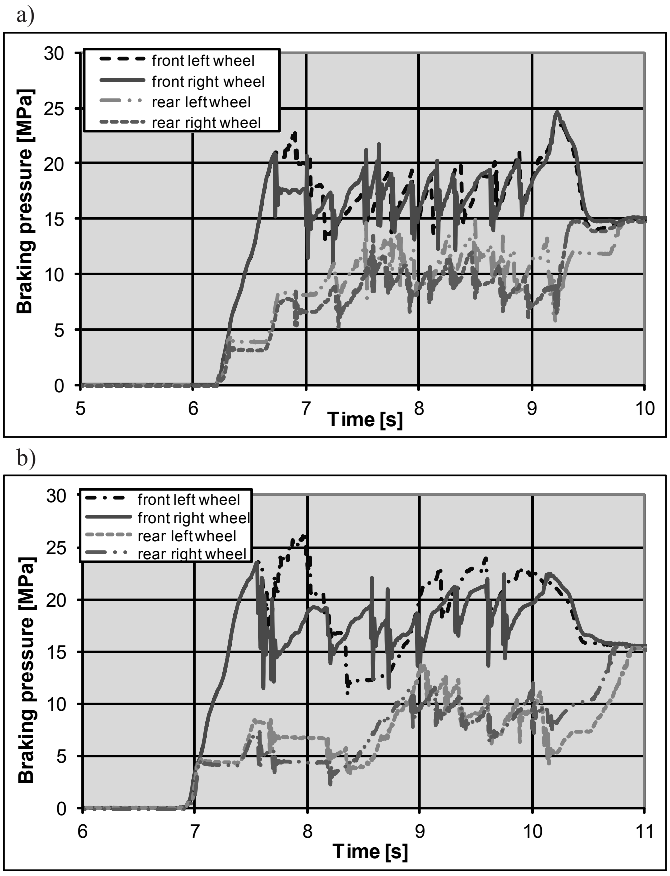

Fig. 8. Pressure in the brake circuit acting on each wheel (right front tire inflation pressure was nominal (a) and reduced (b))

In Figure 8, for the braking of reduced inflation pressure in the right front wheel, are shown in greater braking pressure correction (leading to a reduction in braking force) in the individual circuit of the wheel, and much more time offset to ensure straight track.

4.3. Braking test of the curvilinear section of road

The second test was carried out on the curvilinear section of road. The driver held the steering wheel in such a way that the vehicle is moving along a circular path. After defeating about 15 m pushing on the brake pedal. Pedal force provided a launch of the ABS system. Figure 9 shows the paths of the vehicle during the test. Driving tracks of both vehicles are similar despite considerable differences in the angle of the steering wheel rotation. For a similar trajectory, the angle of the steering wheel of a vehicle with a reduced inflation pressure in one of the wheels, was greater by about 35 degrees.

On the following graphs shows the waveforms pressure in the brake system acting on the brakes at individual wheels of the vehicle (Fig. 10) as well as waveforms changes in wheels normal forces performed under the turning maneuvers and the braking (Fig. 11).

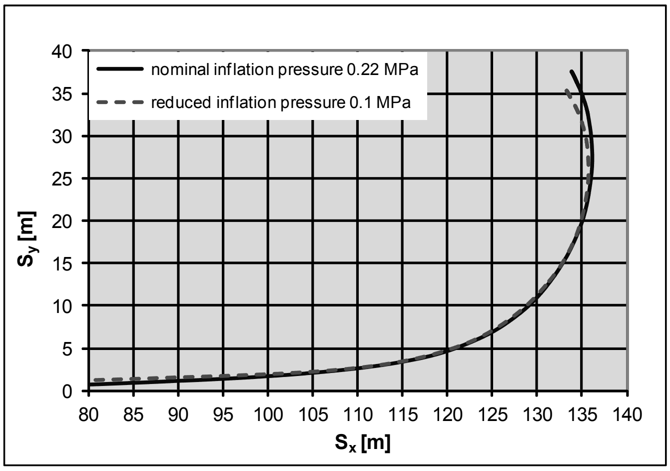

Fig. 9. The path of the vehicle during test to brake in a curvilinear section of road

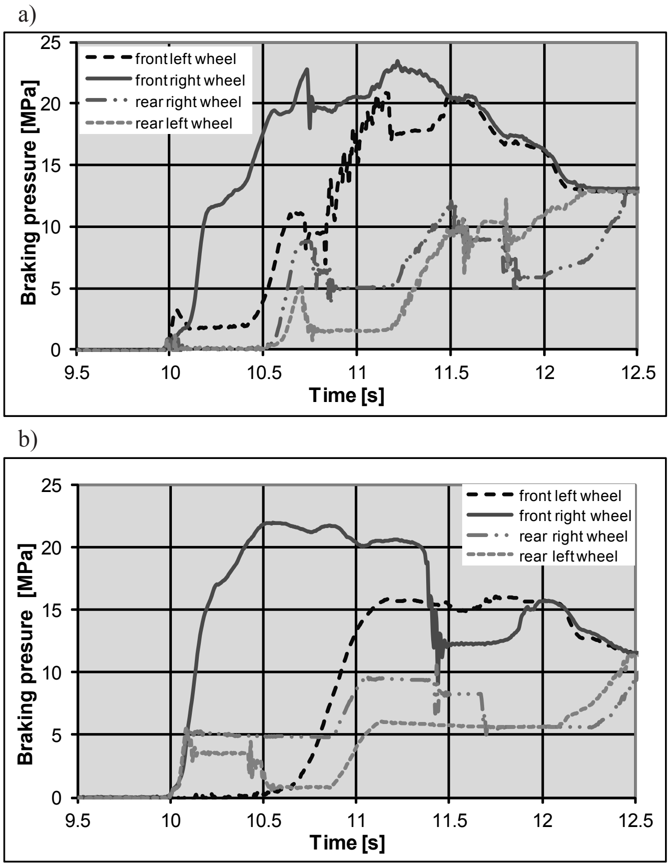

Fig. 10. Pressure in the brake circuit acting on each wheel (right front tire inflation pressure was nominal (a) and reduced (b))

Figure 10 shows the apparent size differences pressures (and consequently braking forces) front and rear axles, corrected for the normal force distribution and the centripetal force acting on the vehicle during braking on curved track. It can be seen that in the initial phase of braking the rear left wheel normal force is close to zero, resulting in a reduction of pressure, by the system ABS in the rear wheel brake circuit, and thus decrease the braking forces to small values. In the case of braking with the lower inflation pressure in the front right wheel, there is a significant adjustment braking pressures acting on the front left wheel and increasing the pressure in the rear axle braking circuit. The pressure in the front brake circuit is greatly increased in the first stage of braking and then rapidly decreases in the second stage of braking. There is a marked increase in the pressure in the rear wheel brake circuits.

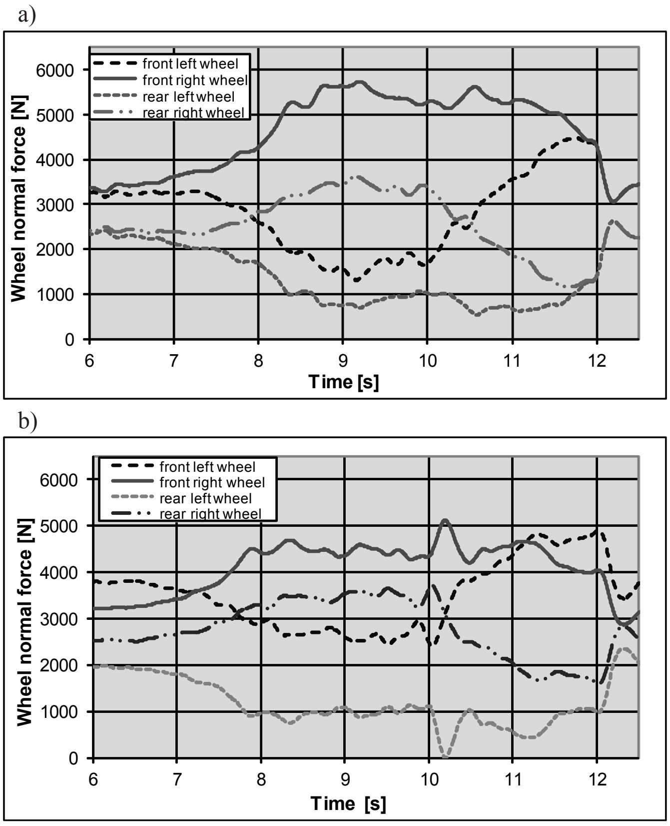

Fig. 11. Wheel load of the vehicle during test to brake on a curvilinear section of the road (the inflation pressure in the right front tire was nominal (a) and reduced (b))

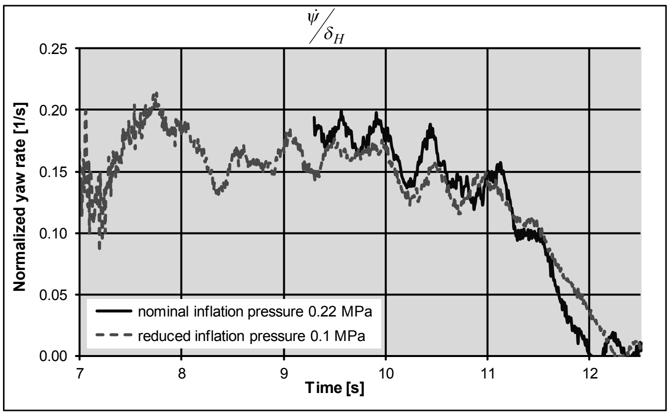

Fig. 12. The normalized yaw rate $\dot{\psi}/\delta_H$ *(right front tire inflation pressure: nominal and reduced)*

The graph (Fig. 11) shows that the decrease of normal force in the front right wheel and changes significantly normal forces affect the behavior of the vehicle during a maneuver. Lowering the front right wheel normal force is compensated by changing normal forces on the rear wheel right and front left. Correction of the left rear wheel load is a bit smaller. It causes the behavior of the vehicle during the test, as shown in the following charts.

Figure 12 shows the effect of lowering the inflation pressure in the tire for the normalized yaw rate. Lowering the standard yaw rate shows a magnification of the vehicle understeer, which confirms the standardized yaw angle of graph shown in Figure 13.

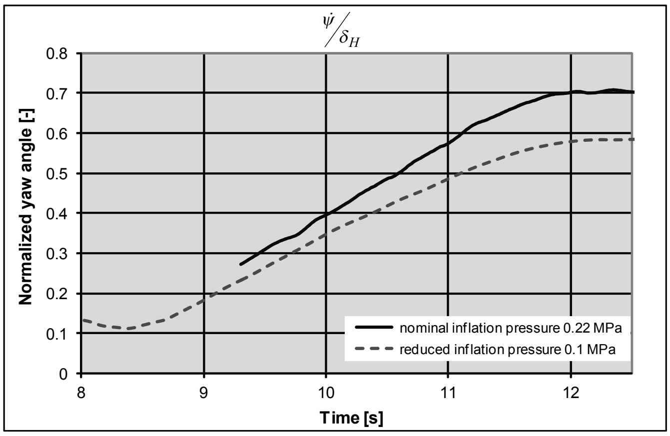

Fig. 13. The normalized yaw angle ψ/δ_H *(right front tire inflation pressure: nominal and reduced)*

The analysis of the graph that the yaw rate, in the case of executing a vehicle braking maneuver on curved track, will be smaller in the case of motion of the vehicle tire with reduced inflation pressure, and will therefore be at the same angle of rotation of the steering wheel moves along a track with a larger radius .

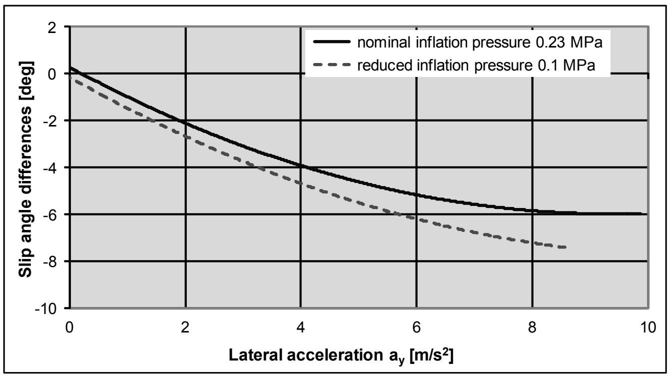

Fig. 14. The slip angle differences on front and rear wheels (right front tire inflation pressure: nominal and reduced)

The vehicle understeer determines difference of slip angles of front and rear wheels. From the graph (Figure 14) clearly shows that the vehicle with reduced inflation pressure in right front wheel has a much greater slip angles difference in the front and rear wheels, and is more understeer throughout the range of acceleration. Determined on this basis, the value of the model parameter MF, $q_{Mz3} = -0.091$ for inflation pressure of 0.1 MPa.

5. Conclusions and discussion

Based on the above analysis and the results of the measurements can be seen that reducing the inflation pressure in the tire results in:

- Change of the vertical replacement stiffness resulting from the stiffness of tires and wheel suspension. Reducing the stiffness is greater at the lower the inflation pressure in the tire. This reduces the lateral stiffness of the tire.
- Increased stopping distance of the vehicle, both on the track straight and curved.
- Increase vehicle understeer, especially during turning maneuvers that increase the normal load of wheel with reduced inflation pressure.
- Change of the tire model parameters MF (magic formula) on the effect of reducing pressure on the tire stiffness characteristics, explicitly for the coefficients associated with radial and lateral stiffness and less important for longitudinal stiffness.

With the tests and analyzes show that the effect of tire inflation pressure has a significant impact on the behavior of the vehicle during braking maneuver and thus the safety of the road traffic. Typically, lowering the inflation pressure in one of the tires is not enough appreciated by road users, shown above tests indicate a significant deterioration in control of the vehicle and increase stopping distances.

References

1. Andrzejewski R. Dynamika pneumatycznego koła jezdnego. Warszawa: WNT, 2010.
2. Arczyński St. Mechanika ruchu samochodu. Warszawa: WNT, 1993.
3. Besselink IJM, Schmeitz A J C, Pacejka, H B. An improved Magic Formula/Swift tyre model that can handle inflation pressure changes. Vehicle System Dynamics, 2010; 48,1: 337–352.
4. Clark SK and others, Machanics of pneumatic tires. Washington DC: National Buremu of Standards, 1971: Monograph 122.
5. Fundowicz P. Droga hamowania na łuku drogi. Warszawa: Politechnika Warszawska, Zeszyty Instytutu Pojazdów; 2010; 1: 103–110.
6. Gillespie TD. Fundamentals of vehicle dynamics. Warrendale: SAE Inc., 1992.
7. Grzegożek W. Modelowanie dynamiki samochodu przy stabilizującym sterowaniu siłami hamowania. Kraków: Zeszyty Naukowe Politechniki Krakowskiej, 2000; Seria Mechanika, monografia 275.
8. Jazar R. Vehicle Dynamics, Theory and applications. Springer Science + Bussines Media, 2009.
9. Lacombe J. Tire model for simulations of vehicle motion on high and low friction road surfaces. San Diego CA: 2000; Proceedings of the 32nd conference on winter simulation.
10. Nijmeijer H, Schmeitz AJC, Besselink IJM. Enhancing the MF-Swift Tyre Model for Inflation Pressure: I.B.A. op het Veld, Eindhoven, 2007;11.
11. Pacejka HB. Tire and vehicle dynamics. Warrendale, SAE, 2006.
12. Parczewski K, Wnęk H. Utilization of the car model to the analysis of the vehicle movement after the curvilinear track. Eksploatacja i Niezawodnosc – Maintenance and Reliability, 2010; 4: 37–46.
13. Parczewski K, Wnęk H. Wpływ niesprawności zawieszeń na stateczność ruchu pojazdu - porównanie badań symulacyjnych i pomiarów. Archiwum Motoryzacji, 2006; 2: 159–169.
14. Parczewski K. Exploration of the shock-absorber damage influence on the steerability and stability of the car motion. Journal of KONES, Powertrain and Transport, 2011; 18-3: 331–338.
15. Pillai PS. Efect of tyre overload and inflation preasure on olling loss (resistance) and fuel consumption of automobile and truck/bus tires. Indian Journal of Engineering & Materaial Science, 2004; 11: 406–412.
16. Prochowski L, Unarski J, Wach W, Wicher J. Podstawy rekonstrukcji wypadków drogowych. Warszawa: WKL, 2008.

Krzysztof PARCZEWSKI, Ph.D. (Eng.)
Department of Internal Combustion Engines and Vehicles
University of Bielsko-Biała
ul. Willowa 2, 43-309 Bielsko-Biała, Poland
e-mail: kparczewski@ath.bielsko.pl