Static tests the stiffness of car tires

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Abstract. Safe driving requires from the driver a number of manual actions related to the existing traffic situation. The vehicle, reacting to the imposed extortions, is subjected to three-axle loads, which are transferred by friction-shaped coupling of the tire with the surface. The generated forces affect the tread and the side of the tire, the suspension of the vehicle and the steering. The article presents the results of bench tests of two types of tires: tires with special tread (coloured) made to order and popular tires available in retail sales. The tests were carried out under static conditions. The tests were carried out in cooperation with the Stomil Tire Research and Development Center in Poznan on the position enabling acquisition and archiving of the values of forces in the function of displacement (deformation of the tire). The obtained results made it possible to determine the directional stiffness of the radial, peripheral, lateral and torsional tires. It allowed to build the stiffness characteristics and compare the response to the forced testing tires. The results obtained form the basis for analysing the scope of vehicle traffic safety, and can also be used as input data in simulation tests.

1. Introduction

The ability of the vehicle to move on the road directly depends on the possibility of transferring forces and moments at the contact surface of the tire with the road. In both rectilinear and curvilinear motion, the contact surface area plays an important role in implementing the motion. The track surface depends on the exploitation conditions [1, 2] (load, pressure, tire temperature) as well as on the tire construction (type of compound, number of layers, cord material and strapping). These parameters affect the radial, circumferential, lateral and torsional stiffness of the tire and, as a consequence, the traction features, vehicle traffic safety and comfort of travellers [3–7].

Knowing tire stiffness parameters allows a more detailed analysis of vehicle movement during both road tests and simulation tests. Software used in modelling car behaviour on the road often requires entering a number of data related to tires, which influences the accuracy of simulation tests. Such an example may be a nonlinear model of a tire TMeasy used in simulation [8–10]. This model requires entering a number of tire parameters influencing the traction characteristics and the conditions of tire - surface contact.

The value of load and the tire pressure affects greatly the length of the contact surface, and not significantly on the width and it also determines the value of radial stiffness. This affects both the subjective feelings of the driver and passengers as well as the parameters of the tire - surface cooperation. Too low radial stiffness leads to excessive bending of the sides of the tire [11], causing its
excessive heating and an increase in susceptibility to delamination of the internal structure. High rigidity reduces comfort and causes increased susceptibility to damage and puncture [12].

Circumferential stiffness is responsible for the tire's ability to transfer longitudinal forces at the contact surface. The characteristics of circumferential stiffness in the initial load phase are characterized by deformation of the tire tread without displacement relative to the ground (so-called deformation slip, adhesion phenomenon) [13, 14]. After exceeding the adhesion limit, actual slip occurs.

The occurrence of lateral forces caused by curvilinear motion or e.g. side wind during vehicle movement may cause a change in the direction of movement. This causes that in the contact area of the tire tread with the ground, internal elastic forces act to counteract the movement of the vehicle and elemental lateral tangential reactions of the surface associated with frictional forces that do not allow the tread to move on the surface. As a result of the processes of tread deformation, the resultant sum of elementary tangential forces is not located in the axis of symmetry of the wheel, but is shifted backwards (figure 1).

![Figure 1. The deflection of the tire movement direction due to lateral drift force.](image)

The relationship between the lateral displacement of the tire and the lateral force applied to the wheel axle is called the lateral stiffness of the tire. Lateral stiffness is particularly important in so-called the phenomenon of tire overdrive during the drift process [15]. Tire overrun during the change of lateral drift conditions is the result of the deformation changes of the tire coating in the transverse direction [16]. The increase in lateral force results in a loss of adhesion of individual tread elements within the contact with the surface. Due to lateral stiffness, the elastic properties of the tire in the transverse direction can be determined [15]. The lateral stiffness also affects the image of the vehicle casting traces left on the road.

A change in the normal reaction position relative to the road surface in curvilinear motion creates a stabilizing moment and a wheel inclination moment. The angle that results from the application of these forces between the wheel movement direction and its rotation plane is called the lateral drift angle. The value of the lateral drift angle depends among others on the torsional stiffness of the tire [17, 18]. Torsional stiffness is the dependence of the obtained tire rotation angle on the torsional moment.

For the experimental tests, carried out at the Institute of Forensic Research, of the characteristics of traces formed on the road during curvilinear movement special experimental tires with multi-coloured tread were used. In order to identify them, special tires were subjected to bench tests on the device for static measurement of multidirectional tire stiffness and their features were compared with standard tires available in current sales. The tests included the determination of radial, circumferential, lateral and torsional stiffness. The determined stiffness will be helpful when comparing casting traces left on the road during experimental tests. The article presents the results of static experimental tests on tire stiffness.
2. Methodology and research object

In order to perform the measurements a device for static measurement of multidirectional tire stiffness was used. This device was designed by the Stomil Tire Research and Development Center in Poznań (figure 2). The developed measuring set allows the measurement of the value of force acting on the tire and the displacement of the measuring table, which allows calculating the circumferential, lateral and torsional stiffness of the tested tire. An electric motor was used to drive the device. The position of the table is recorded by means of displacement sensors included in the device. The measurement of forces generated during table movement is carried out by using a strain gauge bridge system with four active strain gauges.

![Figure 2. Measurement set to determine the displacements and forces acting on a tire.](image)

The characteristic of the measurement device:

- measuring range of peripheral and lateral forces up to 10 kN,
- torque measuring range up to 1000 Nm,
- maximum radial load of the measuring table 25 kN,
- 0.4 kW drive motor power.

Measurements of table displacement and forces acting on the tires were taken at the stand, which included:

- specialized mechanical press,
- laboratory scale,
- device for measuring static stiffness of omnidirectional tires,
- Sp Hottinger Spider-8 measuring apparatus.

In order to determine the stiffness values, the following was carried out:

- calibration of strain gauge force sensors of the measuring device,
- determination of the measurement conditions corresponding to the required tire pressing on the measuring table,
- collecting waveforms on the wheel as a function of measuring table displacement.

Measurement signals from the strain gauges were recorded with the use of Spider-8 device, in a setting that covered 32 measurement channels and Catman-32 software. The processing of the measurement signals (filtering and integration) was carried out using Matlab software. Two tires with size 185/65 R15 88H were selected for radial, circumferential, lateral and torsional stiffness tests: a special tire with a multi-coloured tread and a standard tire. Five measurement tests were carried out for each tire stiffness test. The standard tire was the reference base for the results obtained for the special tire. During tests of circumferential, lateral and torsional stiffness, the tires were loaded with a constant force adequate in the field of use to the level of wheel load of the test vehicle. In order to avoid
interference (the beginning of the process) and eliminate the range in which tire slip occurred (obtaining the maximum force transmitted by the tire), each of the measurement had a set range for determining the values of individual stiffness.

3. Research results

3.1. Radial stiffness
Radial stiffness is the ratio of tire load to its radial deformation and is expressed by the equation:

\[ k_p = \frac{F}{a} \]  

(1)

where \( k_p \) – radial stiffness (N mm\(^{-1}\)), \( F \) – vertical force loading the tire (N), \( a \) – tire deflection due to the acting force (mm).

This stiffness influences the driving comfort and the rolling resistance. The radial stiffness measurement method consists in increasing the tire load with a given step at a known pressure and reading the deformation value from a measuring scale. During testing, the tire was set on a scale that showed the tire's current load in real time. The change in load caused deformation of the tire, which was read on the measuring scale, with markings every 1 mm, permanently attached to a mechanical press. Two tires were selected for the measurement: a special tire and a standard tire for a pressure value of 0.22 MPa. The load range used during the tests was 4 kN with a measuring step of 200 N.

| Tire type | pressure 0.22 MPa | Radial stiffness \( k_p \) (N mm\(^{-1}\)) average value of 5 measurements | Standard deviation of a single measurement (N mm\(^{-1}\)) |
|-----------|-------------------|-----------------------------------------------------------------|-------------------------------------------------|
| Special tire | 161.8 | 19.3 |
| Standard tire | 144.9 | 28.2 |

3.2. Circumferential stiffness
Circumferential stiffness is the ratio of the force acting on the tire in the longitudinal direction (e.g. during the braking process) to its circumferential deformation and is expressed by the equation:

\[ k_o = \frac{F_o}{a_o} \]  

(2)

where \( k_o \) – circumferential stiffness (N mm\(^{-1}\)), \( F_o \) – circumferential force loading the tire (N), \( a_o \) – tire deflection due to the acting force (mm).

| Tire type | pressure 0.22 MPa | Circumferential stiffness \( k_o \) (N mm\(^{-1}\)) average value of 5 measurements | Standard deviation of a single measurement (N mm\(^{-1}\)) |
|-----------|-------------------|-----------------------------------------------------------------|-------------------------------------------------|
| Special tire | 130.51 | 22.69 |
| Standard tire | 173.99 | 17.29 |

3.3. Lateral stiffness
Lateral stiffness is the ratio of the force acting on the tire in the lateral direction (e.g. when driving in a turn or lateral wind) to its lateral deformation and is expressed by the equation:

\[ k_b = \frac{F_b}{a_b} \]  

(3)
where $k_b$ – lateral stiffness (N mm$^{-1}$), $F_b$ – lateral force loading the tire (N), $a_b$ – tire deflection due to the acting force (mm). Figure 3 shows a view of a standard tire while lateral stiffness tests.

![Figure 3. A view of a standard tire while lateral stiffness tests.](image)

### Table 3. The values of the lateral stiffness for particular tires.

| Tire type       | Pressure 0.22 MPa | Lateral stiffness $k_b$ (N mm$^{-1}$) | Standard deviation of a single measurement (N mm$^{-1}$) |
|-----------------|-------------------|--------------------------------------|--------------------------------------------------------|
|                 |                   | average value of 5 measurements       |                                                        |
| Special tire    |                   | 115.43                               | 6.79                                                   |
| Standard tire   |                   | 141.91                               | 10.32                                                  |

#### 3.4. Torsional stiffness

Torsional stiffness is the ratio of the torque acting on the tire (e.g. during the maneuvering process at a standstill) to the torsional angle and is expressed by the equation:

$$k_s = \frac{M}{\alpha} \tag{4}$$

where $k_s$ – torsional stiffness (Nm rad$^{-1}$), $M$ – torque moment loading the tire (Nm), $\alpha$ – torsional angle (rad).

Torsional stiffness results from the action of force around the perpendicular symmetry axis of the tire. It is caused by the steering wheel turning.

### Table 4. The values of the torsional stiffness for particular tires.

| Tire type       | Pressure 0.22 MPa | Torsional stiffness $k_s$ (Nm rad$^{-1}$) | Standard deviation of a single measurement (N mm$^{-1}$) |
|-----------------|-------------------|---------------------------------------|--------------------------------------------------------|
|                 |                   | average value of 5 measurements       |                                                        |
| Special tire    |                   | 1497.82                               | 396.63                                                 |
| Standard tire   |                   | 2080.67                               | 392.32                                                 |

#### 4. Results analysis

The carried out experimental tests to determine the radial, circumferential, lateral and torsional stiffness showed differences in the results between the tires. The factors directly influencing the results and load-deformation characteristics, as well as the stiffness-deformation are: tire pressure and normal load. All results were subject to statistical analysis, in which the values burdened with excessive errors were rejected. After rejecting the erroneous results, the value of the standard deviation of a single measurement was calculated, which is included in the tables below. In the case of radial stiffness, a large impact of tire relaxation on the mean measurement value and standard deviation value was observed. The obtained large values of standard deviations of radial stiffness do not allow to clearly determine which tire, special or standard, is more rigid.
Examples of load-deformation and stiffness-deformation characteristics are presented in figure 4.

**Figure 4.** The exemplary characteristics load-deformation and stiffness-deformation for standard tire and multi-coloured tread tire: a) radial stiffness, b) circumferential stiffness, c) lateral stiffness, d) torsional stiffness.
The value of the special tire circumferential stiffness was less than 43.48 N mm\(^{-1}\) compared to standard tires. In the case of lateral stiffness, the special tire with a multi-coloured tread had lower stiffness than the standard tire, and the stiffness difference was 26.47 N mm\(^{-1}\).

The results of torsional stiffness calculations showed that the special tire has about ¼ lower average stiffness value from 5 measurements compared to a standard tire purchased at retail sale. The determined torsional stiffness values for both tires are subject to a very high standard deviation value, which is caused by a large force fluctuation and non-linearity of the process of torsion of the tire front layers. The calculated uncertainty of measurement partly overlaps.

In all measurements, apart from radial stiffness values, special tires had lower stiffness than standard tires. This indicates that the tread application process interferes with the structure of the tire material that is the supporting structure for the tread.

Analysing the process of increasing vertical force and lateral force as a function of deformation, it was observed that the nature of changes in force values was close to linear. In the case of the peripheral force build-up characteristics, the value changes were more non-linear. Torque changes as a function of the angle of rotation of the wheel around the vertical axis are characterized by a clear pulsing around the trend line, which affected the value of R2 fit and the value of torsional stiffness.

5. Conclusion
The preliminary road tests that were carried out indicate that due to the differences in the analysis of tire casting traces, the characteristics of the tires used in the tests should be taken into account. In particular, this applies to radial, circumferential, lateral and torsional stiffness. The results of car tires’ stiffness relate to special tires with multi-coloured tread and standard tires available for retail sale. The research was comparative. The obtained stiffness characteristics as well as the average values show that the special manufactured tires have lower circumferential, lateral and torsional stiffness than the tires purchased. In the case of radial stiffness, it cannot be indicated which of the tested tires obtained higher stiffness values.

The obtained results of laboratory tests can be used during simulation tests. It should be remembered, however, that the frictional association of the tire with the running surface layer of the measuring device when determining the stiffness characteristics is different from that which occurs in operating conditions. Nevertheless, the determined values make it possible to compare the features of the tested tires.

6. References
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