

## Article

# Quasi-Static Research of ATV/UTV Non-Pneumatic Tires

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**Abstract:** The non-pneumatic tire (NPT) is a type of wheel which development is related to the beginning of automotive development. The non-pneumatic tire (NPT) is a type of tire that does not contain compressed gases or fluid to provide directional control and traction. Nowadays, this type of wheel is more and more often used in special purpose vehicles, e.g., in military vehicles and working machines. The main feature of the non-pneumatic tire is a flexible support structure (including the part of the wheel between the tread and the rim). This paper presents the results of research aimed at determining the influence of the geometry of the NPT's (intended for All-Terrain Vehicle–ATV/Utility Task Vehicle–UTV) load-bearing structure on its quasi-static directional characteristics. The experimental tests included the determination of the radial stiffness of research objects on a non-deformable flat surface and on a single obstacle, as well as the determination of the degree of deformation for the elastic structure and belt. The significant influence of the elastic structure's shape and the elastomer, as the material forming the NPT, on its radial stiffness was revealed.

**Keywords:** non-pneumatic tire; airless tire; radial stiffness; spoke deformation



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## 1. Introduction

The non-pneumatic tire's (NPT) characteristic feature is the transfer of directional forces of the vehicle to the ground without the need to keep gas or fluid inside under a certain pressure [1]. The obvious advantage of NPT is its resistance to going flat, which is typical for pneumatic tires and often leads to the accelerated necessity of their replacement and their troublesome utilization. [2].

Most current NPTs consist of the following main elements [3–6]: the rim, the supporting structure, and the tread. The NPT tread and rim perform the same functions as they do in a standard pneumatic tire. The supporting structure consists of a shear beam (band) and a flexible structure. The main task of the NPT shear beam is to copy the compressed air properties of a pneumatic tire [3]. In papers modelling the NPT, the shear beam is made of layers of inextensible material between which a core is located [7]. An elastomer (solid core) or a specific structure with a defined geometry can be used as the core. The type of core applied will have an impact on the forming of unit pressures. The solid core is characterized by a more even distribution of pressure in the contact area, while the defined geometry causes their accumulation at the points of core connection with the tread [8].

The task of flexible structure is to connect the wheel rim with the tread (being one part with the shear beam). The flexible structure can be made as single spokes [3,9] or with a cellular structure, e.g., hexagonal structure [10]. The transfer of normal and tangential forces (longitudinal and lateral) of the NPT in the contact area with the ground is carried out mainly by selecting the geometry of the wheel structure and the materials that form it (mainly elastomers). The type of applied structure determines the load transfer mechanism and affects the value of the displacements of the wheel center in relation to its outer shell

under the action of the load with normal and tangential force. For example, loading with a normal force on an NPT with single spokes will cause them to buckle in the part located under the wheel axle and stress the spokes above the axle. This NPT design leads to the main part of the load being transferred by the spokes above the wheel axis [3], and the increase in the spoke curvature results in greater vertical displacements of the wheel center [11,12]. On the other hand, when the flexible NPT load-bearing structure has a cellular structure, the greater load is transferred to the lower part of the wheel [13].

Quasi-static research allows for the assessment of basic tire properties and precise observation of the NPT supporting structure deformation. Radial characteristics, i.e., the dependence of the radial load as a function of deflection, which provides information about the stiffness of the tire and, as a result, determines the smoothness of driving, derives from the cooperation of the wheel with the road surface, rolling resistance, and the state of load transferred to elements of the vehicle suspension [14,15].

The research presented in this paper is aimed at analyzing the deformation state of an NPT's supporting structure (with different designs and shapes) as a function of the radial load. The conducted research were aimed at comparing the elastic properties (in the radial direction) of NPTs with pneumatic tires. At this stage of the research, attention was focused on the comparison of the radial stiffness characteristics, which essentially determine the level of dynamic loads transferred in the ground–wheel–body system of the vehicle. The obtained research results will be used for simulation tests of a multi-body vehicle model.

The “objects, conditions and methodology of research” presents basic information about the tires selected for research. The tires (pneumatic and NPTs) are called research objects later in this article. The method of load selection and the type of ground, which are the test conditions, was presented. The methodology of determining the midline for the hysteresis loop is described, which was recorded during tests. The areas of the tire selected for static tests are presented.

The results of quasi-static tests aimed at determining the radial elasticity are presented in “results”. The characteristics of the center line of the test objects were compared for a specific load range (three different normal loads) and different surfaces (flat rigid surface, single triangular obstacle). The analysis of the radial stiffness of the wheel as a function of the load is presented.

In the “discussion”, the test results are analyzed and the deformation of the elastic structure under the wheel axis is compared. The areas of further research are presented.

## 2. Objects, Conditions and Methodology of Research

Two NPTs and one pneumatic tire for all-terrain vehicles (ATV) or utility terrain vehicles (UTV) were selected for the research:

- NPT\_1 (non-pneumatic tire nr 1)—the flexible part of the support structure consists of 24 pairs of spokes;
- NPT\_2 (non-pneumatic tire nr 2)—equipped with a cellular (hexagonal) flexible cell as a part of the supporting structure;
- PT (pneumatic tire)—diagonal tire with six ply carcass.

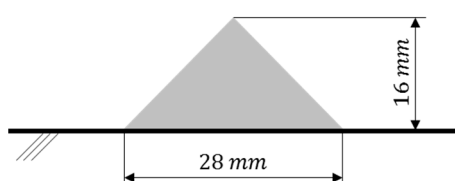
Basic information about the research objects is presented in Table 1. The choice of test conditions was guided by the destination use of the wheels and the range of normal load variability resulting there from  $F_Z$ . The range of the research was established on the basis of observation of changes in normal reactions under the wheels in the tests of an ATV vehicle weighing 460 kg. These tests were carried out in the variant vehicle without and with an additional load of approx. 103 kg, on horizontal ground and on inclined ground at an angle of 15°. On the basis of these measurements, the following test conditions were established: 1000 N, 2000 N, and 3000 N, with two operational inflation pressures of 300 kPa and 400 kPa selected for the PT.

**Table 1.** Basic information of research objects [16–19].

| Research Object | Manufacturer's Designation | Overall Diameter (mm) | Width (mm) | Maximum Speed (km/h) |
|-----------------|----------------------------|-----------------------|------------|----------------------|
| NPT_1           | 26x9N14 NHS                | 660.4                 | 228.6      | 80.5                 |
| NPT_2           | NPT 26X8.00-14 NHS         | 673.1                 | 203.2      | 40.2 <sup>1</sup>    |
| PT              | AT 26x8-14                 | 660.4                 | 203.2      | 140.0                |

<sup>1</sup> manufacturer's guidelines for recommended maximum wheel speed.

The determination of the radial characteristics was carried out for two variants of non-deformable surfaces: flat and with a triangular obstacle. The dimensions of the selected obstacle (Figure 1) reflect the rough road with single roughness (small terrain obstacles).

**Figure 1.** Triangular obstacle used in the wheel radial characterization research.

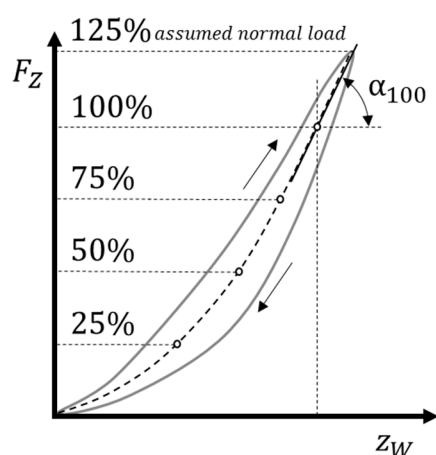
Determination of the radial stiffness characteristics included simultaneous registration of the normal load acting in the wheel axis and the deflection of the structure of the test object. In accordance with the adopted methodology, the load was increased to a value of 125% of the adopted normal load range and then unloaded. The own methodology [20] was used during the tests, which was developed on the basis of domestic and foreign standards for static tire research and on the basis of many years of authors' experience, also in cooperation with tire manufacturers. An example of the radial characteristic along with the direction of load changes is shown in Figure 2, where  $F_Z$  refers to normal load and  $z_W$  refers to vertical displacement of the wheel axis. On the basis of the obtained hysteresis loop, the course of the midline was determined, which was described by a fifth-order polynomial. Then, based on the course of the tangent to the center line at the point corresponding to 25%, 50%, 75%, and 100% of the assumed normal load, the value of the radial stiffness coefficient was calculated (Figure 2) [21]

$$k_Z = \operatorname{tg} \alpha_X \quad (1)$$

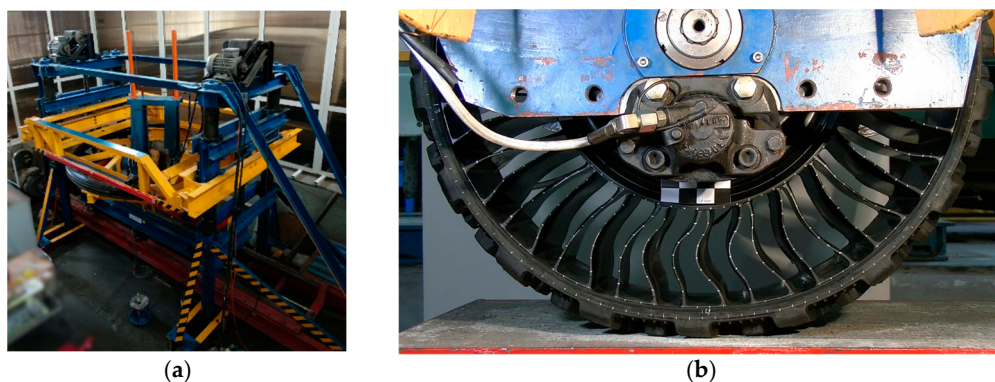
where:

- $k_Z$ —radial stiffness coefficient,
- $\alpha_X$ —the angle between the tangent line to the centerline and a horizontal line with the common point of intersection corresponding to the specified load.

Quasi-static wheels tests were carried out on the universal station for tire research shown in the Figure 3 (a detailed description of the station's capabilities is presented in [22]). Strain gauges placed under the measuring trolley platform are used to measure normal force. The accuracy of the normal force measurement is  $\pm 1$  N. An LVDT sensor with an accuracy of  $\pm 0.1$  mm is used to measure the vertical displacement of the wheel axis.



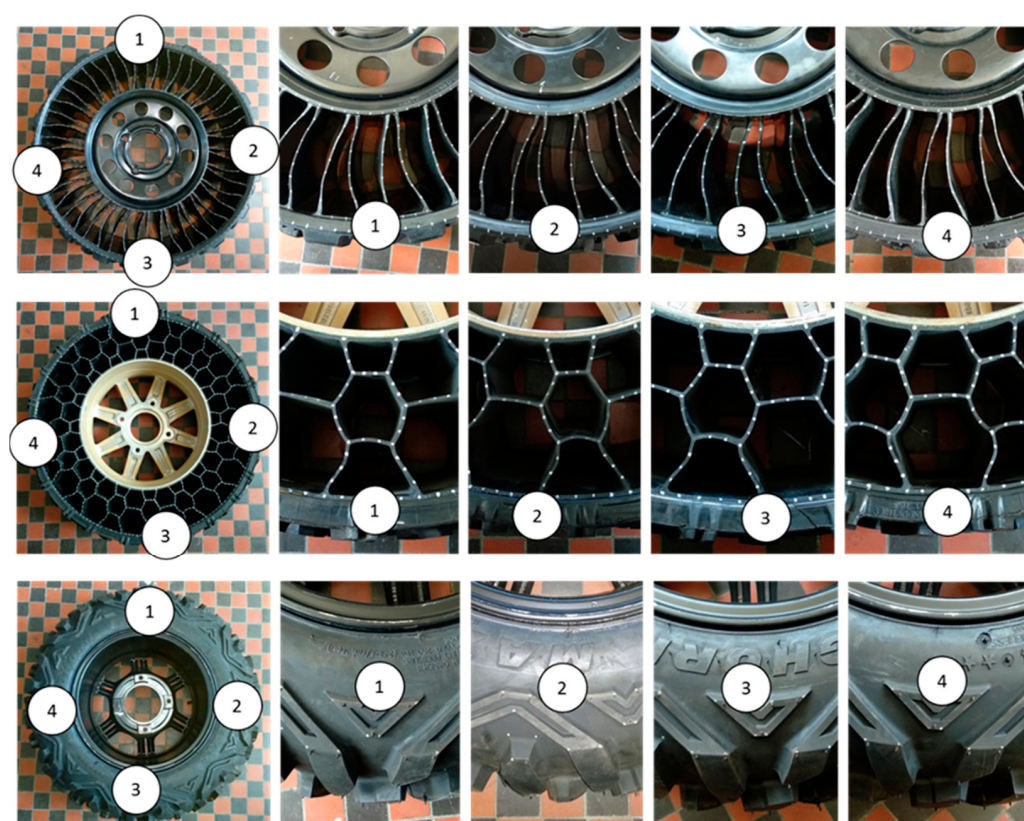
**Figure 2.** Graphical representation of the course of the center line (dashed line) and determination of the value of the radial stiffness coefficient (tan of the angle  $\alpha$ ) on the basis of the measured radial stiffness characteristic (solid line).



**Figure 3.** Universal station for tire research. (a) general view, (b) NPT\_1 during research.

Before starting the research, four evenly distributed points were selected around the perimeter of each object (which were the centers of contact of the test objects with the ground) positioned directly under the wheel axis and, additionally, at the top of the obstacle. Choosing the above-mentioned points, different arrangements of the spokes/cell arms of the elastic part of the NPT and projections of the tread pattern with respect to the center of contact with the ground were taken into account (Figure 4). The research under given conditions was repeated four times at each of these points.

Apart from measuring the normal force and vertical displacement of the wheel axis, the deformation of the elastic structure and shear beam were also recorded. Reference points were deposited on the mentioned elements (Figures 4 and 5). These points were used in the analysis of the video material using the TEMA Automotive software. After the video image was calibrated, the positions of the reference points before loading and for the maximum value of the applied normal load were determined. An example of the use of TEMA Automotive software is shown in Figure 5 (the right figure shows the points for displacement analysis).



**Figure 4.** Cross-sections of the research objects in which the measurements of the radial characteristic were carried out (from the top in the lines NPT\_1, NPT\_2, and PT, respectively).

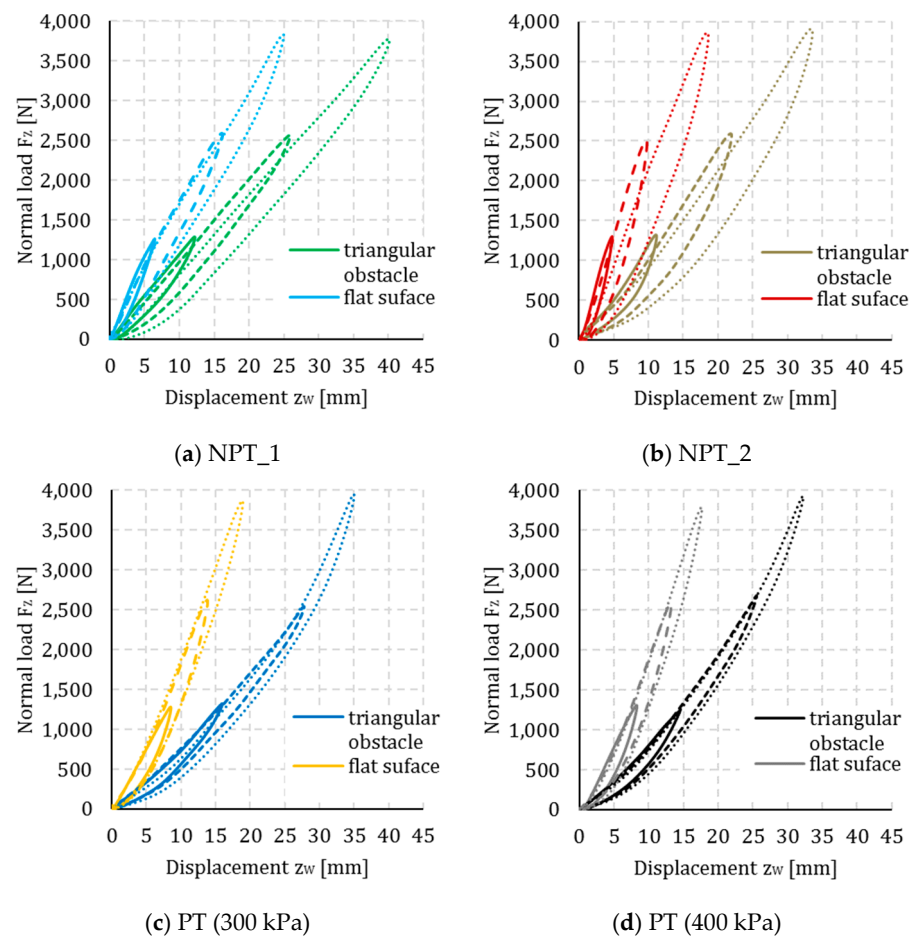


**Figure 5.** Summary of NPT\_1 wheel images unloaded and loaded (image on the left), and preparation of reference points for the displacements analysis in the TEMA Automotive software (image on the right).

Unfortunately, due to the limitations of the universal station, the deformation analysis of the NPT's elastic structure covered the NPT's part between their axis and contact area.

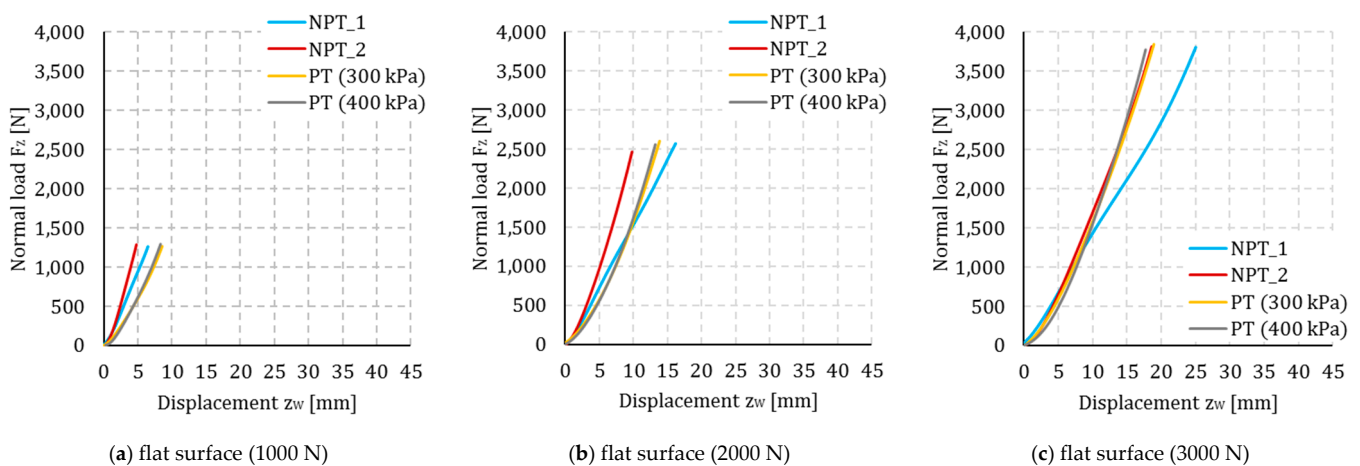
### 3. Results

Figure 6 shows the hysteresis loop obtained in the research. The results for a normal load of 1000 N, 2000 N, and 3000 N were shown by continuous, dashed, and dotted lines, respectively. Different color lines were used on the same figure to distinguish the type of ground (flat, triangular obstacle). Moreover, in order to facilitate the analysis and improve readability, results were included in the same range of changes in the vertical displacement of the wheel axis and normal operating force.

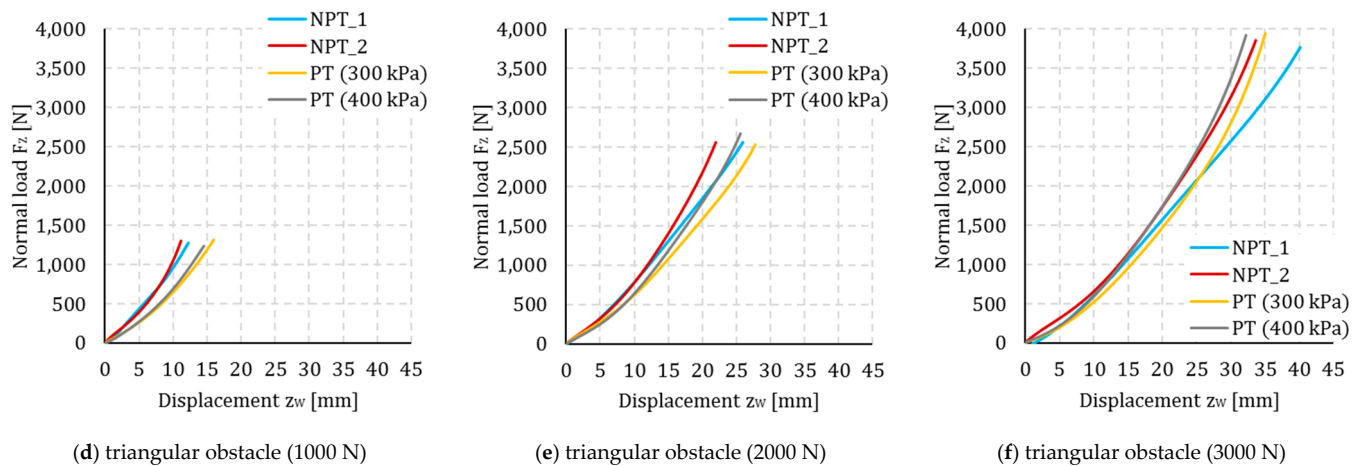


**Figure 6.** Radial characteristic of research object on flat surface and triangular obstacle.

The first stage of analysis included determining the center lines and determining the stiffness coefficient of the research object depending on the adopted range of vertical load. The results are shown in Figure 7, and the estimated numerical values of the radial stiffness coefficients are summarized in Tables 2 and 3 (for a flat surface and a triangular obstacle, respectively) and in Figure 8 (maintaining the method of markings in Figure 6).



**Figure 7.** Cont.



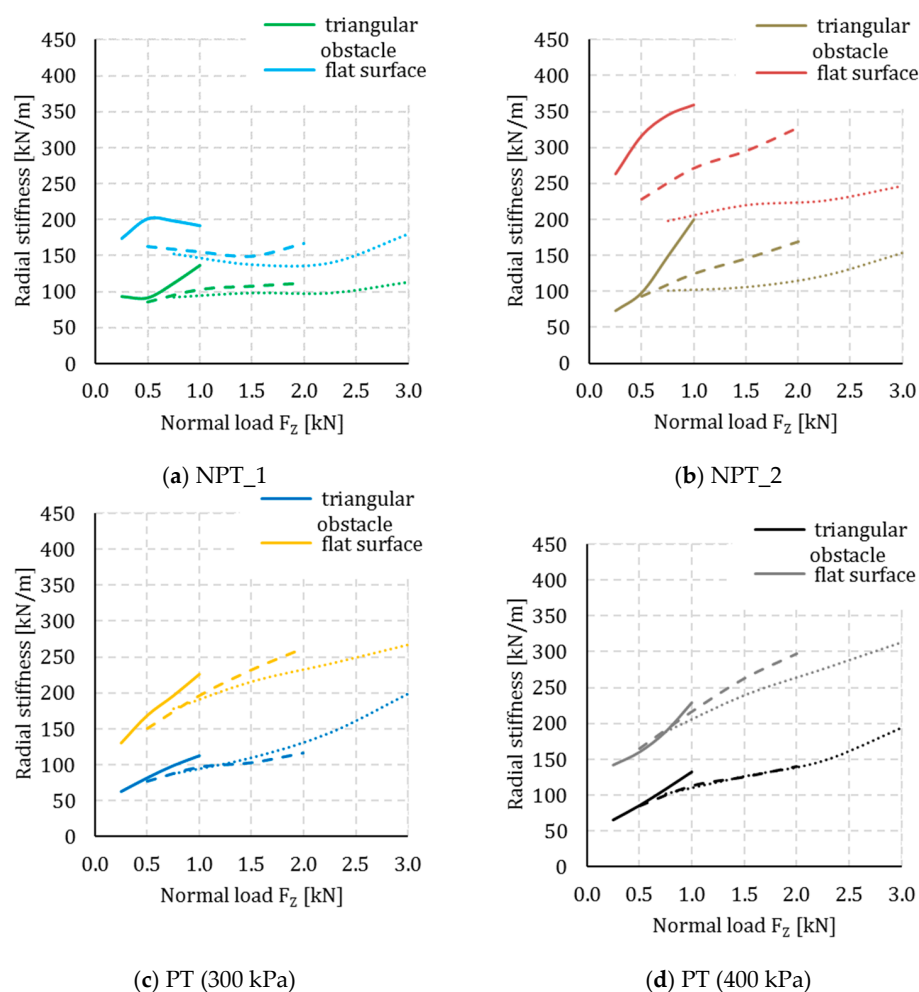
**Figure 7.** Radial stiffness characteristics of research objects.

**Table 2.** Values of research objects radial stiffness on the flat surface.

| Normal Load [N] |      | Radial Stiffness [N/m] |                  |                |                  |
|-----------------|------|------------------------|------------------|----------------|------------------|
|                 |      | NPT_1                  | NPT_2            | PT (300 kPa)   | PT (400 kPa)     |
| 1000            | 25%  | 174,020 ± 7931         | 263,300 ± 10,695 | 130,349 ± 4688 | 142,043 ± 7133   |
|                 | 50%  | 201,423 ± 8331         | 316,383 ± 6578   | 168,680 ± 6823 | 160,095 ± 2574   |
|                 | 75%  | 198,265 ± 1615         | 345,044 ± 7132   | 196,030 ± 8950 | 188,368 ± 7584   |
|                 | 100% | 191,715 ± 7190         | 359,262 ± 11,025 | 226,086 ± 7589 | 229,055 ± 12,808 |
| 2000            | 25%  | 163,057 ± 443          | 227,906 ± 5721   | 150,828 ± 1443 | 164,374 ± 4341   |
|                 | 50%  | 155,139 ± 204          | 270,951 ± 3921   | 196,501 ± 1392 | 216,262 ± 5222   |
|                 | 75%  | 148,790 ± 585          | 294,827 ± 5247   | 232,173 ± 2119 | 262,497 ± 3834   |
|                 | 100% | 167,393 ± 779          | 327,271 ± 5197   | 262,113 ± 4491 | 297,057 ± 6691   |
| 3000            | 25%  | 152,467 ± 2396         | 197,401 ± 4735   | 177,592 ± 2141 | 188,518 ± 8556   |
|                 | 50%  | 137,698 ± 921          | 219,405 ± 4601   | 215,389 ± 1339 | 239,282 ± 8387   |
|                 | 75%  | 139,993 ± 2570         | 225,558 ± 2562   | 240,071 ± 3890 | 275,726 ± 6260   |
|                 | 100% | 179,758 ± 2990         | 246,176 ± 7376   | 266,583 ± 4918 | 312,840 ± 1349   |

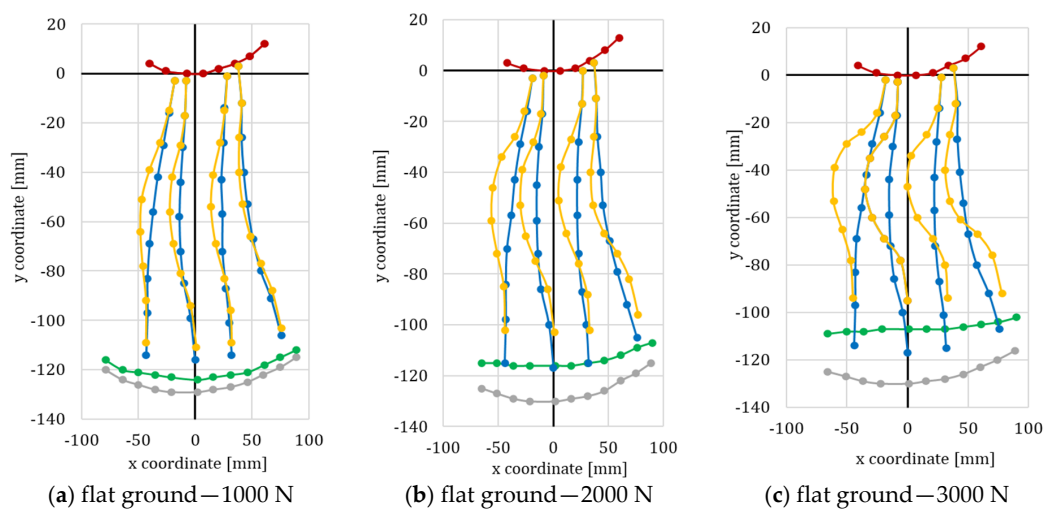
**Table 3.** Values of research objects radial stiffness on the triangular obstacle.

| Normal load [N] |      | Radial Stiffness [N/m] |                |                |                |
|-----------------|------|------------------------|----------------|----------------|----------------|
|                 |      | NPT_1                  | NPT_2          | PT (300 kPa)   | PT (400 kPa)   |
| 1000            | 25%  | 93,326 ± 4474          | 73,212 ± 2644  | 62,836 ± 1409  | 65,545 ± 1593  |
|                 | 50%  | 91,481 ± 2039          | 98,165 ± 4029  | 81,851 ± 510   | 85,582 ± 902   |
|                 | 75%  | 111,877 ± 2801         | 148,508 ± 4109 | 98,898 ± 835   | 108,407 ± 1491 |
|                 | 100% | 136,669 ± 3306         | 199,816 ± 9375 | 112,608 ± 2927 | 132,467 ± 4103 |
| 2000            | 25%  | 85,490 ± 3816          | 92,798 ± 3733  | 77,080 ± 253   | 85,426 ± 796   |
|                 | 50%  | 102,796 ± 1363         | 124,472 ± 4960 | 96,945 ± 903   | 113,298 ± 369  |
|                 | 75%  | 107,363 ± 987          | 145,738 ± 6690 | 103,057 ± 1313 | 125,631 ± 1781 |
|                 | 100% | 111,697 ± 1863         | 169,508 ± 3907 | 116,728 ± 1072 | 140,195 ± 848  |
| 3000            | 25%  | 92,915 ± 2061          | 100,941 ± 3931 | 88,268 ± 1568  | 101,523 ± 623  |
|                 | 50%  | 98,760 ± 1196          | 105,916 ± 4786 | 110,533 ± 2477 | 126,068 ± 271  |
|                 | 75%  | 98,535 ± 494           | 121,795 ± 5610 | 145,009 ± 8305 | 147,586 ± 2164 |
|                 | 100% | 113,349 ± 1250         | 153,718 ± 3901 | 199,243 ± 9681 | 194,120 ± 3578 |



**Figure 8.** Comparison of research objects radial stiffness on a flat surface and a triangular obstacle.

Figures 9 and 10 show the deformation of the elastic structure and shear beam of the NPTs. The dots correspond to the points marked on the observed parts of the research objects, and the colors distinguish different features: a rigid rim (red line), supporting structure (blue line—no load, yellow line—under load), and shear beam (gray line—no load, green line—under load). The displacements are given in the X–Y coordinates, and the non-deformable rim of the NPTs was taken as the reference line.



**Figure 9.** Cont.

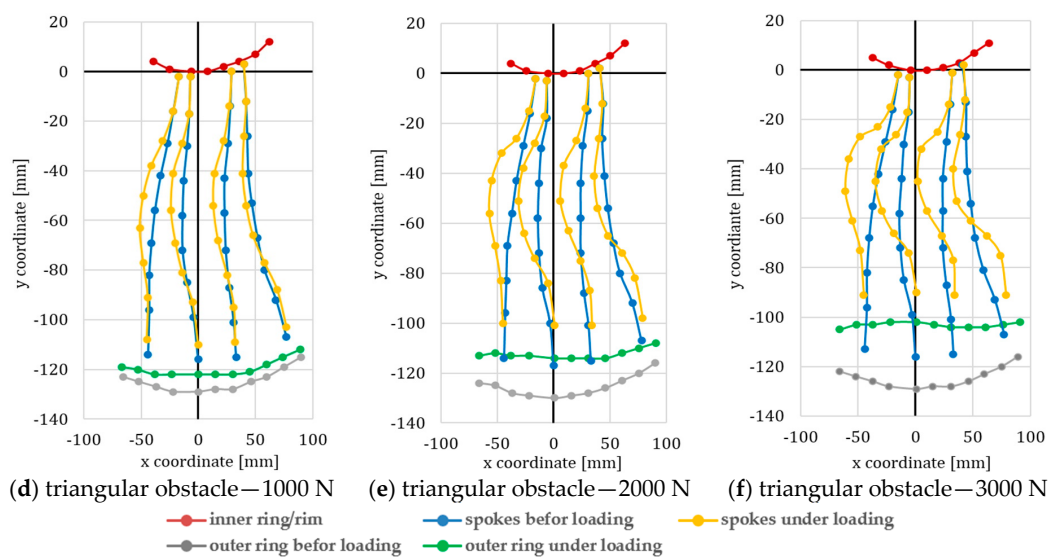


Figure 9. Deformation of the NPT\_1 elastic structure between the wheel axis and different type of surface.

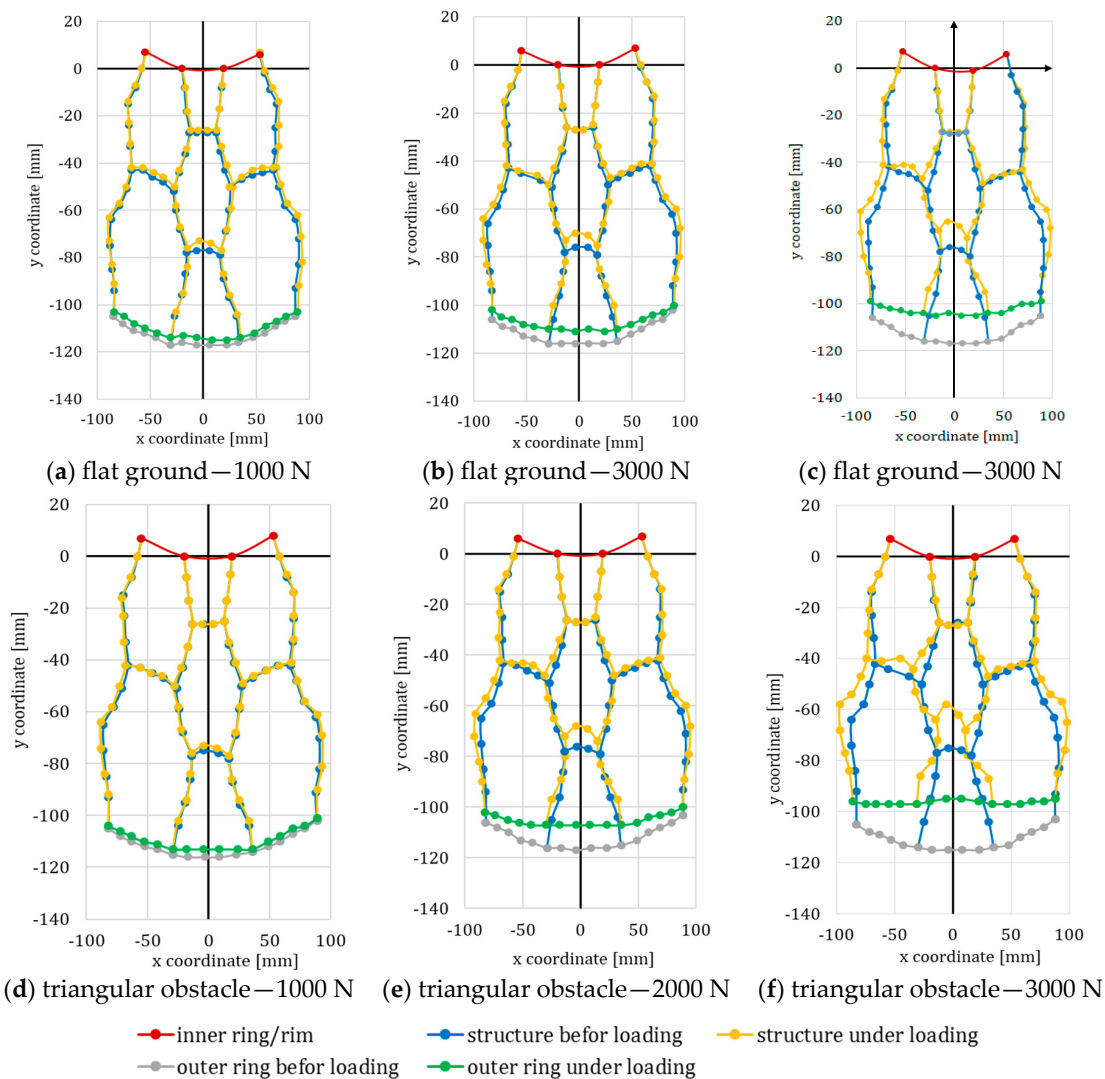


Figure 10. Deformation of the NPT\_2 elastic structure between the wheel axis and different type of surface.

#### 4. Discussion

Due to a different load transfer mechanism and differences in structure, the obtained results were analyzed in terms of similarities and differences.

The course of the radial elasticity characteristics of the tested wheels, shown in Figure 6, is similar. For each of the values of the assumed normal loads, the range of the corresponding vertical displacements of the wheel axis is similar. The influence of a triangular obstacle always increases the vertical deformation of wheels.

On a flat surface, the pneumatic tire, regardless of the inflation pressure value, showed similar hysteresis loop of the radial characteristics. For a load of 1000 N, this may be due to the fact that, for such a low load, the deformation element is the tread blocks. A similar phenomenon was observed for the NPT\_1 and NPT\_2, where similar hysteresis loops were obtained. For a load of 2000 N, the course of the NPT\_1 hysteresis loop is similar to a pneumatic tire with an inflation pressure of 400 kPa (at load equal to 3000 N, the similarity was for the NPT\_2 hysteresis loop).

It can also be seen that with increasing load, the hysteresis loop course recorded for the pneumatic tire coincide, while those determined for NPT are of a different character. As the maximum load of NPTs increased during the research, more sloping hysteresis loops were obtained. This phenomenon is intensified for both NPTs in the case of their interaction with the triangular obstacle and corresponds to the process of reducing rubber stresses under the influence of increasing deformation in subsequent measurement cycles.

The recorded hysteresis loops did not change their course until the load was increased to the next range. After the load change, the course was again fixed in the new position. This is due to the Mullins effect, which causes a change in mechanical properties under the influence of deformation and is characteristic of rubber and rubber-like materials [23–26]. This indicates that the differences in the determined hysteresis loop courses, apart from the design factor resulting from the structure of the elastic structure, are also influenced by the material (elastomer) from which it was made. This material is definitely significantly different in both considered NPTs.

Other differences are also visible. On flat ground and on the triangular obstacle, a pneumatic tire has a progressive characteristic (Figure 8c,d). Under the influence of a normal load of 1000 N, the highest values of the wheel axle displacement were recorded for the pneumatic tire compared to other test objects in this research set. In the case of NPTs, smaller displacements may be related to the resistance of the load-bearing structure to its deformation. Under the influence of the applied load of 2000 N and 3000 N for NPT\_1 on a flat surface, the largest displacements among all research objects were recorded, which is confirmed by the stiffness comparison with Figure 8. Regardless of the ground type, NPT\_1 is characterized by small variability of the radial stiffness value (except for the first set of loading Figure 8a). This may be related to the smooth “switching on” of consecutive spokes located above the axle to load carrying.

On flat ground, NPT\_2 is characterized by significantly higher stiffness compared to other test objects (Figure 8b). This may be related to a different load transfer mechanism and the resistance of the supporting structure located between the axle and the ground surface, as well as the composite material (elastomer) applied. This is confirmed by the largest differences in the stiffness values for individual load sets, where a significant decrease in the NPT\_2 stiffness was observed during increased load range (on both types of ground).

An important reason for the differences in the course of the radial stiffness as a function of the deflection of the NPTs is the design of their supporting (flexible) structure. A detailed analysis of the deformation of its spokes (Figure 9) under the NPT\_1 axis indicates that they buckle. This type of deformation is not accidental and results mainly from the spoke curvature determined at the modeling stage. It is also worth noting that the first two points at each end of the spoke move mainly in the vertical plane, i.e., they do not change their position in relation to rigid rim and stiff shear beam.

Figure 10 shows the behavior of the NPT\_2 supporting structure on flat ground (a, b, c) and against a triangular obstacle (d, e, f). The structure between the wheel axis and the

ground carries loads that cause compression of its components. This is especially noticeable on the shorter section of hexagonal cells (along the  $Y = 0$  coordinate). As a result, NPT\_2 experiences less deformation on flat ground and a triangular obstacle compared to NPT\_1. This property affects the size of the hysteresis loop and the radial stiffness of NPT. It was noticed that, as in the case of NPT\_1, the arms of the NPT\_2 hexagonal cells in the part of contact with the rim and the band are also only slightly deformed.

During analysis, attention was also paid to the energy values (hysteresis loop area), which is dissipated at the deformation of the research objects. However, no results were obtained that could be unequivocally associated with the structure of the NPTs support structure and compared with a pneumatic tire. An obstacle for this analysis is that there are a large number of factors that may co-determine the amount of hysteresis loop; these will be taken into account during further wheel tests. For example, a pneumatic tire has large, sparsely spaced tread blocks that can affect the determined amount of energy losses; high hysteresis losses with loads of up to 1000 N are primarily related to the internal friction of the compressed tread blocks. NPT\_2 energy dissipation is probably mainly related to the shaping of the elastic structure and deformation of the part of the wheel located under the axis of its rotation, i.e., tread, shear beam, and spokes. The smallest energy losses were determined for NPT\_1, whose spokes in the lower part were buckled (which practically did not affect the energy losses) and the stress in the upper part [3,12]. Lower values of hysteresis losses were also recorded in the research with an obstacle, which may be due to the fact that the research objects interacted only with the top of the obstacle, the remaining part of the tread area of the pneumatic tire, or the band of the NPTs that had no contact with the ground.

The conducted research and analysis and the revealed doubts have shown how complex NPTs are. The above will be used to formulate the scope of further work aimed at identifying NPTS properties, including:

1. determining the causes of such a different course of changes in the radial stiffness of these NPTs by extending the observation of deformations of the elastic structure by the area above the wheel axis and making an attempt to identify the details of the elastic and supporting structure and the materials from which they are made;
2. carrying out research while wheels are rolling, with simultaneous observation of temperature distribution and measurement of rolling resistance coefficient and forces occurring in the contact area;
3. checking the influence of the supporting structure on other parameters of the tire, such as longitudinal, lateral, and cornering stiffness;
4. assessing inclination tire angle dependency on the hysteresis behavior and the temperature influence on the overall NPTS dynamic behavior.

All the above-mentioned actions will provide greater credibility in reporting the properties of the NPTs and can be used, for example, in modeling the motion of the vehicle, including its energy consumption.

The authors of this work are currently conducting research in the scopes indicated above. Their results will be presented in subsequent publications.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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