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Analysis of Truck Tractor Tire Damage in the Context of the Study of Road Accident Causes

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Abstract: There are many accidents in road traffic involving both heavy goods vehicles and passenger vehicles, and the interpretation of the causes of some accidents can be very difficult. The paper presents the results of an analysis of the road accident causes involving a truck and two passenger cars. The hypothesis was verified that the incident took place after the damage to the front wheel of the truck, which resulted in an uncontrolled change of the direction of its travel and leaving the lane in the opposite direction of the passenger cars. The damaged tire was inspected, and traces were described in the form of cracks on the side surface, irregular abrasion on the central part of the side surface and near the bead, as well as deformations resulting from damage to the cord. The thesis was made that the tire cracked as a result of its material structure defects. In order to verify it, bench tests were carried out on the deformation of the tire sidewall at various load conditions, which simulated driving with too little air pressure in the tire. Detailed studies of the fracture of the tire sidewall and the wires that make up its steel cord were carried out. Macroscopic examination of the cord wires on eight samples revealed the presence of corrosion changes that should not occur under normal operating conditions. The results of the research work indicate that tire rupture was caused by delamination of the material coatings and corrosion of the steel cord wires. These defects could have arisen due to the earlier cracking of the rubber layer and the ingress of moisture or as a result of the use of corroded steel cord wires in tire production. In the analyzed case, the driver could not regain control of the vehicle and avoid a collision with oncoming vehicles.

Keywords: accident reconstruction; tire damage; macroscopic research; road safety

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1. Introduction

Transport is an integral and indispensable part of human lives, joining everything into one harmonic whole [1]. However, along with the increase in the intensity of transport, we feel its negative effects in the form of exhaust emissions, noise, vibrations and, above all, threats to the safety of road users in the form of road accidents. A tire is an element of a car that directly affects the road surface, transmitting driving, braking and lateral forces. The structural requirements for a tire are related to the necessity to transfer the above-mentioned forces, and therefore it is required to have adequate stiffness. This feature results from the complex construction of the tire, in particular the textile carcass, steel belt, butyl cover and fillers.

Steel wire or products containing it are used to strengthen tires in the form of strands or ropes, the so-called steel cord [2–4], which is embedded in the elastomer to stiffen the structure while giving it adequate strength to tensile forces. Single steel wires have a diameter from 0.15 to 0.38 mm [5], and most often, they are produced as brass-plated or galvanized surfaces. Wires intended for the production of steel cords are made of quality unalloyed steel, containing from 0.70 to 0.95% of carbon. They have a pearlite structure and are suitable for drawing or cold rolling [6–8]. The chemical composition and mechanical properties of the wires should comply with EN 10323 [9]. The fatigue strength of the steel cord affects the operational properties of tires and, consequently, the safety of vehicle traffic. Due to the fact that the steel cord is covered with a layer of rubber, identification of possible adverse phenomena and cord degradation during tire operation is difficult [5]. Steel cords used for the production of passenger car tires have strands of two to five fibers (e.g., 2 + 2 × 0.25; 2 + 1 × 0.30—the first number means the number of middle wires and the second number of braided wires with adequate their diameter in mm), while cords used for tires intended for trucks and special construction machines are of multi-wire constructions (e.g., 2 × 0.30; 3 × 0.25 + 6 × 0.35) [5,10,11]. Depending on the manufacturer and load of the tire, the number of wires and their diameter varies. Regardless of this, the cord reinforcement should meet the appropriate strength requirements.

The technical condition of the tire has a significant impact on road safety, which is confirmed by numerous literature reports [12–20]. Unfortunately, it is often stated that vehicle operators disregard the technical condition of pressure, which has a significant impact on driving comfort, fuel consumption and road safety [20]. Vehicle tire pressure monitoring systems [21,22] and vehicle inspection systems in transport companies are also helpful. The relationship between the drop of pressure in passenger cars and lifetime was studied, among others, by Reiter and Wagner [23] and Andreescu and Stan [24] as well. Their research shows that the use of motor vehicles with reduced pressure by about 7 kPa shortens the service life by almost 2%. When the tire pressure is too low, the temperature of the tire increases while the vehicle is running, which may cause changes in its structure, permanent damage or even an explosion [22]. Moreover, low tire pressure increases fuel consumption and rolling resistance due to the greater contact area of the tire with the ground [25–27]. In these cases, the forces associated with the vehicle wheel load and increased frictional forces resulting from improper tire contact with the ground act synergistically on tire wear [28,29].

In turn, a pressure that is too high causes excessive wear of the tread, reducing the time of safe operation [21,22,27,30]. A high vehicle load combined with incorrect tire pressure also contributes to the vehicle's controllability. The tests of the driving properties of wheels under various friction and tire load conditions were the subjects of, inter alia, the following works: [31–36]. Tires also wear during intensive braking [27,36,37]. In emergency situations, such as the leakage of a tire installed on the axle of the steered wheels of the vehicle, the vehicle's trajectory changes, which is almost impossible for the driver to control in the initial phase. Proper use and inspection of truck tires contribute to extending their useful life. This, in turn, may lead to a reduction in fuel consumption (CO_2 emissions) [38,39], as well as the amount of generated waste [40,41] and an improvement in road traffic safety [42–45].

During production, tires are subject to technical inspection (non-destructive testing) to eliminate possible material defects, such as splits, air pockets and bulges (material defects and failures, such as separations, air pockets and bulges). Separate tests are carried out to assess the adhesion between individual elements of the tire structure [46,47].

The authors of the articles [48,49] conducted laboratory tests of tires involving the use of non-destructive methods to detect material defects causing the propagation of defects and delamination of the structure in tires subjected to dynamic loads. A thesis has been put forward that the place where the defect arises and the speed of its propagation during tire operation have a direct impact on the time of its use and translate into driving safety. Defectoscopic tests of tires were carried out after each completion of the dynamic tire load test in specific time intervals.

The motivation for the study of this particular incident was that there are extremely rare cases of tire damage on the steering wheel in articulated vehicles. Due to the main load on the second axle of the vehicle, under the saddle and axle of the vehicle semi-trailer—this is where the damage most often occurs. Moreover, the event considered here is the most dangerous due to the inability of the driver to react effectively and, consequently, the loss of vehicle stability, which has been presented in this paper. Moreover, the available world literature does not describe analyzes for such a failure case. On the other hand, one can find research on modeling the tires themselves [2,3,25,50], investigating the causes of their damage [51,52] and various aspects of the contact between the tire and the ground, which causes its damage [26,53,54]. Interesting studies involving heavy trucks on a highway in the USA are presented in [55], taking into account factors such as the age of the driver, traffic volume, roadway geometric features, time characteristics, weather and lighting conditions. However, none of the studies cited relates to the analysis of tire damage on a steering wheel.

This study analyzes the causes of a road accident involving a truck and two passenger cars. The hypothesis was verified that the incident took place after the front left wheel of the truck was damaged, which resulted in an uncontrolled change of direction of its driving and turning into the opposite lane in which passenger cars were moving. In the further part of the work, the analyzes and test results of the damaged tire, including macroscopic tests of the fractured cord wires, are described. On this basis, observations and final conclusions were formulated. This test is intended to prove the causes of damage to the tire mounted on the steering wheel (whether it has been unsealed as a result of a material defect or as a result of incorrect tire use). The case at hand is particularly important because, in most cases, there is a "tire shot" on the twin wheel or in the trailer of the vehicle, which is much easier for the driver to control the vehicle. The task of the work was to prove whether the damage visible on the tire sidewall was the result of previous incorrect use or as a result of this road accident.

2. Analyzed Road Incident

Taking into account the location of the tire friction marks on the road as well as the post-accident location of the vehicles, it was found that before the accident, a lorry truck drove into the opposite lane, on which two passenger cars were driving successively. The truck then drove into a not-very-deep ditch and stopped on an adjacent slope (Figure 1).

Figure 1. Photo of the area of the accident site. Lorry truck in the foreground, and cars in the background center.

The analysis of the scratch marks documented on passenger cars made it possible to state with high probability that the Truck came into contact with Car A (first) and only later with Car B. As a result of the collision, the passenger cars rotated around vertical axes; at the same time, the rear part of Car A could be lifted up, hitting concrete segments on the roadside; Figure 2.

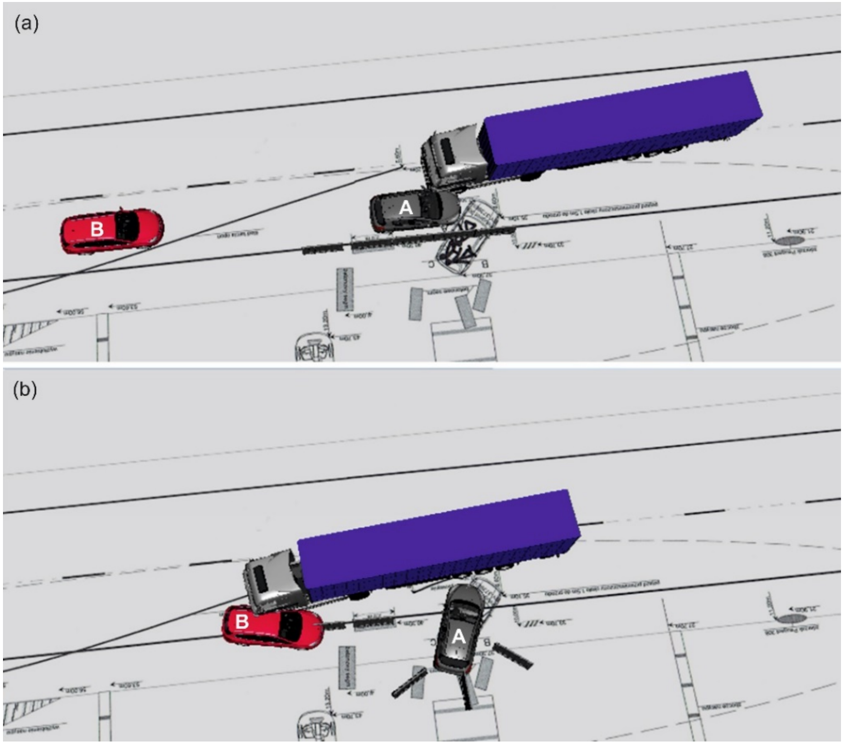

Figure 2. Location of vehicles at various stages of the accident, at the moment of (**a**) crash between Car A and Truck tractor; (**b**) collision between Car B and Truck tractor.

The thesis was put forward that the truck tractor driving over into the lane on which the passenger cars were moving was related to the unsealing of the left front wheel of the truck tractor unit. Taking into account the views of the witnesses of the incident, it was considered unlikely that the articulated vehicle that drove into the opposite lane was related to a circumstance other than that indicated above, e.g., the inappropriate behavior of the driver. In this situation, it was decided to conduct more detailed tests of the tire.

Figure 3 shows the individual phases of the analysis of the considered case of tire damage in a truck tractor with a semi-trailer.

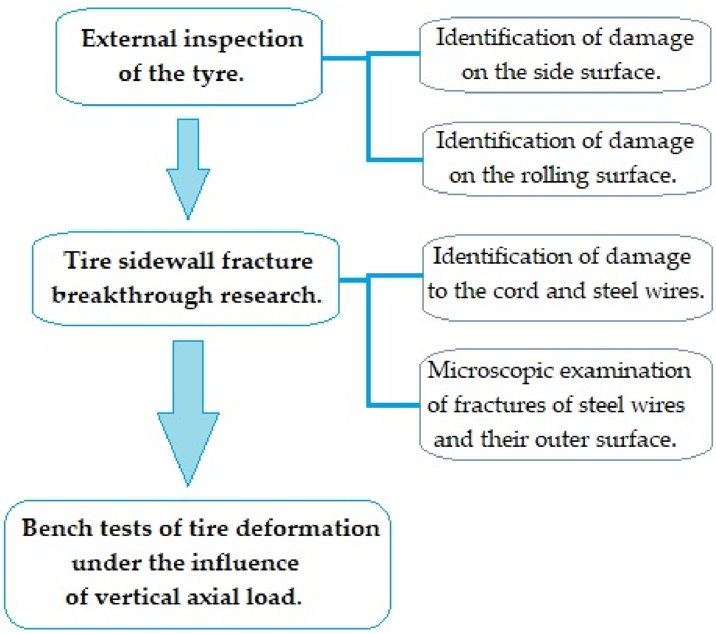

Figure 3. Block diagram of selected analysis phases.

3. Characterization of Damaged Tire and Methods of its Testing

According to the specification found on the tested tire, it was identified as follows:

- Primewell PTL711 tire;
- Size: 385/65R22.5 160K (160-load index: 4500 kg; K-speed index: 110 km/h);
- 18PR-conventional number of canvases (interleaves);
- A radial, tubeless, all-steel cord tire designed for long-distance transport;
- According to the additional load capacity marking on the sidewall, the maximum load is 4500 kg at a pressure of 900 kPa;
- The tire has European approval (E4 0019845 010950-3) and the American safety certificate DOT 9U3W J92;
- The tire is adapted to regeneration by deepening the tread ("regroovable" designation).

During the inspection of the damaged tire, chalk markings were applied to its side surface (Figure 4), by means of which the circumference was divided into fragments, marking them using the approximate values of the angular degrees: 0°, 90°, 270°, 360°. Additionally, the direction of rotation of the tire while driving is marked with an arrow. The applied signs mean the Z-outer side and the W-inner side. The terms inside and outside of a tire correspond to the way it is mounted on the rim and positioned in relation to the direction of movement of the truck tractor.

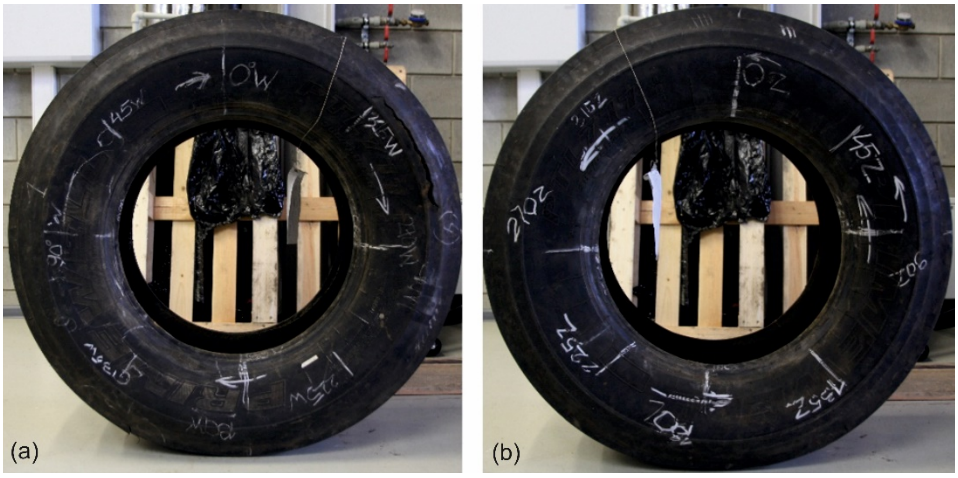

Figure 4. Tire markings applied during the tests: (**a**) inner side of the tire; (**b**) outer side.

Upon visual inspection of the tire sidewall from the "inside" side, the following marks and damages were identified:

- A crack on the side of the tire, approximately 300 mm long (marked with number 4 in Figure 5), located along the angular length of 270 ÷ 315° W on the part of the tire named "belt";
- Irregular sidewall abrasions on the "belt" on both sides of the tire around the entire circumference;
- Scratches on the side of the tire close to the bead (marked with numbers 5 and 6 in Figures 5 and 6) at the angular length of 70 ÷ 180° W;
- Local deformation of the side resulted from damage to the cord (Figure 7), which was at the 110° W site.
- Inspection of the tire tread allowed us to identify the following characteristics:
- Local loss of material on the tread face with the exposed cord (marked with the number 1 in Figure 8), which was in the place marked with 90° Z;
- Tearing of the tread face (marked with number 2 in Figure 9), located in the place marked 140° W;
- The structure of the material in the grooves and edges of the tread indicates that the tire tread has not been regrooved.

Figure 5. View of the inside of the tire of the left front wheel of a truck tractor.

Figure 6. Scratches on the inner side of the tire (near the bead).

Figure 7. Local deformation of the sidewall on the inner side (indicated by an arrow).

Figure 8. Local loss of tire material on the forehead of the tread on its outer side.

Figure 9. Tear in the tread face and a hole in the place where the white chalk is placed.

Damage in the form of deformed edges was found on both sides of the wheel rim, while the extent of deformation on the outer side was greater than on the inner side. The deformation of the rim on the outer side was (during the post-accident inspection) on the side opposite to the crack in the tire sidewall; Figure 10.

Relating the location of the damage to the wheel rim on its outer side to the damage to the tire, it was found that the local material loss on the tread face (Figure 8) was on a plane perpendicular to the side of the wheel and passing through the place of maximum deformation of the rim edge. The deformation of the wheel rim on its outer side can be explained as a result of a collision with Car A with which the wheel first came into contact or as a result of the wheel contacting with deformed parts of the truck's shell, e.g., cab steps, which were deformed and disintegrated as a result of successive impacts to the vehicle.

It was assumed that the point of application of the force resulting from an impact is at the point of maximum deformation of the rim. This point is, therefore, on the opposite side of the circumference and on the opposite side of the wheel, where the tire sidewall fracture (which was found on the inside) was identified.

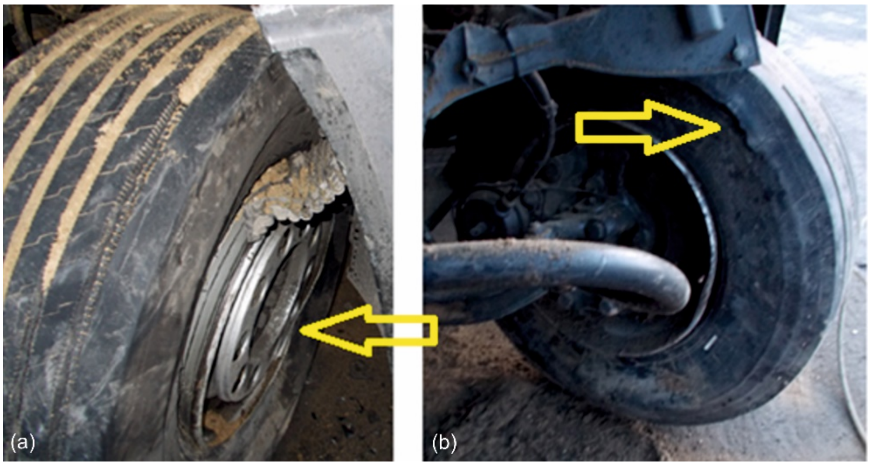

Figure 10. Relative position (indicated by the yellow arrow) of deformation: (**a**) of the outer edge of the rim of the left front wheel of the truck tractor; (**b**) the fracture of the tire sidewall on the inner side.

During the visual examination of the tire sidewall fracture, no features were identified that would indicate the effect of a sharp edge that could cut the tire sidewall initiating its fracture and unsealing. Such an edge could have undefined elements on the road (if the leakage occurred before the truck tractor left its lane to the opposite one) or elements of the truck tractor suspension (if the leakage occurred after a Car A or Car B collision).

From a technical point of view, it is unlikely that the sidewall rupture was caused by a sudden increase in air pressure associated with an impact. The authors of the article conducted research on an event of a similar nature and consequences, in which, with a deformation of the truck tractor rim similar to the subject, the tire did not break at all. However, this possibility cannot be clearly ruled out.

Accepting the thesis that the breakage of the tire in question (in a place other than the action of contact forces) was related to an increase in air pressure during a collision would have to be supported by evidence that the tire structure in the place of the break (on the opposite side to the place where the impact took place) was significantly weakened as a result of the operation or a material defect. Further tests of the tire were carried out to verify the existence of such evidence.

It was decided that in this case, macroscopic examinations of the damage to the tire's skin and its vicinity as well as the assessment of the type of damage to the steel cord, were sufficient in terms of accuracy. For testing the wire surface and fractography of their fractures' optical dissecting, NIKON SMZ 1500 microscopes were used.

Moreover, a method of testing a disassembled tire was developed in order to simulate the conditions in which the material around its circumference, described as a "belt", could be worn, could be simulated (Figure 5). Tests were carried out in which the tire in question was pressed against a flat surface with a steel pipe with a diameter of 550 mm, which was smaller than the diameter of the tire seat by about 20 mm. The use of a pipe as a clamping element was justified, among others, by the inability to put a rim in the tire-without mechanical impact on the tire (during the necessary assembly and disassembly), which could cause further damage and an attempt to press the tread face against the surface evenly. The pressure on the pipe was transmitted by a beam through two belts anchored to the ground. When loading the tire, the pressure value was read using an electronic scale indicator (accuracy class III) on which the tire rested. The method of applying the load and the profile of the tire loaded with the mass, resulting only from the mass of the pipe and the beam (60 kg), is shown in Figure 11. Before starting the test, the tare equal to the weight of the tire and the beam with belts was taken into account. The measured height of the lower part of the beam above the surface of the weighing table (before starting the test) was 250 mm (Figure 11).

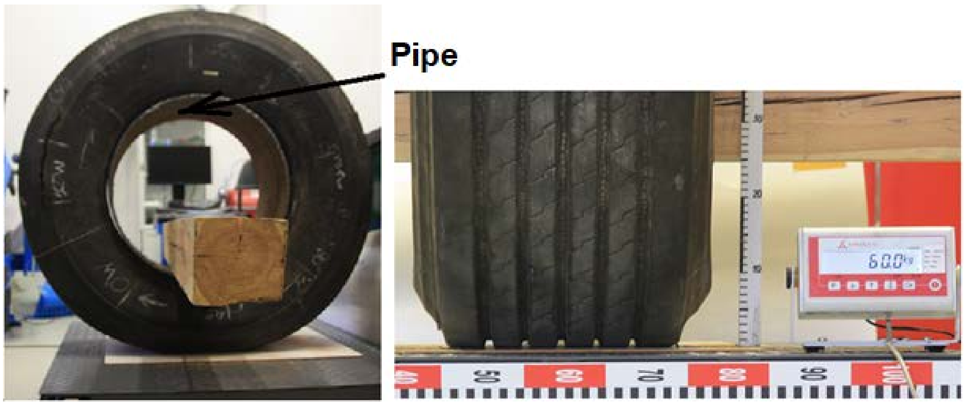

Figure 11. Method of loading the test tire and measuring the initial deflection of a tire loaded with a mass of 60 kg.

4. Tire Testing Results and Discussion

Detailed studies of the area of the rupture of the tire sidewall and the wires forming the steel cord were carried out. The crack (marking 4 in Figure 5), approximately 300 mm long, had an approximately rectilinear path in the central part and a sinusoidal course at both ends (Figure 12a). If the rupture of the tire was caused by a sharp edge, the period and amplitude of the sine wave would be greater and greater. In the case under study, however, initially (from the edge), the period is small, and the amplitude is large. Then the period is very large, and the amplitude is small (almost straight). The other end of the burst is an almost symmetrical reflection of the first. Sometimes the cut starts only by scratching the surface of the tire, which is not present here. It can, therefore, be concluded that the tire is unlikely to undergo a mechanical cut initiated from the outside.

Figure 12. View of the crack in the sidewall of the tire.

In its central part, on both sides of the cord, the layers of the material were separated: in the zone located below the fracture line closer to the flange, the delamination depth (in the "deepest" part) was about 20 mm (Figure 12b), above the fracture line-delaminated about 5 mm. The surface of the rubber was smooth with visible grains (Figure 12b). In the areas near both ends of the cracks, local losses of rubber and cord were visible in the form of "faults" of the material, forming lines in a direction close to perpendicular to the side of the tire (Figure 12c). On the surface of the fracture of the rubber, no traces of any cause of the fracture were working "from the outside".

Steel cord samples were taken from places in the area of the tire sidewall fracture. The place of sampling and the method of their determination are shown in Figure 13. The samples marked as "1", "2", "4" and "7" were taken from the central fracture zone. The samples marked "3", "5" and "6" were taken from the part above the fracture line from zones where the fracture was already sinusoidal. Samples "1", "2", "4" were located in the zone where the tire material coatings were delaminated (separated from the cord coating). In the area where the delamination depth was the greatest (about 20 mm) below the fracture line, the sample designated "7" was taken. This sample was cut approximately 10 mm below the edge of the sidewall fracture.

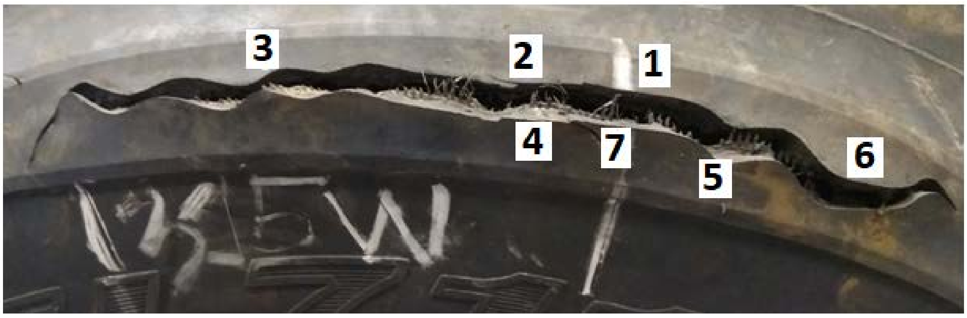

Figure 13. Places of sampling and method of marking samples.

The wire fragments forming the steel cord were subjected to macroscopic examination using the NIKON SMZ 1500 stereoscopic microscope. Figure 14 shows the view of selected steel wires under the microscope (wire fractures and their side surfaces). The cord consisted of a strand of nin steel wires, each 0.35 mm in diameter. There were corrosion changes on each of the analyzed samples, which proves that the wires were in contact with moisture.

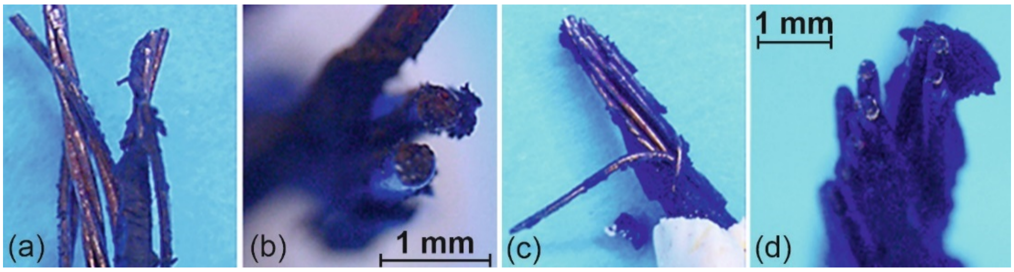

Figure 14. View of selected steel wires: (**a**,**b**)—sample 3; (**c**,**d**)—sample 5.

The observation of several fractures shows that there were no corrosion changes, but contamination is visible (Figure 14c,d, sample number 5). It should also be stated that the corrosion (on the breakthroughs and on the side part of the wires), visible in Figure 14a,b, occurred unevenly and with varying intensity. Assuming the homogeneity of the cord material and comparable corrosion incubation time, it can be concluded that the surfaces with visible corrosion traces of a higher degree of advancement were exposed to aggressive factors for a longer time than the fragments on which the wear level was lower during the test (Figure 14). It is also important that under the rubber cladding (covering the bundle of wires) in sample "7", in the part below the fracture line, corrosion traces of steel wires were also observed. This fragment was located in an "insulated" area sheltered during the tire storage as evidence and was not exposed to external factors, as was the case with "exposed" wire fragments. This clearly indicates that before the accident, there were corrosion centers on the wires of the steel cord, which weakened the tire structure (Figure 14). On the cross-section of the wires, no traces were noticed that would indicate interference of a sharp metal element with the tire.

The presence of corrosion of the steel cord at the fracture site (which has been proven before the accident) allows the conclusion that in this place (marking 4, Figure 5), the tire sidewall was weakened. This fact cannot be interpreted as the cause of an impact fracture but only as a necessary condition for such a fracture to occur at all. It cannot be ruled out that with such a weakening of the tire structure, its breakage may have occurred while driving.

The surfaces of the wire fractures (Figure 14b,d) are rough and intercrystallite. There was also observed small necking at the sectional area. However, in the steel of pearlitic structure, there is an expected visible cup or cone shape of the material deformation. Due to the lack of occurrence of these breakthrough features, it can be concluded that the damage to the wires took place at a relatively high speed or that the damage was caused by the presence of intercrystallite corrosion. Non-destructive tests to control the occurrence of this type of corrosion are practically not carried out even for elements to which there is unlimited access. In the case of a cord placed as reinforcement in the tire material, it is not possible to conduct direct corrosion tests at all. Even small cracks in the tire carcass can cause the penetration of moisture by capillary action and the development of corrosion of the steel cord, which can lead to its significant weakening and, at the same time, an increase in the temperature of the tire material in the area of corrosion.

Subsequent tests concerned the formation of irregular sidewall abrasions on the so-called belt on both sides of the tire (Figure 5). A thesis was formulated which assumed the appearance of abrasions as a result of operation with too low air pressure in the tires. In order to confirm the probability of this thesis, the key test was to examine how the sides of the tire pressed to the surface by the wheel rim deform.

During the analysis of the successive stages of loading the tire, it was noticed that the side of the tire was deforming in the place where the "belt" was located (Figure 5). The static deflection of the tire profile, loaded with a mass of 603 kg, was equal to 250–140 = 110 mm. The results of deflection vs. load of the tire tests are shown in Figure 15. For a sample size of 20, in five levels of tire deformation, a regression function was found as well as a 95% confidence interval for the regression equations. These parameters were determined in accordance with the rules applicable in scientific works [56,57]. The method of deformation of the profile (and "belt") with a mass of 603 kg is shown in Figure 16a. With such deflection, the side of the non-rotating tire did not touch the ground surface. The static deflection of the tire profile, loaded with a mass of 676 kg, was equal to 250–120 = 130 mm. The method of deformation of the profile (and the "belt" of the tire), when loaded with a mass of 676 kg, is shown in Figure 16b.

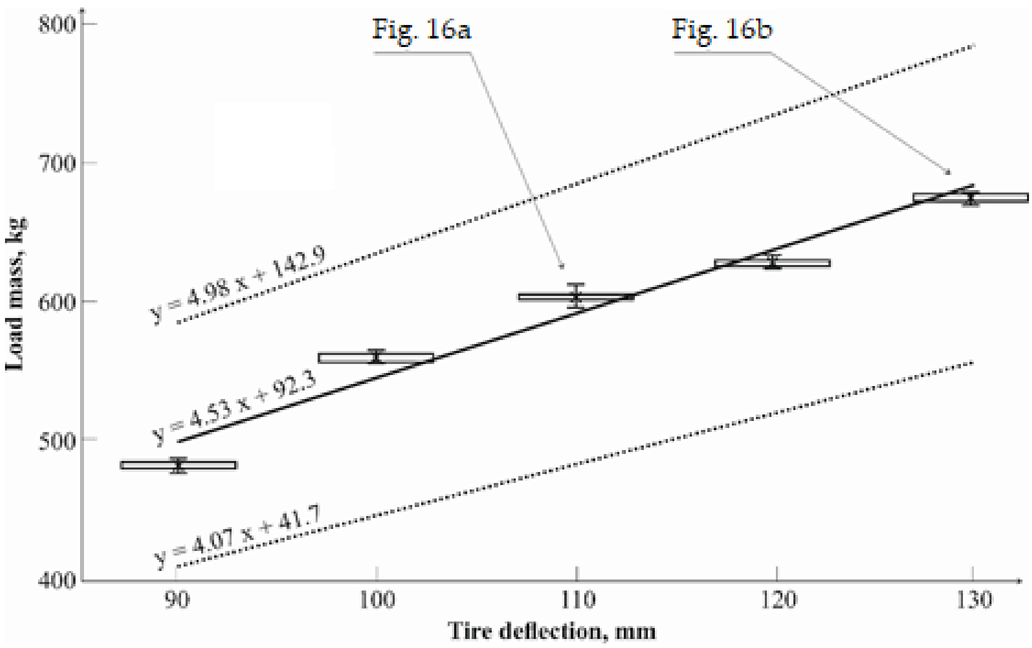

Figure 15. Results of testing load mass for particular deformation of tire up to contact of the "belt" with ground.

Figure 16. Profile deformation under a load of (**a**) 603 kg; (**b**) 676 kg.

The way the profile deformed during the static load test indicates that the "belt" on the sidewall of the tire was not making contact with the road surface. In this context, it should be considered unlikely that the scratches on the side of the tire ("belt") were related to the long-term operation of the tire with a lower tire pressure value. In such a case, the abrasions would be below the "belt" and would be uniform.

The event that the tire sidewall ("belt") is likely to be in contact with the road surface at the time of a sudden leakage and/or transverse forces acting on the tread face. Sudden unsealing, air loss and a temporary change in the shape of the tire cause vibrations related to the imbalance of the rolling wheel [34,53]. In this case, abrasions of varying intensity on the "belt", around the circumference and on both sides of the tire should be considered likely.

Therefore, there are strong reasons to conclude that the leakage of the tire took place before the collision with passenger cars and that the phenomenon was sudden because the driver did not manage to correct the direction of movement or significantly reduce the speed of the vehicle.

This paper allows for a discussion on additional research in this aspect of truck tire operation and the prospects for detecting this type of tire damage in order to prevent such events in the future. An example of a solution that improves the safety of trucks is the installation of pressure monitoring systems, which was signaled in the studies by Szczucka-Lasota et al. [22]; unfortunately, in the case under discussion, the truck was not equipped with such a monitoring system. However, in many scientific works, it was pointed out that the correct pressure and tire operation have a key impact on the safety of road transport [21,58–63]. The tire is the only component of the vehicle that makes direct contact with the ground and allows the vehicle to be steered. As shown in the studies by Caban et al. [21], drivers often ignore checking the technical condition of tires, including the pressure recommended by the manufacturer.

5. Conclusions

On the basis of the conducted tests, the following conclusions can be drawn regarding tire damage on a truck tractor:

1. There were no indications that the tire rupture was caused by external exposure to the metal part.

2. Crack analysis (e.g., delamination of material coatings and traces of corrosion on steel wires) shows that the structure of the tire was weakened in the place of the crack. This could be the result of two independent reasons. The first of them could have been caused by much earlier damage to the tire, followed by the ingress of moisture inside, which initiated the corrosion processes of the steel cord wires. The second reason may be related to the tire's design defect in the use of a cord with traces of corrosion during production.
3. As indicated in the literature, in cases where the structure of the tire is weakened, it may become unsealed (cracked) during the operation of the vehicle. Taking into account the authors' experience, there has not been a case of tire fracture in a situation where the place of weakening of its structure did not coincide with the place of external force. However, such a possibility cannot be categorically ruled out.
4. Disclosed traces of abrasions on the tire sidewall, on both sides (on the "belt"), are a significant premise for accepting with a very high probability that before the collision with Car A, the left front wheel of the truck tractor made at least one full turn during which the tire vibrated, indicating a leakage occurred prior to the crash.

There is a very high probability of material evidence that the leakage of the left front tire on the truck tractor took place before the collision with Car A. In situations where the tires of trucks mounted on the axle of the steered wheels become unsealed, the vehicle's trajectory changes, which at the initial stage are not able to be controlled by the drivers. There are known cases where such incidents did not produce physical effects. Occasionally, if sufficient space was available, drivers were able to regain control of the vehicle and keep it safely within the road. In most cases, however, the leakage phenomenon is so dynamic, sudden and surprising for the driver that it results in the destruction of the vehicle and/or a collision with other vehicles on its uncontrolled path. In the analyzed case, it can be stated that the road section in question was not wide enough to regain control of the articulated vehicle and avoid a collision with oncoming vehicles.

The utilitarian conclusion from work is that it is suggested to withdraw tires with cracks on the side surface from service. Progressive degradation of this surface may cause penetration of moisture and aggressive agents (road maintenance agents in winter) and cause corrosion of steel wires. In addition, testing of wire samples from each series of deliveries should be introduced in production plants. This would eliminate the material with initiated corrosion directed to the production line. This procedure would increase production costs, but it would clearly increase the quality of the product and the safety of operation in road traffic.

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