

The use of 3D scanning to assess the technical condition of passenger car bodies

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ABSTRACT

This paper proposes a new method for diagnosing passenger car bodywork during service. The method is based on the process of 3D scanning specific areas of the bodywork. The study involved tests using this method on cars exposed during use to various factors contributing to bodywork wear. This allowed the method's suitability to be verified. The tests were carried out on a car that had undergone bodywork repairs following a road collision, on a car that had been used intensively, and on a car with low mileage. Following the 3D scan of the bodywork, measurements of the floor panel geometry and the upper sections of the bodywork were carried out using traditional methods and diagnostic tools. This allowed the results of the 3D scan to be compared with those obtained in previous studies. A comparative analysis of 3D scanning of three passenger cars, which were exposed to various factors contributing to bodywork wear during their service life, shows that the method proposed in this study can be used to assess the condition of the bodywork whilst the vehicle is in use. By applying the described method, the most likely cause of bodywork wear can be identified. Comparing the results of the analysis of changes in bodywork geometry using 3D scanning with measurements of the floor panel and upper bodywork sections using traditional diagnostic methods, it can be concluded that similar relationships were obtained. The greatest extent of bodywork deformation was observed in the car that had undergone bodywork repairs to the left side of the body, which had been damaged in a road collision. Minor changes in body geometry were found in the car that had been used intensively by many drivers. In contrast, the smallest changes in body geometry were found in the car with the lowest mileage, which had been used by only one driver.

Keywords: vehicle, 3D scanning, bodywork, diagnostics, maintenance, safety, body geometry.

INTRODUCTION

Nowadays, we can observe a very high level of mobility among the population and an increase in the volume of goods transported. This contributes to a significant increase in the number of cars used on local, national, and international roads [1]. This necessitates large investments in road infrastructure and improvements in road quality [2–4]. Large-scale migration and high demand for goods and services also contribute to increasing car mileage [2,5,6]. Unfortunately, the increase in the number of cars operating on congested roads increases the risk of accidents or collisions. Unfortunately, body repairs often fail to restore

the correct geometry of the bodywork [7]. As a result, they may not ensure an adequate level of safety during [7–9]. Vehicle safety is currently one of the most important parameters taken into account during vehicle design and operation [10].

Wear and damage to the bodywork, as well as changes to its geometry, occur not only as a result of accidents and collisions [11]. Wear and damage to the bodywork also occur in accident-free vehicles. However, wear and changes to the geometry of the bodywork are much less intense. The bodywork degradation process is spread out over time, without contributing to sudden damage to the bodywork [4,12,13]. High vehicle mileage, especially on roads in poor technical condition,

contributes to bodywork wear and changes in its geometry [14,15]. The mileage of cars and the conditions in which they were operated have a very significant impact on the extent of changes in the geometry of the floor panel and upper body parts during operation [16–18]. During vehicle operation, various types of reactions are transferred to the bodywork, contributing to gradual wear and changes in body geometry. Every car is subjected to static loads caused by torsional and bending moments resulting from the weight of the vehicle and the suspension system [12,19]. This results in changes to the geometry of the bodywork in the area of the floor panel and upper bodywork. Particularly large changes in geometry can be observed in the area where the front and rear axle suspension components are attached, as this is the area of the body that is subjected to the greatest forces and moments resulting from driving conditions [20,21]. Changes in body geometry, especially around the suspension and steering system components, can contribute to changes in wheel geometry parameters [18,22].

A major challenge associated with vehicle operation is the proper diagnosis and maintenance of vehicles in good technical condition. Design changes in modern vehicles necessitate the introduction of new, advanced diagnostic techniques. An example of such a method is the inspection of the shape and fit of body parts using a 3D optical laser scanner, which is used during production processes [7]. This method is much more advanced than the methods still used to inspect mirror surfaces (body parts) using only human vision [23,24]. When assessing the technical condition and quality of the bodywork during the production process, particular attention is paid to the correctness of the shape and fit of the body panels [25,26]. Any kind of non-compliance not only affects the visual effect, but can also contribute to accelerating the wear and tear of the bodywork during operation and shortening the service life of vehicles [27]. The development of modern diagnostic methods is also moving towards the use of optical and photonic techniques, which enable non-contact assessment of the object under examination [28]. This group of techniques also includes 3D scanning, which enables precise analysis of the geometry of objects and the identification of changes in their shape.

During the operational phase, it is extremely important to ensure that vehicles are in good technical condition, which requires a proper process

for diagnosing individual vehicle components. It is necessary to introduce modern automated diagnostic methods, which in the future could speed up body diagnostics and contribute to increasing their accuracy [18,20]. One direction in the development of this issue could be the use of 3D scanning. Currently, 3D scanning is increasingly used to identify wear processes and changes in the geometry of machine components. However, this technique is mainly used to identify micro-area changes in relatively small working machine components. There is no application of 3D scanning technology for the identification of large-area components [29,30].

3D scanning technology is particularly often used to identify changes in shape and material loss as a result of use. The literature contains studies in which 3D scanning is used to identify the extent of wear and tear on machine components and to determine the correctness of the machining process. For example, 3D scanning technology has made it possible to determine the wear of forging dies used in the production of engine valves [30]. This technique is used to identify volume changes in specific areas of the tools used [29]. These tests can be carried out periodically and compared to a reference model. This allows for quick identification of the current technical condition of the tested elements [29]. 3D scanning also allows the determination of the wear limit value of machine components [31]. Based on 3D scanning, the intensity of wear of working components can be determined with high accuracy [32]. There are also studies in the literature in which 3D scanning was used to identify the amount of wear on plough blades and to assess changes in their geometry [33,34]. 3D scanning has also been used to identify changes in the shape of the working part of plough blades operating in different soil conditions [35].

When identifying changes occurring in vehicles, studies based on digital image correlation (DIC) systems are found in the literature for the analysis of large-area changes. This technique was used to analyse the effect of tyre pressure on tyre deformation in a three-coordinate (3D) system and on vehicle performance parameters [36]. DIC was also used to analyse tyre deformation during movement [37]. The method based on DIC systems was also used by NASA to determine the behaviour of the SCARB rover when descending on a sandy road. Thanks to this technique, it was possible to identify differences in the descent of the front and rear wheels of the vehicle [38]. The

DIC method was also used to identify the impact of changes in vehicle load on the shape and deformation of the tyre and rim, up to the point where the tyre reached its maximum load capacity [39]. Using the DIC method, differences in radial deflection values for several different types of wheels were also identified [40].

An analysis of the methods used to date to assess the technical condition of passenger car bodies shows that there are no methods that allow the identification of changes in more than one parameter related to wear or damage to the body. Each of the methods used to date, namely body geometry measurements, stiffness assessment, measurement of gaps between body components, visual assessment of the condition of the body, assessment of the degree of corrosion, measurements of paint thickness, etc., allows for the diagnosis of changes in only one parameter. These methods are completely independent of each other [20,41]. The primary challenge in evaluating the body's condition is determining the impact of individual parameters on its overall technical condition, which is directly related to the level of safety a given vehicle can provide [18,42]. The question arises as to whether it is possible to develop an innovative method for assessing the technical condition of the bodywork that would take into account changes in the shape (geometry) of the bodywork and the loss of its rigidity.

The main aim of the thesis is to develop a method for identifying changes in many body parameters during operation under the influence of various factors acting on the body during operation, as well as to identify the actual state of deformation of a passenger car body. Another aim is to verify this method during tests on several cars exposed to different operating factors, and to compare the results obtained using the proposed method with those from methods used to date. This method could be used in a quick and automated manner for periodic inspection of the technical condition of the body during operation. The method is based on the technique of 3D scanning of the entire body.

The scope of research conducted in this study included the following stages:

- presentation of the research methodology using the developed 3D scanning method to identify the technical condition of the car body;
- verification by means of 3D scanning of the technical condition of the bodywork of three

passenger cars exposed during operation to different factors contributing to the wear and tear of vehicle components;

- comparison of the results of the technical condition assessment of the car bodies of the tested cars obtained using the proposed method based on 3D scanning with the results of the car body diagnostic methods used so far.

Proposing a 3D scanning method for diagnosing and identifying changes in body geometry during passenger car operation, and then conducting tests using this method on cars exposed to various factors contributing to wear and tear during operation, should be considered a novelty of this work.

METHODOLOGY

For this study, a new method for assessing the condition of passenger car bodies based on 3D scanning of body areas was developed. The method was verified for use in diagnosing passenger car bodies during operation. A diagram with the research methodology is shown in Figure 1. Experimental tests were carried out on three vehicles manufactured by the same car manufacturer. During their operation to date, each of the cars had been exposed to different operating conditions, contributing to the degradation of the bodywork and changes in its geometry. Each of the cars belonged to the B segment according to the European classification and had a five-door hatchback body. The first was an eight-year-old car (Figure 1a) with a mileage of 115,000 km, operated by a private individual mainly on high-standard roads. The vehicle was involved in a road collision and subsequently had the left side of the bodywork repaired. The sill, B-pillar, and front and rear doors were replaced. The A- and C-pillars, bonnet, and front and rear wings were repaired (straightened and filled). The second car (Figure 1b) was three years old at the time of the inspection and had a mileage of 110,000 km. This vehicle had been used as a company car by several drivers. It had not undergone any previous bodywork repairs. The third car (Figure 1c), on the other hand, had a mileage of approximately 50,000 km and had been used for about a year by a single driver. This vehicle had also not been involved in any road collisions. During the operation of this vehicle, no conditions exceeding

standard operation were recorded. All the cars tested had engines with a displacement of approximately 1.2 dm^3 with spark ignition and were equipped with five-speed manual gearboxes. All the cars tested had McPherson independent suspension on the front axle and semi-independent suspension with a torsion beam on the rear axle. In the course of his previous research, the author found that the operating conditions of vehicles and their mileage have a significant impact on changes in body geometry. To a lesser extent, changes in body geometry are influenced by the vehicles' design parameters. Three cars with similar design parameters were selected for the study, but which had been exposed to different factors causing body wear during use and had varying mileage, as this allowed the suitability of the proposed diagnostic method for testing different vehicles to be verified. As the cars selected had different mileage and had been operated under different conditions, there were significant differences in changes to the body geometry between these vehicles. If the vehicles had been identical, the differences in geometry between them would have been minimal, and the suitability of the method for diagnostic testing would have been more difficult to verify.

The Scan3D Surface scanner (Figure 2) with a 5MPix matrix, a resolution of 0.5 mm, and a

measuring volume of $1400 \times 1000 \times 500$ was used for the 3D scanning of the car body. The non-contact device emitted an LED light source. The Scan3D Surface scanner was equipped with two high-class detectors, supporting two independent volumes.

Identifying changes in the technical condition of the bodywork using 3D scanning consisted of three main stages:

- determining the geometry of the bodywork by means of 3D scanning;
- processing and preparing the data for analysis using appropriate software;
- analysing the condition of the bodywork by comparing shape parameters and determining differences.

In order to identify the condition of the body in terms of body rigidity control, additional loads were applied to the vehicle, particularly to its body. For this purpose, two wheels of the vehicles (the front left and rear right wheels) were lifted by driving onto specially prepared plates (Figure 3). During the tests using 3D scanning, the geometry of the right side of the bodywork was compared with the left side. Any discrepancies in shape and differences in position between symmetrical parts of the vehicle bodywork may indicate that its technical condition is poor.

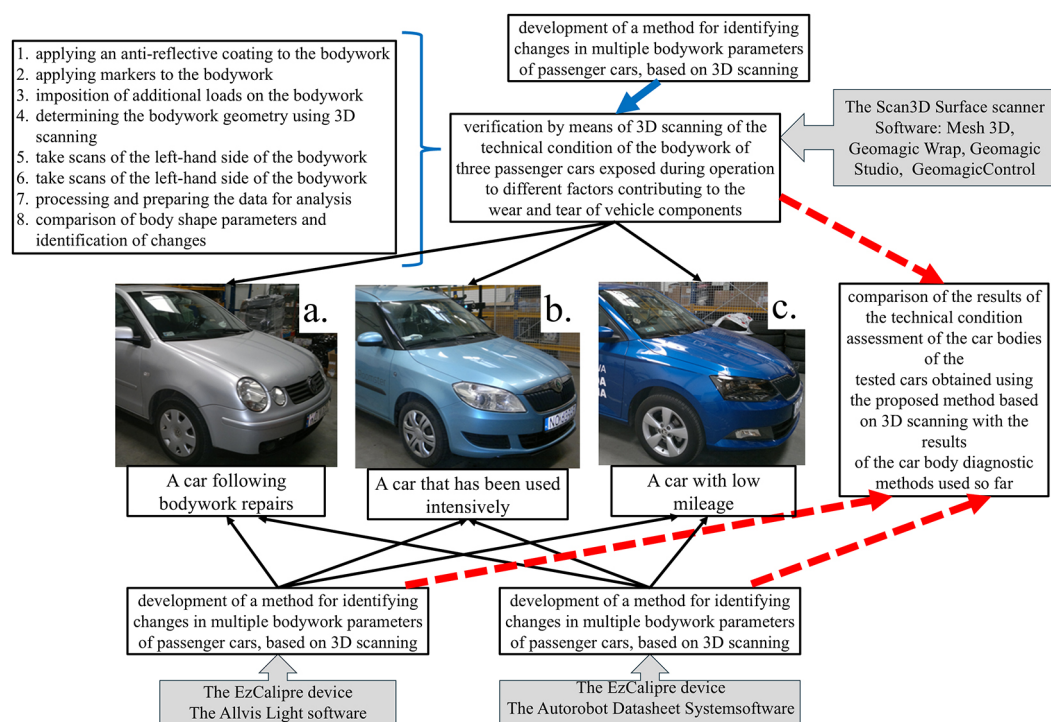


Figure 1. Diagram with the research methodology

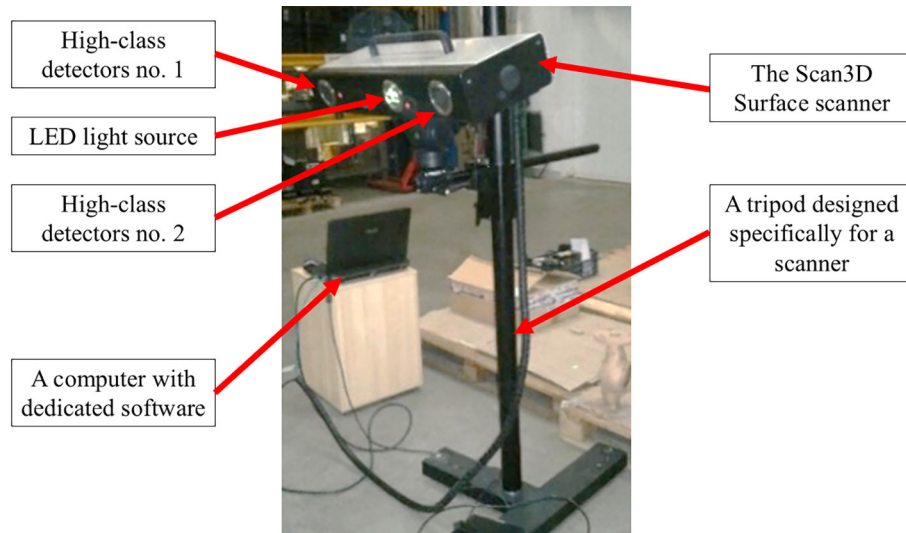


Figure 2. Scan3D Surface scanner used during research



Figure 3. Plates allowing additional loads to be applied to the bodywork

After applying a special washable preparation to the bodywork, which caused it to become matte and prevented light reflections that would interfere with the scanning process, special adhesive markers were placed on the bodywork to automate the process of matching the scanned fragments of the bodywork during data processing. Then, the right side of the vehicles was scanned, followed by the left side. During the scanning of each side of the bodywork, between a dozen and more than twenty individual scans were performed, which were then combined using markers. Laser pointers installed on the scanner were used to position the individual scans. Each scan resulted in a point cloud, where each point was described in three coordinates: x , y , z . The following software was used to process the results of 3D body scanning measurements and data analysis: Mesh 3D, Geomagic Wrap, Geomagic Studio, and Geomagic Control.

After performing a 3D scan of the bodywork, measurements of the body geometry were taken using traditional methods and diagnostic tools. For this purpose, a modern EzCalipre device

from Autorobot was used. It was a mobile device. Measurements using the EzCalipre device were performed on a two-post lift. During the body geometry measurements, it was not necessary to remove any covers or components attached to the vehicle floor panel. The accuracy of the measurements taken with this device was 1 mm. During the floor panel geometry measurements, a change in the distance between the individual base points (1, 2, 3, 4, 5, and 6) and the reference points (D) shown in Figure 4 was identified. The measurements were taken for the right and left sides of the floor panel.

During measurements of the upper body geometry, the position of each of the 15 reference points on the right and left sides of the body was identified in three coordinates relative to the corresponding reference planes. The reference points are shown in Figure 5. For this study, the distance by which each point was displaced was calculated.

Allvis Light software was used to measure the geometry of the floor panel, and Autorobot Data System software was used to measure the

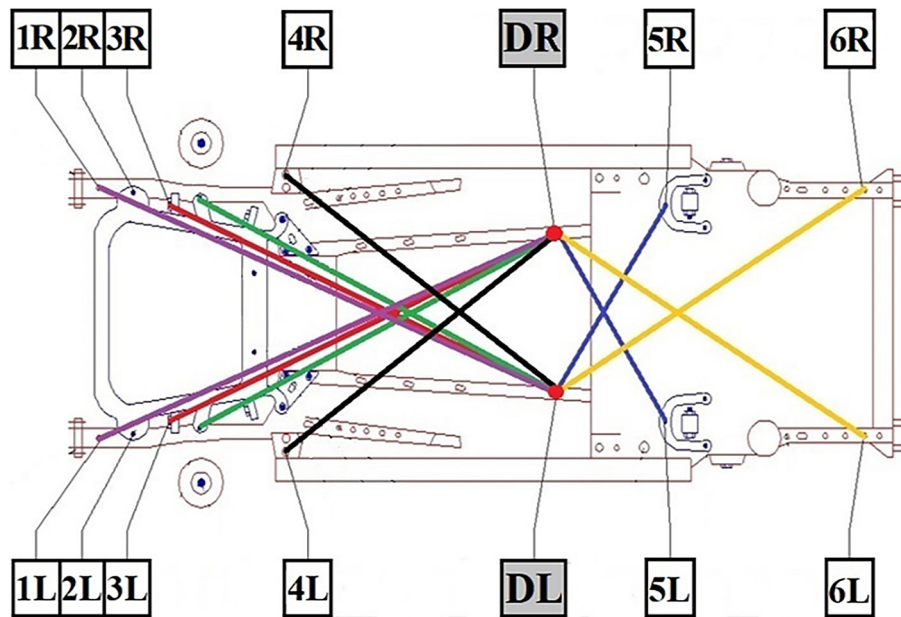


Figure 4. Vehicle's floorpan view in Allvis Light software, where: 1 – points in front longitudinal members, 2 – fixing points for the front suspension, 3 – fixing points for front profile, 4 – points in the vicinity of bulkhead wall, 5 – fixing points for rear suspension, 6 – points in rear longitudinal members, D – reference points used during measurements, P – right-hand side, L – left-hand side

geometry of the upper body parts. During the measurements, a database contained in both programmes was used, with information on the location of all available reference points of the floor panel and upper body parts.

RESULTS

The first tests were performed on a car that had undergone bodywork repairs on the left side after a road collision. The right side of the vehicle had never been repaired. During the scanning stage, the positions of 502,829 points on each side of the vehicle were identified. Figure 6 shows the results of the 3D scan of the accident-damaged car. Several intervals with different values were defined, representing the range of changes in the positions of points between the right and left sides. The critical ranges were those for which the largest deviations between the right and left sides of the vehicle were recorded, amounting to ± 30 mm. In turn, the smallest deviations between the right and left sides, amounting to ± 0.5 mm, were observed for the nominal ranges. In many areas of the bodywork, significant deviations in the position of points between both sides of the vehicle were found. Table 1 shows the number of points falling within the given deviation ranges

between the right and left sides, as well as the percentage share of these points in the given ranges.

In the case of the vehicle described, only 14% of the points fell within the range where the deviations in the position of the points between the right and left sides of the vehicle did not exceed ± 0.5 mm. The largest number of points, almost 74%, fell within the range where the difference was between 0.5 mm and 5 mm. Unfortunately, as many as 10% of the points fell within the range where the differences were between 5 and 10 mm. The difference between the positions of points above 10 mm affected 2% of the vehicle's surface.

For the tests carried out on the car described, the standard deviation was 6.4656. Table 2 shows the number of points falling within the standard deviation ranges. For example:

- for a standard deviation in the range from $-\sigma$ to σ (in this case from -6.4656 to 6.4656 mm), there were $217,887 + 254,779 = 472,666$ points, or 94.0013% of the points;
- while for a standard deviation in the range from -3σ to 3σ (in this case ± 19.3968 mm, or 3×6.4656), there were $217,887 + 254,779 + 22,671 + 1,485 = 496,822$ points, or 98.8053% of the points.

Figures 7, 8 and 9 show the differences in the position of the relevant points between the left

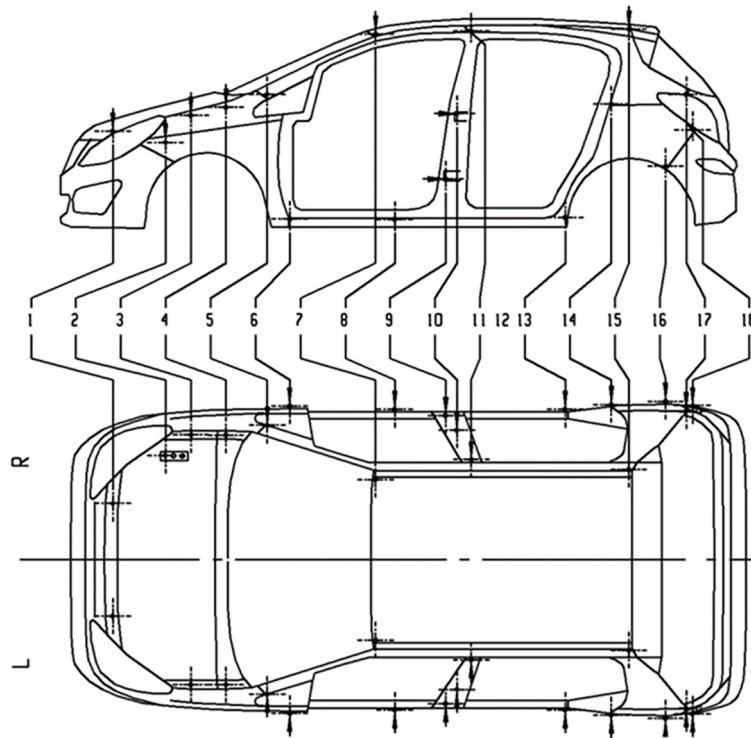


Figure 5. Measurement points on the upper parts of the bodywork for an example car [example card from the Autorobot Datasheet System programme], where: 1. Front reinforcement; 2. Start of wing reinforcement; 3. End of wing reinforcement; 4. Start of sill; 5. Centre of A-pillar; 6. Top of A-pillar; 7. Bottom of B-pillar; 8. Centre of B-pillar; 9. Top of B-pillar; 10. End of sill; 11. Centre of C-pillar; 12. Top of C-pillar; 13. End of rear wheel arch; 14. Bottom end of rear mudguard; 15. Top end of rear mudguard

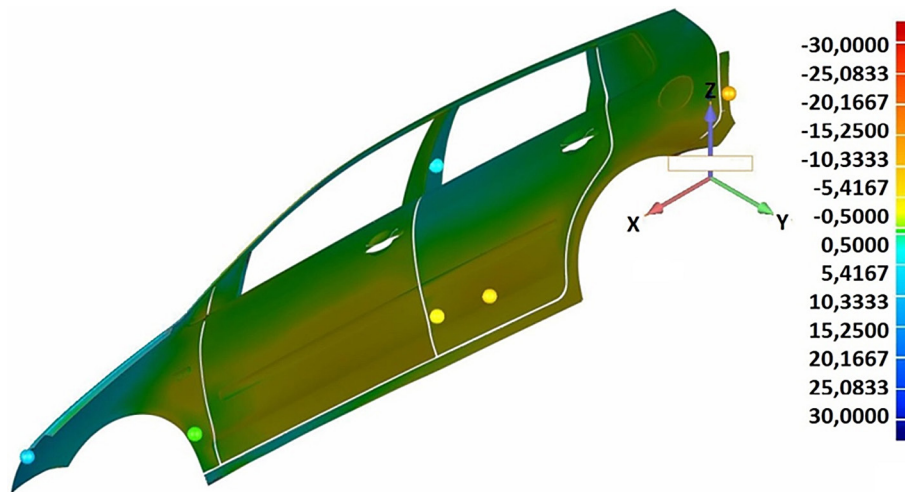


Figure 6. Results of 3D scanning of the bodywork of a damaged car

and right sides of the vehicle (deviations between symmetrical parts of the vehicle) that were identified during the 3D scanning of the bodywork.

Significant bodywork deformations and distortions were found in the tested car after lifting two wheels. Significant deviations in the position of points between both sides of the vehicle were noted in many parts of the bodywork of this car.

Very large negative deviations could be observed on the front fender, the beginning of the front sill, the middle part of the rear door, and the front door frame. On the other hand, large positive deviations were visible in the rear part of the sill, the lower part of the rear fender, the lower part of the rear door, and the front door. Such large differences between the right and left sides of the

Table 1. Results of 3D scanning of the bodywork of a damaged car

No.	Range [mm]	Number of points in the range	Percentage share
1	Below -30	2238	0.4451
2	(-30,0000;-25,0833)	344	0.0684
3	(-25,0833;-20,1667)	403	0.0801
4	(-20,1667;-15,2500)	474	0.0943
5	(-15,2500;-10,3333)	557	0.1108
6	(-10,3333;-5,4167)	25272	5.0260
7	(-5,4167;-0,5000)	128486	25.5526
8	(-0,5000;0,5000)	74895	14.8947
9	(0,5000;5,4167)	242649	48.2568
10	(5,4167;10,3333)	24976	4.9671
11	(10,3333;15,2500)	378	0.0752
12	(15,2500;20,1667)	123	0.0245
13	(20,1667;25,0833)	103	0.0205
14	(25,0833;30,0000)	136	0.0270
15	Above +30	1795	0.3570

bodywork indicate not only changes in the geometry of the bodywork, but also a lack of adequate bodywork rigidity, which was caused by improperly performed bodywork repairs.

Slightly different results were obtained in the case of a car used intensively by several drivers. In this case, during the 3D scanning stage, the location of 3,718,211 points on each side of the vehicle was identified. For this car, the critical areas were those where the deviations between the right and left sides of the vehicle were greatest, amounting to ± 20 mm. In contrast, the smallest deviations occurred in the nominal areas and amounted to less than ± 0.5 mm. Figure 10 and Table 3 show the results of a 3D scan of the

bodywork of a car that had been used intensively by several drivers. As in the case of the first vehicle, there were significant differences between the positions of points on the right and left sides in many areas of the bodywork.

Only about 25% of points were in the range where the deviations between the right and left sides of the vehicle did not exceed ± 0.5 mm. In the next range, where the difference was between 0.5 mm and 3.75 mm, there were 63% of points. As many as 10% of points fell within the range where the difference was between 3.75 mm and 7 mm. Approximately 1% of points fell within the range where the differences between the right and left sides exceeded 10 mm. For the analysed

Table 2. Number of points falling within individual standard deviation ranges for a damaged car

Range	Number of points	Percentage share
$(-6\sigma \div -5\sigma)$	2121	0.4218
$(-5\sigma \div -4\sigma)$	451	0.0897
$(-4\sigma \div -3\sigma)$	555	0.1104
$(-3\sigma \div -2\sigma)$	640	0.1273
$(-2\sigma \div -\sigma)$	22671	4.5087
$(-\sigma \div 0)$	217887	43.3322
$(0 \div \sigma)$	254779	50.6691
$(\sigma \div 2\sigma)$	1485	0.2953
$(2\sigma \div 3\sigma)$	203	0.0404
$(3\sigma \div 4\sigma)$	138	0.0274
$(4\sigma \div 5\sigma)$	192	0.0382
$(5\sigma \div 6\sigma)$	1707	0.3395

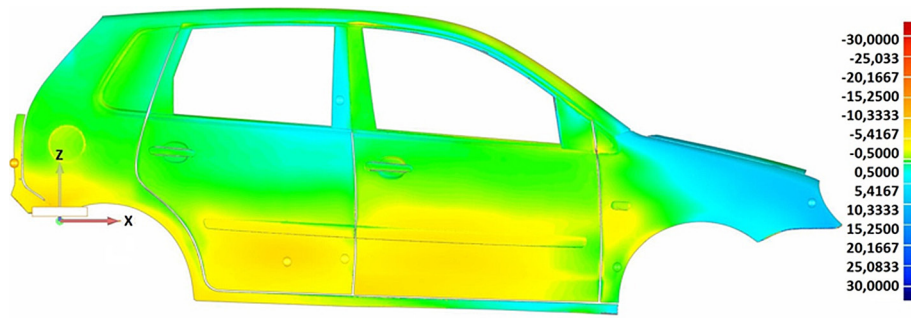


Figure 7. View from the right side of a car body after an accident

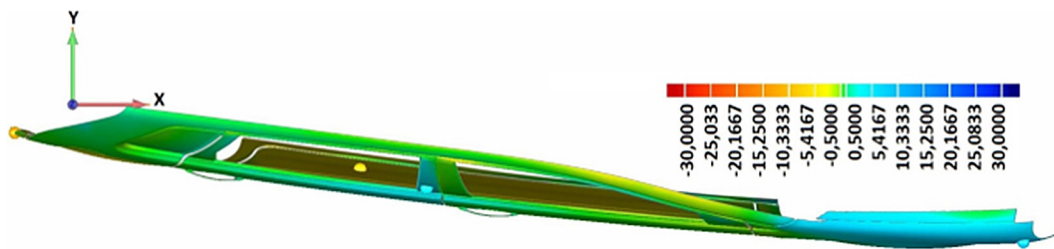


Figure 8. View from above the vehicle to the right side of a car body after an accident

Table 3. Results of 3D scanning of the body of a heavily used car

No.	Range [mm]	Number of points in the range	Percentage share
1	Below -20	19684	0.5294
2	(-20,0000; -16,7500)	2820	0.0758
3	(-16,7500; -13,5000)	3075	0.0827
4	(-13,5000;-10,2500)	3610	0.0971
5	(-10,2500; -7,0000)	5512	0.1482
6	(-7,0000;-3,7500)	141167	3.7966
7	(-3,7500; -0,5000)	1142076	30.7157
8	(-0,5000; 0,5000)	925455	24.8898
9	(0,5000; 3,7500)	1189267	31.9849
10	(3,7500; 7,0000)	235428	6.3318
11	(7,0000; 10,2500)	43728	1.1760
12	(10,2500; 13,5000)	2463	0.0662
13	(13,5000; 16,7500)	465	0.0125
14	(16,7500; 20,0000)	392	0.0105
15	Above +20	3069	0.0825

vehicle, which was heavily used, the standard deviation for the tests was 4.5642. Table 4 shows the number of points falling within the standard deviation ranges. For example:

- for a standard deviation in the range from $-\sigma$ to σ (in this case from -4.5642 to 4.5642 mm), there were $1722776+1650294=3373070$ points, or 90.7176% of the points.
- while for a standard deviation in the range from -3σ to 3σ (in this case ± 13.6926 mm,

or $3*4.5642$), there were $1,722,776+1,650,294+98,527+205,972=3,677,569$ points, or 98.9069% of the points.

Figures 11, 12 and 13 show the results of measurements taken during 3D scanning of the bodywork, illustrating the deviations between symmetrical parts of the vehicle.

Based on the analysis of the test results presented in the figures, it can be concluded that

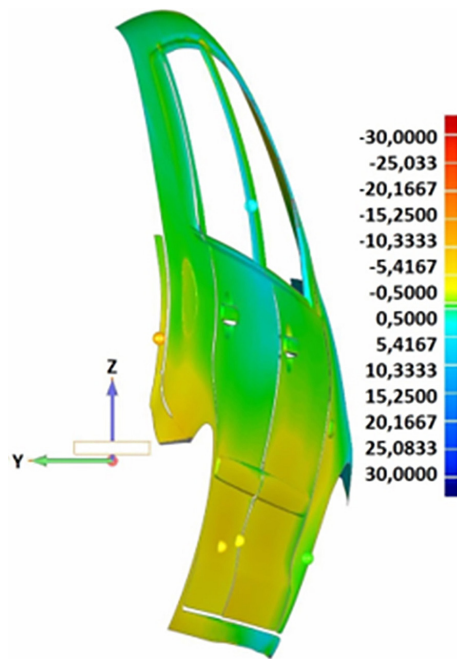


Figure 9. View from the rear of the vehicle on the right side of a car body after an accident

although the vehicle was not involved in any collision, its bodywork showed significant deformation. Significant deformation appeared after lifting two wheels of the car. This was visible in many areas of the bodywork. The deviations in the position of the points between the right and left sides of the vehicle body were significant. Negative deviations occurred in the rear part of the sill, in the lower part of the rear fender, in the upper part of the front door, on the A-pillar, and in the front part of the roof gutter. Positive deviations were visible on the D-pillar, in the upper part of the rear fender, in the rear part of the roof gutter, in the front part of the sill, in the lower part of the front door, and in the lower part of the front fender. This car also suffered a loss of body rigidity. Both the changes in body geometry and the loss of rigidity are the result of intensive use of the vehicle by many drivers who were not directly responsible for maintaining the vehicle in proper technical condition.

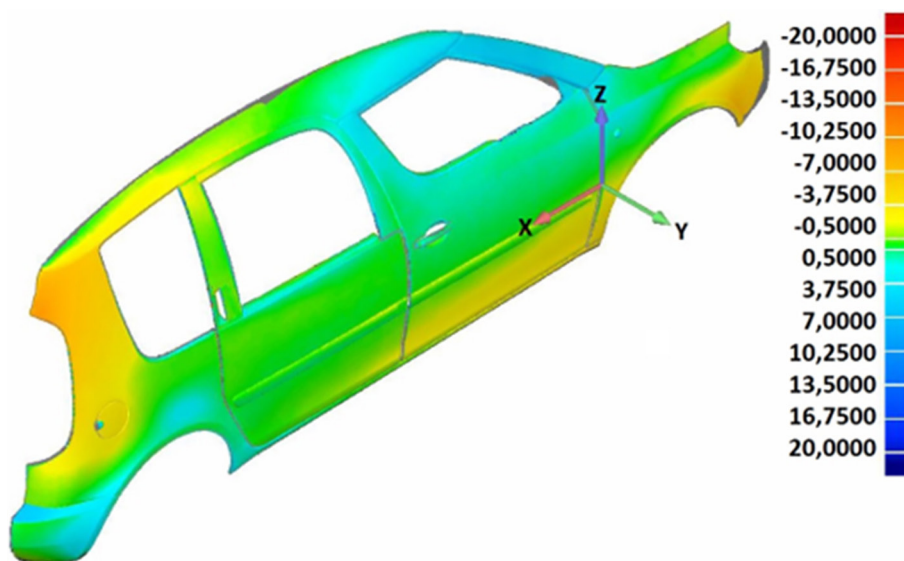


Figure 10. Results of 3D scanning of the body of a heavily used car

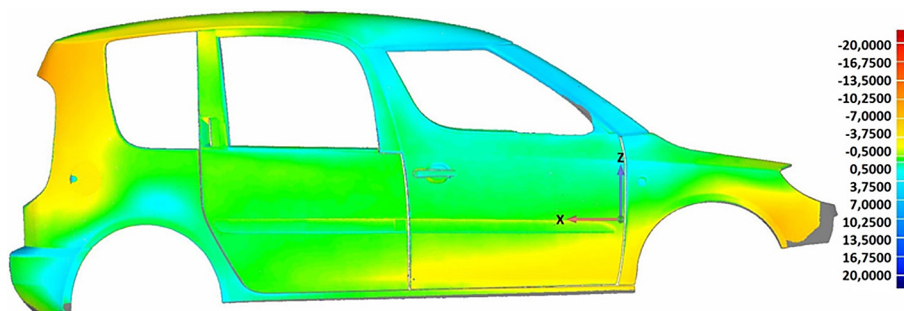
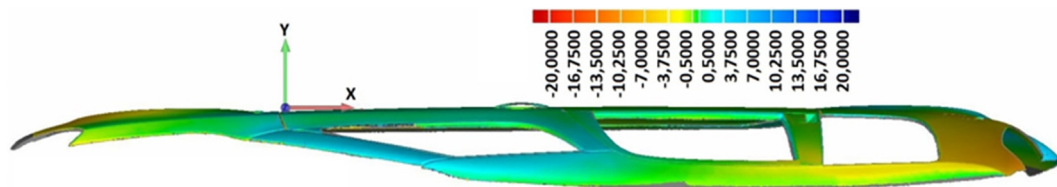


Figure 11. View from the right side of the bodywork of a heavily used car

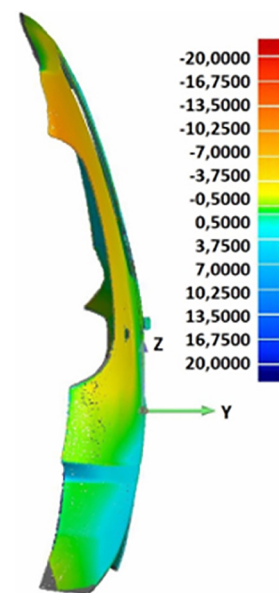
Table 4. Number of points falling within individual standard deviation ranges for a heavily used car

Range	Number of points	Percentage share
$(-6\sigma \div -5\sigma)$	18019	0.4846
$(-5\sigma \div -4\sigma)$	3322	0.0893
$(-4\sigma \div -3\sigma)$	4146	0.1115
$(-3\sigma \div -2\sigma)$	5189	0.1396
$(-2\sigma \div -\sigma)$	98527	2.6498
$(-\sigma \div 0)$	1722776	46.3335
$(0 \div \sigma)$	1650294	44.3841
$(\sigma \div 2\sigma)$	205972	5.5395
$(2\sigma \div 3\sigma)$	6076	0.1634
$(3\sigma \div 4\sigma)$	630	0.0169
$(4\sigma \div 5\sigma)$	480	0.0129
$(5\sigma \div 6\sigma)$	2780	0.0748


Figure 12. View from above the vehicle to the right side of the bodywork of a heavily used car

The next car to undergo 3D scanning was the vehicle with the lowest mileage, used under standard operating conditions by a single driver. In this case, 1,384,793 points were identified on each side of the vehicle during the testing phase. In the case of this car, several intervals were also selected during the analysis, for which the number of points falling within these intervals was determined. As in the case of the second vehicle, the critical intervals were those for which the largest deviations between the right and left sides of the vehicle occurred, amounting to ± 20 mm. In turn, the nominal ranges for this vehicle were those for which the deviations between the right and left sides of the vehicle were the smallest, amounting to ± 0.5 mm. The results of the 3D scan of the third car are presented in Figure 14 and Table 5. In this car, there were many smaller differences between the positions of the points on the right and left sides of the vehicle than in the previous vehicles.

Nevertheless, this vehicle also exhibited relatively large differences between the right and left sides, which may be related to the relatively low rigidity of the vehicle body. Based on the analysis of the measurement results, it was found that over 27% of the points were within a range where the


Figure 13. View from the rear of the vehicle to the right side of the bodywork of a heavily used car

deviations in position between the right and left sides of the vehicle did not exceed ± 0.5 mm. The majority, over 65% of points, were within the range where the difference between the right and left sides was between 0.5 mm and 3.75 mm. In the case of 7% of points, it was found that they were within the range where the difference between the

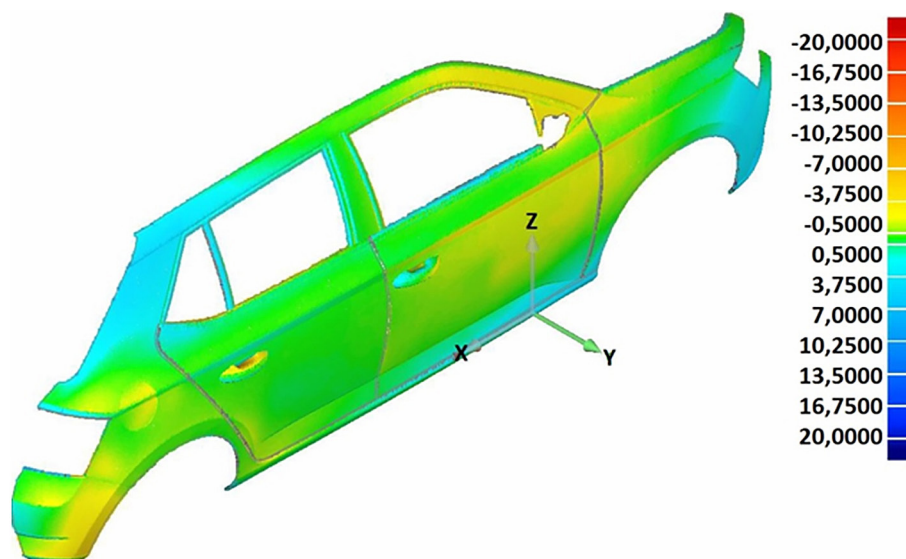


Figure 14. Results of 3D scanning of the body of a car with low mileage

Table 5. Results of 3D scanning of the body of a car with low mileage

No.	Range [mm]	Number of points in the range	Percentage share
1	Below -20	8	0.0006
2	(-20,0000; -16,7500)	0	0
3	(-16,7500; -13,5000)	14	0.001
4	(-13,5000;-10,2500)	60	0.0043
5	(-10,2500; -7,0000)	2557	0.1846
6	(-7,0000;-3,7500)	58709	4.2396
7	(-3,7500; -0,5000)	381691	27.563
8	(-0,5000;0,5000)	377360	27.2503
9	(0,5000; 3,7500)	521980	37.6937
10	(3,7500; 7,0000)	38465	2.7777
11	(7,0000; 10,2500)	2270	0.1639
12	(10,2500; 13,5000)	576	0.0416
13	(13,5000; 16,7500)	196	0.0142
14	(16,7500; 20,0000)	135	0.0097
15	Above +20	772	0.0557

two values was between 3.75 mm and 7 mm. Only about 0.1% were in the range where the difference in point position was greater than 10 mm. The standard deviation for the tests in the third car was 2.9695. Table 6 shows the number of points within the standard deviation ranges. For example:

- for a standard deviation in the range from $-\sigma$ to σ (in this case from -2.9695 to 2.9695 mm), there were $522,038 + 668,897 = 1,190,935$ points, or 86.0009% of the points.
- however, for a standard deviation in the range from 3σ to 3σ (in this case ± 8.9085 mm, or 3×2.9695), there were $117,560 + 522,038 + 668$

$,897 + 64,461 = 1,372,956$ points, or 99.1452% of the points.

Figures 15, 16 and 17 show the deviations between the symmetrical parts of the vehicle on the right and left sides obtained during 3D scanning. Unlike the two previous vehicles, which underwent 3D scanning, it can be concluded that the bodywork of the car with the lowest mileage, which was used by a single driver, had significantly less deformation. In the case of this car, there was much less deformation after lifting two wheels of the vehicle. In many areas of the

Table 6. Number of points falling within individual standard deviation ranges for a car with low mileage

Range	Number of points	Percentage share
$(-6\sigma \div -5\sigma)$	16	0.0012
$(-5\sigma \div -4\sigma)$	15	0.0011
$(-4\sigma \div -3\sigma)$	371	0.0268
$(-3\sigma \div -2\sigma)$	5511	0.398
$(-2\sigma \div -\sigma)$	117560	8.4894
$(-\sigma \div 0)$	522038	37.6979
$(0 \div \sigma)$	668897	48.303
$(\sigma \div 2\sigma)$	64461	4.6549
$(2\sigma \div 3\sigma)$	3737	0.2699
$(3\sigma \div 4\sigma)$	959	0.0693
$(4\sigma \div 5\sigma)$	175	0.0126
$(5\sigma \div 6\sigma)$	1053	0.076

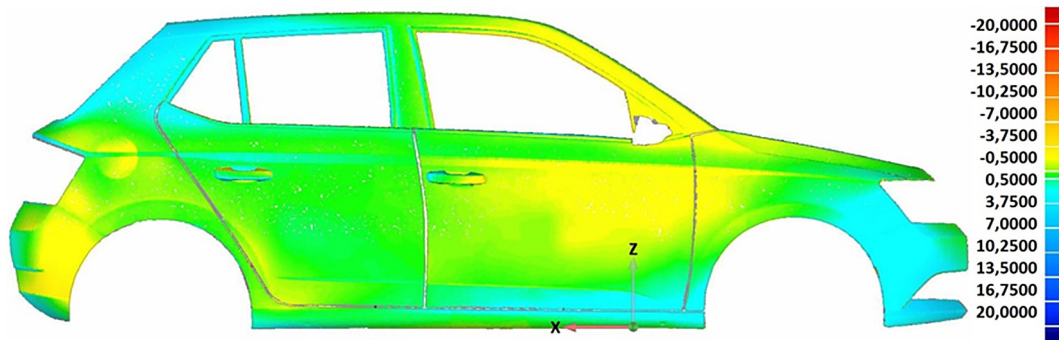


Figure 15. View from the right side of the bodywork of a car with low mileage

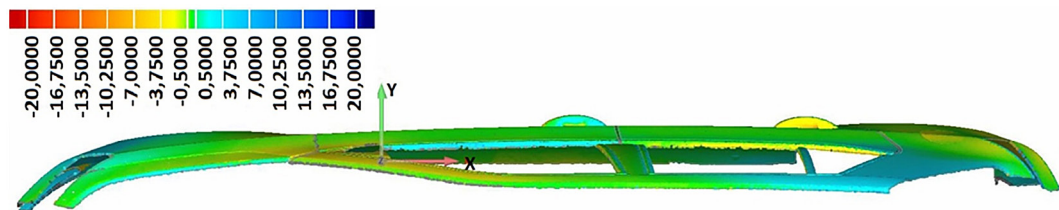


Figure 16. View from above the vehicle to the right side of the bodywork of a car with low mileage

bodywork, there were much smaller deviations in the position of points between the two symmetrical sides of the car body. Negative deviations occurred in the front part of the sill, the lower part of the front doors, around the C-pillar, the front part of the front fender and the front bumper. Positive deviations, on the other hand, occurred in the area of the A-pillar, in the middle of the front door, on the rear bumper, and in the middle of the rear fender. The deformations occurring in the body of this car were due to a certain loss of body stiffness, but they were significantly smaller than in the case of the two vehicles described above.

In order to verify whether the method based on 3D scanning of the bodywork allows for the identification of changes in the geometry of passenger car bodywork during operation, which depend on the impact of varying operating conditions, tests were carried out using the bodywork geometry measurements used to date. Measurements of the floor panel and upper body geometry were performed on all three cars using the EzCalipre device from Autorobot.

The results of changes in the geometry of the floor panel on the left and right sides of the tested cars are shown in Figures 18 and 19, respectively. On the left side of the body (Figure 18),

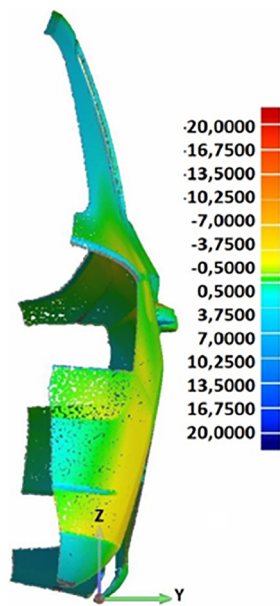


Figure 17. View from behind the vehicle to the right side of the bodywork of a car with low mileage

the greatest changes in the geometry of the floor panel were found in car S1, which was involved in a road collision and underwent bodywork repairs after the accident. The difference between the required and actual position of the reference point located on the front longitudinal member was 17 mm. The difference between the required and actual position of the reference point on the rear longitudinal member was 8 mm. In car S2, which was used intensively by many drivers, significantly smaller displacement values were found for both points in the described area. They were 3 mm and 1 mm, respectively. In contrast, in car

S3, which was used by a single driver and had low mileage, no changes in geometry were found on the left side of the vehicle for both side members. The reference point located near the bulkhead on the left side was displaced by 4 mm in the car after a road collision and by 1 mm in the car that had been used intensively. However, in the car with the lowest mileage, this point did not shift at all during operation. Changes in the geometry of the floor panel within the base points responsible for active safety, i.e., the points where the front suspension, front suspension bench, and rear suspension are attached, were also greatest in the car that had undergone bodywork repairs after a road collision. In the case of this vehicle, the displacements of the points were 12 mm, 13 mm, and 10 mm, respectively. Significantly smaller values of base point displacement were found in a car that had been used intensively by several drivers for business purposes. In this car, the difference between the required and actual position of the base point attaching the front suspension was 6 mm, the base point attaching the front suspension bench was also 6 mm, and the base point attaching the rear suspension was 4 mm. In the car with the lowest mileage, which was used by only one driver, all three points had the smallest displacement, which was only 1 mm. Based on the measurement results presented in the figure, it can be concluded that the previous use of the vehicles and conditions exceeding standard use had a significant impact on the extent of changes in the body geometry of the tested cars. Particularly large changes in the geometry of the floor panel were found in car S1, which was involved in a road collision and

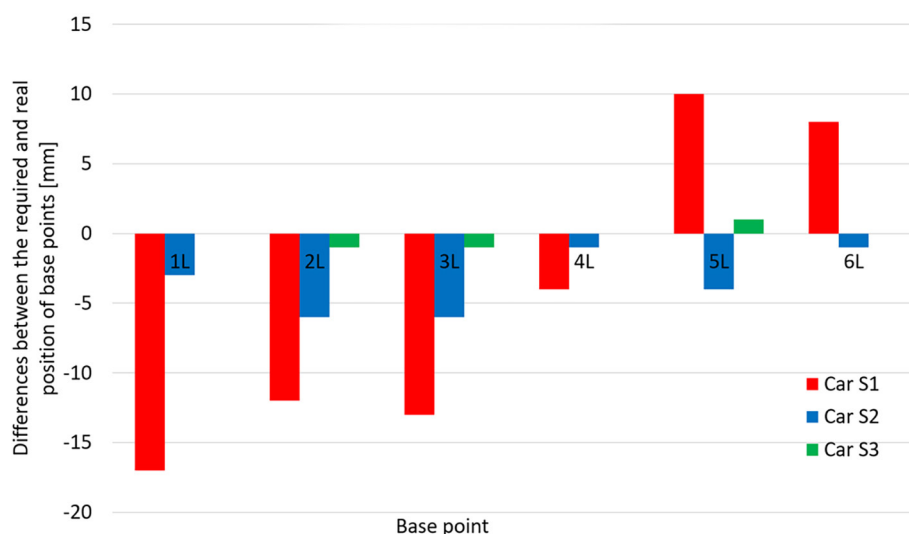


Figure 18. Results of measurements of changes in the geometry of the floor panel on the left side in the tested cars

underwent bodywork repairs on the left side of the vehicle after the accident. The displacement values of all analysed points exceeded the permissible change values, i.e., 3 mm. In the case of car S2, which had been used intensively, the displacement of the reference points also exceeded the permissible change values, i.e., 3 mm. However, in this car, this only applied to the suspension mounting points and the suspension bench.

Figure 19 shows the results of measurements of changes in the geometry of the floor panel on the right side of the tested cars. The nature of the changes is slightly different from that on the left side of the vehicles. In car S3, as on the left side of the vehicle, no changes in geometry were found on the right side within the reference points located on the front and rear side members and in the vicinity of the bulkhead. In contrast, in car S1, in which the left side of the vehicle was repaired after a road collision, a displacement of 11 mm was found in the reference point on the front longitudinal member and 3 mm in the reference point on the rear longitudinal member. The point located in the vicinity of the bulkhead moved by 1 mm. In car S2, which had been used intensively by several drivers, the reference points on the right side of the front and rear side members were found to have shifted by 4 mm and 2 mm, respectively, and the point near the bulkhead wall had also shifted by 2 mm. The smallest displacements of base points related to active safety were found in car S3. The mounting points for the front suspension, front bench, and rear suspension moved by 2 mm. In car S1, which had undergone bodywork repairs after a road collision, and in car S2, which had been used intensively by many drivers, a similar level of geometric change was found within these three points. In car S1, the front suspension mounting point moved by 9 mm, and in car S2 by 8 mm. The front suspension mounting point moved by 8 mm in car S1 and by 7 mm in car S2. The rear suspension mounting point in these cars moved by 5 mm and 4 mm, respectively. The significantly greater changes in the geometry of the floor panel on the left than on the right in car S1, which had undergone bodywork repairs, were because the left side of the vehicle was seriously damaged in a road collision. However, the base points on the right side were also displaced as a result of the forces generated during the impact, causing deformation. Unfortunately, the bodywork repair of this vehicle did not restore the floor panel to its proper geometry. In turn, in the S2 car, which was used

intensively by many drivers, greater changes in the geometry of the floor panel on the right side of the vehicle were found. These changes were the result of forces and moments acting on the bodywork due to traffic conditions. The values of these changes resulted from the mileage of the vehicles and the nature of their previous use. The greater displacement of points on the right-hand side than on the left-hand side was caused by the poorer condition of the road infrastructure on the right-hand side of the road than on the centre line. In addition, the suspension and steering components are subjected to high forces and moments when parking and driving up kerbs, which contribute to greater changes in the geometry of the bodywork. In the S3 car, which was used by a single driver and had relatively low mileage, greater displacement of the reference points on the right side of the floor panel than on the left could also be observed. These changes were also the result of the same factors. The fact that significant forces and moments resulting from driving conditions act on the bodywork is largely confirmed by the deformation of the floor panel in the area of the front suspension mounting points, the front suspension bench, and the rear suspension. In this car, due to its low mileage, only minor deformations were found in this area. No displacement of the other points has been found yet.

The results of the floor panel geometry measurements allowed for accurate identification of the extent and nature of deformation of this part of the bodywork. Significant differences in the displacement values of the reference points were found between the tested cars, which were the result of various factors contributing to wear and tear on the bodywork. To summarise the results of the floor panel geometry measurements, it can be concluded that the greatest deformations of the floor panel, i.e., the greatest differences between the required and actual positions of the reference points in this area, occurred in car S1, which had undergone bodywork repairs after a road collision. Smaller changes in geometry occurred in car S2, which was used intensively by several drivers. On the other hand, the smallest displacements of the reference points occurred in car S3, which had the lowest mileage and was used by a single driver. The same relationships resulted from measurements obtained using the proposed and developed method of 3D scanning of the bodywork.

The results of changes in the geometry of the upper parts of the bodywork on the left and

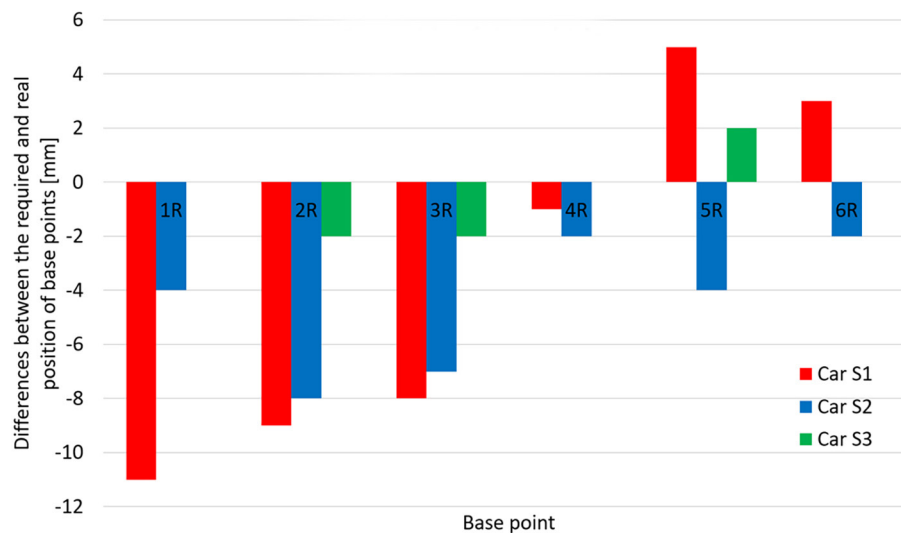


Figure 19. Results of measurements of changes in the geometry of the floor panel on the right side in the tested cars

right sides of the tested cars are presented for vehicles S1, S2, and S3 in Figures 20, 21, and 22, respectively. In car S1, which underwent bodywork repairs after a road collision, there were

significant changes in the geometry of the upper body parts. These changes are shown in Figure 20. Significantly greater changes in geometry within the same reference points occurred on the

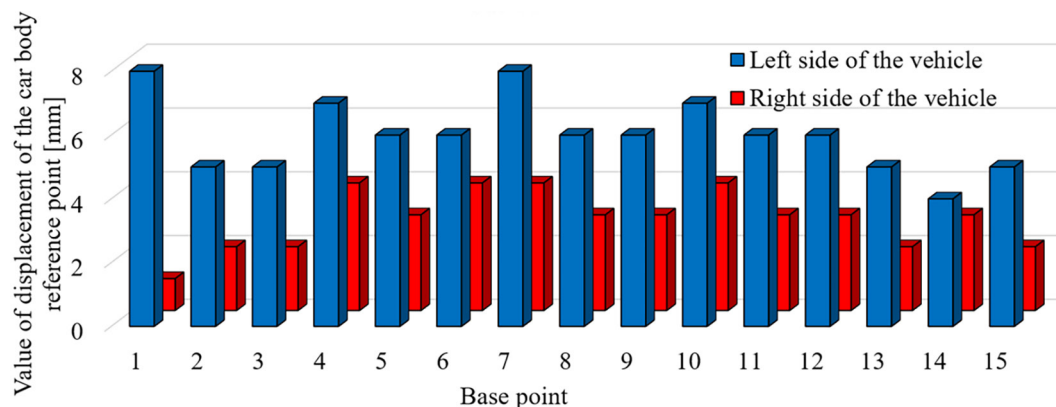


Figure 20. Results of measurements of changes in the geometry of the upper parts of the body in car S1, which underwent bodywork repairs after a road collision

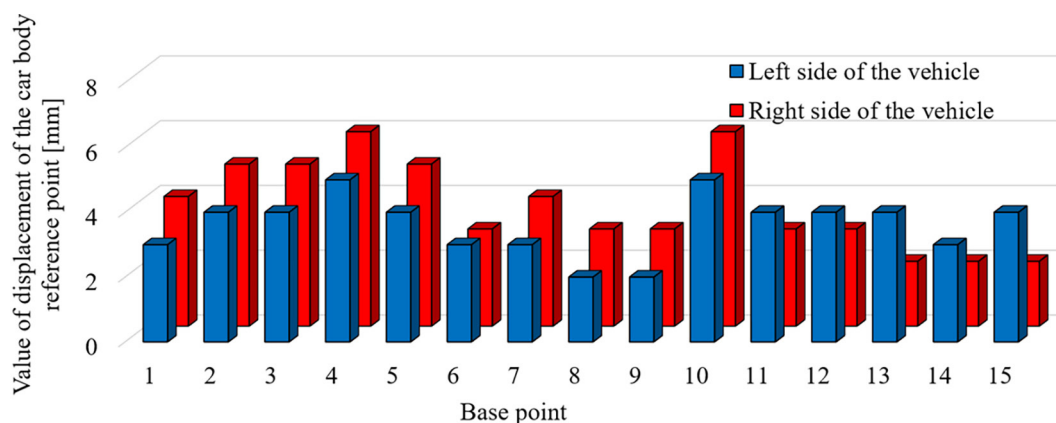


Figure 21. Results of measurements of changes in the geometry of the upper parts of the body in car S2, which was intensively used by many drivers

left side than on the right side of the bodywork. This was due to the impact on the left side of the vehicle during the collision and the significant extent of deformation of this part of the car. Although the impact occurred on the left side of the vehicle and caused greater deformation on the left side, the deformation also affected the right side of the vehicle. This was due to the impact of the forces generated during the collision on the load-bearing structure of the entire body. In this car, the greatest displacements on the left side were found at points located on the front reinforcement and in the lower part of the A-pillar. They amounted to 8 mm. On the right side, they were 1 mm and 4 mm, respectively. Significant displacements on the left side were also found at the points located at the beginning and end of the sill. These displacements amounted to 7 mm. On the right side, they amounted to 4 mm each. In the case of many points, a displacement of 6 mm was observed. These were points located in the middle and at the top of posts A, B, and C (points 5, 6, 8, 9, 11, and 12). On the right-hand side, most of these points were displaced by 3 mm, except the point at the top of pillar A, which was displaced by 4 mm. The points at the beginning and end of the front fender reinforcement, at the end of the rear wheel arch, and at the end of the rear fender at the top moved 5 mm on the left side and 2 mm on the right side. On the left side, the smallest displacement of the reference point on the upper parts of the body was found for the point located at the end of the rear mudguard at the bottom. It was 4 mm. On the right side, it was 3 mm. On the left side of the body, it was found that the displacement of all reference points in the upper parts of the body exceeded the permissible displacement values for reference points, i.e., 3 mm. This indicates significant deformation of the body and improper bodywork repair. Even on the right side of the bodywork, it was found that the displacement of some of the reference points exceeded 3 mm. The results of measurements of changes in the geometry of the upper parts of the body confirm, similarly to the results of measurements using the method proposed in the thesis, based on 3D scanning of the body and the results of measurements of the geometry of the body floor panel, that in the tested S1 car, there were significant deformations of the entire body structure. As a result of the described changes in geometry, both passive and active safety levels may be reduced in this car.

The results of measurements of the geometry of the upper body parts in the S2 car, which was intensively used by many drivers, are presented in Figure 21. Based on the measurement results, it can be concluded that in the tested car, there was a greater displacement of the reference points on the right than on the left side of the vehicle in the front and middle parts of the vehicle. In contrast, in the rear part of the vehicle, there was greater displacement of the reference points on the left than on the right side of the vehicle. The largest displacements were found on the right side for the points located at the beginning and end of the sill. These displacements amounted to 6 mm. Among all the points on the left side of the vehicle, the largest displacements of the reference points were also found for the points located at the beginning and end of the sill. In this case, they amounted to 5 mm. Significant displacement of the reference points also occurred at the points located at the beginning and end of the front fender reinforcement and in the middle of the A-pillar. The displacement of these points was 5 mm on the right side of the vehicles and 4 mm on the left side. The reference points located on the front reinforcement and at the bottom of the B-pillar moved by 4 mm on the right side and 3 mm on the left side. In turn, the points located in the middle and at the top of pillar B moved 3 mm to the right and 2 mm to the left. In the case of the reference points in the upper part of pillar A, the same displacement values were recorded on the right and left sides of the vehicle, which was 3 mm. In the rear part of the vehicle, greater displacements of the reference points were found on the left side of the vehicle. The displacements of the reference points located in the middle and at the top of pillar C were 4 mm on the left side and 3 mm on the right side. In turn, the points located at the end of the rear wheel arch and at the end of the rear fender, at the top, were displaced by 4 mm on the left side and 2 mm on the right side. However, the points located at the end of the rear fender, at the bottom, were displaced by 3 mm on the left side and 2 mm on the right side of the vehicle. The greater changes in the geometry at the front and in the middle of the vehicle on the right than on the left are due to intensive use of the vehicle, during which greater forces and moments resulting from traffic conditions affect the right side of the car. This is related to the poorer condition of the road infrastructure on the shoulder side than on the centre line side. In addition, during vehicle

operation, the wheels on the right side often hit kerbs. Greater changes in geometry in the upper parts of the body at the rear of the vehicle on the left than on the right indicate some loss of rigidity in the body's load-bearing structure. The forces and moments resulting from driving conditions also act on the body diagonally across the vehicle, and the deformations of the body are transferred diagonally across the vehicle. In the case of the displacement of many reference points in the upper parts of the bodywork in the tested car, both on the right and left sides of the vehicle, the permissible displacement of reference points, which is 3 mm, was exceeded. This may affect the active and passive safety of the vehicle. The results of the measurements of the geometry of the upper parts of the body confirm that, as a result of intensive use of the vehicle by many drivers, there have been significant changes in the geometry of the entire body. Significant changes in the geometry of the body were also confirmed by the results of measurements of the body geometry using the 3D scanning method and the results of measurements of the geometry of the body floor panel.

Figure 22 shows the results of measurements of the geometry of the upper body parts in an S3 car, which had low mileage and was used by only one driver. Compared to the cars described earlier, this vehicle had the smallest changes in geometry in the upper body parts. In the case of many reference points, no displacement was found. The displacement of none of the reference points exceeded the permissible displacement of reference points, which is 3 mm. The reference points on the right side of the vehicle were displaced by a maximum of 2 mm, and on the left side by a maximum of 1 mm. On both the left and right

sides of the vehicle, the displacement of the reference points located at the end of the front fender reinforcement, in the middle of the A-pillar, at the end of the rear wheel arch, and at the end of the rear fender at the bottom was 1 mm. However, the reference points at the beginning and end of the sill were displaced by 2 mm on the right side and 1 mm on the left side. In the case of the reference point at the bottom of the B-pillar, a displacement of 1 mm was found on the right side of the vehicle. On the left side of the vehicle, no displacement of this point was found. Slightly greater changes in the geometry of the upper parts of the bodywork on the right than on the left side of the vehicles are the result of greater forces and moments arising from traffic conditions and related to the poorer condition of the road infrastructure on the right side of the road and kerbs. Such minor changes in geometry indicate the best technical condition of the body in terms of the parameters tested among all the vehicles examined. Minor changes should not have any impact on the safety level of this vehicle. Also, when identifying changes in body geometry using 3D scanning and floor panel geometry measurements, the smallest changes in geometry were found in this vehicle.

The main advantage of the 3D body scanning method proposed in this thesis is the potential for rapid, non-contact assessment of the geometric condition of vehicle bodies in the future. Another advantage is the very high accuracy of the measurements, as well as the comprehensive assessment of both changes in stiffness and changes in body geometry. Furthermore, it is possible to measure changes in body geometry under additional loads. At present, a major drawback of the method is the need to use expensive testing equipment and

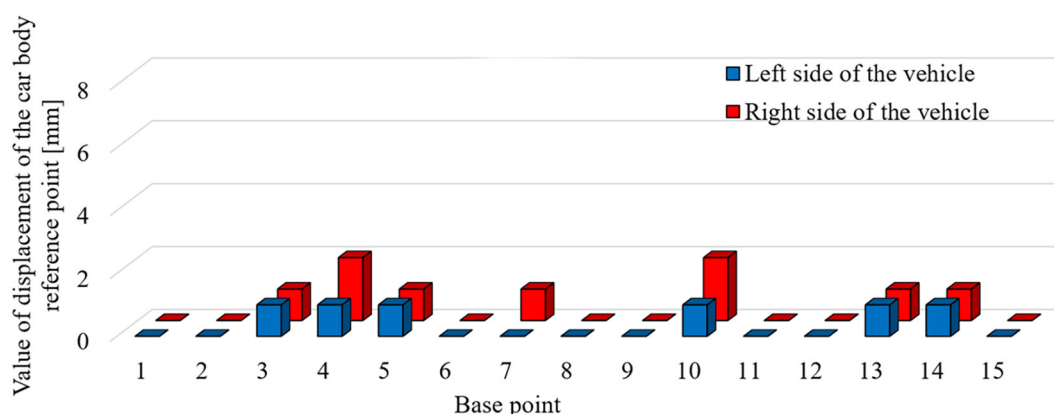


Figure 22. Results of measurements of changes in the geometry of the upper body parts in car S3, which was used by one driver and had low mileage

to carry out numerous individual scans of specific areas of the body, followed by multi-stage data processing using computer software.

CONCLUSIONS

As a result of a comparative analysis of 3D scans of three passenger cars that have been exposed to various factors contributing to bodywork wear during their operation to date, it can be concluded that the method proposed in this paper can be used to assess the condition of the bodywork during operation. Using the described method, which was based on 3D scanning of the bodywork, it is possible to identify the most likely cause of bodywork wear. This method identifies not only changes in shape but also loss of bodywork rigidity. 3D scanning of the body can be used both to identify large-area shape differences between the right and left sides of the vehicle, as well as to diagnose small-area differences, i.e., minor damage of the bodywork.

Comparing the results of the analysis of body geometry changes using 3D scanning with measurements of the floor panel and upper body geometry using traditional diagnostic methods, it can be concluded that similar relationships were obtained. The greatest extent of body deformation was observed in the car that had undergone bodywork repairs, which had been damaged in a road collision. Smaller changes in body geometry were found in a car that was used intensively by many drivers. On the other hand, the smallest changes in body geometry were found in the car with the lowest mileage, which was used by only one driver.

Currently, the use of 3D scanning to identify the technical condition of a vehicle body seems very innovative but difficult to apply. However, after significant automation of measurements in the future, this type of testing will be easily repeatable and applicable during periodic technical inspections of vehicles. This method allows for a detailed determination of the technical condition of the bodywork by identifying geometric shifts occurring across the entire surface of the bodywork. The proposed synthetic method of 3D scanning of the bodywork allows for accurate identification of changes in the technical condition of car bodies during operation in terms of safety of use and the utility value of the vehicle.

Following a comprehensive assessment of the technical condition of the bodywork (geometry

and rigidity), it would be possible to take vehicles with incorrect bodywork geometry off the road. It should be borne in mind that changes to body geometry relate to both passive and active vehicle safety. In the former respect, changes to body geometry may contribute to a reduction in the body's strength and alterations to the structure of the crumple zones. This may result in more serious injuries to occupants in the event of a collision or road accident. Concerning active safety, however, a change in body geometry may lead to significant changes in wheel alignment parameters, which may affect the vehicle's handling and its ability to maintain the intended trajectory.

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