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GEOMETRIC ANALYSIS OF MANEUVERABILITY PERFORMANCE FOR VEHICLES WITH TWO STEERING AXLES

Summary. One of the most important features of motor vehicles is their steering maneuverability. Ways of determining single axle steering are well known. This paper presents an idea of how to determine maneuverability of motor vehicles with two steering axles. The concept makes use of elements of kinematic analysis as well as of a 3D model of the steering system. It is based on the theoretical analysis of the most unfavorable situations, such as parallel and perpendicular parking techniques, on the basis of which wheel-steering angles are specified. As a result, it was possible to create a 3D model to simulate the actual operation of the steering system. This made it possible to compare the theoretical approach with the actual system design.

1. INTRODUCTION

In our times, motor vehicles constitute the dominating means of transport all over the world. In Poland alone, according to various data sources, there are between 15 and 19 million registered cars and their number is growing. Most of them are used in cities, especially in large cities; therefore, one of the challenges faced by city planners is to ensure sufficient number of car parks. In order to create more parking spaces, there has been a tendency to reduce the dimension of each parking spot so that more parking spaces are created in a limited parking area. As a result, reduced dimensions of parking spots make it more and more difficult to park a car in a safe way. In addition, city centers, in many cases, are networks of narrow one-way streets where driving larger cars becomes very difficult. Due to these difficulties as well as other problems, car designers pay considerable attention to maximum maneuverability in their new models. Car maneuverability can be greatly improved by the use of rear-wheel steering, whose geometric analysis and actual construction has been described below.

2. A REVIEW OF TWO STEERING AXLE SYSTEMS

Two steering axle systems are subject to the same requirements as the conventional ones. They have been described in UN Regulation No. 79 [11]. The main requirements include the following elements:

- the system should ensure easy and safe handling of the vehicle to its maximum design speed,
- the system must demonstrate a tendency to self-center wheels,
- the system must ensure the possibility of driving straight without a necessity for extraordinary adjustment of the driving direction,
- the rear wheels cannot be the only steerable wheels.

Steering systems with two steering axles, often called 4WS (Four Wheel Steering) are not a new solution. Their first designs, based on combinations of mechanical rods and levers, were created at the beginning of the twentieth century. However, they gained the greatest popularity before World War II, when they were used, among others, in off-road models of Mercedes, for example G5 or in PZInz 303, designed in Poland. They were characterized by a small turning radius, resulting in a significantly smaller vehicle stability in cornering. The next step in the development of two steering axle systems was a 4WS proposed by Honda in the eighties of the last century. Its design was based on the shaft connecting the front steering gear with the rear one being a combination of a planetary gear and an eccentric setup. The design made it possible to turn the rear wheels harmonized with and opposite to the direction of the front wheels. The procedure depended exclusively on the turning of the steering wheel [13-14].

Mazda's design, known as Mazda 4WS, has a similar structure. Also in this case, there is a shaft connected to the front gear. On its other side there is a turn phase controller, which works together with the central unit, collecting the data from the speed sensor. The data make it possible to control the operation of the rear wheels by adjusting a steering valve, which is responsible for the operation of a hydraulic actuator - the element enabling rear-axle steering. Since the design includes both hydraulic and electronic mechanisms, it is often called an electro-hydraulic system [14]. Currently, the most common are electric systems in which electric actuators constitute the operation elements. In these systems there are no mechanical connections between the front and rear axles of the vehicle. As a result, ABS and ESP systems can co-operate freely, without any interference from the steering wheel [13]. These systems have been used in a great number of car makes, for example, Renault (Fig. 1) or Porsche.

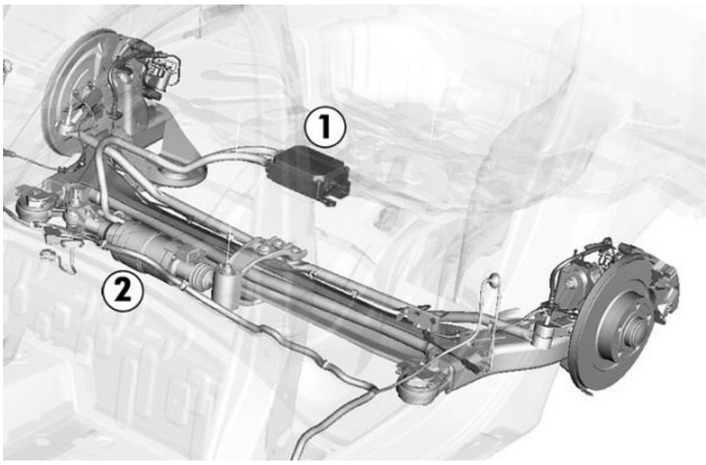

Fig. 1. Rear steering with Renault Active Drive electrical system: 1-steering system, 2-electrical actuator [5]

Compared to conventional steering systems, systems with additional rear steering axles, including the wheels turning either with the front wheels or in the opposite direction, all have the following advantages [7]:

1. improved vehicle stability in cornering,
2. better response of the system to the movement of the steering wheel and improved steering precision,
3. increased vehicle stability while driving straight at higher speeds,
4. improved vehicle stability when changing lanes while driving on highways,
5. reduced turning radius and increased vehicle maneuverability at low speeds.

3. KINEMATICS OF A VEHICLE WITH TWO STEERING AXLES

In our analysis of steering system geometry, a Skoda Octavia III was used as a base car. The model, both in its present and former generations, has been one of the best-selling cars in Poland. In addition, it is a part of the popular segment of compact cars. These features have made the car most suitable for further analysis.

Since two steering axle systems, with the rear axle steered in the opposite direction to the front axle, improve the maneuverability of a vehicle, their parking efficiency greatly increases. Thus, in order to investigate the kinematics of the system and to determine the optimal steering angles, two parking maneuvers have been analyzed, namely parallel front and perpendicular ones. The former one requires high maneuverability of the vehicle because of a generally limited width of parking space and limited width of the road. In the latter case, it is usually insufficient length of the parking space. Considering the fact that the length of the parking space when moving onward is greater than reversing [6], and that the maneuver is generally performed in reverse gear, only the reverse move of a vehicle was used for the analysis. The dimensions of the road and parking spaces for both tests were based on a ministerial regulation [10] and are presented in Fig. 2. In both cases, in the occupied spaces, vehicles with dimensions of base vehicles were parked exactly in the middle of the parking spaces.

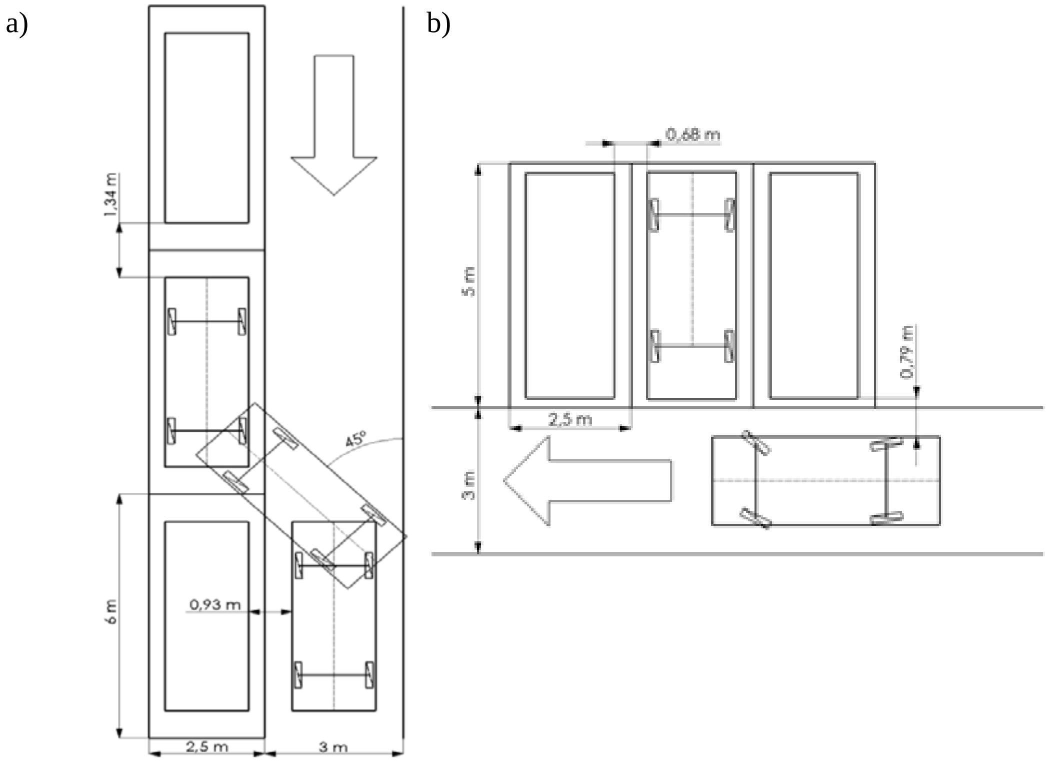

Fig. 2. Adopted dimensions of parking spaces and position of vehicles: a) parallel parking, b) perpendicular parking

The main assumption regarding the vehicle, apart from its dimensions, adopted in order to analyze the system, is that the vehicle should move in a circle without side slippage. This means that the axes of all the wheels of a vehicle in curvilinear motion should intersect at one point (Fig. 3). Making use of these lines, it is possible to determine the minimum turning radius R. The radius is defined as the distance from the intersection point of the wheel axis to the center of the front outer wheel tire footprint in circular motion [5]. As can be seen in Fig. 3, already at the initial stage, there is a clear reduction of the radius when using the rear steering axle.

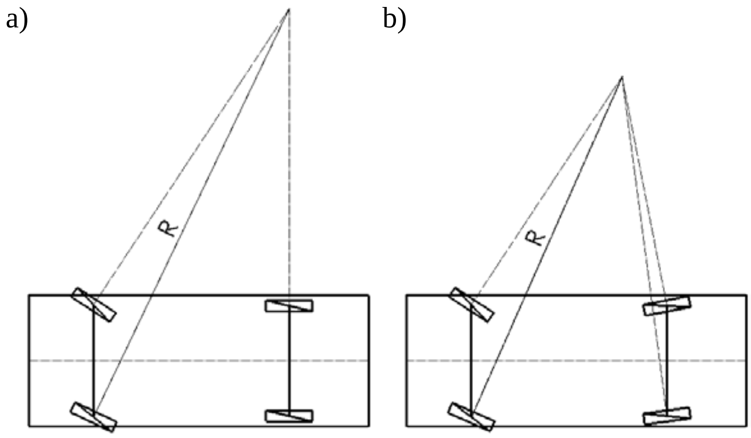

Fig. 3. Determining the minimum turning radius: a) one steering axle, b) two steering axles, R-minimum turning radius

The analysis made it possible to determine optimal positions of the vehicle before and after the parking maneuver. In the case of parallel parking, the car, before starting the maneuver, is in the middle of the lane, precisely parallel to a vehicle parked in front of the free space (Fig 2a). After the parking operation, the vehicle is positioned exactly in the middle of the parking space. Additionally, it is assumed that the maneuver should be performed in three consecutive stages: the first one involving a maximum turning of the wheels in the direction of the free space and driving the vehicle back so that its longitudinal axis is at an angle of approx. 45° to the axis of road. Then, further reversing is continued with straightened wheels, so that the rear axle of the vehicle is at the height of the parking space line. The final stage involves a maximum turning of the steering wheels in the direction of the axis of the road and reversing the vehicle to park it parallel to the road axis. In the case of perpendicular parking, the adopted positions are as follows: prior to the maneuver, the car is exactly in the middle of the lane; after the operation, the car is exactly in the middle of the parking space (Fig 2b). In addition, it is assumed that the maneuver should be performed in a single, maximum turn of the wheels in the direction of free space, and then moved until it is positioned with its axis is perpendicular to the road axis. In both cases the wheel tracks of the vehicle as well as the edges of its theoretical lines have been marked. The comparative spaces have been defined and illustrated on the respective drawings.

At first, parallel parking analysis dealt with the optimal case. The resulting wheel-steering angles of individual wheels and a minimum turning radius (Fig. 4a) were assumed to be basic for further testing. The length of the motion corridor was 10.66 m, while the vehicle when parked protruded by 0.24 m on the adjacent lane. It should be noted that the adopted positions of the vehicle, prior to and after its parking, caused a collision with the vehicle parked in front of the free parking space. The width of the collision area was equal to 0.5 m. In order to eliminate this collision, it was decided that the vehicle should be moved back by 0.55 m before the parking operation, which would result in shifting of the motion corridor back by the same width value. Another case considered in the analysis involved a vehicle with one steering axle and the turning radius identical to that of the base vehicle (Fig. 4b). In comparison to the first test, the main difference was the necessity to move the vehicle ahead by 0.77 m before starting the maneuver and effectively park the vehicle at the exact center of the parking space. Furthermore, in this case there was no need of backing the vehicle with its wheels in the straight driving position. The length of the motion corridor increased to 11.44 m and the protrusion was 0.42 m. Also, in this case, there was a collision area 0.6 m wide, which could be removed by backing the motion corridor by 0.65 m.

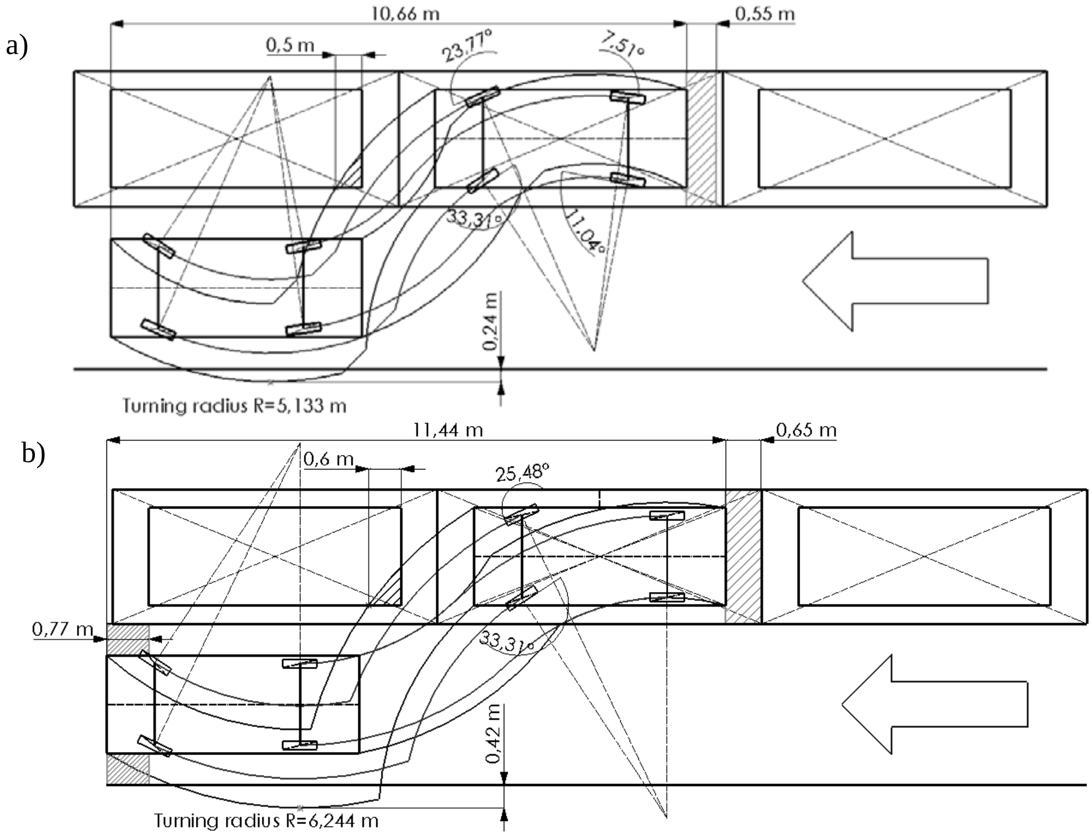

Fig. 4. Kinematic analysis of parallel parking: a) optimal parking, b) base vehicle parking

The perpendicular parking analysis opened with the optimal case (Fig. 5a). The dimensions of the motion corridor were 6.9 m x 7.56 m. The maneuver started with the front of the vehicle parked at a distance of 1.18m from the left side of the vehicle parked to the right of the selected place. Also, in this case, there was a collision area 0.24 m wide, which could be removed, eg. by moving the motion corridor to the right or making a necessary correction while parking so that the vehicle could be positioned exactly in the middle of the parking space. The other case involved analysis of the vehicle with both the turning angles and turning radius recognized as optimal in parallel parking (Fig. 5b). In this case, the dimensions of the motion corridor increased and amounted to 7.37 m x 8.08 m. The distance of the front of the vehicle from the side of a neighboring car prior to the commencement of the parking operation amounted to 0.63 m. It is also evident that, at the same time, the vehicle should have been located closer to the road axis. The width of the collision area decreased to 0.15 m.

Finally, it was determined that the most optimal values of individual wheel-steering angles were the angles obtained in the optimal parallel parking test. The results have made it possible to conclude that turning of the second axle will reduce the turning radius by 17.79% with respect to the base vehicle and it is close to such cars as Skoda Fabia III (5.2 m) and Peugeot 206 (5.1 m), which are typically urban cars [12]. Further increase of the values of the rear-axle steering angles would result in an even greater reduction of the turning angle and, by the same token, improve maneuverability and virtual reduction of the car size. In this analysis, the effect of speed on the vehicle stability was ignored because of the relatively low speeds used for parking maneuvers. However, it should be remembered here that increasing vehicle's maneuverability, for example by adding a second steering axis will reduce stability at higher speeds.

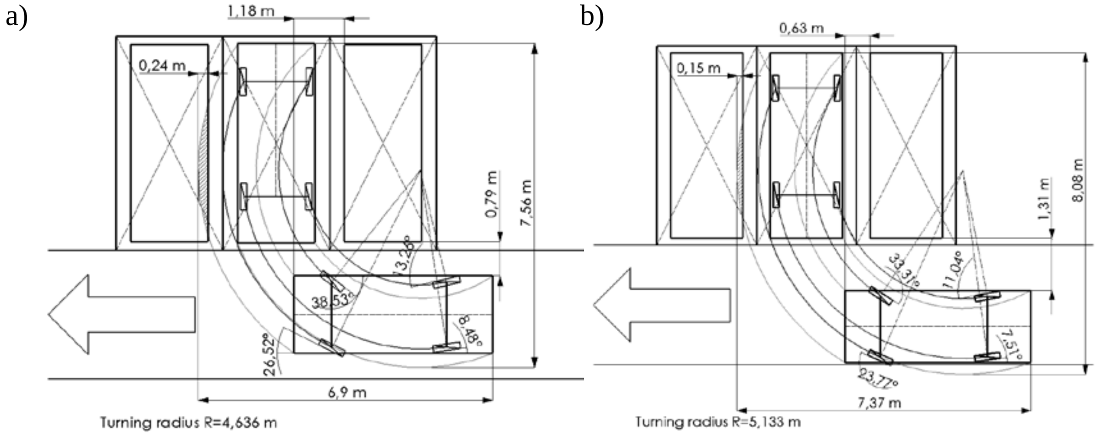

Fig. 5. Kinematic analysis of perpendicular parking: a) optimal parking, b) parking with the turning angles optimal in parallel parking

It should be noted that the best solution in both cases would be a steering system enabling the vehicle to rotate around its own vertical axis (rotation in place). This would be particularly valuable when attempting parallel parking in a space of the length limited to the length of the vehicle [9] plus the necessary safety margin. This means that in the analyzed case the motion corridor could be reduced by more than a half. So far, systems of this type have existed exclusively at the conceptual stage and although they may appear in prototype cars, they have not been implemented in cars available on the market.

4. ANALYSIS OF WHEEL STEERING BASED ON THE DESIGNED MODEL

Following the assessment of available structural solutions of steering systems, it was assumed that the test system should be composed of two toothed transmission gear racks connected by a jointed shaft with a claw clutch, which can be disconnected by an electric actuator. The diagram of the system is presented in Fig. 6.

On the basis of the results of the kinematic analysis and assumptions on system construction, it was possible to carry out necessary calculations based on the research of L. Kurmaz & O. Kurmaz and E. Mazanek [3-4]. Their scope included the gear rack size and strength parameters as well as size and strength conditions of the shafts. Suitable bearings were also selected. Taking into account the results, a 3D model of the system was made. It is presented in Fig. 7. Using the model made it possible to verify the operation of the steering mechanism and compliance of wheel turning angles with the values obtained in the theoretical analysis.

The basic elements of the system are: front steering gear (1), rear steering gear (2) as well as and linking jointed shaft with claw clutch (3). The turning of the wheels is effected by the use of front (4) and rear (5) steering knuckles, which are also connected to the wheel hubs. Curvilinear motion of the vehicle is controlled by the driver using steering wheel (6) connected to the front steering gear by steering shaft (7). Its rotation activates the rack (8) causing rotation of the pinion (14) with an articulated shaft and then through the pinion (25) causes a progressive movement of the rear gear rack (23). Position changes of toothed racks move the rods that act on the crossovers and make the wheels turn by appropriate angles.

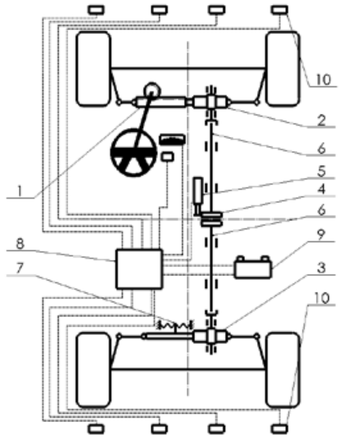

Fig. 6. System diagram: 1-main steering gear, 2-additional front steering gear, 3-rear steering gear, 4-clutch, 5-electric actuator, 6-bearing supported shaft, 7-centering springs, 8-control unit, 9-battery, 10-parking sensor system

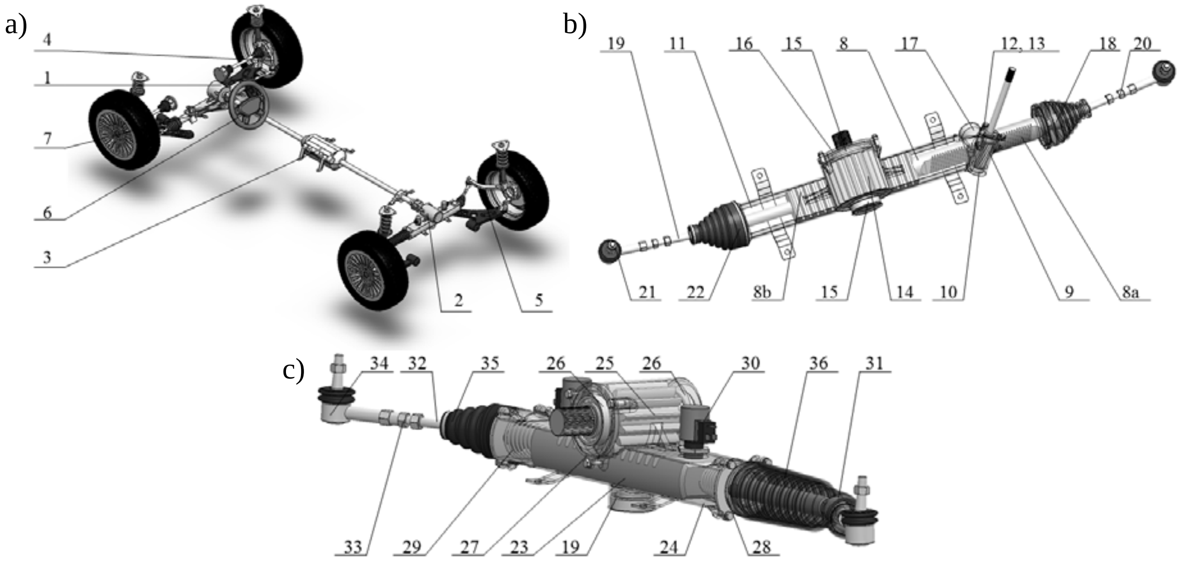

Fig. 7. The system with two steering axles: a) general view, b) front steering gear, c) rear steering gear: 1-front steering gear, 2-rear steering gear, 3-shaft with a clutch, 4-front steering knuckle, 5-rear steering knuckle, 6-steering wheel, 7-steering column, 8-rack, 8a-main toothing, 8b-additional toothing, 9-main pinion, 10- angular contact ball bearing, 11-casing, 12-regulation shim, 13-main gear cover, 14-output shaft cover, 15-ball bearing, 16,27-cover, 17-slide, 18,31-rod socket, 19,32-tie rod, 20,33-M12 nut, 21,34-tie-rod end, 22-rubber cover, 23-rear rack, 24-rear casing, 25-input shaft, 26-ball bearing, 28-side cover, 29-spring, 30-electro-lock, 35-short rubber cover, 36-long rubber cover

Using the 3D model, it was possible to measure the steering angles of individual wheels depending on the angle of the steering wheel. The values of the measurements are presented in Fig. 8.

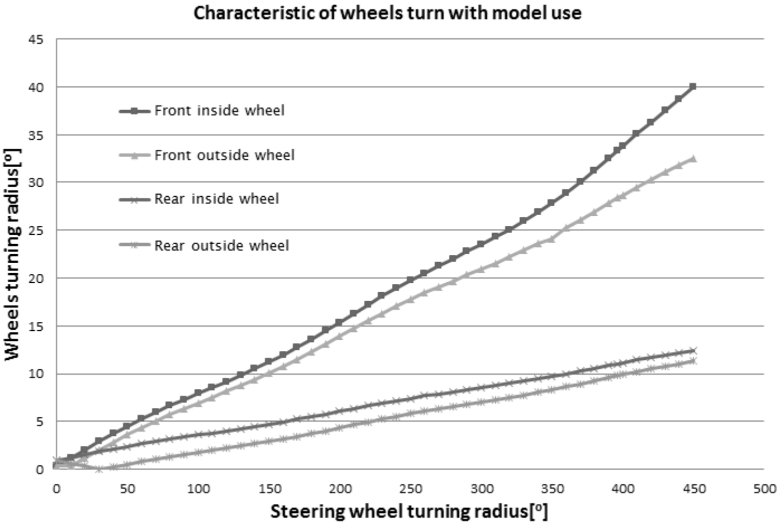

Fig. 8. Characteristic of individual wheel steering depending on the steering wheel angle

The analytical values considered optimal were obtained for the steering wheel angle of 396° only for the inner wheels of the vehicle. This was due to difficulties in obtaining theoretical angles in a practical system. Hence, when constructing the system, the principle stating that for an outer wheel angle of 20° the inner wheel should be turned by an angle close to 23° was applied [2]. Fig. 9 shows that the points of intersection of the front wheel axes in the model system do not intersect at the same point as the rear wheels. In addition, the point of intersection of the front wheels is situated behind the vehicle, which means that even with a rigid rear axle, the theoretical assumptions do not match the conditions derived from the model.

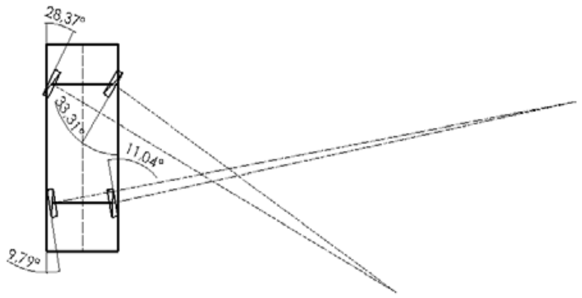

Fig. 9. Intersection of the turned wheels

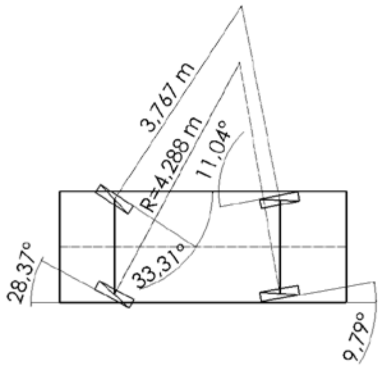

Fig. 10. Determining the smallest turning radius

In addition, as can be seen in the figure, small angles of the steering wheel rotation cause the outer wheels (especially the rear ones) to reduce the turning angle, whereas the inner wheels increase the turning angle. This is due to the method of measurement and setting the wheels in a position for driving straight (ie. in alignment). Further rotation of the steering wheel results in an almost perfectly linear increase in steering angles of all wheels. In addition, for the maximum steering angle of 450° the values of the front wheels steering are close to the values of the base vehicle. This makes it possible to drive it, after disconnecting the rear axle system, in the same way as we drive a vehicle of conventional design. Making use of the measurement results a kinematic diagram of a vehicle (similar to the one shown in Section 3) was created. It was used to test the minimum turning radius. Owing to the problem of wheel axis intersection mentioned earlier, it was proposed that, in this case, the smallest turning radius would be the distance from the outer front tyre print to the point of intersection with the axis of the rear outer tyre (Fig. 10). Its value is higher than in case of the outer wheels and it is 4.288 m, which is 22.34% smaller than the value obtained for the base vehicle. This value is close to a great number of smaller vehicles seen on Polish streets such as the Fiat 126p (4.3 m) or the second-generation Smart For Two (4,35 m) [12]. This value is similar to those found in the literature where the reduction of turning radius fluctuates around 20% [8].

5. CONCLUSION

The investigations have shown that steering systems with two steering axles significantly affect the driving ability of the vehicle. In the case where rear axle wheels turn in the opposite direction to the front axle, there is a reduction of the turning radius of the car. The reduction was observed to be over 17% already at the stage of graphical analysis and increased to over 22% on model tests. The results demonstrate that even a large size vehicle can efficiently turn tight corners and be much easier to park than a vehicle with a single steering axle. The dimensions of motion corridors required to effect individual maneuvers were also reduced. It should be noted, however, that the reduction of the turning radius by almost one quarter leads to a significant decrease in vehicle stability at higher speeds. Hence, systems of this type should have a possibility to disconnect the steering of the rear axle at speeds that exceed the ones used during parking maneuvers.

It was a great challenge to devise such a design model of the system so as to keep the required wheel steering angles. It involved creating an appropriate design of the steering rod lengths as well as the resultant shapes and dimensions of steering knuckles that are also crucial for the relationship between different angles. This made it necessary to look for a compromise between theoretical and practical values.

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