SIMULATION METHOD OF COMPARATIVE EVALUATION OF THE AGILITY OF A PASSENGER CAR WHEN MOVING "FORWARDS" AND "BACKWARDS"

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Summary

The objective of this study is to compare the agility of a specific motor vehicle (ability of the vehicle to follow paths having small radii of curvature) when moving "forwards" and "backwards". These terms have been put here in quotation marks because their meaning depends on the point of view individually adopted. In this study, the vehicle is understood as moving "forwards" when the vector of the predefined vehicle velocity is pointing towards the vehicle front. The vehicle may also be said to move "backwards" when it is reversing and to move "forwards" when it is driven in any other gear. To accomplish the objective of this study, a simulation method was employed. Instead of the Ackermann model, a three-dimensional dynamic model was used where the tyre slip angles were taken into account. The vehicle manoeuvres simulated during the tests included vehicle drive along a path with a constant curvature radius on a road surface affording good adhesion, vehicle drive with a "saw-tooth" input applied to the steering wheel, and vehicle drive into a parking place parallel to a roadway edge. The vehicle speed was limited to 40 km/h because of the nature of the manoeuvres simulated (aimed at the evaluation of vehicle agility) and because it would be difficult to achieve higher velocities of the vehicle reversing in real conditions. The results obtained have shown significant differences in the vehicle behaviour when it moved "forwards" and "backwards". Some of them are known to every experienced driver and this fact may rather be considered just confirmation of the usefulness of the simulation method adopted.

Keywords: simulation, vehicle agility, reversing

1. Introduction

The objective of this study is to compare the agility of a specific motor vehicle (ability of the vehicle to follow paths having small radii of curvature) when moving "forwards" and "backwards". These terms have been put here in quotation marks because of their conventional nature and because the answer to a question whether the vehicle moves

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"forwards" or "backwards" depends on an individual point of view. In this study, the movement "forwards" is understood as the one during which the vector of the predefined vehicle velocity is pointing towards the vehicle front. The vehicle may also be said to move "backwards" when it is reversing and to move "forwards" when it is driven in any other gear.

The term "agility" is understood by the authors as vehicle's ability to follow paths having small radii of curvature [1]. The vehicles with good agility may be more easily manoeuvred. The procedures to examine this property of a vehicle are described in normative documents issued by the United Nations Economic Organization for Europe (UN ECE) [2].

The vehicle tests presented herein were carried out as computer simulations. Instead of the Ackermann model, a three-dimensional dynamic model was used where the tyre slip angles were taken into account. Although the tests were merely simulations, endeavours were made for the simulations to be as close to the reality as possible; for this reason, the vehicle speed was limited to 40 km/h because it would be difficult to achieve higher velocities when driving the vehicle "backwards" in real conditions.

2. Model and simulation program

A physical model of a two-axle vehicle has been shown in Fig. 1 [15, 16]. An assumption has been made that the vehicle modelled moves on an even horizontal road surface.

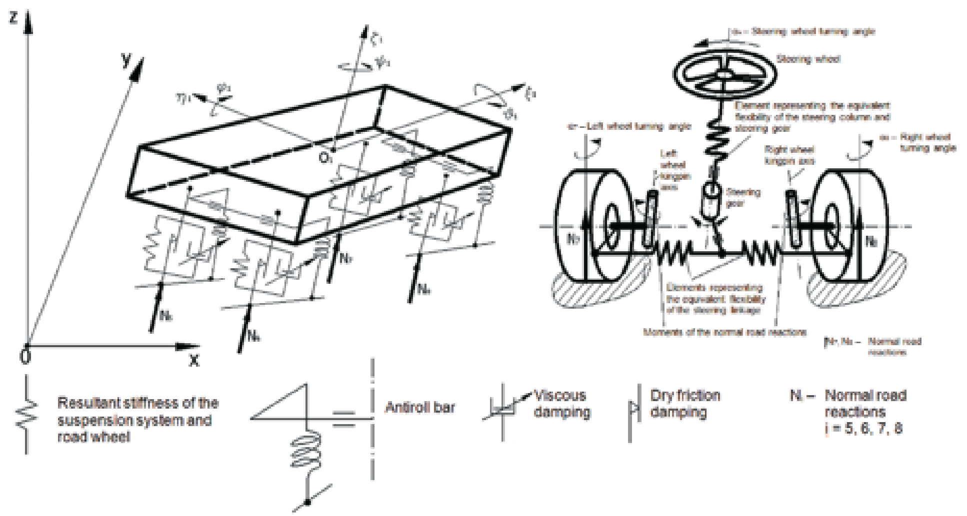

Fig. 1. Physical model of a two-axle motor vehicle and model of a motor vehicle steering system with a parallel structure [15, 16]

Ten independent generalized coordinates have been adopted to describe the model motion: coordinates x_{O1}, y_{O1}, and z_{O1} of point O_1 (centre of vehicle mass) in the Oxyz inertial reference frame, yaw angle (directional angle) ψ_1, pitch angle φ_1, and roll angle ϑ_1 of the vehicle body, and road wheel rotation angles φ_5, φ_6, φ_7, and φ_8. The equations of motion were derived with employing the principle of dynamic force analysis.

The simulation of some manoeuvres requires that driver's actions should be defined. In "*open-loop tests*" [15, 16], the driver is represented by time functions of steering wheel turning angle, brake pedal effort, accelerator pedal depressing degree, and transmission gear ratio.

3. Vehicle data and description of the manoeuvres simulated

The data of the simulation model corresponded to a medium-class passenger car, fully loaded (with about 1 500 kg total mass) [18]. To compare the agility characteristics of the vehicle moving "forwards" and "backwards" with each other, three different manoeuvres were simulated: steady-speed vehicle drive along a path with a constant curvature radius on a road surface affording good adhesion; vehicle drive with a "saw-tooth" input applied to the steering wheel, in accordance with UN ECE Regulation No. 79 [2]; and vehicle drive into a parking place parallel to a roadway edge.

The simulations were carried out, depending on the manoeuvre simulated, for different vehicle velocities, for dry and wet road surface, and for the vehicle being driven "forwards" and "backwards"[18].

4. Steady-speed vehicle drive along a path with a constant curvature radius on a road surface affording good adhesion

This test was a simulation of vehicle drive with a constant value of the steering wheel turning angle. This angle was set to its maximum (9.42 rad) from the beginning to the end of the simulation process. The signs of the steering wheel turning angle for the vehicle moving "forwards" and "backwards" were opposite to each other.

The simulations were only carried out for a vehicle speed of 10 km/h and for the tangential tyre-road interaction characteristics corresponding to dry asphalt concrete. The simulations for wet asphalt concrete and for higher vehicle speeds were skipped because authors' interest was exclusively focused in this case on the comparison of vehicle behaviour during the "forward" and "backward" movement at low tyre slip angle values. Thanks to such an assumption made, the vehicle could follow a path having a constant curvature radius and could return to its initial position when the yaw angle of 2π was reached.

The trajectory of the centre of vehicle mass during the "forward" and "backward" movement has been shown in Fig. 2. The vehicle contour in its initial position (which was roughly identical with the final position) has been presented in a simplified form as a rectangle with dimensions corresponding to the overall vehicle width and length.

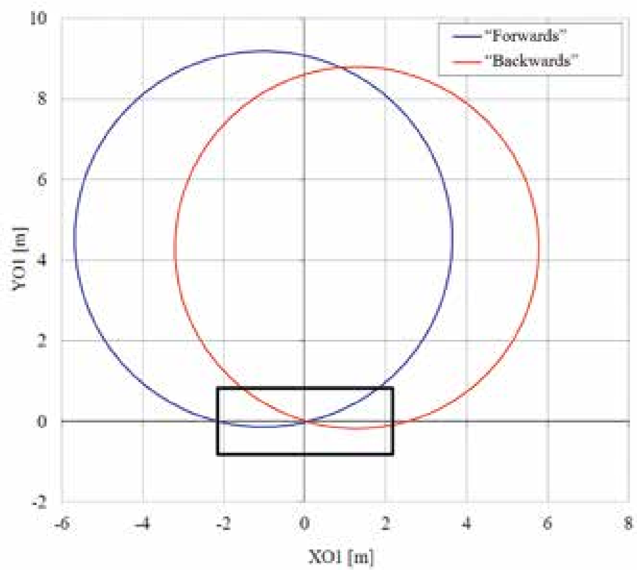

Fig. 2. Trajectory of the centre of vehicle mass at a constant value of the steering wheel turning angle

The trajectories of the centre of mass of the vehicle driven "forwards" and "backwards" as shown in Fig. 2 could be considered symmetrical to each other about the OY axis, if it were not for the difference in the radii of the circles that represent them. For this difference to be more clearly visible, another simulation was carried out where only the initial vehicle positions were changed. The results can be seen in Fig. 3. Thanks to appropriate changes in the initial vehicle positions, the trajectories of the vehicle centre of mass could be brought to a form of concentric circles. Additionally, a simplified contour of the vehicle for the "forward" and "backward" movement and the maximum and minimum circles described by this contour have been drawn.

Fig. 4 shows the values of radii of the circles described by the centre of vehicle mass and by the vehicle contour. The average absolute values of the moments of forces applied to the steering wheel have been presented in Fig.5

As regards the vehicle trajectory, the differences in the results obtained are not particularly big, chiefly because of low velocity of the vehicle. However, they are noticeable, with the radii observed at the "backward" movement being somewhat smaller. The differences can be explained by different locations of the instantaneous centre of rotation for each of the directions (or, more precisely, the senses) of the vehicle motion and by deformations of the steering system.

The lower value of this moment means smaller deformations in the steering system. Hence, a specific steering wheel turning angle translates in such a case into bigger angles of turning the steerable wheels and, in consequence, into smaller values of the turning radius.

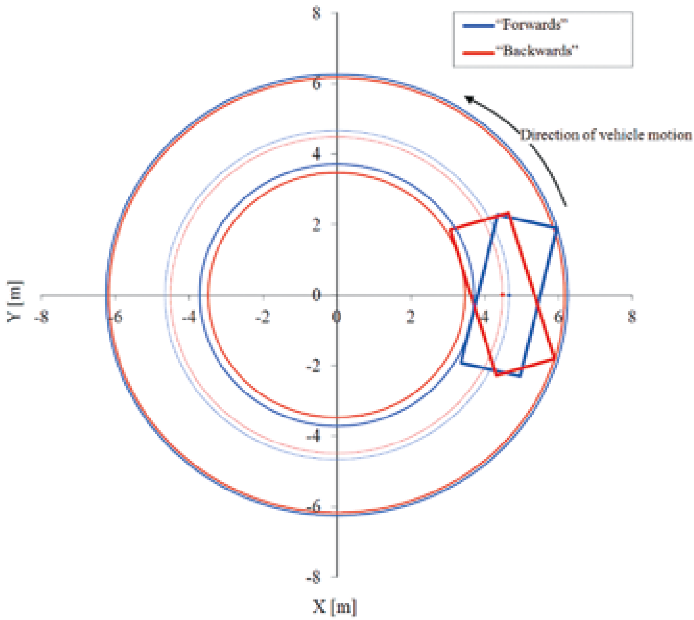

Fig. 3. Trajectory of the centre of vehicle mass at a constant value of the steering wheel turning angle, after changes in the initial vehicle position

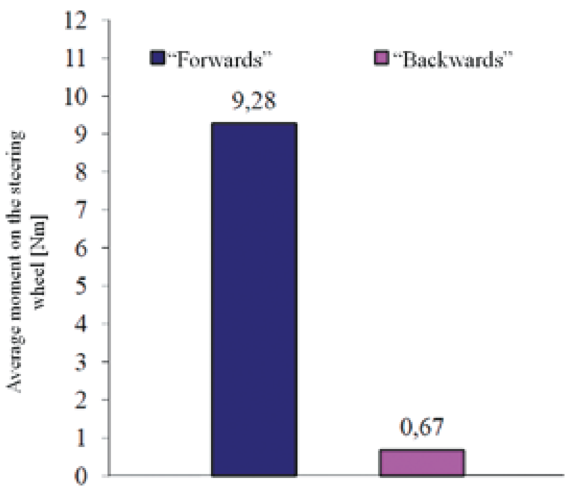

Fig. 4. Average absolute values of the moments on the steering wheel of the vehicle driven along a path with a constant curvature radius

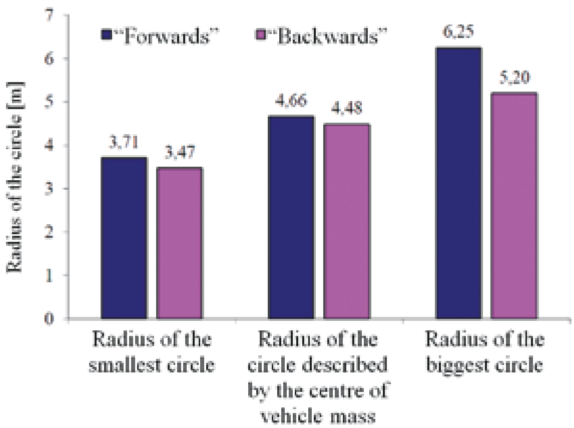

Fig. 5. Radii of the circles described by the vehicle driven "forwards" and "backwards"

5. Vehicle drive with a "saw-tooth" input applied to the steering wheel

This manoeuvre, performed in accordance with UN ECE Regulation No. 79 [2], is also referred to as "parking operation". It is used to evaluate the agility of a motor vehicle. During the manoeuvre, a "saw-tooth" input is applied to the steering wheel of the test vehicle moving with a constant velocity; the time history of such an input has been presented in Fig. 6. The turning angles applied as an input to the steering wheel when the vehicle moved "forwards" and "backwards" have been given opposite signs in order to facilitate direct comparisons between the resulting vehicle trajectories.

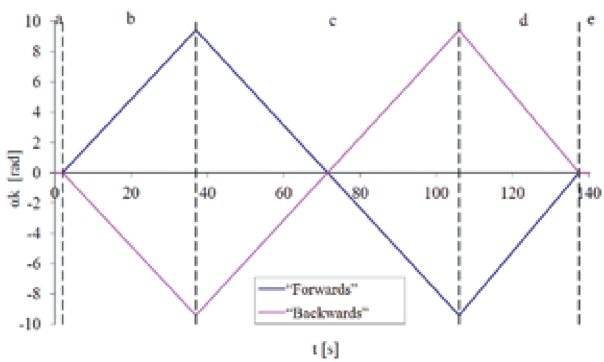

Fig. 6. Time history of the "saw-tooth" steering wheel input; individual stages of the manoeuvre have been shown

This manoeuvre for the vehicle moving "forwards" is carried out as described below.

a. The vehicle is moving with a constant velocity, with its wheels being set straight ahead (Fig. 6, stage "a"); this stage may be skipped in the analysis.
b. The steerable wheel turning angle is being increased by turning the steering wheel with a constant rate to the left to its extreme position (Fig. 6, stage "b").
c. The steering wheel is being turned with a constant rate to the right to its opposite extreme position (Fig. 6, stage "c").
d. The steerable wheels are being reset to the straight ahead position by turning the steering wheel with a constant rate to the left (Fig. 6, stage "d").
e. The vehicle is moving again with its wheels being set straight ahead (Fig. 6, stage "e"); this stage, like the first one, may also be skipped in the analysis.

For the vehicle moving "backwards", the input is symmetric to that described above about the time coordinate axis.

This manoeuvre was simulated for two different vehicle speeds (10 km/h and 40 m/h), two road surface types (dry asphalt concrete and wet asphalt concrete), and for the vehicle moving "forwards" and "backwards", which resulted in eight simulations in total.

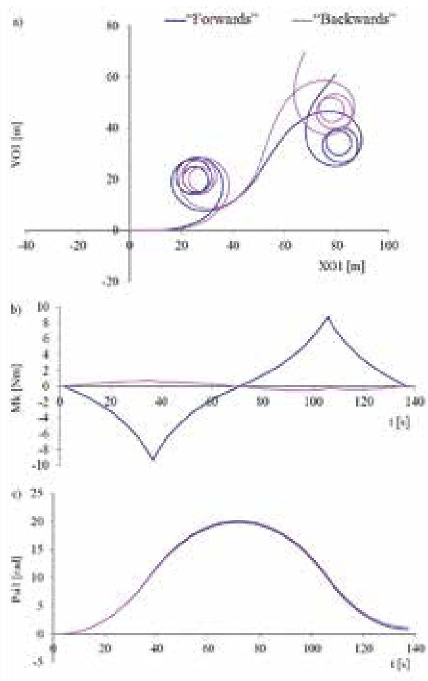

Fig. 7. Vehicle driven with a speed of 10 km/h on dry asphalt concrete:
a) Trajectory of the centre of vehicle mass
b) Moment on the steering wheel vs. time
c) Vehicle yaw angle vs. time

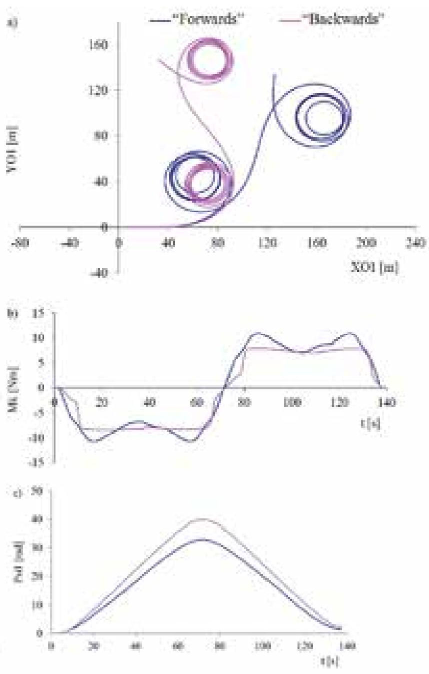

Fig. 8. Vehicle driven with a speed of 40 km/h on dry asphalt concrete:
a) Trajectory of the centre of vehicle mass
b) Moment on the steering wheel vs. time
c) Vehicle yaw angle vs. time

Figs. 7–10 show the simulation results for the vehicle being driven on dry and wet asphalt concrete. They represent trajectories of the centre of vehicle mass and time histories of the moment of forces applied to the steering wheel and of the vehicle yaw angle.

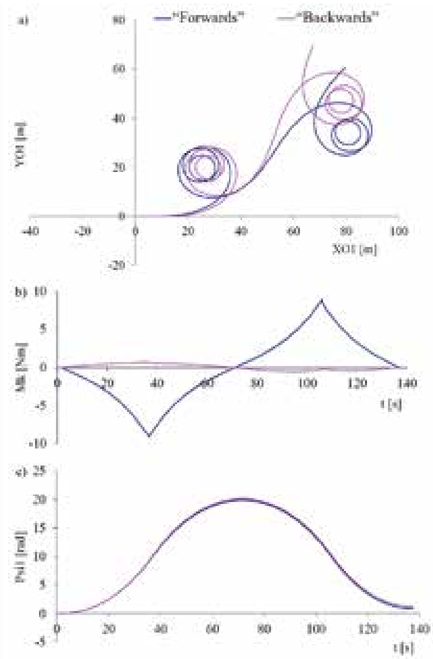

Fig. 9. Vehicle driven with a speed of 10 km/h on wet asphalt concrete:
a) Trajectory of the centre of vehicle mass
b) Moment on the steering wheel vs. time
c) Vehicle yaw angle vs. time

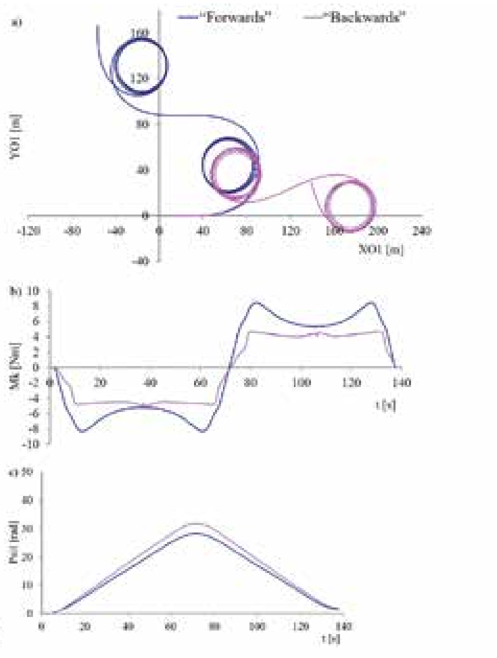

Fig. 10. Vehicle driven with a speed of 40 km/h on wet asphalt concrete:
a) Trajectory of the centre of vehicle mass
b) Moment on the steering wheel vs. time
c) Vehicle yaw angle vs. time

For the purposes of quantitative evaluation of the simulation results, the total number of vehicle trajectory loops made during the simulation test was chosen as a criterion. It was determined from the vehicle yaw angle according to the equation:

$$n_p = \frac{\psi_{1max}}{2\pi} + \frac{\psi_{1max} - \psi_{1k}}{2\pi} \tag{5.1}$$

where: n_p – total number of vehicle trajectory loops;
ψ_{1max} – maximum vehicle yaw angle;
ψ_{1k} – final vehicle yaw angle.

In formula (5.1), the first and second term defines the number of loops made by the vehicle when moving "leftwards" and "rightwards", respectively.

The simulation results have been presented in the form of a graph in Fig. 11. The bigger number of the loops has the meaning of better agility of the vehicle. The radius of the smallest vehicle trajectory loop was also found out; it was determined as the average value of the loop radii observed for the vehicle when moving "leftwards" and "rightwards". The results of such calculations have been given in Fig. 12. The vehicle agility is better when the value of this parameter is lower.

The differences in the simulation results are most clearly visible in the time histories of the moment applied to the steering wheel (Figs. 7b and 8b and Figs. 9b and 10b). At the speed of 10 km/h, the greatest impact is exerted by the stabilization of the steerable wheels, determined by the wheel geometry angles (chiefly the castor angle). When the vehicle moves "backwards", the castor angle has a destabilizing impact and this explains the difference in the sign and modulus of the moment. At the speed of 40 km/h, the stabilizing moment generated by the tyre, which does not depend on the castor angle, plays a more important part and the time histories of the moment applied to the steering wheel do not differ so much from each other.

Although the moment on the steering wheel does not characterize the vehicle behaviour, it is important for the course of the manoeuvre in real conditions. This is because high values of this moment may make the manoeuvre considerably more difficult or even infeasible for the driver. The sign of the moment of forces on the steering wheel changed during the manoeuvre; therefore, only the absolute value (modulus) of this moment was taken into account. The maximum and average absolute values of the moment of forces on the steering wheel during the simulation of this manoeuvre have been presented in Figs. 13 and 14. For the average value to be calculated, only stages "b", "c", and "d" of the manoeuvre were taken into account because the values of this moment during stages "a" and "e" were close to zero.

The results of all the simulations have shown the vehicle agility to be better when the vehicle was driven "backwards". However, significant differences were only observed at the speed of 40 km/h; for the speed of 10 km/h, the differences may be considered inconsiderable. The value of the moment applied to the steering wheel was in every case higher when the vehicle moved "forwards"; this difference was better visible at the test speed of 10 km/h as against that observed at 40 km/h. On the one hand, lower values of the moment on the steering wheel facilitate the manoeuvre because not much driver's effort is required in this case. On the other hand, very low values of this moment make it more difficult for the driver to assess properly the vehicle behaviour (the driver "does not feel the vehicle") and this detrimentally affects the traffic safety.

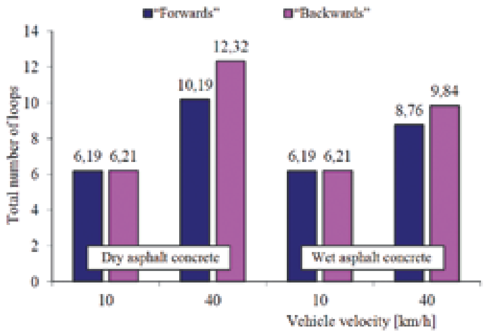

Fig. 11. Total number of vehicle trajectory loops vs. vehicle velocity and road surface type

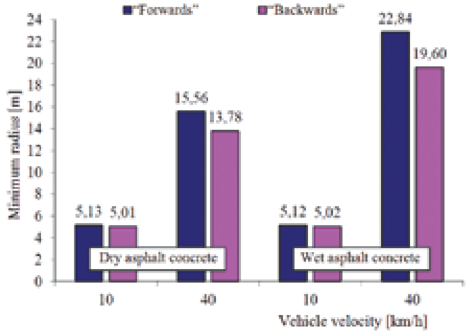

Fig. 12. Radius of the smallest vehicle trajectory loop vs. vehicle velocity and road surface type

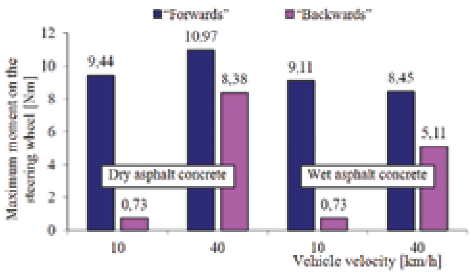

Fig. 13. Maximum absolute values of the moment on the steering wheel vs. vehicle velocity and road surface type

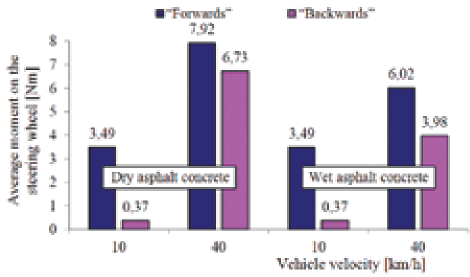

Fig. 14. Average absolute values of the moment on the steering wheel vs. vehicle velocity and road surface type

6. Vehicle drive into a parking place parallel to a roadway edge

This manoeuvre is carried out at a low vehicle velocity (at this study, the velocity was assumed as 2 m/s = 7.2 km/h). To perform such a manoeuvre, the driver turns the steering wheel through large angles. In consideration of the vehicle velocity being low, only the vehicle drive on dry asphalt concrete was simulated (at low vehicle speeds, the impact of changes in the road surface type on simulation results is very small and may be ignored). The tyre slip angles were very small, too. Chiefly the trajectories of selected vehicle points, including the points of the simplified vehicle contour, were subject to the analysis.

The simulation parameters were specially selected for the lateral displacement of the centre of vehicle mass to be 2.5 m from the initial position. The steering wheel input, illustrated in Fig. 15, had the form of a single complete sinusoidal cycle, as normally used by vehicle drivers at a manoeuvre of this kind.

The trajectories of the centre of vehicle mass and of the simplified vehicle contour and the time history of the moment of forces applied to the steering wheel have been shown in Fig. 16.

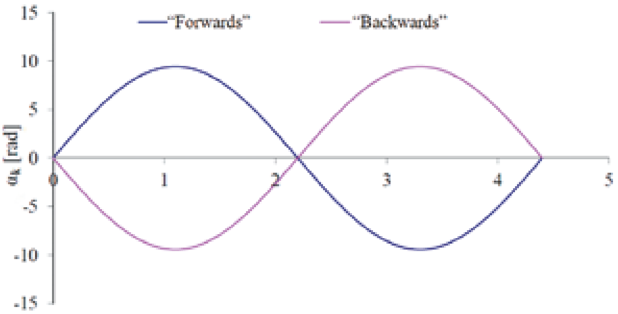

Fig. 15. Manoeuvre 3. Time history of the steering wheel input

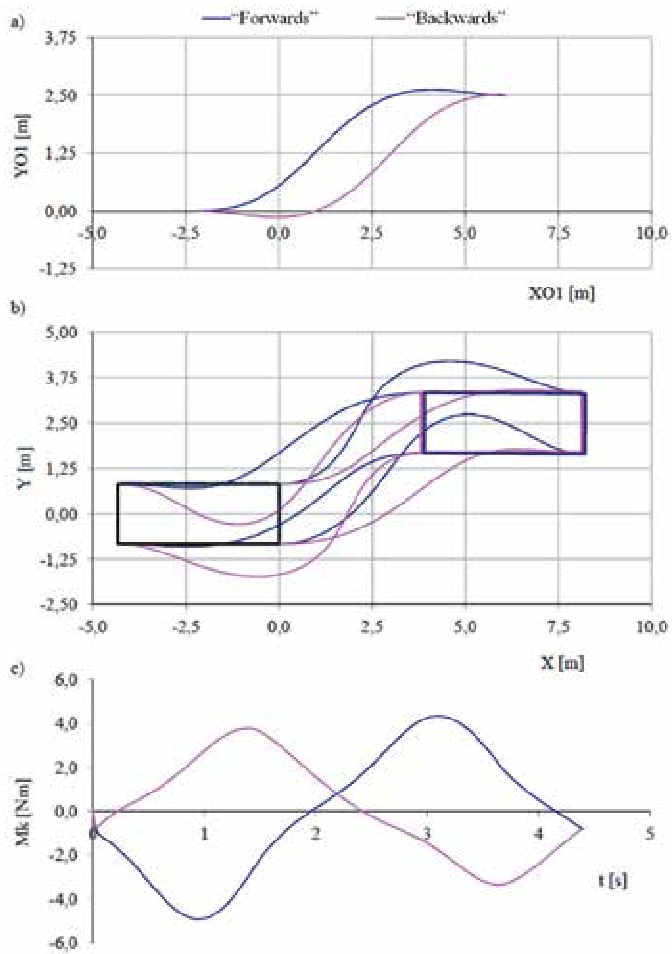

Fig. 16. Trajectory of the centre of vehicle mass (a), trajectory of the vehicle contour (b), and time history of the moment on the steering wheel (c)

For the simulation results to be easier to read and analyse, the contour of a vehicle "standing" in front of the vehicle covered by the simulation has been marked on some of the drawings to follow. In Fig. 17, the additional vehicle has been placed in a position enabling the manoeuvre to be carried out. Based on the positions of both vehicles, lines have been drawn to determine the shortest length of the parking place necessary for the manoeuvre to be successful. The width of the parking place, equal to 2.5 m, was adopted in accordance with the regulations in force [17]. It can be seen at first glance that the minimum parking place must be longer when the vehicle is driven "forwards". If the red solid line at the top of the drawing is taken as a borderline (e.g. a curb), then this manoeuvre cannot be considered as completed successfully for the vehicle moving "forwards" (unless crossing of the borderline representing a curb is allowed). For successful completion of this manoeuvre to be made possible with the vehicle moving "forwards", the initial position of the vehicle should be changed by increasing its distance from the edge of the roadway (or parking place). This would also affect the final vehicle position (the vehicle would be parked very close to the curb).

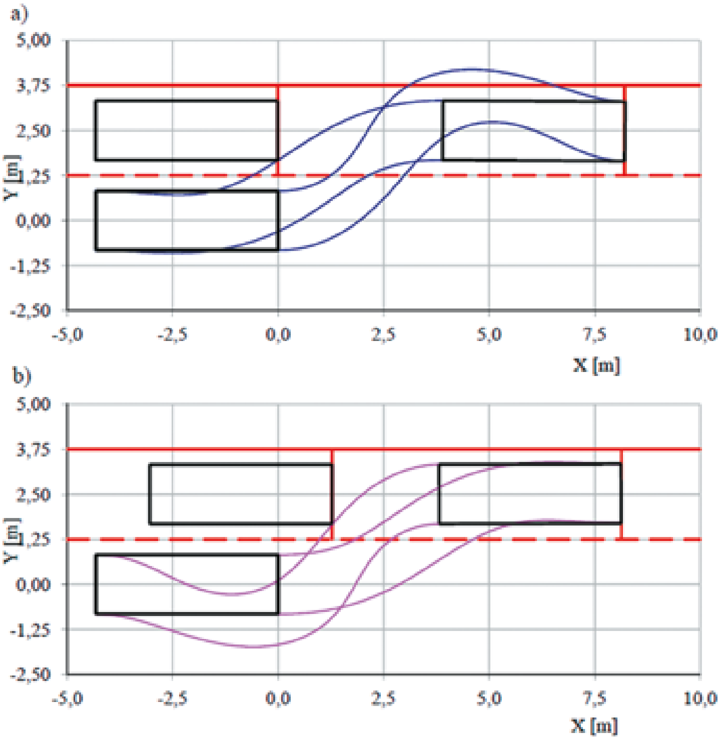

Fig. 17. Trajectory of the vehicle contour: a) for the vehicle moving "forwards"; b) for the vehicle moving "backwards"

As another method of making it possible to complete the manoeuvre successfully, i.e. without the line representing the curb being crossed by the vehicle and without the initial and final distance between the vehicle and the curb (i.e. the lateral vehicle position) being changed, when the vehicle is driven "forwards", the steering wheel input may be modified. This, however, would result in increasing the minimum required length of the parking place. The authors managed to achieve this (with the use of an iterative method) for the input presented in Fig. 18 (by lengthening the period and reducing the amplitude of the steering wheel turning angle). The successful performance of the manoeuvre, although characterized by the required parking place being much longer, has been illustrated in Fig. 19. The minimum required length of the parking place is defined by the front line of the contour of the vehicle having been parked and the red vertical line drawn in Figs. 17 and 19. This dimension should be considered the minimum distance between two vehicles that enables the third one to be driven without collision into the parking place between them at a predefined steering wheel input and vehicle velocity. The values of this dimension for the simulations described above have been presented in Fig. 20. In real conditions, these distances might be different depending on the type of the steering wheel input. During such a manoeuvre, the driver would not have to apply an input in the form of a single complete sinusoidal cycle to the steering wheel; instead, he/she would apply an input optimized to reduce the analysed length of the distance between the vehicles to a minimum. The optimization might be accomplished, first of all, by changing the steering wheel turning angle at a zero or very low vehicle velocity.

The average and maximum moment applied to the steering wheel during the parking manoeuvre has been shown in Fig. 21.

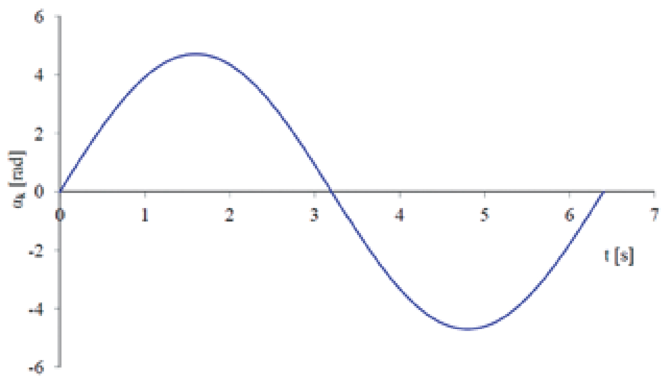

Fig. 18. Manoeuvre 3. Time history of the steering wheel input during the "forward" movement, with the parameters (period and amplitude) of this input having been modified

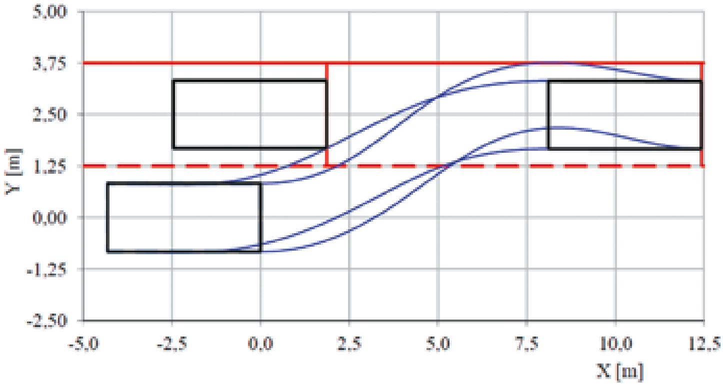

Fig. 19. Trajectory of the vehicle contour for the vehicle moving "forwards" after modification of the steering wheel input

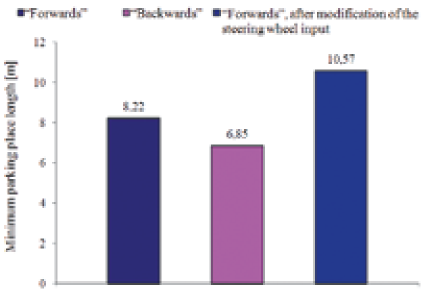

Fig. 20. Minimum parking place length

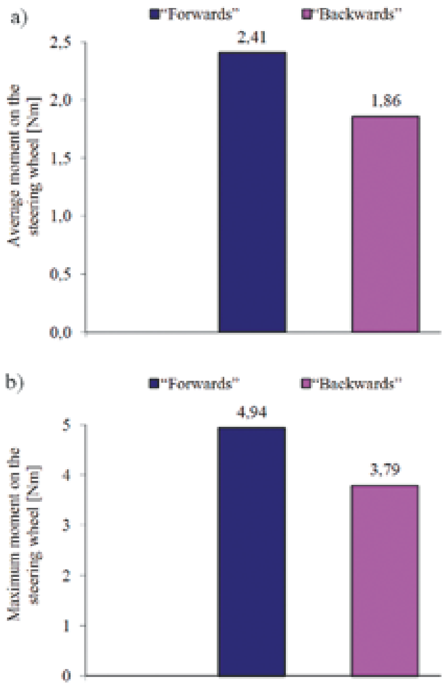

Fig. 21. Average (a) and maximum (b) moment applied to the steering wheel during the parking manoeuvre

In all the cases simulated, the required length of the parking place exceeded the minimum value of 6 m allowed by the regulations in force [17]. Obviously, the value of 6 m is meant here as the one that must be met by the parking places marked on the road surface pursuant to the regulation referred to above [17] and it is not applicable to vehicles. Shorter lengths might also be obtained as simulation results, but this would require the application of more complicated steering wheel inputs, like those occurring in real conditions where neither the vehicle velocity nor the steering wheel turning rate is constant. However, the manoeuvres thus simulated cannot be counted among "open-loop tests" [15, 16], i.e. tests without a driver–vehicle–environment feedback.

The simulation results have confirmed the fact that a vehicle moving "backwards" can be driven into a parking place parallel to a roadway edge even if the parking place length is too short for such a manoeuvre to be carried out with the vehicle being driven "forwards".

When examining the shapes of the vehicle trajectories during the "forward" and "backward" movement, one can conclude that if a vehicle can only be driven into a specific parking place when moving "backwards" then the vehicle can be driven out of such a place only when moving "forwards".

7. Recapitulation

The results obtained have unequivocally shown that the agility of a motor vehicle is better when the vehicle moves "backwards". Primarily the castor angle and additionally the kingpin inclination angle are so selected that they fulfil their stabilizing function during the "forward" movement. When the vehicle moves "backwards", the castor angle has a destabilizing impact, reducing the values of the stabilizing moment and of the moment of forces on the steering wheel. At higher velocities, the main part is played by the stabilizing moment generated by the tyre rather than the wheel angles and the values of the moment of forces on the steering wheel are more close to each other for the "forward" and "backward" movements.

When carrying out the manoeuvres such as the vehicle drive into a parking place parallel to a roadway edge, it is better to drive the vehicle "backwards". Such a finding is well known to every experienced driver and this fact may rather be considered just confirmation of the usefulness of the simulation method adopted.

References

[1] ARCZYŃSKI S., *Mechanika ruchu samochodu* (*Mechanics of motion of a motor vehicle*). WNT, Warszawa 1993.

[2] E/ECE/324, E/ECE/TRANS/505. UNECE *Regulation No. 79. Revision 2. Uniform provisions concerning the approval of vehicles with regard to steering equipment.* 21 April 2005.

[3] Komenda Główna Policji. Biuro Ruchu Drogowego. Zespół Profilaktyki i Analiz (National Police Headquarters. Road Traffic Office. Team for Prophylactics and Analyses), *Wypadki drogowe w Polsce w 2012 roku* (*Road accidents in Poland in 2012*). Warszawa, 2013 r. (Worked out by: Elżbieta Symon).

[4] Komenda Główna Policji. Biuro Ruchu Drogowego. Zespół Profilaktyki i Analiz (National Police Headquarters. Road Traffic Office. Team for Prophylactics and Analyses), *Wypadki drogowe w Polsce w 2011 roku* (*Road accidents in Poland in 2011*). Warszawa, 2012 r. (Worked out by: Elżbieta Symon).

[5] http://moto.wp.pl/kat,1035925,title,Oddzial-5-Wymijanie-omijanie-i-cofanie,wid,15290037,kodeks_drogowy_rozdzial.html?ticaid=111f4c (The Polish Highway Code, visited on: 3 Jan. 2014).

[6] http://kodeks-drogowy.org/ruch-drogowy/ruch-pojazdow/wymijanie-omijanie-i-cofanie (The Polish Highway Code, visited on: 3 Jan. 2014).

[7] http://www.ciop.pl/26905. Centralny Instytut Ochrony Pracy (Central Institute for Labour Protection). E-Facts. *Zapobieganie wypadkom z udziałem pojazdów w budownictwie* (*Prevention of accidents with vehicles in the construction industry*) (visited on: 3 Jan. 2014).

[8] http://hw.osha.europa.eu – *Recommendations of the European Agency for Safety and Health at Work*.

[9] http://www.roadingnz.org.nz. *Guideline for Controlling Reversing Vehicles*. Roading New Zealand, ISBN 978-0-9582827-1-0, December 2009 (visited on: 3 Jan. 2014).

[10] http://patentynamanewry.blogspot.com/2012/08/jazda-pasem-ruchu-do-przodu-i-do-tyu-i.html (visited on: 3 Jan. 2014).

[11] http://www.ckprawko.pl/poradnik-kursanta/egzamin-jazda-po-luku/ (visited on: 3 Jan. 2014).

[12] http://www.linkedin.com/company/networp/vehicle-reversing-safety-systems-136679/product?trk=biz_product (visited on: 3 Jan. 2014).

[13] http://www-cvdc.eng.cam.ac.uk/photo-and-video-gallery/active-steering-of-european-combination-vehicles/unsteered-roundabount-manoeuvre (visited on: 3 Jan. 2014).

[14] http://www-cvdc.eng.cam.ac.uk/photo-and-video-gallery/actively-steered-b-double-lorry/teardrop-reversing-manoeuvre (visited on: 3 Jan. 2014).

[15] LOZIA Z., *Symulacja testów otwartych układu kierowca-pojazd-otoczenie* (*Simulation of open-loop tests of the driver–vehicle–environment system*). Files of the Scientific and Problem Committee of the Automotive Industry, Polish Academy of Sciences, Division in Cracow, Vol. 26–27, Kraków 2003, pp. 229–234.

[16] LOZIA Z., *Analiza ruchu samochodu dwuosiowego na tle modelowania jego dynamiki* (*Analysis of motion of a two-axle automotive vehicle against the background of modelling of its dynamics*). Oficyna Wydawnicza Politechniki Warszawskiej (Publishing House of the Warsaw University of Technology). Warszawa 1998.

[17] Rozporządzenie Ministra Transportu i Gospodarki Morskiej z dnia 2 marca 1999 r. w sprawie warunków technicznych, jakim powinny odpowiadać drogi publiczne i ich usytuowanie (Regulation of the Minister of Transportation and the Maritime Economy on the technical requirements to be met by public roads and their siting). Dz. U. 1999 No. 43, item 430.

[18] *Simulation method of comparative evaluation of the steerability of a passenger car when moving forwards and backwards*. Archiwum Motoryzacji / The Archives of Automotive Engineering, Vol. 63, Nr 1, 2014. Str. 157-176. s. 51-70. ISSN 12345-754X.