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

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Summary

The objective of this work was to compare the characteristics of steerability (ease of steering) of a specific motor vehicle when moving "forwards" and "backwards" ("reversing"). These terms have been put here in quotation marks because they depend on the convention adopted and because the answer to a question whether the vehicle moves "forwards" or "backwards" depends on an individual point of view. In this paper, the movement "forwards" is understood as the one where the vector of the predefined vehicle movement velocity is pointing towards the vehicle front. The movement "backwards" ("reversing") may also be defined as vehicle movement in reverse gear and the movement "forwards" may be defined as the one in any other gear. To accomplish the objective of this work, a simulation method was employed. The vehicle velocity was limited to 40 km/h because it would be difficult to achieve higher velocities when "reversing" in real conditions and it would not be possible then to consider the results obtained in relation to actual manoeuvring. The steerability characteristics were more favourable when the vehicle moved forwards: the vehicle remained understeering over the whole range of lateral accelerations under consideration. In general, the understeering is considered better than the varying characteristics observed at "reversing", when the vehicle may be understeering or oversteering depending on the value of its lateral acceleration and, in result of this, the vehicle behaviour becomes unpredictable and requires higher psychomotor capabilities of the driver.

Keywords: simulation, vehicle steerability, reversing

1. Introduction

The objective of this work was to compare the characteristics of steerability (ease of steering) of a specific motor vehicle when moving "forwards" and "backwards" ("reversing"). These terms have been put here in quotation marks because they depend on the convention adopted and because the answer to a question whether the vehicle

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moves "forwards" or "backwards" depends on an individual point of view. In this paper, the movement "forwards" is understood as the one where the vector of the predefined vehicle movement velocity is pointing towards the vehicle front. The movement "backwards" ("reversing") may also be defined as vehicle movement in reverse gear and the movement "forwards" may be defined as the one in any other gear.

The term "steerability" is understood by the authors as vehicle's capability to react quickly and precisely to steering wheel movements [1]. This enables the driver to manoeuvre the vehicle easily and to keep it on the intended path. The procedures to examine this property of a vehicle are described in normative documents issued by the International Organization for Standardization (ISO) [2]), Polish Committee for Standardization (PKN) [3], and United Nations Economic Organization for Europe (UN ECE) [4].

Normally, all drivers drive their motor vehicles "forwards" or "backwards" and very few of them think about the issue how the characteristics of their vehicles change with a change in the direction of vehicle motion. This paper is to be an attempt to present and explain differences in the steerability characteristics of a motor vehicle driven "forwards" and "backwards".

The literature dealing with the issues under consideration is very scanty and, as regards details, quite distant from the subject matter of this work. It is known [5] that among the 37 046 road accidents that took place in Poland in 2012, 30 186, i.e. 81.5% of the total, were caused by vehicle operators. In this number, 592 accidents (2.0%) occurred when vehicles were reversing, which resulted in 28 killed and 596 injured. A predominating part of these casualties consisted of pedestrians (16 killed and 456 injured). Similar data were recorded in 2011 [6]. These figures provide grounds for taking up the dynamic properties of vehicles when moving backwards ("reversing"). According to the Polish Highway Code, Chapter 3, Section 5, Article 23, items 1 and 2 [7, 8], the vehicle driver "when reversing, shall give way to another participant in the traffic and exercise special caution", "the vehicle operator shall arrange for another person's assistance in the reversing", and "any reversing in a tunnel, on a bridge or flyover, in a motorway or dual carriageway shall be forbidden".

The hazard accompanying the "backward" driving is taken into consideration at the training of vehicle drivers and operators of mobile machines, especially those used in the construction industry [9, 10, 11]. Publication [11] includes instructions regarding the reversing, with information about the dangerous zones, methods of carrying out the manoeuvre, clothing of the person who assists the driver, and signs given by such a person. Internet guides (e.g. [12, 13]) offer texts, schematic diagrams, photos, and movies that are to help students of driver schools in the performing of a reversing manoeuvre.

Assistance systems such as VRSS (Vehicle Reversing Safety Systems) [14] assist the driver in reversing by detecting obstacles present in the vehicle path and warn the driver that such obstacles exist in the blind spots. Research on systems of this kind is carried out by e.g. Cambridge Vehicle Dynamics Consortium [15, 16].

The authors, however, did not come across any publication presenting a comparison between the steerability of a vehicle moving "forwards" and "backwards".

The vehicle tests presented herein were simulations carried out with the use of an authorial model and a computer program. 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 velocity was limited to 40 km/h because it would be difficult to achieve higher velocities when "reversing" in real conditions.

2. Model and simulation program

A physical model of a two-axle vehicle has been shown in Fig. 1 [17]. An assumption has been made that the vehicle modelled moves on an even horizontal road surface. The vehicle body and road wheels are treated as rigid bodies. The description of vibrations of the unsprung masses of the suspension system has been omitted. The vehicle body solid has six degrees of freedom; the other four degrees of freedom are related to the rotational motion of road wheels.

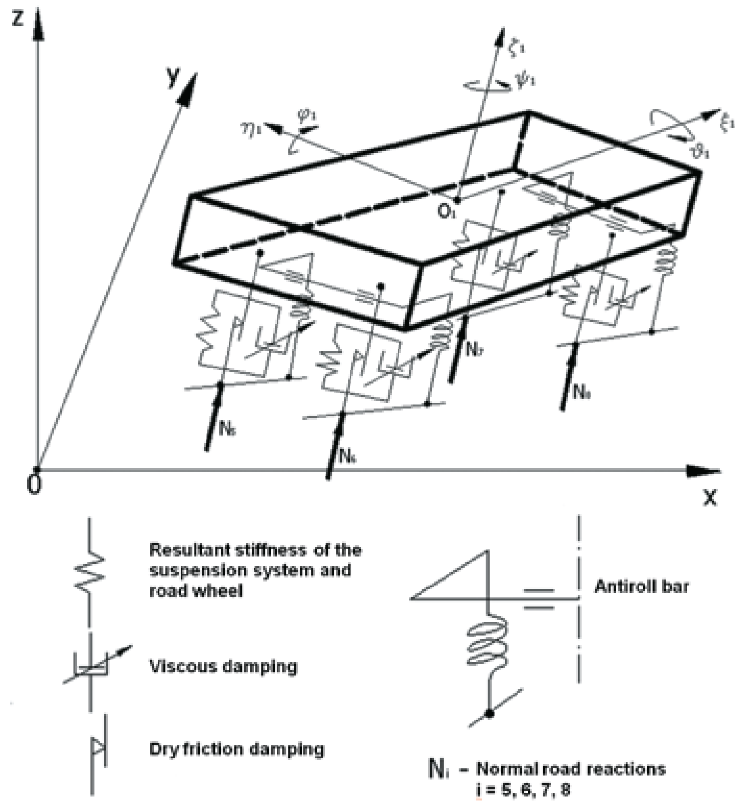

Fig. 1. Physical model of a two-axle motor vehicle [17]

The model includes the description of spring forces, dry friction, and viscous damping in the suspension system of each wheel as well as the description of the impact exerted by antiroll bars. The contact forces and the stabilizing moment of a tyre have been modelled with taking into account the impact of vehicle velocity and normal road reaction. The transient states of the lateral force and the stabilizing moment are described by a first-order differential equation (IPG-Tire model) [17].

In the steering system model (Fig. 2), description of stabilization of the steered wheels, geometrical characteristics of the steering linkage, and flexibility of the steering column, steering gear, and steering rods have been taken into account. The modelling of a 4WS system with a variable speed-dependent ratio between the front and rear steered wheel turning angles is also possible (in compliance with Bosch recommendations).

The plays and dry friction in the steering system and the gyroscopic moments accompanying the turning of rotating steered wheels have been disregarded.

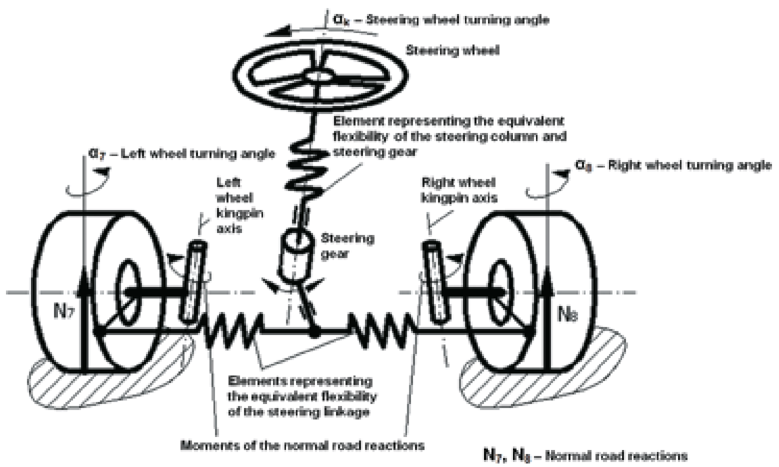

Fig. 2. Model of a motor vehicle steering system with a parallel structure [17, 18]

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 authorial simulation program ZL_FL_3D solves the equations by approximate methods with maintaining high computation accuracy. The simulation tests were carried out with the use of a standard personal computer. The simulations were not real-time processes. This has the meaning that the time necessary for the computations to be completed depended not only on the model parameters but also on computing capacity of the computer used. Moreover, the vehicle could not be controlled during the simulation and the course of the simulation process exclusively depended on the parameters loaded before the process was started. Text files were used to load the input data, to define the range of the output data recorded, and to record the simulation results. The vehicle data described the geometric, inertial, and aerodynamic characteristics of the vehicle; spring characteristics of the suspension system and pneumatic tyres in the vertical direction; pneumatic tyre characteristics in the tangent direction and rolling resistance; geometric and spring characteristics of the steering system; and characteristics of the braking and driving systems. Moreover, parameters describing the environment in which the vehicle was moving, such as wind velocity components, ambient air density, and road surface characteristics, were entered as well. The other data necessary to start the simulation included the variables that controlled the simulation (e.g. time increment and number of steps in the simulation), initial conditions (vehicle position and velocity, angular velocities of individual wheels), and control parameters of vehicle's braking, driving, and steering systems.

The simulation model may be tested in conditions corresponding to high risk and at big changes in vehicle characteristics and vehicle motion parameters.

The simulation of some manoeuvres requires that driver's actions should be defined. In *"open-loop tests"* [17, 18], the driver is represented by time functions of steering wheel turning angle, brake pedal effort, accelerator pedal depressing degree, and transmission gear ratio.

The simulation of "reversing" in the ZL_FL_3D program was actually accomplished as a simulation of vehicle movement forwards, but the vehicle was steered by turning rear axle wheels, with interchanging the parameters describing the front and rear vehicle ends and the location of the centre of mass and with altering the parameters describing the aerodynamic properties of the vehicle.

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). To compare the steerability characteristics of the vehicle moving "forwards" and "backwards" with each other, two different manoeuvres were simulated. The first one was quasi-steady motion of the vehicle along a path with a varying curvature radius, aimed at determining the vehicle steerability characteristics making it possible to assess whether the vehicle was understeering, neutral, oversteering, or had varying steerability characteristics [2, 3, 18]. The other one was a single dynamic lane-change manoeuvre, considered typical for the driving of a vehicle in road conditions [18].

The simulations were carried out for two different vehicle velocities, two road surface types, and vehicle movements "forwards" and "backwards". The parameters describing the following were modified: road surface type, initial vehicle velocity, vehicle driving system control mode (transmission gear ratio and vehicle velocity to be maintained during the simulation), type of the input applied to the steering wheel, and number of simulation steps, which in connection with the time increment adopted for the simulation (0.0001 s in all cases) determined the test duration time; this time should be long enough for all the important manoeuvre stages to be completed and for the parameters describing the vehicle motion at the end of the simulation to be stabilized (the parameters meant here are, first of all, the direction of motion, vehicle accelerations, and value of the moment applied to the steering wheel).

The parameters characteristic for individual manoeuvres will be presented when they are analysed. The parameters depending on vehicle velocity, road surface type, and vehicle movement direction ("forwards" or "backwards") have been given in Tables 1, 2, and 3.

Table 1. Initial conditions depending on vehicle velocity

Vehicle velocity	Velocity of point O_1 in the O_x direction	Angular velocities of road wheels			
		Movement "forwards"		Movement "backwards"	
		Front wheels	Rear wheels	Front wheels	Rear wheels
[km/h]	[m/s]	[rad/s]	[rad/s]	[rad/s]	[rad/s]
10	2.78	10.11	10.22	10.22	10.11
40	11.11	40.60	40.75	40.75	40.60

Table 2. Pneumatic tyre characteristics in the tangent direction, depending on the road surface type

Road surface type	Maximum value of the coefficient of adhesion	Coefficient defining the dependence of the coefficient of adhesion on the slip velocity
[–]	[–]	[s/m]
Dry asphalt concrete	0.95	0.01
Wet asphalt concrete	0.75	0.016

Table 3. Driving system control parameters

Vehicle velocity	Driving system control mode	Controlled constant vehicle velocity	Current transmission gear ratio	
			Movement "forwards"	Movement "backwards"
[km/h]	[–]	[m/s	[–]	[–]
10	Keeping the vehicle velocity constant	2.78	3.778	3.526
40		11.11	1.944	3.526

3.1. Vehicle motion along a path with a varying curvature radius

The most typical vehicle steerability tests are those carried out in the conditions of steady motion along a circular path, with different vehicle velocities and different radii of the circle. Pursuant to standard ISO 4138 [2] and the corresponding Polish Standard PN 90/S 47350 [3], vehicle test drives with different velocities along a path with a constant curvature radius are recommended. Hence, such a test is a *"closed-loop test"* with a driver–vehicle–environment–driver feedback [18].

In simulation tests, an *"open-loop"* version of this test (without the said feedback) is allowed, which is impracticable in real conditions because of the required dimensions of a road stretch on which the measurements could be carried out. The vehicle velocity is kept constant and the curvature radius of the vehicle path varies due to gradual increase in the steering wheel turning angle.

Simulation tests of vehicle motion along paths with varying curvature radii were carried out for two different vehicle velocities (10 km/h and 40 m/h) and two road surface types (dry asphalt concrete and wet asphalt concrete). At each test, the vehicle velocity during the simulation was constant, if disregarding small fluctuations caused by varying resistance to vehicle motion. The steering wheel turning angle was linearly increased during the simulation; in consequence, the vehicle path changed as well. Since these parameters were changed slowly, the motion may be considered as taking place in steady-state conditions. The input values of the steering wheel turning angle at the "forward" and "backward" movements had opposite signs, which caused the vehicle to turn in the same direction ("leftwards" or "rightwards") and facilitated the comparisons between results.

The time history of the input applied to the steering wheel has been presented in Fig. 3 and the parameters characteristic for the simulation of vehicle motion along a path with a varying curvature radius (quasi-steady-state motion simulation tests) have been given in Table 4.

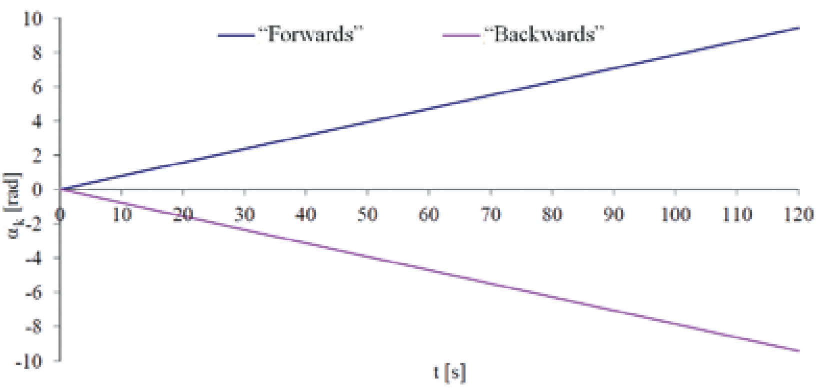

Fig. 3. Time history of the input (turning angle) applied to the steering wheel

Table 4. Parameters for all the quasi-steady-state motion simulation tests

Parameter	Value	Unit
Number of steps in the simulation	1 200 000	[–]
Type of the input applied to the steering wheel	Linear increase from a constant value	0.016
Increase in the steering wheel turning angle	9.42	[rad]
Time of increase in the steering wheel turning angle	120	[s]
Initial value of the steering wheel turning angle	0	[rad]

3.2. Single lane-change manoeuvre

The single lane-change manoeuvre is typical for vehicle driving in road conditions. It may be treated as a manoeuvre to avoid an obstacle present in the vehicle driving lane or one of the phases of an overtaking manoeuvre. It is a "closed-loop test". The results of such a test depend to a significant degree on the driver who observes the effects of his/her actions and who corrects them by changing the steering wheel turning angle. The authors of this paper were exclusively interested in vehicle properties; therefore, they adopted the "open-loop test" procedure, pursuant to standard ISO TR 8725 [19], where the input applied to the steering wheel has the form of one period of a sinusoid. Such an input represents quite well the input actually applied by the driver during a single lane-change manoeuvre in real conditions. It should be borne in mind, however, that actually the input may be more complex because the driver (in a "closed-loop test") can correct the steering wheel turning angle depending on changing conditions of vehicle motion and traffic situation.

The single lane-change manoeuvre may be divided into three separate phases:
- vehicle movement along a rectilinear path;
- lane change proper;
- continuation of movement along a rectilinear path on the neighbouring road lane.

In the simulation, the first phase of the manoeuvre was skipped because in this phase, the vehicle moves in steady-state conditions and the parameters of this motion when the vehicle moves "forwards" and "backwards" are close to each other. Thanks to the skipping of the first phase of the manoeuvre, the vehicle was in both cases in an identical position at the instant of starting the second phase, while this instant is most important. The time of simulation of the third phase of the manoeuvre was limited to a value sufficient for the vehicle motion parameters to return to the steady-state conditions.

The simulation of this manoeuvre was carried out for a vehicle velocity of 40 km/h and two road surface types, i.e. dry asphalt concrete and wet asphalt concrete. The values of the parameters characteristic for the simulation of this manoeuvre have been specified in Table 5. The input was so selected that the vehicle path remained within the prescribed "corridor", which has been shown in Fig. 4.

Table 5. Parameters for all the single lane-change manoeuvre simulation tests

Parameter	Value	Unit
Number of steps in the simulation	30 000	[–]
Type of the input applied to the steering wheel	One period of sinusoidal input	
Amplitude of changes in the steering wheel turning angle	2	[rad]
Period of changes in the steering wheel turning angle	2	[s]

When analysing the drawings provided in the subsequent part of this paper and showing the path of vehicle motion, one should bear in mind the following:

- In Fig. 4, the red horizontal solid lines mark out and separate individual traffic lanes;

this means that they delimit the desired vehicle path (the path of vehicle contour); the dashed lines delimit the desired path of the centre of vehicle mass.

- As mentioned above, the horizontal solid lines delimit the traffic lanes, but the vertical solid line represents an obstacle extending to the middle of width of the traffic lane in which the vehicle moved before start of the manoeuvre.
- The horizontal dashed lines are shifted from the corresponding solid lines towards the centreline of the appropriate traffic lane by a distance equal to a half of the vehicle width and the vertical dashed line is an extension of the corresponding solid line, with its length being equal to a half of the vehicle width.
- The gap between the central horizontal solid lines (separating the traffic lanes from each other) marks out the allowed distance of the lane-change manoeuvre; this gap is 20 m long.
- The manoeuvre is considered successful if none of the trajectories of the vertices of vehicle contour exceeded the red solid lines and, additionally, the trajectory of the centre of vehicle mass did not exceed the dashed lines.

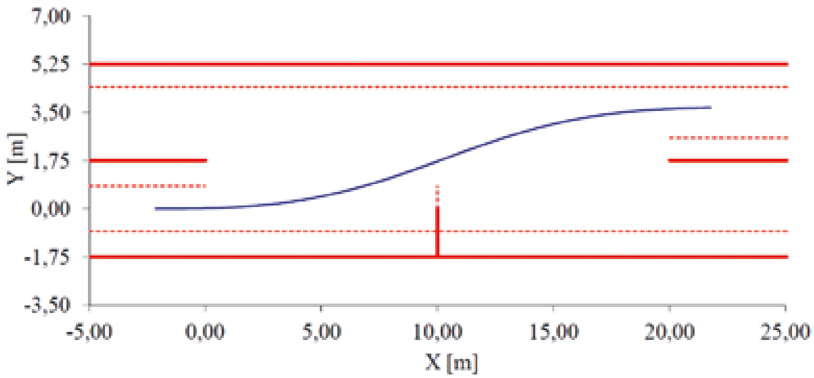

Fig. 4. The prescribed "corridor" of vehicle motion during a single lane-change manoeuvre, with an example trajectory of the centre of vehicle mass O_1

To analyse the vehicle position on the horizontal road plane, the vehicle contour has been assumed to have a simplified form of a rectangle. The X coordinate of the initial position of point O_1 (centre of vehicle mass) was so adjusted that the X coordinates of the two vertices of the rectangle representing the vehicle contour that were most advanced in the O_x direction were equal to zero. The input applied to the steering wheel as presented in Fig. 5 was so selected that the manoeuvre ended in success when the vehicle moved "forwards" (i.e. the vehicle contour passed as close as possible the lines delimiting the prescribed "corridor" with simultaneously adequate readability of drawings being secured). The end position of the vehicle in the drawings presenting the vehicle motion was assumed to be the one where the vehicle was situated at an instant of 2.21 s from the beginning of the simulation process. This is the time after which the X coordinates of the vertices of the vehicle contour moving "backwards" reached a value exceeding 20 m (this is the length of the allowed distance of the lane-change manoeuvre).

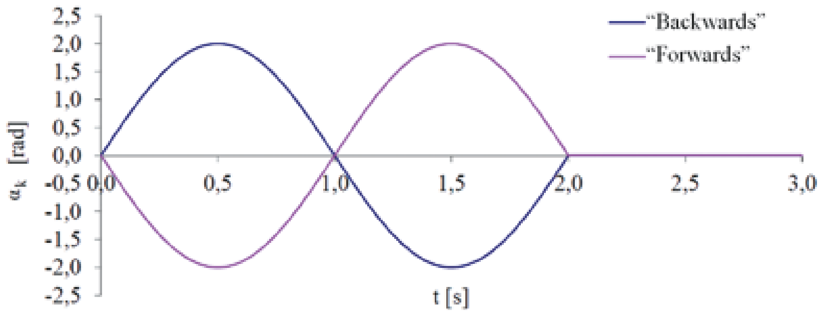

Fig. 5. Input applied to the steering wheel during a single lane-change manoeuvre

4. Results of simulation computations

4.1. Simulation results for the vehicle motion along a path with a varying curvature radius

Results of the simulation for a vehicle velocity of 40 km/h and the road surface being dry and wet have been presented in Figs. 6 and 7. When comparing the trajectories of the centre of vehicle mass at movements "forwards" and "backwards" between each other, one may notice the graph plotted for the movement "backwards" to be shifted to the right in relation to that for the movement "forwards". Similar results, including the shift (although the shift was smaller in this case), were recorded for the movements with a velocity of 10 km/h. The said shift results from a difference in the position (shift to the right at the "backward" movement) of the instantaneous centre of vehicle rotation at the beginning of the manoeuvre. If the tyre sideslip angles are so small that they may be disregarded, the instantaneous centre of vehicle rotation lies on a straight line that is a projection of the axis of the non-steered road wheels on the road plane [1]. With an increase in the tyre sideslip angles, which takes place simultaneously with an increase in the vehicle velocity and/or steering wheel turning angle, the instantaneous centre of vehicle rotation is shifted and its location depends on the tyre sideslip angle values.

One of the criteria of assessment of the simulation results was the number of loops made by the centre of vehicle mass during the simulation test, determined from the total vehicle yaw angle according to the equation:

$$n_p = \frac{\psi_{1k}}{2\pi} \tag{1}$$

where: n_p – number of loops in the trajectory of the centre of vehicle mass;
ψ_{1k} – total vehicle yaw angle.

The simulation results obtained for different vehicle velocities and road surface types and for vehicle movements "forwards" and "backwards" have been brought together in Fig. 8.

In all the cases, the number of loops was higher for the movement "backwards", with the biggest difference being recorded for the velocity of 40 km/h and dry asphalt concrete. The growth in the difference with increasing velocity may be explained, *inter alia*, by longer distance travelled by the vehicle, which translated into a higher number of the loops in the trajectory of the centre of vehicle mass and, in consequence, bigger differences in the numbers of loops. On the road with a wet asphalt-concrete surface and at the vehicle velocity of 40 km/h, lower values were recorded because of bigger tyre sideslip angles (which are ignorable at low velocities) and, in consequence, a bigger radius of the trajectory of the vehicle centre of mass (in this range of lateral accelerations, the vehicle was chiefly understeering; this will be discussed in a subsequent part of this paper).

The steerability of a motor vehicle is defined, *inter alia,* by the ease of steering of the vehicle; it is obvious, therefore, that the value of the moment of forces applied to the steering wheel has been chosen as one of the steerability assessment criteria. Although this moment does not directly characterize the vehicle behaviour, it is important for the course of the manoeuvre in real conditions, because it may make the manoeuvre considerably more difficult or even infeasible for the driver. The sign of the moment of forces on the steering wheel depended on the sign of the steering wheel rotation angle; therefore, the absolute value of this moment was taken into account. The maximum and average values of the modulus of the moment of forces on the steering wheel during the simulation of this manoeuvre have been presented in Figs. 9 and 10.

In all the cases, the absolute value of the moment of forces on the steering wheel was higher when the vehicle moved "forwards". It is worth pointing out here that 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 "backward", the castor angle has a destabilizing impact, reducing the values of the stabilizing moment and of the moment of forces on the steering wheel, and this explains the very big drop in the moment on the steering wheel at low vehicle velocities. At higher velocities, the main role 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 "forwards" and "backwards" movements. The lower value of the moment of forces on the steering wheel when the vehicle moved on the road with a wet asphalt-concrete surface can be explained by a decrease in the value of the coefficient of adhesion and, in consequence, in the stabilizing moment generated by the tyre.

The main goal of the simulation tests carried out was to determine the characteristic curves describing the steerability. These curves may be determined on the grounds of an analysis of the input signal in the form of the steering wheel turning angle in the domain of lateral vehicle acceleration. Figs. 11 and 12 present the characteristic curves of the steerability, showing the dependence of the difference between the steering wheel turning angle and the angle of turning the steering wheel of the Ackermann vehicle (i.e. a vehicle where the tyre sideslip angles are negligible) on the lateral acceleration [1, 2, 3, 18]. These characteristic curves were only determined for the vehicle velocity of 40 km/h because the accelerations developed at the velocity of 10 km/h are too low for the sideslip to have any considerable impact on the vehicle motion. A criterion of the steerability assessment is the angle of inclination of the tangent to the characteristic curve $\alpha_k - \alpha_{k\_Ack} = f(a_{\eta 1})$ in relation to the Ackermann line lying on the horizontal axis. The vehicle is oversteering when the values of this angle are negative, neutral when this angle is equal to zero, and understeering when the values of this angle are positive.

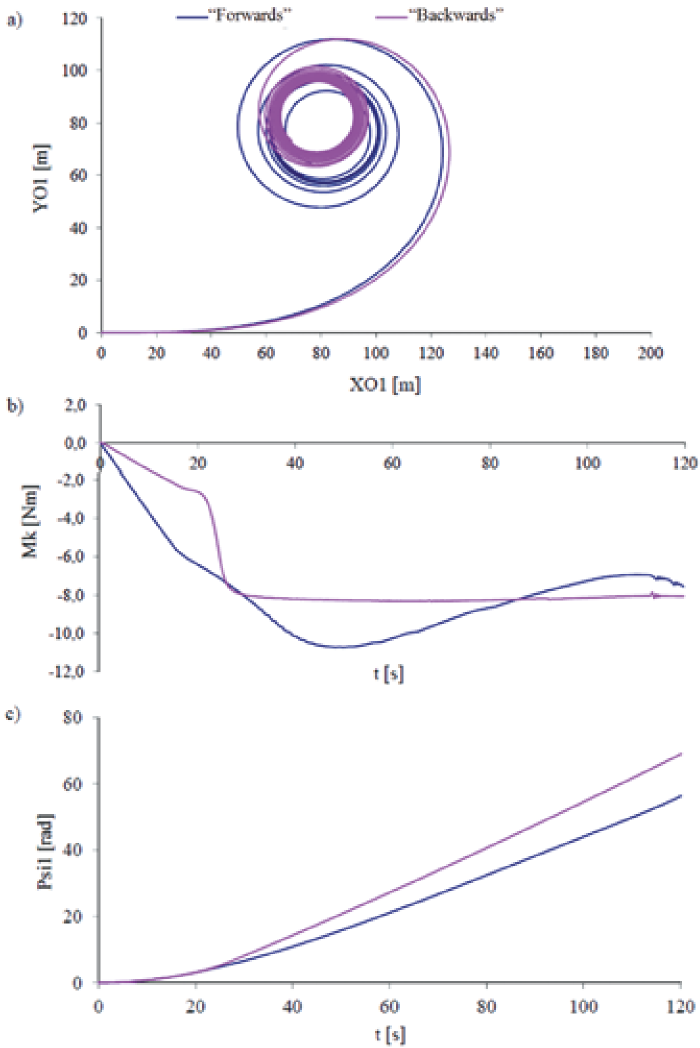

Fig. 6. Vehicle motion with a velocity of 40 km/h on dry asphalt concrete:
a) trajectory of the centre of vehicle mass O_1; b) time history of the moment of forces on the steering wheel; c) time history of the yaw angle

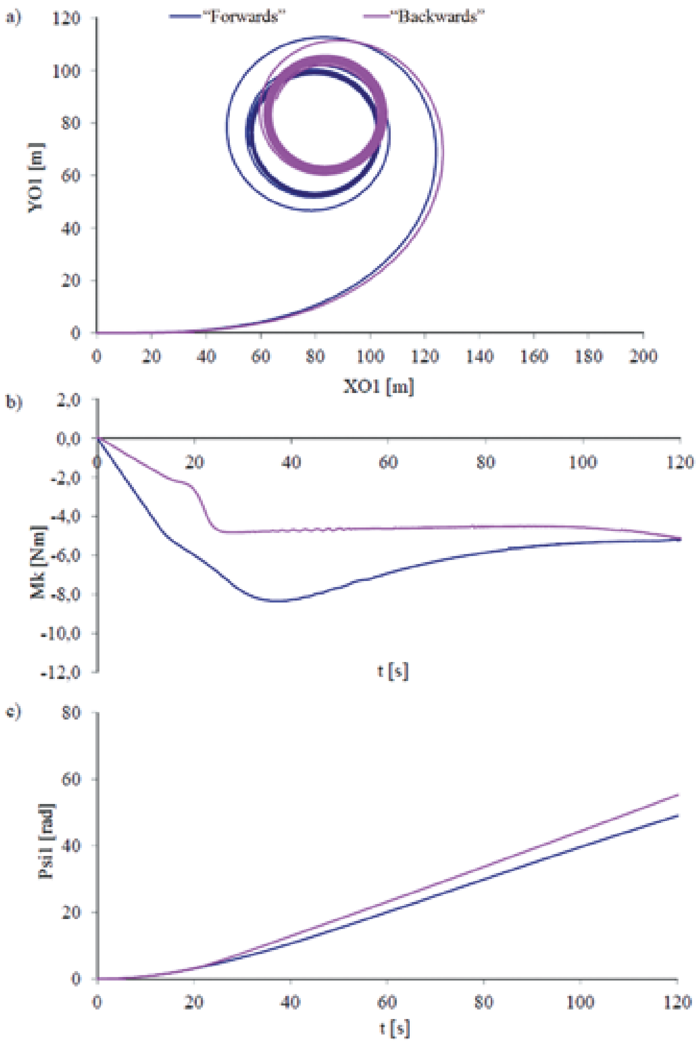

Fig. 7. Vehicle motion with a velocity of 40 km/h on wet asphalt concrete: a) trajectory of the centre of vehicle mass O_1; b) time history of the moment of forces applied to the steering wheel; c) time history of the yaw angle

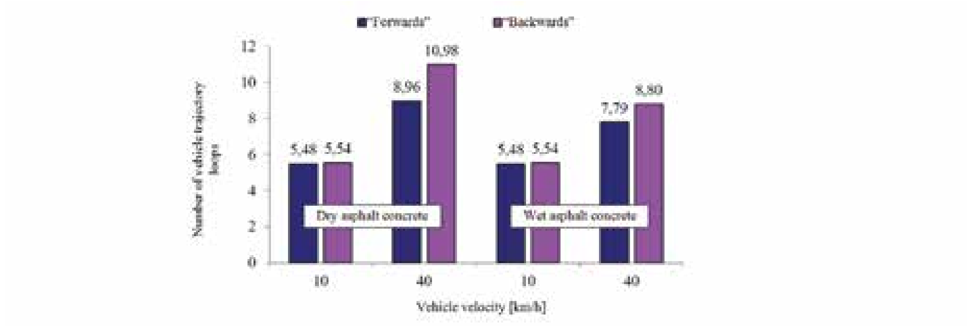

Fig. 8. Number of vehicle trajectory loops vs. vehicle velocity and road surface type

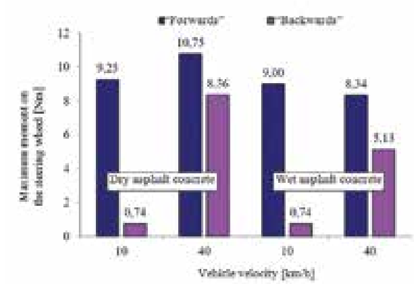

Fig. 9. Maximum value of the modulus of the moment of forces on the steering wheel vs. vehicle velocity and road surface type

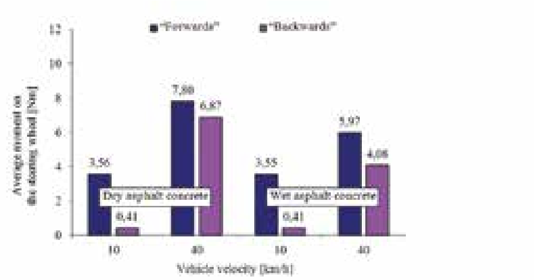

Fig. 10. Average value of the modulus of the moment of forces on the steering wheel vs. vehicle velocity and road surface type

For the "forward" movement, the steerability curves obtained (Figs. 11 and 12) show the vehicle to be understeering in the whole range under consideration. What is conspicuous is a radical increase in the curve slope, starting from a lateral acceleration value of about 2.8 m/s^2 and about 2.5 m/s^2 for the vehicle moving on dry and wet asphalt concrete, respectively. The vehicle moving "backwards" is understeering, similarly to the vehicle moving "forwards", within a lateral acceleration range of up to 3.10 m/s^2 for dry asphalt concrete and up to 2.76 m/s^2 for wet asphalt concrete. At the lateral acceleration values as specified above (3.10 m/s^2 and 2.76 m/s^2), the vehicle steerability curves turn to neutral; for higher accelerations, the vehicle becomes oversteering. The slope of the tangent to the characteristic curve changes again at lateral acceleration values of 6.17 m/s^2 and 4.92 m/s^2 for the vehicle being driven on dry and wet asphalt concrete, respectively. For the acceleration values exceeding these thresholds, the vehicle motion becomes unsteady; for the sake of readability of the characteristic curves, the range corresponding to the absolute values of the steering wheel turning angle exceeding 3 rad has been omitted.

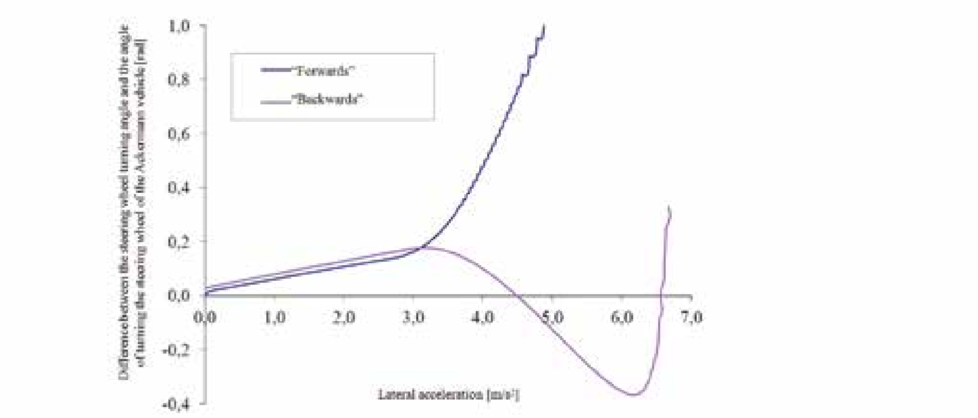

Fig. 11. Steerability curves for the vehicle moving on dry asphalt concrete with a velocity of 40 km/h

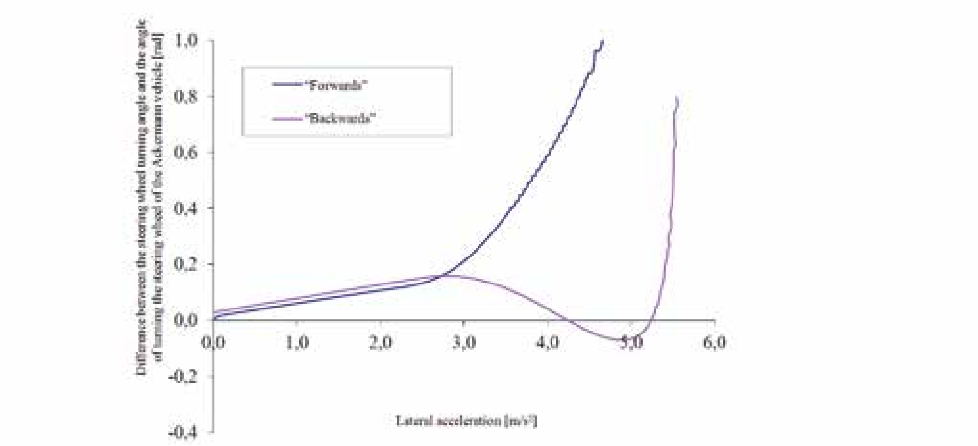

Fig. 12. Steerability curves for the vehicle moving on wet asphalt concrete with a velocity of 40 km/h

An analysis of the steerability curves shows that the vehicle under tests may be considered neutral or almost neutral only when moving "backwards" and only within narrow ranges of lateral acceleration values. For the lateral acceleration values different from those specified previously, the vehicle is either understeering or oversteering. Significant understeering or oversteering is a disadvantageous property of a vehicle. In consideration of the ease of steering, however, the understeering is a more desirable feature because when an understeering vehicle is cornering, the steering wheel turning angle must be increased for the vehicle to be maintained on the intended path while for an oversteering vehicle, the driver must appropriately reduce this angle and the behaviour of this kind is less intuitive and requires higher psychomotor capabilities of the driver. There are cases where some oversteering is a desirable feature, but this is chiefly useful in motor sports where the result achieved (driving time as short as possible) may be preferred to the ease of manoeuvring.

The most unfavourable feature is the switching from understeering to oversteering or vice versa, depending on the lateral acceleration value, because the behaviour of such a vehicle is very difficult to be predicted. The characteristic curves obtained show that the vehicle under tests should be very easily steerable at lateral accelerations of up to about 3.1 m/s^2 when driven on dry asphalt concrete and up to about 2.8 m/s^2 when driven on wet asphalt concrete. At higher lateral accelerations, the vehicle becomes considerably more understeering when moving "forwards" and turns to oversteering when moving "backwards". As stated before, the latter behaviour is unfavourable and may result in a loss of diver's control of the vehicle. The behaviour like this when the vehicle moves "backwards" should not pose a hazard in normal vehicle operation conditions, if the vehicle moves with a low velocity and, in consequence, with a low lateral acceleration.

4.2. Simulation results for the single lane-change manoeuvre

Fig. 13 shows the trajectories of the centre of vehicle mass and of the vertices of the vehicle contour during the "forward" movement on dry asphalt concrete. In the case of the "backward" movement, the manoeuvre would end in success (as it happened when the vehicle moved "forwards") if it were not for the crossing of the vertical line representing an obstacle. For such a situation to be prevented, the lane-change manoeuvre should have been started appropriately in advance. In the conditions of a simulation test, this might be accomplished by shifting the initial position of point O_1 in the Ox direction. The driver must take this difference into account when performing this manoeuvre. The vehicle trajectory with this shift having been taken into account has been presented in Fig. 14. The input applied to the steering wheel remained unchanged; therefore, the time histories of the moment of forces on the steering wheel, of the vehicle yaw angle, and of the lateral acceleration did not change, either.

The simulation results for the parameters corresponding to the vehicle drive on wet asphalt concrete are close, in qualitative terms, to those obtained for dry asphalt concrete; however, an increase in the quantitative differences has been observed, as presented in the form of quantities describing the manoeuvre as a whole. The input applied to the steering wheel was always identical; therefore, the final vehicle positions may be directly compared with each other. The following criteria were adopted for the assessment of vehicle behaviour: final position of the centre of vehicle mass in the Oy direction (Fig. 15), adjustment of the initial vehicle position necessary for the manoeuvre to be successful (Fig. 16), maximum and final vehicle body yaw angle (Figs. 17 and 18, respectively), and maximum and average moment of forces on the steering wheel (Figs. 19 and 20).

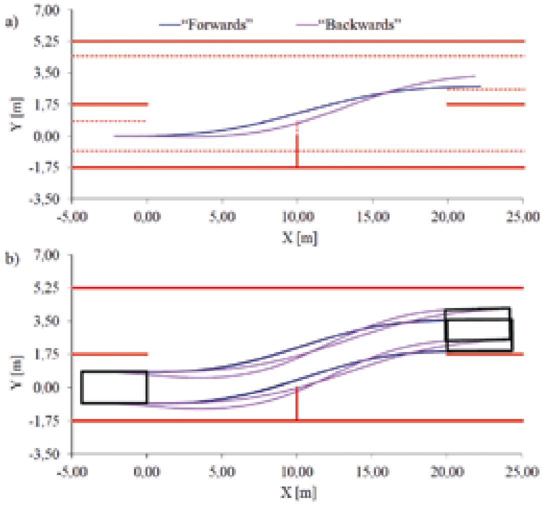

Fig. 13. Trajectories of characteristic points of the vehicle driven on dry asphalt concrete: a) centre of vehicle mass; b) vertices of the vehicle contour

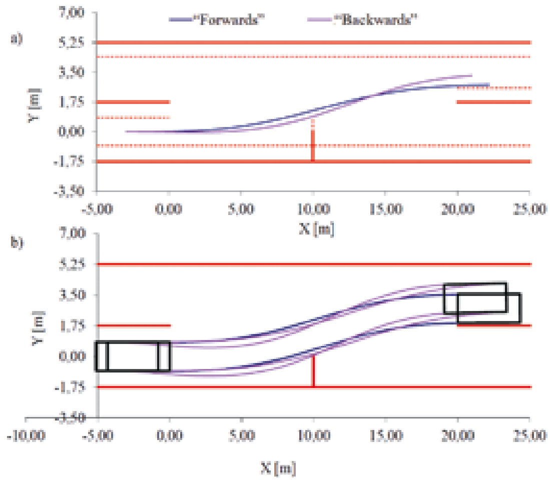

Fig. 14. Trajectories of characteristic points of the vehicle driven on dry asphalt concrete, with the initial vehicle position for the movement "backwards" having been adjusted: a) centre of vehicle mass; b) vertices of the vehicle contour

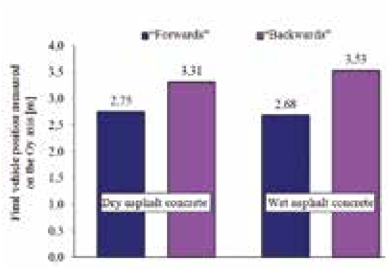

Fig. 15. Comparison between the final vehicle positions in the Oy direction

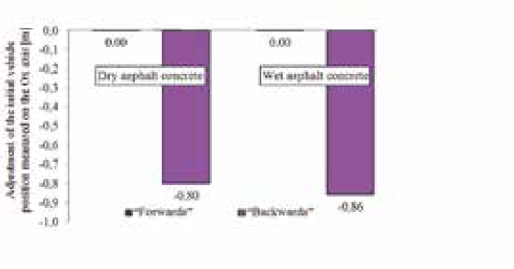

Fig. 16. Adjustment of the initial position of the vehicle centre of mass in the Ox direction, necessary for the manoeuvre to be successful

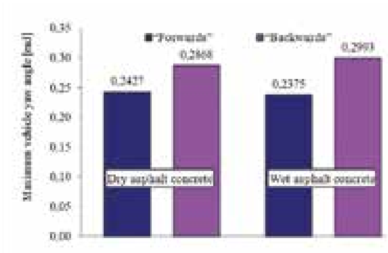

Fig. 17. Maximum vehicle body yaw angle during the manoeuvre

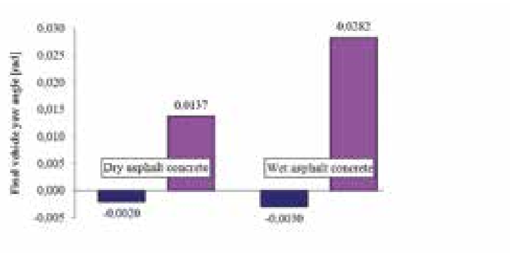

Fig. 18. Final vehicle body yaw angle during the manoeuvre

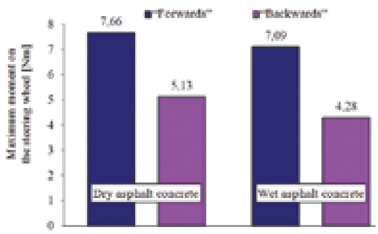

Fig. 19. Maximum moment of forces on the steering wheel during the manoeuvre

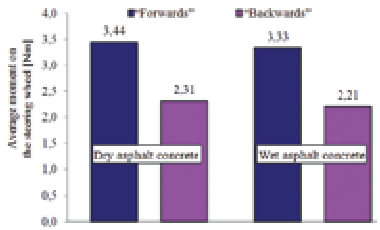

Fig. 20. Average moment of forces on the steering wheel during the manoeuvre

Based on the results obtained, a statement may be made that at identical inputs applied to the steering wheel, the lateral displacement of the vehicle moving "backwards" exceeds that of the vehicle moving "forwards". The final vehicle yaw angle is also bigger when the vehicle moves "backwards" (the vehicle does not return to its initial angular position). At the "backward" movement, the values of the moment of forces on the steering wheel are considerably lower than those recorded at the movement "forwards". For this reason, the driver should perform the "reversing" manoeuvre much more carefully.

5. Conclusions

Due to the fact that the vehicle under tests was oversteering when moving "backwards" (at high lateral acceleration values), the steering of the "reversing" vehicle may be more difficult. This is because the driver of an understeering vehicle moving along a path of a constant curvature radius must adjust the steering wheel turning angle but he/she turns the steering wheel in the same direction. Conversely, an oversteering vehicle moving along the same path has a tendency to reduce the radius of the actual trajectory, forcing the driver to adjust the steering wheel turning angle by rotating the wheel in the opposite direction.

The castor angle and the kingpin inclination angle (with the role of the former being much more important) are so selected that they fulfil their stabilizing function during the "forward" movement. When the vehicle moves "backward", 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 role 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. The lower value of the moment of forces on the steering wheel when the vehicle moved on wet asphalt concrete can be explained by a decrease in the value of the coefficient of adhesion and, in consequence, in the stabilizing moment generated by the tyre.

The results obtained show that the making of violent manoeuvres when "reversing" is more risky than it is during the movement "forwards". At "reversing", the values of the moment of forces on the steering wheel are considerably lower; for this reason, the driver should perform this manoeuvre much more carefully.

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