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SIMULATION TESTING OF TWO WAYS OF DISTURBING THE MOTION OF A MOTOR VEHICLE ENTERING A SKID PAD AS USED FOR TESTS AT DRIVER IMPROVEMENT CENTRES

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Summary

The paper concerns digital simulation of a disturbance caused to vehicle motion during tests carried out with the use of a skid pad, i.e. a test facility normally operated at Driver Improvement Centres (DIC). The disturbance is induced with the use of a dynamic "kick plate", which is a mandatory element of the equipment of "driving technique improvement centres of the higher degree", pursuant to the Regulation of the Polish Minister of Transport, Construction and Maritime Economy of 16 January 2013 on the improving of driving techniques.

The disturbance caused by a lateral displacement of the kick plate (relative to the vehicle path) forces the driver to undertake defensive manoeuvres such as turning the steering wheel, braking, or accelerating, separately or in combinations.

This paper is a continuation of a previous author's publication, where the modelling and assessment of tests with the disturbing of motion of the rear vehicle axle have been dealt with. Now, the effects of disturbing the motion of wheels of the front and rear vehicle axle have been compared with each other. The simulation results, showing the scale of the disturbance to vehicle motion to which the driver being trained must respond, have been included.

Keywords: simulation, kick plate, motor vehicle dynamics, Driver Improvement Centres

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1. Introduction

At Driver Improvement Centres (DIC), tests are carried out where, before the vehicle under test enters a skid pad with reduced tyre-to-road adhesion, the vehicle motion is disturbed by means of a dynamic "kick plate". Such a kick plate must be available at every Centre of this kind, according to the Regulation of the Polish Minister of Transport, Construction and Maritime Economy of 16 January 2013 on the improving of driving techniques [5]. In practice, the said disturbance is induced in most cases by causing a lateral displacement (jerk) of the kick plate (relative to the vehicle path) at the instant when the wheels of one vehicle axle are outside of the kick plate and the wheels of the other vehicle axle are moving on it. The disturbance caused by such a movement of the plate forces the driver to undertake defensive manoeuvres, in most cases to turn the steering wheel. However, other driver's actions, even most surprising, are also possible, e.g. applying the brakes, pressing the accelerator pedal, or doing such things in various combinations, which translate into various vehicle manoeuvres.

This paper is a continuation of a previous author's publication [2], where the modelling and assessment of tests with the disturbing of motion of the rear vehicle axle have been dealt with. The publication cited here [2] includes a description of the construction of the track on which the tests with disturbing the vehicle motion are usually carried out. The role of a destabilizing device is played by a "dynamic plate", also referred to as "kick plate" [8]. In most cases, the motion-disturbing action is applied to the rear wheels [6, 7, 8, 9]. In this paper, the effects of disturbing the motion of wheels of the front and rear vehicle axle have been compared with each other. The simulation results, showing the scale of the disturbance to vehicle motion to which the driver being trained must respond, have been presented as well. Only the behaviour of the vehicle as such in the period corresponding to the driver's reaction time, i.e. without driver's interference, was subject to the assessment. Publication [2] also presents the used model of motion and dynamics of a two-axle road vehicle, with 14 degrees of freedom. The model corresponds to a medium-class passenger car KIA Cee'd, for which very good results of experimental verification were obtained at the tests recommended by ISO [3, 4]. The method of applying a disturbance to the vehicle motion model, in the form of a lateral displacement of the kick plate (Fig. 1) placed before the entrance to the skid pad, has been described as well.

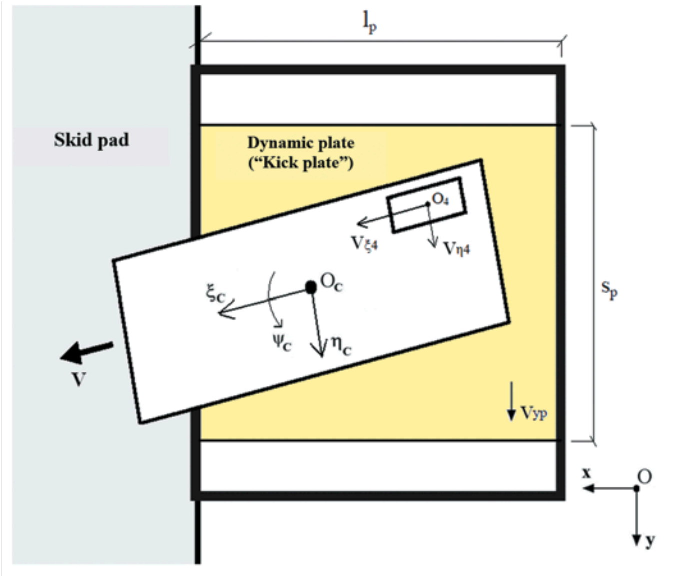

Fig. 1. Schematic diagram taken as a basis for the modification to the model and to the program simulating the vehicle motion on a DIC's test track provided with a skid pad and a dynamic plate ("kick plate") (see [2])

2. Data assumed to characterize the vehicle under test, the disturbance applied, and the conditions of vehicle motion

The data of the vehicle modelled corresponded to the nominal specifications of the Kia Cee'd car in running order, loaded with a driver and a driving instructor. The total mass of the vehicle under test was 1 570 kg, wheelbase was l = 2.655 m, distances between the centre of vehicle mass and the front and rear axle planes were l_1 = 0.976 m and l_2 = 1.679 m, respectively, and static height of the centre of mass was z_{Oc} = 0.516 m.

The kick plate (Fig. 1) parameters were assumed in accordance with the specifications of the facility made by a Polish company UNIMETAL [9], i.e. length l_p = 3.0 m, width s_p = 2.7 m, lateral displacement velocity v_{yp} equal to −1.5 m/s and 1.5 m/s for the disturbance applied to the front and rear wheels, respectively, and extreme lateral displacement s_{yp} equal to −0.3 m and 0.3 m for the disturbance applied to the front and rear wheels, respectively. The plate was coated with a material for which the maximum value of the coefficient of adhesion was 0.8. The author interprets this figure as the value of the coefficient of adhesion for a tyre slip velocity close to zero. For the data adopted, the kick plate displacement time was t_{yp} = 0.2 s. For the skid pad, the maximum value of the coefficient of adhesion was assumed as 0.5. The road, skid pad, and kick plate surfaces were assumed as being horizontal and even.

The simulation tests were carried out for seven values of the vehicle drive speed V, i.e. 20, 30, 40, 50, 60, 70, and 80 km/h. It was assumed that at the beginning of the test, the vehicle moved rectilinearly with a constant speed V, in parallel to axis 0x of the coordinate system fixed to the road (Fig. 1), and the vehicle travel path went through the centre of the moving part of the kick plate. The test was carried out according to a typical "open-loop" test procedure, i.e. with no feedback in the vehicle handling system considered as a driver-vehicle-environment-driver loop [3]. During the test, the driver did not react, i.e. he/she did not change the steering wheel turning angle or the accelerator pedal position and did not press the brake pedal or the clutch pedal. The driver assistance systems (ABS, ASR, and ESP) were deactivated (off), which often takes place when drivers undergo training at a higher (than basic) level.

3. Example results of the simulation in the time domain

Figs. 2, 3, and 4 show results of simulation calculations of selected quantities as functions of time for a vehicle speed value of V = 60 km/h. The time scale has been modified so that the time value t = 0 represents the instant when the front vehicle wheels are entering the kick plate. In the case of the disturbance being applied to the front wheels, this is the instant when the lateral movement of the kick plate begins. If the motion of the rear wheels is disturbed, the kick plate begins to move when the front wheels have just left the kick plate surface. In consequence of such a definition of the t = 0 point in the graphs (the instant when the time is equal to zero), the curves representing the test results for the disturbance applied to the rear wheels are shifted by 0.18 s (for the vehicle speed value of V = 60 km/h), which corresponds to the time of a vehicle wheel travelling the kick plate length (equal to 3 m).

The following values have been presented in Fig. 2:

- lateral displacement of the centre of vehicle mass, y_{Oc} (denoted by "yOC" in the graph),
- vehicle yaw (heading) angle ψ_C ("psiC" in the graph),
- vehicle yaw velocity $d\psi C/dt$ ("psiCp" in the graph),
- lateral acceleration of the vehicle $a_{\eta h}$ ("aetah" in the graph).

In Fig. 3, the following values have been shown:

- moment of forces on the steering wheel EMK,
- sum of the lateral forces on the front wheels F_{boczp} and on the rear wheels F_{boczt} ("Fboczp" and "Fboczt" in the graph, respectively),
- necessary effective power of the kick plate driving system P_{boczp} and P_{boczt} ("Pboczp" and "Pboczt" in the graph, respectively); it is calculated as a product of F_{boczp} or F_{boczt} and kick plate velocity v_{yp}.

Fig. 4 shows time histories of the normal reactions N_k on vehicle wheels ("ENC(k)" in the graph), where k = 1, ..., 4 indicates individual wheels.

The driver senses a disturbance to the vehicle motion chiefly through the following quantities:

- lateral acceleration $a_{\eta h}$ and yaw velocity $d\psi C/dt$ of the vehicle (these define the force

of inertia acting on driver's body and detected by the balance organs in driver's inner ear and by sensory receptors in his/her limbs and trunk),
- lateral displacement of the centre of vehicle mass yOc and vehicle yaw (heading) angle ψC, detected by the sense of sight,
- moment of forces on the steering wheel EMK, detected by hands (more precisely: by sensory receptors in the upper limbs.

It is the time histories and extremums of these quantities that have a decisive impact on driver's reactions.

The results presented in Figs. 2, 3, and 4 show the great importance of the disturbance to vehicle motion applied in the form of a lateral displacement of the kick plate. A big difference can be clearly seen between the two analysed ways of disturbing the vehicle motion, i.e. between the disturbance being applied to the front and rear vehicle wheels. Within four seconds from disturbing the motion of the front vehicle wheels, the lateral vehicle displacement (in terms of absolute extreme values) exceeded about 2.6 m, the yaw angle reached a level of 0.0419 rad, the yaw velocity did not exceed 0.2412, and the maximum lateral acceleration was 4.43 m/s^2. The moment of forces on the steering wheel (calculated from the stabilizing moments on vehicle wheels and from the steering linkage and steering gear ratios, i.e. without the effect of operation of the power steering system being taken into account) reached a value of 18.25 Nm. The necessary effective power of the kick plate driving system exceeded a value of about 8500 W. Significant diversification can be observed in the normal road reactions on the vehicle wheels (Fig. 4).

For the disturbance being applied to the rear wheels, the corresponding results were as follows. The lateral vehicle displacement was much bigger and exceeded 15 m, the yaw angle stabilized at a level of over 0.3 rad, i.e. more than seven times as high as that recorded for the disturbance applied to the front wheels. The vehicle yaw velocity reached an extremum at a level of 0.45 rad/s, i.e. almost twice as high as that observed in the compared case. The extreme value of the lateral acceleration was 4.5 m/s^2, i.e. it was close to the corresponding value in the other case. The moment of forces on the steering wheel was lower and slightly exceeded 10 Nm. The necessary effective power of the kick plate driving system was in this case much lower, i.e. about 5500 W. The normal road reactions on the vehicle wheels were also considerably diversified (Fig. 4).

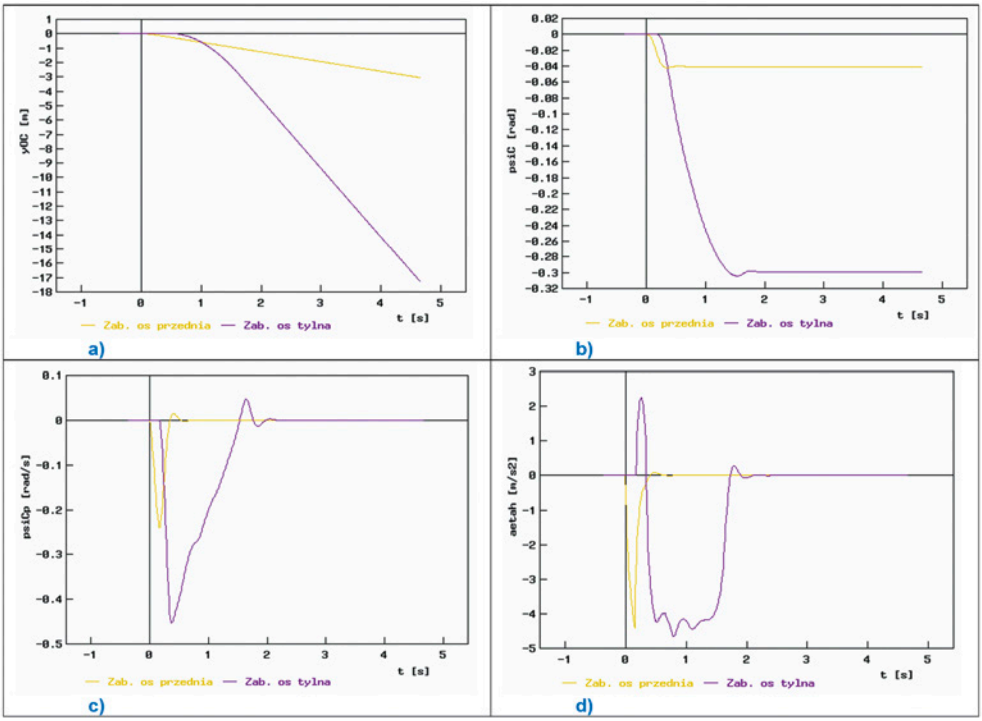

Fig. 2. Results of simulation calculations of selected quantities vs. time; V = 60 km/h.
a – lateral displacement of the centre of vehicle mass, y_{Oc} ("yOC" in the graph);
b – vehicle yaw (heading) angle ψ_C ("psiC" in the graph);
c – vehicle yaw velocity dψC/dt ("psiCp" in the graph);
d –lateral acceleration of the vehicle $a_{\eta h}$ ("aetah" in the graph)

A comparison between the results obtained for the two cases of disturbing the vehicle motion shows (see Figs. 2, 3, and 4) that the disturbance applied to the rear wheels resulted in higher absolute values of the quantities adopted as the criteria of assessment of vehicle motion. The effect of the disturbance lasted for a much longer time, which is particularly well visible in the vehicle yaw velocity, lateral vehicle acceleration, moment of forces on the steering wheel, and lateral forces on the vehicle wheels. An exception is the high extreme value of the moment of forces on the steering wheel, recorded for the disturbance being applied to the front wheels (this value was 1.8 times as high as that observed when the rear wheel motion was disturbed, although this effect lasted for a much shorter time in this case, see Fig. 3a), and the higher value of the necessary effective power of the kick plate driving system (1.55 times as high as the other one, see Fig. 3c), which results in a higher cost of the equipment that must be used in the kick plate design.

The time-dependent curves presented as examples indicate that the disturbance applied exerts a strong impact on the motion and dynamics of the vehicle in which the driver being examined or trained is present. This impact is much stronger when the disturbance is applied to the rear vehicle wheels.

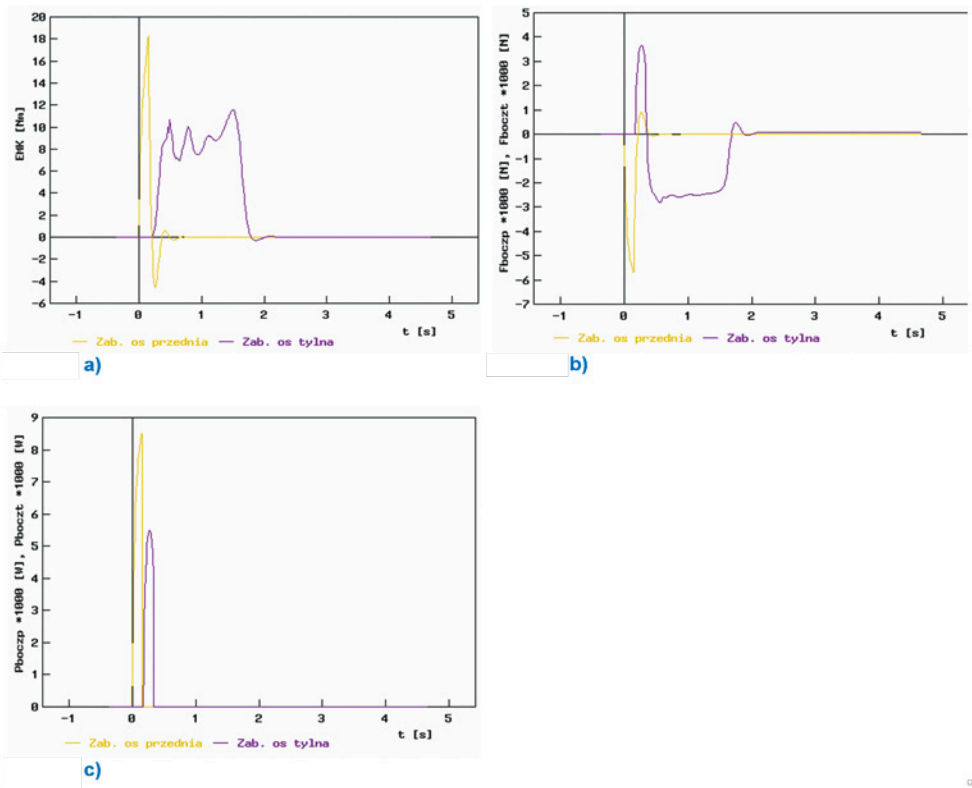

Fig. 3. Results of simulation calculations of selected quantities vs. time; V = 60 km/h.
a – moment of forces on the steering wheel EMK;
b – sum of the lateral forces on the front wheels F_{boczp} and on the rear wheels F_{boczt} ("Fboczp" and "Fboczt" in the graph, respectively);
c – necessary effective power of the kick plate driving system P_{boczp} and P_{boczt} ("Pboczp" and "Pboczt" in the graph, respectively)

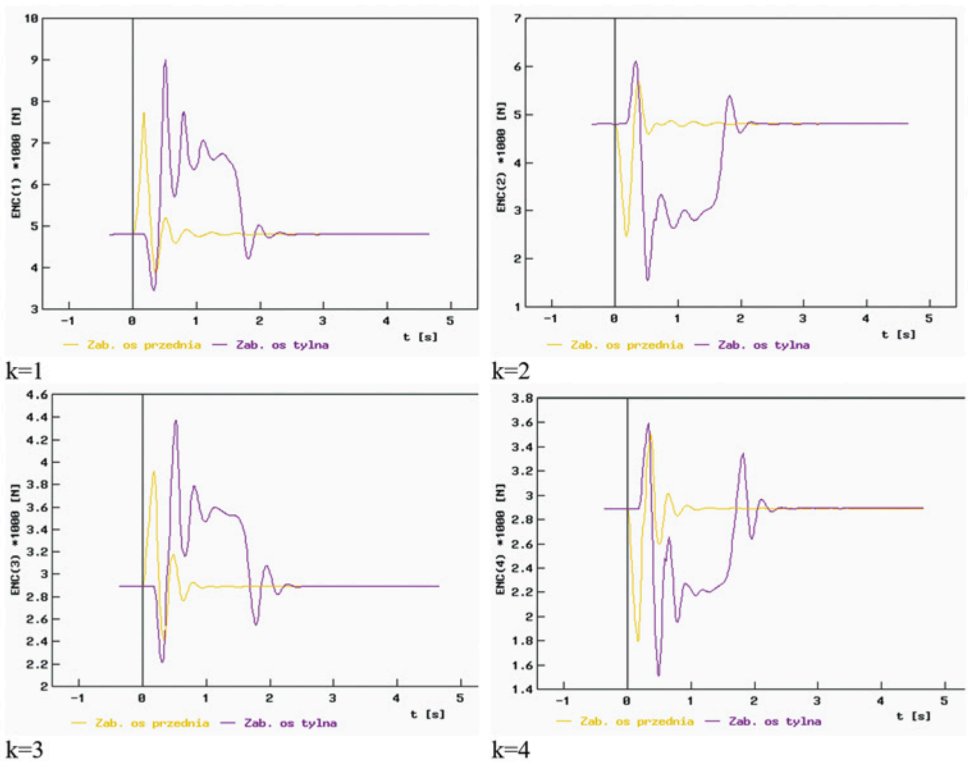

Fig. 4. Results of simulation calculations of selected quantities vs. time; V = 60 km/h. Normal reactions N_{Ck} on vehicle wheels ("ENC(k)" in the graph), where k = 1, ..., 4 indicates individual wheels: 1 – front left (FL) wheel; 2 – front right (FR) wheel; 3 – rear left (RL) wheel; 4 – rear right (RR) wheel

4. Criteria adopted to select the vehicle speed at the test with disturbing the vehicle motion on a kick plate

To select the vehicle speed at the test with disturbing the vehicle motion on a kick plate, the following nine criteria were adopted.

Criterion 1: Absolute value of the extremum of the lateral displacement y_{Oc} [m] of the centre of vehicle mass (extremum of "yOC" in the graph) within the first second from the disturbance.

Criterion 2: Absolute value of the extremum of the vehicle body solid yaw (heading) angle ψ_C [rad] (extremum of "psiC" in the graph) within the first second from the disturbance.

Criterion 3: Absolute value of the extremum of the vehicle yaw velocity $d\psi C/dt$ [rad/s] (extremum of "psiCp" in the graph) within the first second from the disturbance.

Criterion 4: Absolute value of the extremum of the lateral acceleration of the centre of vehicle mass $a_{\eta h}$ [m/s²] (extremum of "aetah" in the graph) within the first second from the disturbance.

Criterion 5: Absolute value of the extremum of the moment of forces on the steering wheel EMK [Nm] (extremum of "EMK" in the graph) within the first second from the disturbance.

Criterion 6: Absolute value of the extremum of the sum of the lateral forces on the front wheels F_{boczp} [N] and on the rear wheels F_{boczt} [N] (extremum of "Fboczp" and "Fboczt" in the graph) within the first second from the disturbance.

Criterion 7: Absolute value of the extremum of the power of resistance P_{boczp} and P_{boczt} [W] (resulting from the sum of the lateral forces F_{boczp} on the front wheels and F_{boczt} on the rear wheels, respectively) on the surface of the moving part of the kick plate (the necessary effective power of the kick plate driving system; extremum of "Pboczp" and "Pboczt" in the graph) within the first second from the disturbance.

Criterion 8: Time [s] of the disturbed vehicle wheels being in contact with the kick plate (i.e. the time during which the disturbed vehicle wheels are present on the kick plate), separately determined for the left and right wheel.

Criterion 9: Time [s] during which the disturbed vehicle wheels are present on the kick plate while the kick plate performs its lateral movement; separately determined for the left and right wheel.

In the criteria from 1 to 7, the absolute value of the extremum of a specific quantity, observed during the first second from the disturbance, is taken into account. This is a consequence of an assumption made that during the typical driver reaction time, estimated at 1 s [1], the driver is unable to undertake any action (i.e. to operate any of the vehicle controls) that might change the state of vehicle motion. The driver's reactions can only affect the vehicle motion during the next seconds (which is not represented in the simulation tests performed) and only these reactions may be taken as a basis to assess the driver at the examination or training carried out.

5. Results of the calculations carried out to select the vehicle speed at the test with disturbing the vehicle motion on a kick plate

Figs. 5, 6, and 7 show results of simulation calculations of the quantities used as criteria 1–9. In criteria 1–6, higher absolute values of specific quantities, i.e. y_{Oc}, ψ_C, $d\psi C/dt$, $a_{\eta h}$, EMK, F_{boczp}, and F_{boczt}, translate into better opinion about the disturbing system and vehicle speeds.

In criterion 7, lower absolute values of Pboczp and Pboczt translate into lower requirements for the kick plate driving system.

In criterion 9, it is important that the time of the disturbed wheels being present on the kick plate should be close to the time of this plate being in motion. High vehicle speeds reduce this time below the value of t_{yp} (in the case of the kick plate design adopted for these tests, t_{yp} = 0.2 s), because this time is dictated by the vehicle wheelbase (l = 2.655 m).

As it was in the case of the time-dependent curves plotted for the vehicle speed of V = 60 km/h and presented in Figs. 2, 3, and 4, the calculation results shown in Figs. 5, 6, and 7 indicate that the disturbance applied exerts a strong impact on the vehicle motion. This impact is much stronger when the disturbance is applied to the rear vehicle wheels. An exception is the extreme value of the moment of forces on the steering wheel. Apart from that, a much higher effective power of the kick plate driving system is required in the case of the disturbance being applied to the front wheels, which is a disadvantage of such a solution because the equipment that is to be used in such a case in the kick plate design must be more expensive.

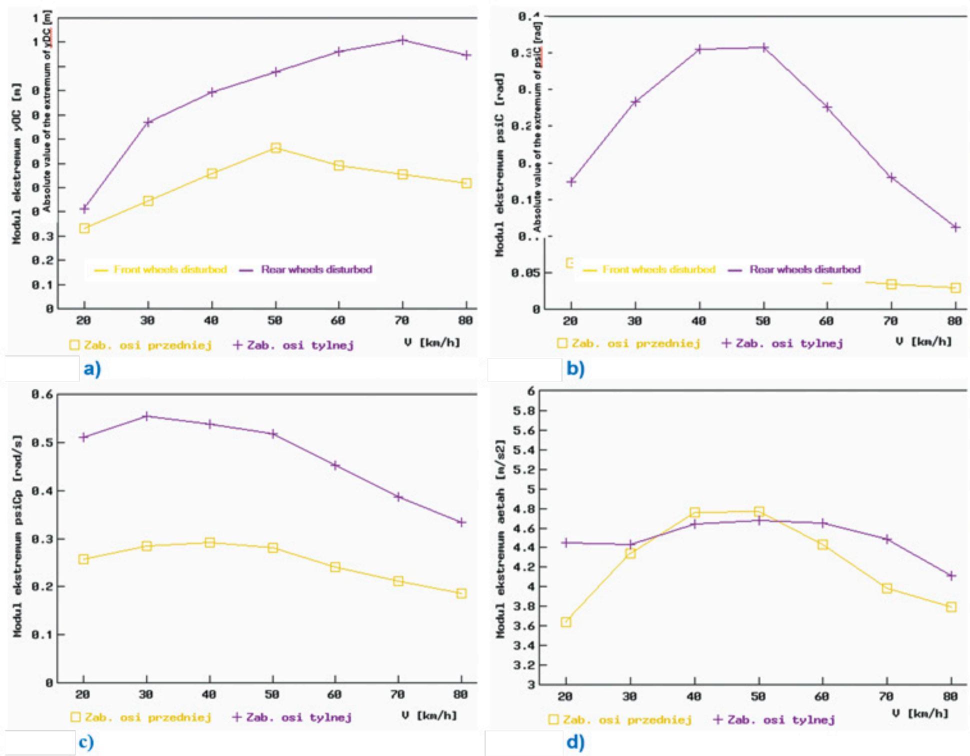

Fig. 5. Results of simulation calculations of the quantities used as individual criteria:
a – criterion 1; b – criterion 2; c – criterion 3; d – criterion 4

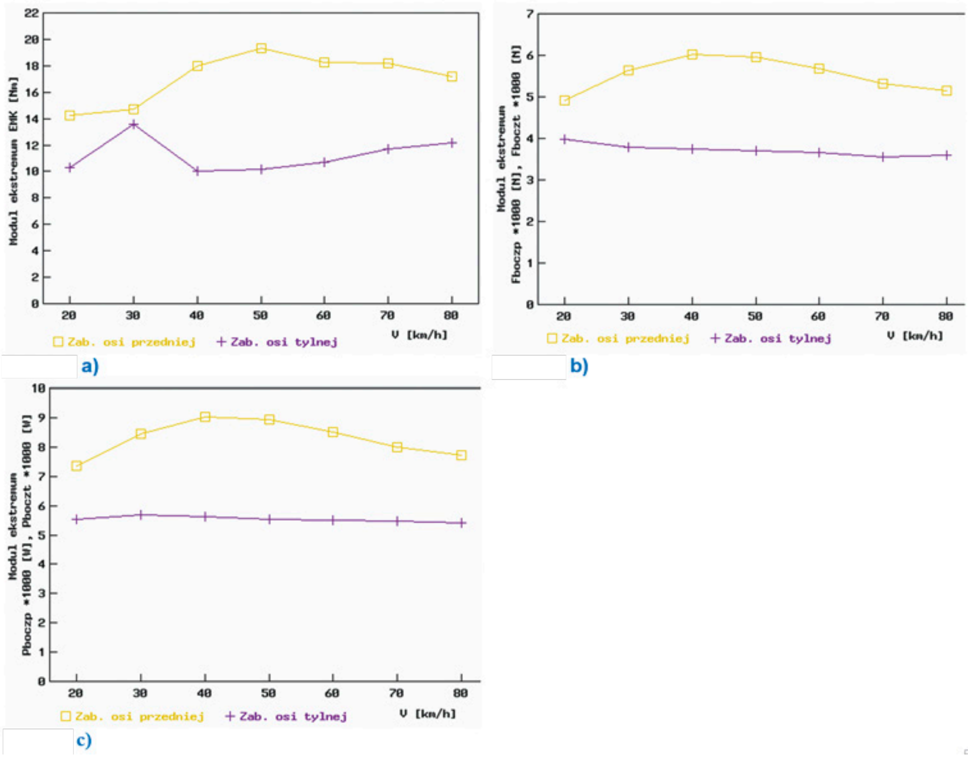

Fig. 6. Results of simulation calculations of the quantities used as individual criteria:
a – criterion 5; b – criterion 6; c – criterion 7

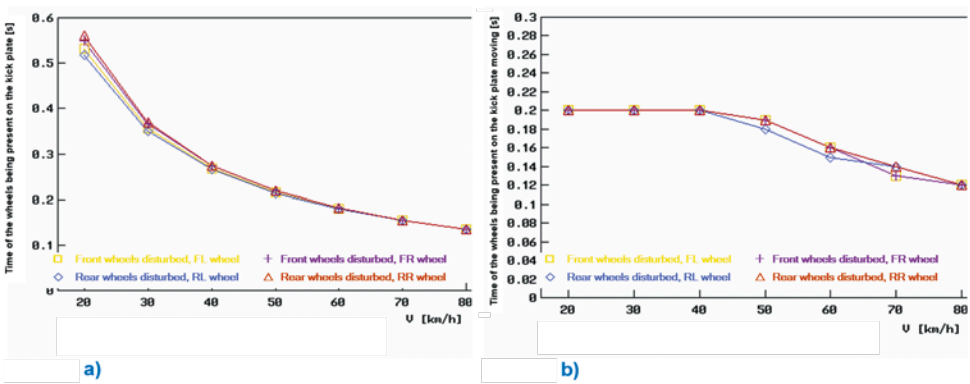

Fig. 7. Results of simulation calculations of the quantities used as individual criteria:
a – criterion 8; b – criterion 9

Based on the calculation results presented in Figs. 5, 6, and 7, the vehicle speed ranges preferred in consideration of the above selection criteria were defined.

In the case of the motion of the front axle wheels being disturbed, the preferable speed ranges were found to be as follows for individual selection criteria:
For criterion 1, 40-80 km/h;
For criterion 2, 20-50 km/h;
For criterion 3, 20-60 km/h;
For criterion 4, 40-60 km/h;
For criterion 5, 40-80 km/h;
For criterion 6, 30-60 km/h;
For criterion 7, 30-60 km/h;
For criterion 8, 20-50 km/h, because this is the range where the criterion value is ≥ 0.2 s;
For criterion 9, 20-40 km/h, because this is the range where the criterion value is equal to 0.2 s.

When all the above sets were taken together and an intersection was sought that could be considered common to the greatest possible extent, a speed of 40 km/h was chosen, because all the 9 criteria were met for it. For the speed of 50 km/h, only one of the optimization criteria was not met; therefore, a statement may be formulated that **the speed range from 40 km/h to 50 km/h leads to solutions close to the optimum.**

In the case of the motion of the rear axle wheels being disturbed, the preferable speed ranges were found to be as follows for individual selection criteria:
For criterion 1, 50-80 km/h;
For criterion 2, 40-50 km/h;
For criterion 3, 20-50 km/h;
For criterion 4, 40-60 km/h;
For criterion 5, 20-80 km/h;
For criterion 6, 20-80 km/h;
For criterion 7, 20 km/h and 50-80 km/h;
For criterion 8, 20-50 km/h, because this is the range where the criterion value is ≥ 0.2 s;
For criterion 9, 20-40 km/h, because this is the range where the criterion value is equal to 0.2 s.

When all the above sets were taken together and an intersection was sought that could be considered common to the greatest possible extent, **a speed range of 40-50 km/h was obtained**, because not more than two criteria were not met for it (criteria 1 and 7 for the speed of 40 km/h and criterion 9 for the speed of 50 km/h).

The results of this assessment may also be presented in a tabular form. Tables 1 and 2 show the preferences of the judging person (the author of this paper in this case). It visualizes the result of the process of searching for a vehicle speed range where the assessment criteria adopted would be met to the greatest extent. Number 0 (zero) has been assigned to the vehicle speed value for which the result of measurement of a quantity taken as a specific criterion was found unsatisfactory; on the other hand, number 1 (one) has been assigned when the measurement result met judging person's expectations. In the bottom row of the table ("Score"), the assessment results for all the criteria have been summed up. The highest scores have been achieved at the speeds of 40 and 50 km/h mentioned above.

Table 1. Table of preferences of the judging person (the author of this paper) for the case of the motion of the front axle wheels being disturbed

Criterion	Vehicle speed during the test V [km/h]						
	20	30	40	50	60	70	80
1	0	0	1	1	1	1	1
2	1	1	1	1	0	0	0
3	1	1	1	1	1	0	0
4	0	0	1	1	0	0	0
5	0	0	1	1	1	1	1
6	0	1	1	1	1	0	0
7	0	1	1	1	1	0	0
8	1	1	1	1	0	0	0
9	1	1	1	0	0	0	0
Score:	4	6	9	8	5	2	2

Table 2. Table of preferences of the judging person (the author of this paper) for the case of the motion of the rear axle wheels being disturbed

Criterion	Vehicle speed during the test V [km/h]						
	20	30	40	50	60	70	80
1	0	0	0	1	1	1	1
2	0	0	1	1	0	0	0
3	1	1	1	1	0	0	0
4	0	0	1	1	1	0	0
5	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1
7	1	0	0	1	1	1	1
8	1	1	1	1	0	0	0
9	1	1	1	0	0	0	0
Score:	6	5	7	8	5	4	4

6. Recapitulation

At Driver Improvement Centres, tests are carried out during which, before the vehicle under test enters a skid pad characterized by reduced tyre-to-road adhesion, the vehicle motion is disturbed by means of a dynamic "kick plate" and the driver is thus forced to undertake defensive manoeuvres. This paper presents simulation results that illustrate the scale of the disturbance to vehicle motion to which the driver being trained must respond. The methodology and results of choosing the speed with which the vehicle is to be driven during the test have also been shown.

The simulations carried out with the use of an advanced and experimentally verified mathematical model of motion of a motor car make it possible to determine critical parameters of the kick plate design, such as the force required to disturb the vehicle motion and the effective power of the system that is to cause a jerk of the kick plate, as well as the optimum initial vehicle speed during a test, depending on the assessment criterion adopted. Only the vehicle behaviour is assessed, without taking into account the impact of driver's actions on it. Therefore, the results presented will only be applicable to the period corresponding to the driver reaction time.

The results of this study indicate that the effect of the disturbance applied is much stronger when the motion of the rear axle wheels is disturbed. An exception is the extreme value of the moment of forces on the steering wheel. Apart from that, a higher effective power of the kick plate driving system is required in the case of the disturbance being applied to the front wheels, which is a disadvantage of such a solution because the equipment that is to be used in such a case in the kick plate design must be more expensive.

Acknowledgements

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