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USE OF TRACES OF A ROAD ACCIDENT FOR DETERMINING THE PRE-IMPACT SPEEDS OF THE VEHICLES INVOLVED – RESULTS OF EXPERIMENTAL AND SIMULATION TESTS

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Summary

Results of two physical simulations of motor vehicle collisions in road traffic have been presented, where the front of one vehicle hit a side of the other vehicle close to the front axle of the latter. The traces left on the road surface and on the vehicles in result of the collisions made it possible to carry out several simulations of the collisions under consideration with the use of the V-SIM program. Three possible versions of the course of the collisions, consistent with the traces left at the accident site, have been shown. For two versions of the collision, the pre-impact vehicle velocities were assumed as identical with those actually applied during the experiments; for the third version, they were calculated from the traces left. The vehicle velocity values thus determined were compared with the values of the actual velocities recorded during the experiments. The sources of, and reasons for, the possible errors made by the experts when carrying out the simulations of real vehicle collisions have been indicated.

Keywords: road accidents, right-angle collisions of motor vehicles, experimental and simulation tests

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1. Introduction

At the Automotive Industry Institute (PIMOT) in Warsaw, a research project was carried out, which was aimed at broadening the knowledge of the processes taking place during a right-angle ("T-bone") collision of motor vehicles. The methods of performing the tests was prepared on the grounds of conclusions drawn from an in-depth review of the literature dedicated to experimental investigations of the right-angle collisions of motor vehicles [1-5]. Within the project, six crash tests were performed, where the front of vehicle A crashed into a side of vehicle B (see Fig. 1), with the relative positions of vehicles A and B being changed in successive tests. The crash tests were carried out on a test yard with dry and clean plane concrete surface. Immediately before the collision, vehicle A moved in each test with a speed of about 50 km/h, which was twice as high as that of vehicle B. For the whole test duration time, the steering wheels of both vehicles were left free and their road wheels were not braked. The results of these tests were presented earlier in publications [6-11]. Here, results obtained in two crash tests (Z3 and Z4) have been shown, where the front of vehicle A hit a side of vehicle B close to the front axle of the latter. Both tests were carried out in comparable conditions. The results of the experimental tests were compared with results of simulations of the collisions under consideration, obtained for three sets of input data with the use of the V-SIM program.

2. The course and traces of the vehicle collision

The pre-impact vehicle velocities (i.e. those with which the vehicles were moving immediately before the collision) and the values of the distance between the longitudinal plane of symmetry of vehicle A and the front wheel axis of vehicle B at the instant of the first contact between the vehicles, measured during the two crash tests, have been specified in Table 1.

Table 1. Velocities and relative position of the vehicles at the instant of the first contact

Number of cylinders	**Test Z3**	**Test Z4**
Velocity of vehicle A, V_A [m/s]	13.6	13.1
Velocity of vehicle B, V_B [m/s]	6.8	6.5
Distance between the point of the first contact of the vehicles and the centreline of the front axle of vehicle B, L_{AB} [m]	−0.04	−0.17

In both crash tests, the vehicles entered in result of the collision into contact with each other and began to move unstably. After about 0.14 s from the first touch, the contact between the vehicles was lost and they moved separately since then. After another while, the vehicles regained steerability and the directions of their further motion were determined by the setting of their steered wheels.

Fig. 1 shows the marks left by the vehicles on the road in result of the collision against the background of a coordinate system whose origin has been situated at the point where the first contact between the vehicles took place. The red and blue colours indicate vehicle A and B, respectively. The lines representing the marks made by vehicle tyres on the road surface have been coloured accordingly. The post-accident vehicle rest positions and the vehicle positions at the instant of the first contact have been shown in the illustration as well.

Both in test Z3 and Z4, the scuffmarks on the road were chiefly left by the front wheels of vehicle B. The front left wheel of vehicle B began to make a scuffmark on the road practically from the very instant of the first contact between the vehicles. Therefore, this mark may be used to identify the position of vehicle B on the road at the instant of the collision. The right wheel of vehicle B began to make the mark on the road at a later instant, but the end of this mark practically shows the position of the front right wheel at the instant when the vehicle regained steerability. The front left wheel of vehicle B3 (i.e. vehicle B in test Z3) made also a scuffmark after the steerability was regained (the collision resulted in damage to the front left wheel suspension system and in blocking this wheel in a permanently turned position). Vehicle A made wheel scuffmarks on the road surface in test Z4 only. The mark left by the rear right wheel began when the vehicle was already moving unstably and ended before the vehicle regained steerability. For this reason, this mark cannot be used for the identification of the vehicle position on the road at the instant when the vehicle regained steerability. In vehicle A3, coolant radiator was damaged in result of the collision. In consequence, the coolant leaking out of the radiator left a trace that could be used for the reconstruction of the post-impact vehicle trajectory.

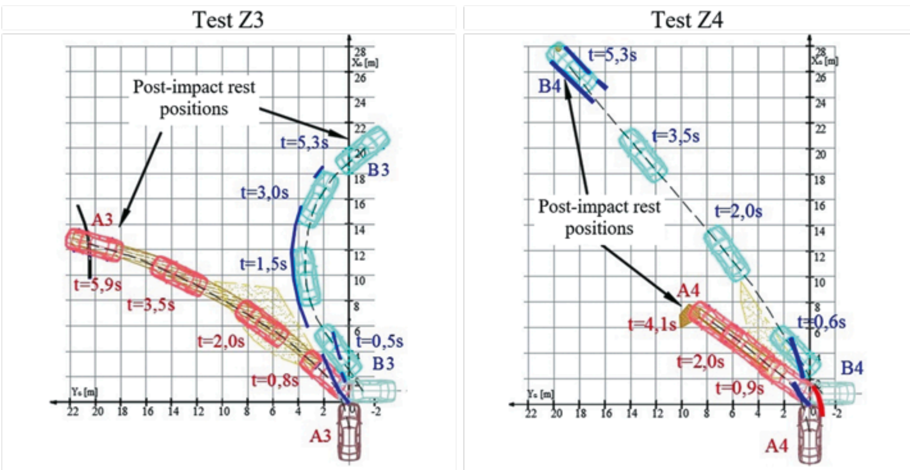

Fig. 1. Marks left on the road in result of the collision in tests Z3 and Z4

The mechanism of making wheel scuffmarks on the road surface as described above (Fig. 1) has been confirmed by the instantaneous vehicle positions presented in Fig 2, obtained by a frame-by-frame analysis of the video records made with the use of special cameras installed over the place of the experiment.

In spite of close similarity between the tyre scuffmarks on the road surface during and immediately after the collision in the crash tests under consideration, the post-impact rest positions of the vehicles were different. In test Z3, vehicle B having regained steerability moved along a curve to the right due to damage to the suspension system and steering linkage, which resulted in the front left wheel being permanently blocked in a turned position. Vehicle A was braked in the final phase of its movement because it approached the boundary of the testing yard. In test Z4, vehicle B was intensively braked in the final phase of its movement because it approached the boundary of the testing yard. In vehicle A, a movement of dummy's left arm caused engagement of the 5th gear and, in consequence, a growth in the vehicle deceleration in the post-impact motion.

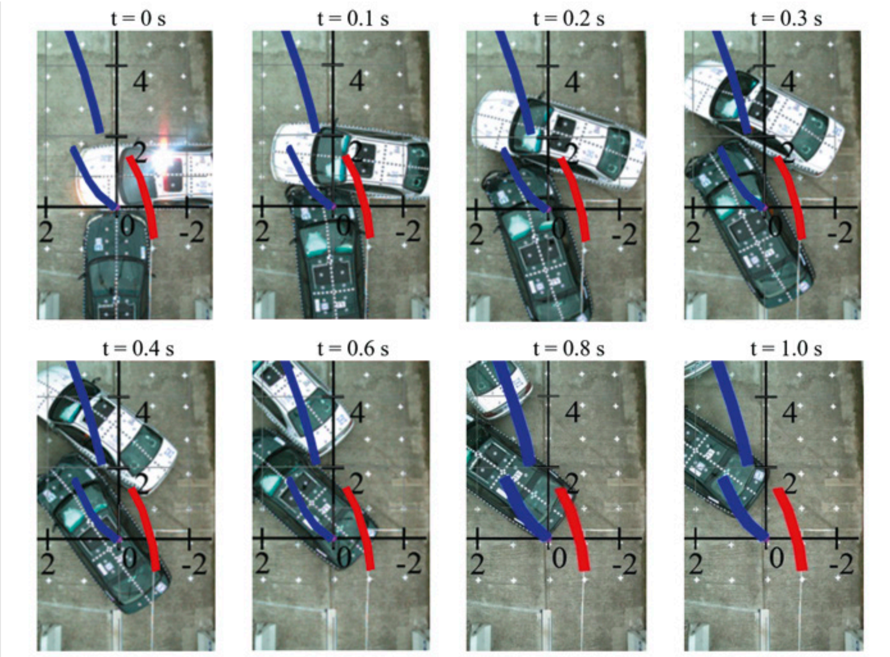

Fig. 2. Mechanism of the wheel scuffmarks being made during test Z4

Graphs showing changes in the values of the parameters of motion of vehicles A and B in the crash tests have been presented in Fig. 3. The curves in the successive rows represent angular velocity of vehicle yaw ($d\Psi/dt$), resultant velocity of the centre of vehicle mass (V_w), and angle of deviation of the resultant velocity from the direction of pre-impact motion (α) as functions of time (t). The curves plotted as solid lines in brighter colours represent the results recorded in test Z3; the corresponding results of test 4 have been plotted as dashed lines in darker colours. Changes in the resultant velocity of the centre of vehicle mass (V_w) and in the angle of deviation of the direction of this velocity (α) (Fig. 3) as well as trajectories of the centres of vehicle mass and vehicle yaw angles (Ψ) (Fig. 1) were determined by time integration of the results of measurements of the accelerations and angular velocities of the vehicles under test. The calculation results were verified by comparison with the frame-by-frame analysis of the video records made with the use of special cameras during the crash tests. Fig. 1 shows the vehicle positions on the road at successive time instants (the first post-impact position of each vehicle shows the position at the instant when the vehicle regained stability). The trajectories of the centre of mass of each vehicle have been plotted as black dashed lines.

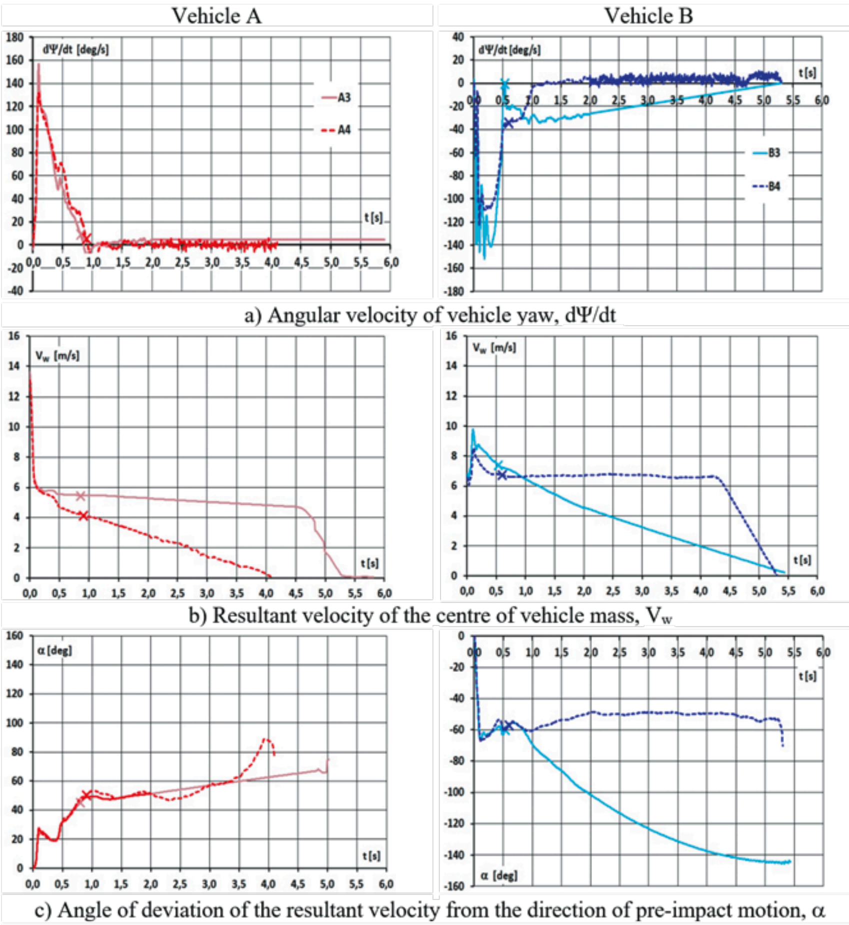

Fig. 3. Time histories of the values of the parameters of motion of vehicles A and B in tests Z3 and Z4

The vehicle collisions resulted in deformations of the front part of vehicle A and the side of vehicle B. The permanent deformations of the vehicles involved in tests Z3 and Z4 have been presented in Fig. 4. The type and nature of the damage to the vehicles made it possible to identify the vehicle positions in relation to each other at the instant of the first contact.

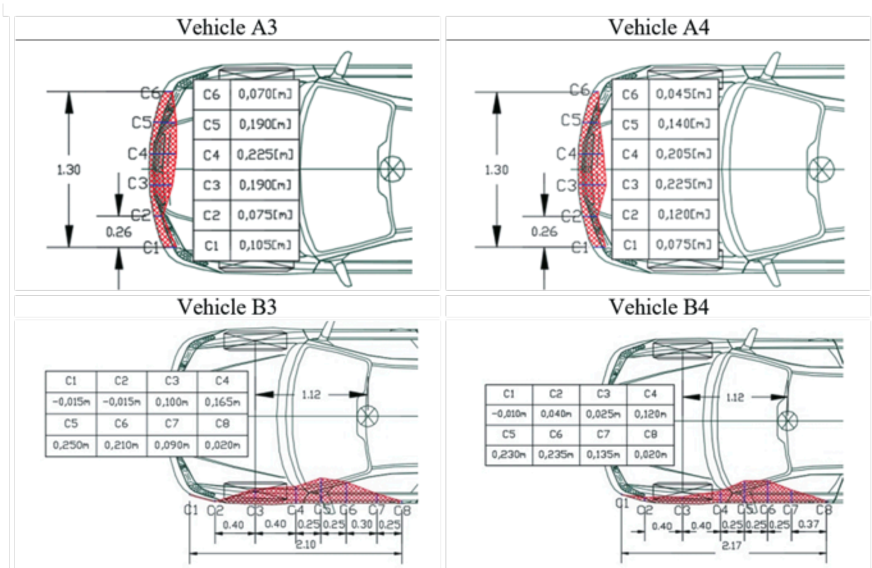

Fig. 4. Permanent deformations of the vehicles involved in tests Z3 and Z4

3. Results of simulation tests

The simulation tests of the vehicle collisions under consideration were carried out with the use of the V SIM program, version 4.0, in the manual mode, with employing the impulse model of vehicle collision. In the manual mode, the user may select by oneself the collision parameters such as the point of application of the force impulse or the value of the coefficient of restitution.

At the simulations of the collisions under consideration, three options of the input data were applied.

In option I, the following parameters were assumed as identical with those recorded during the real crash tests: pre-impact directions of motion and values of vehicle velocities, technical specifications of the vehicles involved, vehicle positions in relation to each other at the instant of the first contact, value of the tyre-to-road adhesion coefficient (μ = 0.8, based on experimental measurements), course of changes in the steering wheel angle during and after the collision (inclusive of the permanent turn of the front left wheel of vehicle B3), and absence of intensive vehicle braking immediately after the collision because the brakes were not applied in this case. However, the post-impact vehicle decelerations arising from other reasons were reproduced. In result of the collision, the front left wheel of vehicle B3 rubbed against the fender liner, the front wheels of vehicles A3 and A4 rubbed against deformed vehicle body parts, and the 5th gear got engaged in vehicle A4. Moreover, vehicles A3 and B4 were intensively braked in the final phase of their movement because of approaching the boundary of the testing yard. The values of the coordinates of the point of application of the force impulse and the values of the coefficient of restitution were so selected by the method of successive approximations that the vehicle motion parameters at the beginning of the free motion stage were identical with those recorded during the experimental tests.

Option II of the input data differed from option I only in the fact that changes in the vehicle steering wheel angles during the post-impact motion were not taken into account. When the course of real vehicle collisions is analysed, the expert usually has no information in this respect.

In option III, differently from options I and II, an assumption was made that the pre-impact vehicle velocities, values of the coordinates of the point of application of the force impulse, and value of the tyre-to-road adhesion coefficient were unknown. For tests Z3 and Z4, the adhesion coefficient values were assumed as $\mu = 0.75$ and $\mu = 0.9$, respectively (i.e. the lower and upper limit of the values usually assumed by experts for dry concrete road surface). The angles of turn of the steered wheels were only taken into account for vehicle B3. The pre-impact velocity values (with the velocity of vehicle A being assumed as twice as high as that of vehicle B, as it was in the experiments) and the parameters of the collision proper were selected by the method of successive approximations so that the post-impact vehicle rest positions and the wheel scuffmarks in the simulation and experimental tests were satisfactorily close to each other. Option III is consistent with expert's proceedings at simulations of vehicle collisions.

Fig. 5 and Table 2 show values of the coordinates of the point of application of the force impulse and values of the restitution coefficient for the three options of the input data applied in the simulation tests. Attention is attracted by considerable differences in the values of the lateral coordinates of the point of application of the force impulse (y_A and y_B) in option III in comparison with those determined for options I and II.

Table 2. Values of the coordinates of the point of application of the force impulse and values of the restitution coefficient for the three options of the input data applied in the vehicle collision simulation tests

Test	**Z3**		**Z4**	
Option	**I and II**	**III**	**I and II**	**III**
Coordinate xA of point P [m]	1.79	1.77	1.8	1.76
Coordinate yA of point P [m]	–0.07	–0.20	0.02	–0.19
Coordinate xB of point P [m]	–0.67	–0.68	–0.72	–0.72
Coordinate yB of point P [m]	0.89	0.72	0.75	0.60
Vertical coordinate z of the point of application of the force impulse, measured from the road surface [m]	0.45	0.44	0.41	0.43
Coefficient of restitution k	0.3	0.26	0.33	0.24

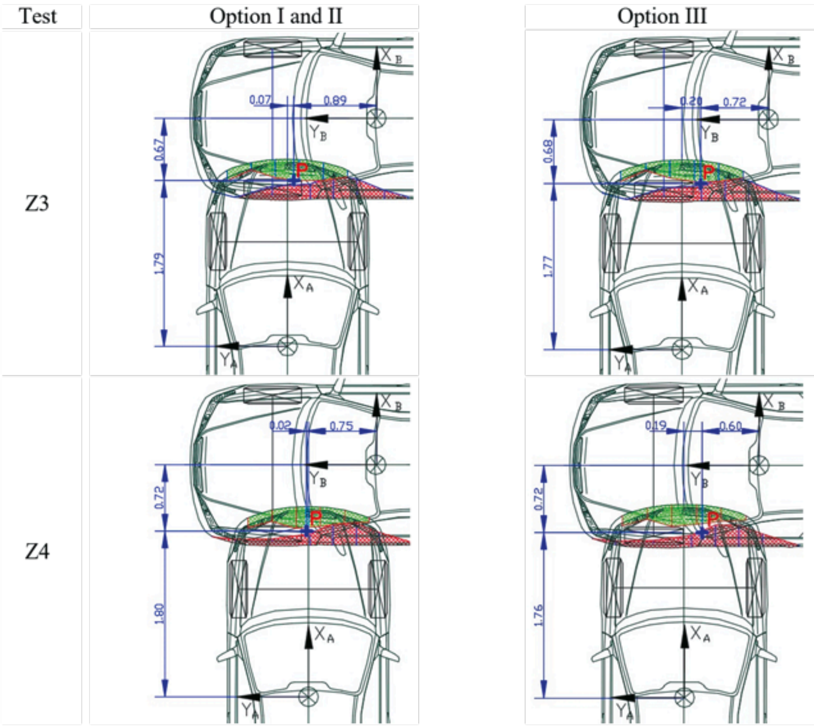

Fig. 5. Determining the coordinates of the point of application of the force impulse (point P) for the three options of the input data applied in the vehicle collision simulation tests

Comparisons between the curves that represent selected parameters of motion of vehicles A and B determined from the experiment (blue) and from the simulation, plotted for option I in yellow, for option II in green, and for option III in red, have been shown in Figs. 6 (for test Z3) and 7 (for test Z4). The resultant velocity of the centre of vehicle mass (Vw), angle of deviation of the resultant vehicle velocity vector from the direction of pre-impact motion (α), angular velocity of vehicle yaw ($d\Psi/dt$), and vehicle yaw angle (Ψ) have been presented as functions of time t; the trajectories of the centres of vehicle mass have also been shown in the graphs. Fig. 8 shows the post-impact vehicle rest positions and wheel scuffmarks made on the road during the experiment (drawn in black) and obtained from the simulation (red for vehicle A and blue for vehicle B) for the three options of the input data.

The values of the vehicle velocities immediately preceding the collision, measured during the experiment and determined in the simulation tests for option III of the input data (with the velocity of vehicle A being assumed as twice as high as that of vehicle B, as it was in the experiments) have been compared with each other in Table 3.

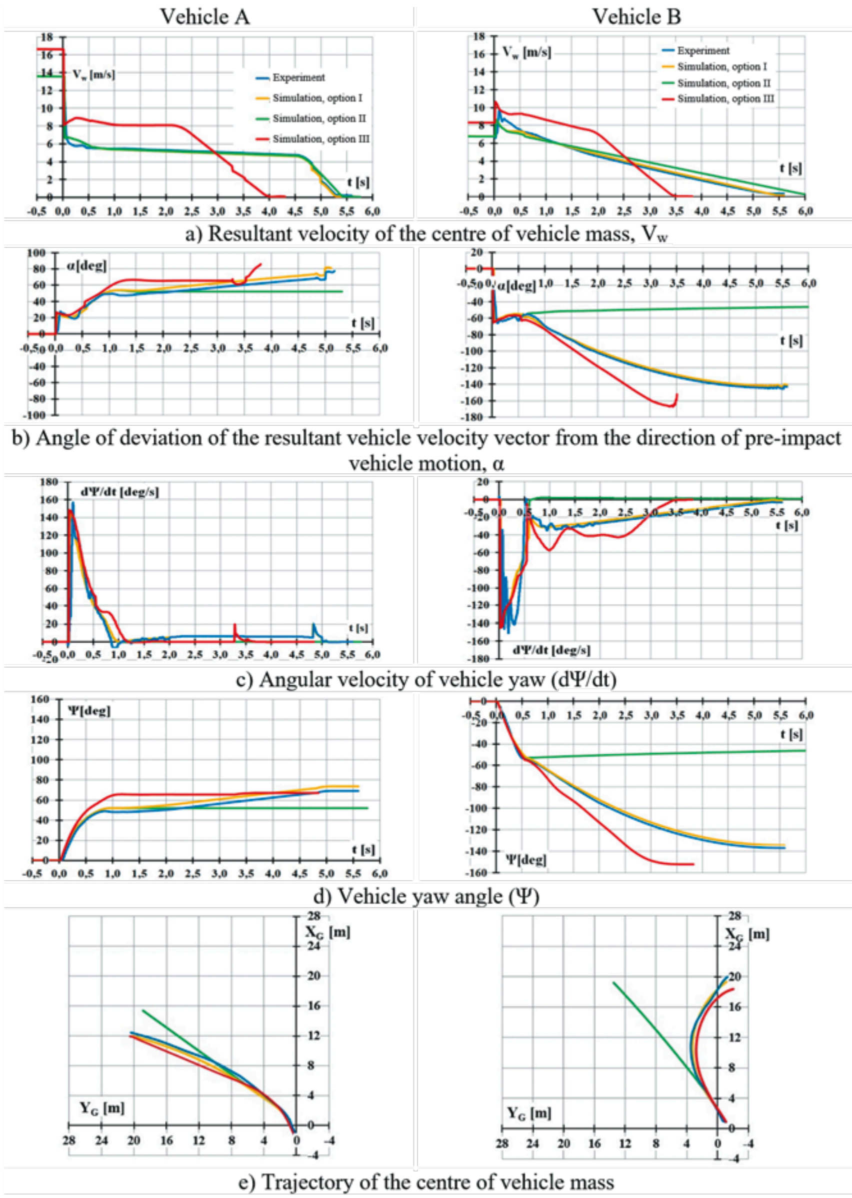

Fig. 6. Comparison between experimental and simulation test results for test Z3

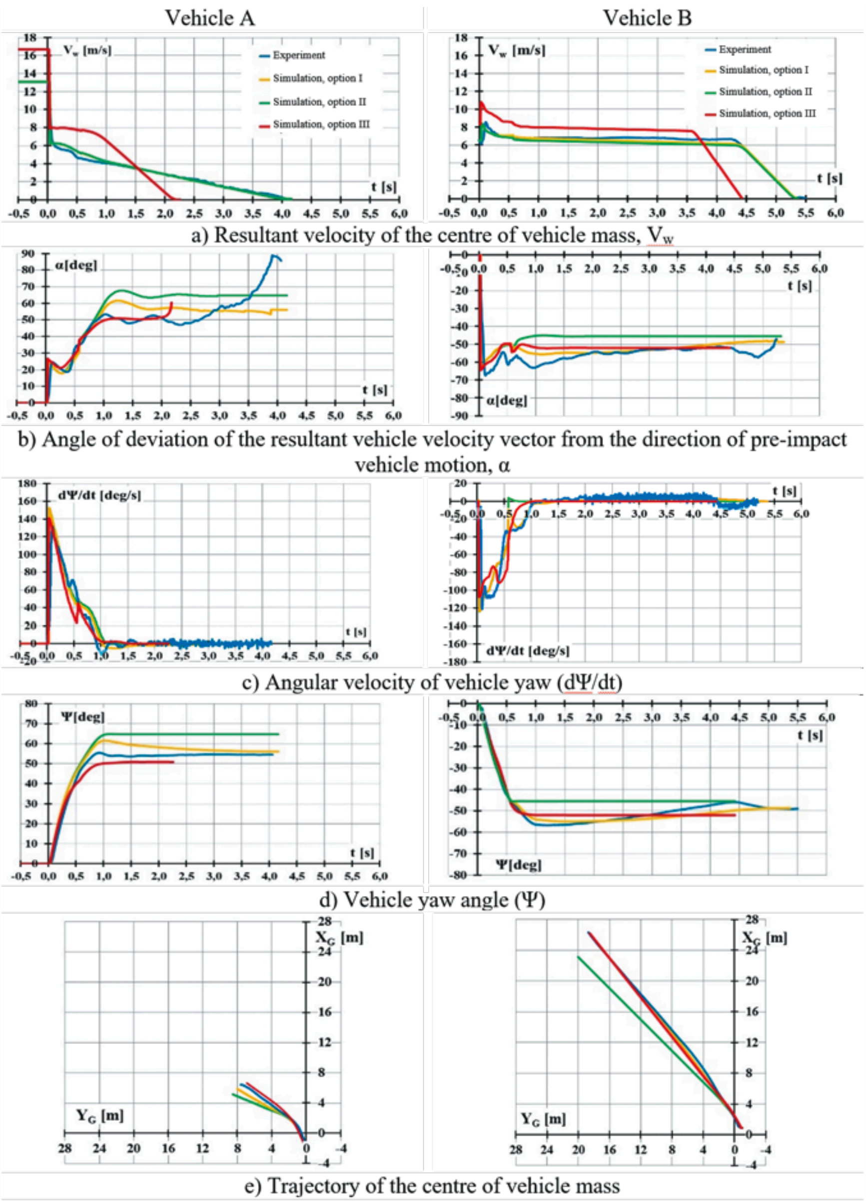

Fig. 7. Comparison between experimental and simulation test results for test Z4

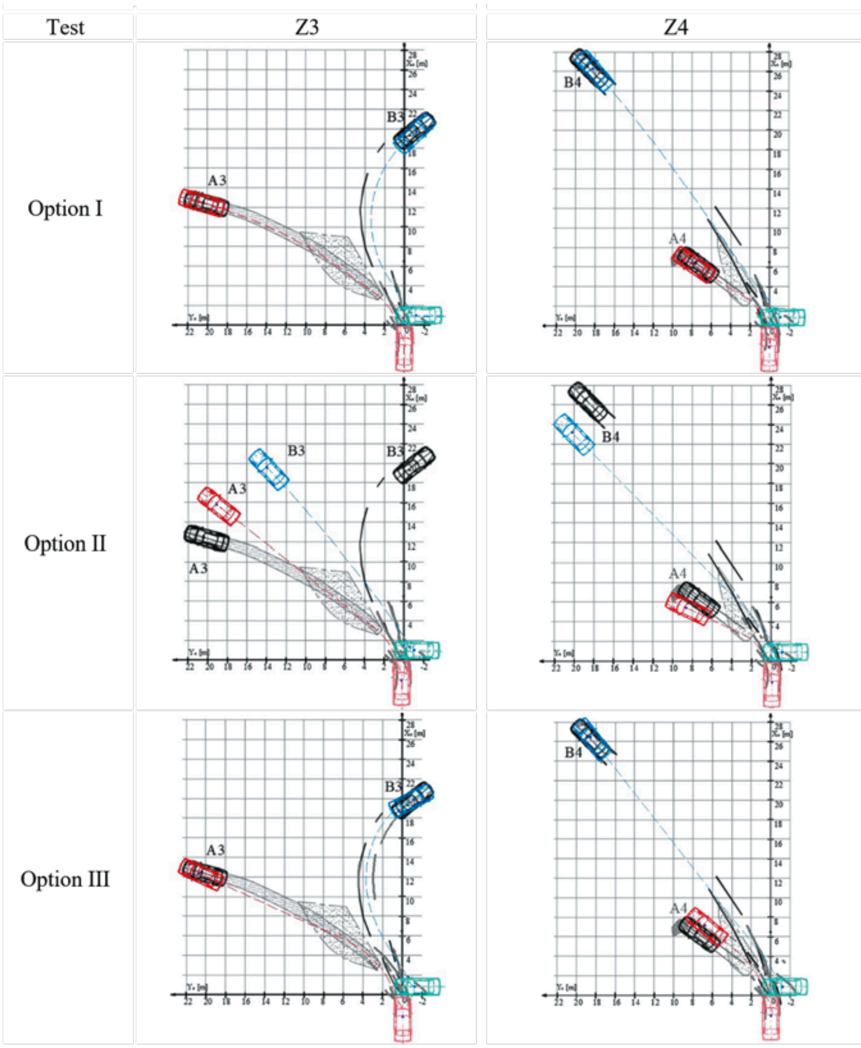

Fig. 8. Post-impact rest positions of vehicles A and B and wheel scuffmarks made on the road during the experiment (drawn in black) and obtained from the simulation (red for vehicle A and blue for vehicle B) for the three options of the input data

Table 3. Comparison of the pre-impact vehicle velocities measured during the experiment and determined in the simulation tests for option III of the input data

Test		**Velocity (experiment)**	**Velocity (simulation, option III)**	**Error**
Z3	Pre-impact velocity of vehicle A V_A [m/s]	13.6	16.7	23 %
	Pre-impact velocity of vehicle B V_B [m/s]	6.8	8.3	22 %
Z4	Pre-impact velocity of vehicle A V_A [m/s]	13.1	16.7	27 %
	Pre-impact velocity of vehicle B V_B [m/s]	6.5	8.3	28 %

Based on the graphs in Figs. 6, 7, and 8 and on the data presented in Table 3, the following conclusions may be formulated.

- The results of the simulation carried out for option III of the input data are very close to those obtained from the research experiment. The conformity between the curves representing practically all the vehicle motion parameters was obtained both for the unstable vehicle motion and for the phase that followed the regaining of steerability by the vehicles. This confirms correctness of the models representing the vehicle and the vehicle motion in the simulation program. However, it should be noted here that in practice, the expert cannot carry out a simulation of a vehicle collision with taking into account all the data used in option III, as the set of the collision data available to the expert is limited and depends on the analysis of traces left by the vehicles on the road, post-impact vehicle rest positions, and vehicle damage. When real vehicle collisions are reconstructed, usually it is not clear whether the vehicles were braked after the collision and, if they actually were, the braking decelerations, history of vehicle steering angles, and tyre-to-road friction coefficient value are not known. Variations in the values of the quantities mentioned above in the post-impact motion considerably affect the post-impact vehicle rest positions; hence, they indirectly affect the pre-impact vehicle velocity values determined by the simulation of vehicle collision.

- The failure to take into account changes in the steering wheel angle during and after the collision in the simulation of vehicle collision (option II of the input data) resulted in bigger differences (in comparison with those observed for option I) in the curves representing most of the vehicle motion parameters recorded during the simulation and the experiment. This pertains to angle of deviation of the centre of vehicle mass, angular velocity of vehicle yaw, vehicle yaw angle, and trajectory of the centre of vehicle mass, and in consequence to the post-impact vehicle rest positions. Noteworthy is the fact that differences in the curves representing the above quantities were only observed for the phase that followed the regaining of steerability by the vehicles. On the other hand, changes in the steering wheel angle did not affect the time histories of the velocities of the centre of vehicle mass (Figs. 6a and 7a).

- When option III of the input data was used in the simulation, the post-impact vehicle rest positions thus determined were almost identical with those recorded during the experimental tests. The curves representing most of the vehicle motion parameters recorded during the simulation and the experiment are also comparable with each other.

Unfortunately, in spite of good conformity having been obtained between the simulation and experiment results, the pre-impact velocity values determined in result of the simulation exceed those measured during the experiments by about 25 %.

4. Recapitulation

At the Automotive Industry Institute (PIMOT) in Warsaw, two crash tests of moving vehicles were carried out where the front of one vehicle hit a side of the other vehicle close to the front axle of the latter. Computer simulations of the said two crash tests were also performed with the use of the V-SIM 4.0 program, with three different sets of the input data being used as options. The simulation test results were compared with results of the experiments.

When the input data used for the simulation, i.e. technical specifications of the vehicles involved, pre-impact vehicle velocities, vehicle positions in relation to each other at the instant of the first contact, and tyre-to-road adhesion coefficient, were identical with those recorded during the experiment and the operation of the vehicle steering and braking systems during and after the collision was reproduced, good conformity was obtained between the simulation and experiment results. This confirms correctness of the models representing the vehicle and the vehicle motion in the V-SIM simulation program.

When changes in the steering angles of the vehicles during the post-impact motion were not taken into account in the simulations, the post-impact vehicle rest positions and curves representing the vehicle motion parameters obtained from the simulations considerably differed from those actually recorded in the experiments.

It has been shown that the post-impact vehicle rest positions and wheel scuffmarks on the road determined by the simulation may be identical with those recorded during the experiment in spite of the simulated pre-impact vehicle velocities being assumed as higher by about 25 % than the actual ones.

The post-impact vehicle rest positions depend on many factors, which are often difficult for ascertaining. Therefore, the input data adopted for the simulation should be determined with great care and diligence. The problem of reconstruction of the course of a road accident may have an infinite number of solutions; hence, the results of a computer simulation should only be accepted with due criticism. The introduction of incorrect input data may lead to wrong calculation results.

The full text of the article is available in Polish online on the website http://archiwummotoryzacji.pl.

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