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COLLISION MODEL SIMPLIFICATIONS IN THE DYNAMIC ANALYSIS WITH THE SDC METHOD

Summary. The number of motor vehicles in the European Union (EU) is constantly increasing, which is causing an increase in the traffic volume. This, in turn, boosts the economic development of the EU member states. However, an increase in traffic volume leads to road collisions and accidents, which lead to high repair costs. Some accident victims report fake vehicle damage to extort money for repairs. There are criminal groups that stage accidents for this purpose; thus, these claims are very difficult to verify. Thus, it is not enough to verify the sustained damage only by comparing the geometric parameters of the impact traces. New, modern research methods with simulation programs need to be used in order to reconstruct the course of an accident. The SDC (Static Dynamic Characteristic method) provides the possibility of vehicle damage verification, according to this convention. However, simplified modelling with the use of simulation programs involves the necessity of identification of input parameters in order to reconstruct a collision and the vehicle's post- collision movement. If the input parameters are not correct, the simulation results will also be incorrect, which will have a direct impact on the parties involved in potential legal proceedings, both civil and criminal. This study deals with the identification of the impact parameters and sensitivity of the simulation results to input data. Impact verification with the SDC method shows both a knowledge enhancement and a practical value. They can be used by experts, expert witnesses, computer programmers, researchers and students.

1. INTRODUCTION

Insurance crime affects every insurance company in Poland and all over the world. Insurance companies combat this phenomenon by cooperating in data exchange and improving antifraud tools. Insurance crimes, like other offences, including the so-called "grey market", cannot be measured in a direct way. It is impossible to identify each single fraudulent claim and it is difficult to classify the methods due to their diversity. The increase in the incidences of this negative phenomenon requires insurance companies to take appropriate actions. According to the report of the Polish Chamber of Insurance [1], the transport insurance is the most popular group of insurance fraud. In 2016, motor insurance claims accounted for 8.700 out of 9.500 reported fraudulent claims, whose value was 30.000 000 €.

Analyses performed by the author indicate that money extortion with the use of vehicles has always been prevalent, which has been confirmed by experiences of other countries in Europe and worldwide where insurance markets are well developed. Hence, we are facing a serious social-economic problem that needs to be addressed by, e.g., using the SDC method for verification of sustained damage.

This method involves dividing the verification process into three groups of research procedures. Static analysis involves a geometric comparison of the technical object damage, which has been described in the work of [2], where different variants of its application are presented as well. An analysis of characteristic damage includes verification of the marks in the contact area of car bodies during the impact. However, these methods are limited by the fact that a collision of vehicles can be staged and the circumstances are different from those reported. Therefore, dynamic verification with the use of simulation programs can be used for an analysis of collisions of vehicles to reconstruct road accidents in complex verification of an insurance claim by the SDC method. It allows establishing whether, despite the geometric consistence of the damage zones and visible contact marks, the circumstances of a collision were really consistent with the reported ones. However, these programs need input data to perform calculations in order to obtain correct simulation results, which is not an easy task. This is important because acceptance of erroneous results affects the legal action for damages. The problems related to modelling of the process of impact and the vehicle's post impact movement, when different models of the same phenomenon are available and they provide different results, are discussed in the works of [3 - 5]. Another paper [6] discusses various kinds of vehicle crashes and the effect of the type of the road surface on the reconstruction of the simulated vehicle movement, while in [7 - 9], the issues related to autonomous control lock of the differential in a truck are discussed.

The best accuracy of calculation is provided by simulation programs using the finite elements method (FEM). For instance, [10] describe a head-on collision of a passenger car with a non-deformable wall using the LS-Dyna. They have proven that the structure of the engine chamber cover and its hinges need to be improved to provide the passengers with better protection against the detrimental effects of an impact. In turn, [11] discuss application of the LS-Dyna program in the research on the influence of the vehicle structure stiffening elements including front wheels' suspension, beam of the bumper, cross members and engine, on the impact caused by a car collision with an obstacle, for different overlaps of the car body with the obstacle. The authors have obtained good agreement of the simulation results with the experiment conducted. Another paper [12] reports on using LS-Dyna program to model the vehicle front protection system (VFPS) to decrease the vehicle damage for collisions with animals. The authors have presented threshold parameters of gas airbag system activation during the impact of vehicles equipped with this system. FEM simulations for various collision and vehicle scenarios as well as obstacles were also used in [13, 14].

In the practice of liquidation of damages, however, the FEM programs are not used due to computer capacity requirements and the need to enter geometric and material data. In the works of [15 - 17], the authors have carried out research on the properties of a post in the form of a truss that can be used as an element of road infrastructure and the influence of its structure on the impact parameters.

In the practice of reconstructing the accidents and verifying the damage, experts and expert witnesses apply programs modelling in the convention of Multi Body Systems (MBS). Although these programs use simplified contact models, they offer a very short calculation time. These programs include V-SIM, which is commonly used in Poland. The efficiency of the SDC method in addressing fraudulent insurance claims requires appropriate simulation based on identified data, rather than default data proposed by the simulation program. This problem should not be neglected. The appraisers and expert witnesses, unfortunately, usually are not aware of the model simplifications and consider the simulation results as the correct ones and thus draw wrong conclusions during a damage verification. Therefore, the author of this study has addressed this important issue.

The article is divided into sections: the second section deals with a description of the SDC method, in the third section, modelling of a vehicle and a collision in the V-SIM program is discussed, whereas in section four, the issues related to model simplifications in the dynamic verification of insurance claims and the differences between simulation results for default parameters proposed by the V-SIM code and the identified ones are presented. In the fifth section, the issue related to the sensitivity of a simulated collision in the parameters that have been entered is discussed. The last, sixth section of this article includes conclusions and development directions of the MBS programs to provide better conditions for collision modelling, which should contribute towards increasing the efficiency of the SDC method.

2. VERIFICATION OF COLLISION BY THE SDC METHOD

This article presents the results of research on the impact model of the V-SIM4 program; in order to present practical application of the complex SDC method, a video was made as well [18].

Static analysis of vehicle damage (S) involves verification of the geometric consistence of its damage with the damage of the second vehicle or the obstacle hit by the vehicle. The best results are provided by comparing real objects, Fig. 1a. However, this kind of comparison is not very common in practice. Therefore, these are photographs of vehicles and obstacles that are commonly used for comparison of the sustained damage. One of the most often used methods is transparent superposition, which involves placing scaled pictures of vehicles on each other, one with smaller transparency and in a mirror reflection, Fig. 1b, as well as using vector silhouettes of vehicle bodies and images, Fig. 1c, or only silhouettes, Fig. 1d. These silhouettes are presented on a scale and accurately represent the shapes of vehicle bodies.

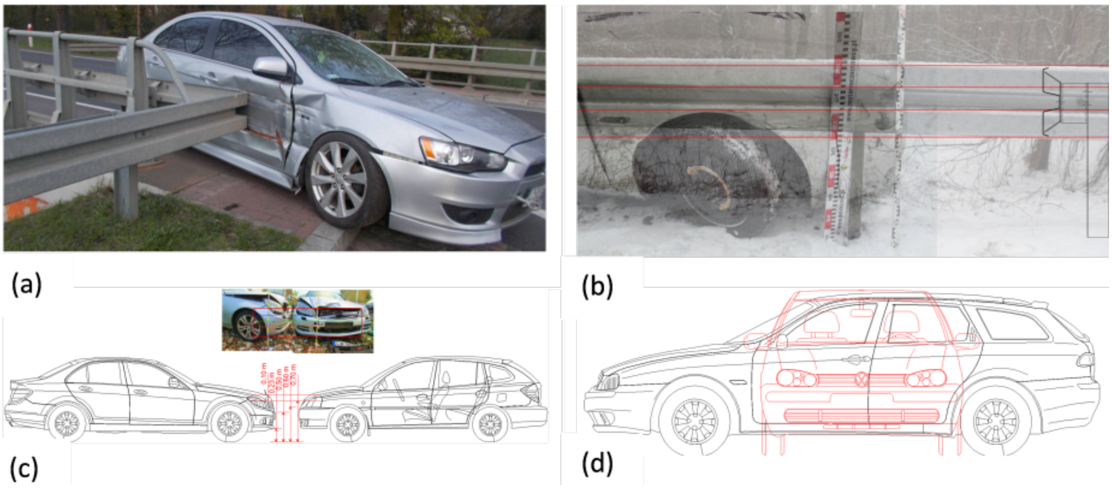


Fig. 1. Comparison of real objects (a), transparent superposition (b), comparison on the basis of scaled pictures and vector images of vehicles (c) and comparison with the use of vehicle vector images (d)

Dynamic analysis (D) allows confirming or ruling out the occurrence of damage in the reported circumstances. Simulation programs are used for the verification of a collision, the vehicle post collision movement and time–space relations between the simulated objects. The procedure uses programs used in the reconstruction of road accidents and requires solving collision modelling problems. The crash modelling has been covered in other papers [19, 20, 21].

Below, there are differences between the collision reconstructed from a simulation with the use of the identified parameters on the basis of the vehicle damage, Fig. 2a, and the collision reconstructed on the basis of data provided by the drivers, Fig. 2b.

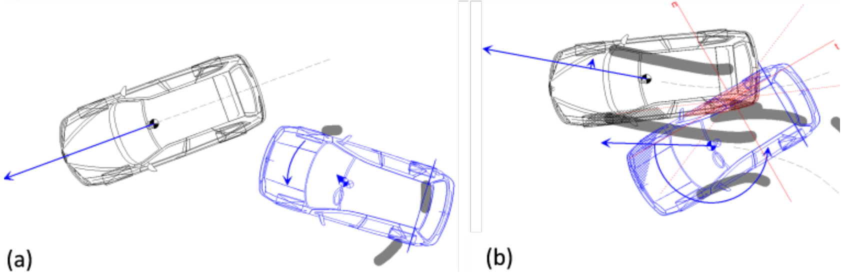


Fig. 2. Results of simulation: identified data (a) and data reported by drivers (b)

An analysis of characteristic damage (C) involves examining marks left on the contact area of two vehicles or within the obstacle.

The most common methods include mapping of shapes, paint or pieces of broken glass and tiles left on the objects involved in a collision.

Below, a mapping of deformation is shown of a vehicle engine chamber cover, Fig. 3a, and blue paint left on the claimant's car by the vehicle of the indicated collision perpetrator, Fig. 3b.

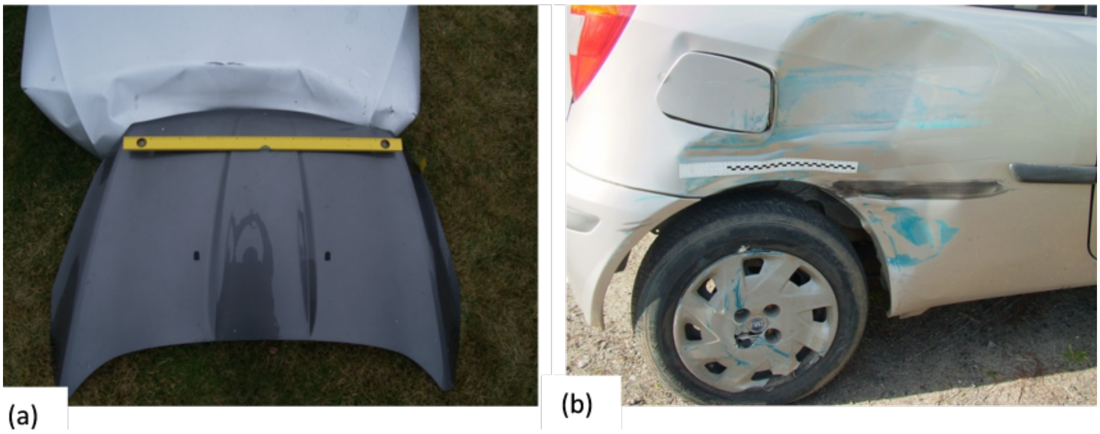


Fig. 3. Mapping of the deformation shape (a) and marks of paint from the perpetrator's car (b)

3. MODEL OF A VEHICLE MOVEMENT IN THE V-SIM PROGRAM

The V-SIM program is used for the simulation of motor vehicle collisions. It also enables the simulation of collisions with terrain obstacles (walls, posts). It enables an analysis of the vehicle impact: before and after movement in the kinetic form progressing during the simulation. The program uses two collision detection models. The first one is a 2D detection model that enables the detection of overlapping parts of vehicle silhouettes. The second is a 3D collision detection model that detects the impact when the vehicle parts interpenetrate each other. In order to obtain correct simulation results, the collision detection model should be chosen by the program operator to match the considered collision, which is described in the work of [22]. The model of a vehicle movement uses two reference systems. The first is a global, inertial system of coordinates. This system describes a momentary position of simulated objects as well as arrangement of the environment elements. Axles of this system are marked as *x, y, z*, whereas axles of a non-inertial system of coordinates connected with the simulated object are marked as *x', y', z'*. This system is used for the determination of external forces acting on the simulated object. Movement of a four-wheeled vehicle in the V-SIM program is described as a movement of a block with ten degrees of freedom, in a 3D space.

Equations of a vehicle movement in a non-inertial system connected with its mass centre and polar radius $\vec{r}$ are as follows:

$$\begin{aligned} \vec{F}' &= \left(\ddot{\vec{r}}' + \dot{\vec{r}}' \times \vec{\omega}'\right) \cdot m \\ \vec{M}' &= \Theta_c \cdot \dot{\vec{\omega}}' + \vec{\omega}' \times \Theta_c \cdot \vec{\omega}' \end{aligned} \tag{1}$$

where: $\vec{F}'$ - sum of external forces acting on the vehicle in the system connected with the vehicle, $\ddot{\vec{r}}'$ - linear acceleration of the vehicle in the system connected with the vehicle, $\dot{\vec{r}}'$ - linear velocity of the vehicle in the system connected with the vehicle, $\vec{\omega}'$ - angular velocity of the vehicle in the system connected with the vehicle, m - mass of the vehicle, $\vec{M}'$ - sum of moments of external forces acting on the vehicle in the system connected with the vehicle, Θ_c - tensor of mass moment of the vehicle inertia and $\dot{\vec{\omega}}'$ - angular acceleration of the vehicle in the system connected with the vehicle.

A tensor of the vehicle mass moment of inertia with zero inertia moments, apart from the main moments, was accepted in the program for the vehicle rotational motion, which is described by a system of scalar equations:

$$\begin{aligned} I_{x'} \cdot \dot{\omega}_{x'} &= M_{x'} - I_{z'} \cdot \omega_{y'} \cdot \omega_{z'} + I_{y'} \cdot \omega_{y'} \cdot \omega_{z'} \\ I_{y'} \cdot \dot{\omega}_{y'} &= M_{y'} + I_{z'} \cdot \omega_{x'} \cdot \omega_{z'} - I_{x'} \cdot \omega_{x'} \cdot \omega_{z'} \\ I_{z'} \cdot \dot{\omega}_{z'} &= M_{z'} - I_{y'} \cdot \omega_{x'} \cdot \omega_{z'} + I_{x'} \cdot \omega_{x'} \cdot \omega_{y'} \end{aligned} \tag{2}$$

where: $I_{x'}$ - mass moment of the vehicle inertia in axis *x'*, $I_{y'}$ - mass moment of the vehicle inertia in axis *y'*, $I_{z'}$ - mass moment of the vehicle inertia in axis *z'*, $\dot{\omega}_{x'}$ - component *x'* of the vehicle linear acceleration in the system connected with the vehicle, $\dot{\omega}_{y'}$ - component *y'* of the vehicle angular acceleration in a system connected with the vehicle, $\dot{\omega}_{z'}$ - component *z'* of the vehicle angular acceleration in the system related to the vehicle, $M_{x'}$ - component *x'* of the moment of external forces acting on the vehicle in a system related to the vehicle, $M_{y'}$ - component *y'* of the moment of external forces acting on the vehicle in the system related to the vehicle, $M_{z'}$ - component *z'* of the moment of external forces acting on the vehicle in the system related to the vehicle, $\omega_{x'}$ - component of the vehicle angular velocity in axle *x'*, $\omega_{y'}$ - component of the vehicle angular velocity in axle *y'* and $\omega_{z'}$ - component of the vehicle angular velocity in axle *z'*.

However, the inertia force and forces caused by wheel suspension as well as aerodynamic resistance forces are used for the summary description of the force acting on the vehicle, which is expressed by the formula:

$$\vec{F}' = \vec{F}'_g + \sum \vec{F}'_i + \vec{F}'_{ax} + \vec{F}'_{ay} \tag{3}$$

where: $\vec{F}'$ - sum of external forces acting on the vehicle in the system related to the car, $\vec{F}'_g$ - inertia force acting on the vehicle, $\vec{F}'_i$ - force of reaction of the vehicle suspension ith wheel, $\vec{F}'_{ax}$ - force of the front aerodynamic resistance and $\vec{F}'_{ay}$ - force of the side aerodynamic resistance.

The V-SIM offers the possibility of using models for the detection of interaction of vehicle tires with the road surface; these models are as follows: HSRI, developed by Dugoff's team, and TM-Easy, another model that can be used for newer types of tires. The steering system is represented in the form of a model operating according to the Ackerman rule, which includes susceptibility of a real system through correction of transverse forces of tire reaction occurring on the vehicle-driven axle. The operator of the V-SIM program can choose two models for the analysis of collisions. The first one is a force model (continuous). In this model, the forces that occur between the simulated objects during an impact develop in a constant manner, from the first contact of the car bodies until they are separated. The second one is a classic impulse collision model, developed by (Kudlich - Slibar). In this model, an exchange of impulses between the simulation objects occurs in one selected moment of simulation [23].

4. SIMPLIFICATIONS OF COLLISION MODELS IN SDC DYNAMIC VERIFICATION

Program V-SIM models a collision by using a car body block with the same stiffness, in the stages of compression and restitution, and the operator can change it. In the V-SIM program, the characteristics of contact force in the vehicle deformation function are close to linear, which is a simplification; this issue is discussed in [24]. Body zones of vehicles, due to their structure, are characterized by different stiffness. It is caused by the structure reinforcements, different materials of the car structural components and arrangement of systems, e.g. the engine, gear box, wheel suspension, and cross members [25]. Moreover, the position of wheels can be changed during a collision or they can even be detached from the surface. However, in modelling, there can occur simplifications that should be taken into consideration by experts who perform simulations as shown in the works [26, 27]. Otherwise, the results obtained from a simulation performed on the basis of default data proposed by the program may be incorrect and the outcome of a claim verification by the SDC method will be incorrect. It is very difficult to obtain experimental data for use by experts in practice; thus, they usually take advantage of the data proposed by the program. Therefore, in order to ensure that the SDC method is more commonly used in practice, a research method enabling the identification of the collision parameters on the basis of filmed crash tests has been proposed. For this purpose, after thorough identification of a vehicle, an expert should immediately start searching for a crash test of the same or similar vehicle involved in a collision similar to the analysed one. The next step is to divide the crash test movie into single images. Crash tests are recorded with the use of efficient video cameras 1000 fps. The collision is filmed from the top and from both sides; hence a possibility of a comparison of the simulation and experimental results. For this purpose, in order to scale single images obtained from the crash test movie, it is necessary to use the vehicle's technical parameters (length, width and wheelbase) and its vector silhouettes. Scaling needs detailed measurements with the use of reference tapes glued on the body of the filmed car. An expert can start matching the images from the vehicle crash test with its vector silhouette no sooner than after the scaled images have been prepared. The next step is to determine the car body displacements during the crash test, measure its deformation and document the vehicle post-impact movement, respectively, since the moment of contact. Special attention needs to be paid to measurement of the vehicle deformation; while doing this task, it is necessary to use unaffected elements of the filmed vehicle body. Next, an expert should enter the identified parameters and adjust stiffness of the simulated vehicle body, restitution coefficient and enter tasks that are not automatic.

The crash test requirements for the low-speed vehicles colliding with a undeformed barrier, applied in the USA and in Europe have been discussed in another paper [28]. The problem related to simplifications of models was analysed with the use of a crash test of Audi A4 produced in 2011 with a mass of 1670 kg. The car hit a rigid barrier at the speed of 56.3 km/h [29].

Scaling was performed according to the above-presented research procedure. The reference tapes glued to the car were used as along with its vector silhouette taken from the database AutoView. The reference tapes are useful for scaling because of the phenomenon of parallax, which occurs when the video camera is placed too low above the vehicle, like in the considered case. However, while measuring the deformation, the roof edge was taken into consideration in the place of the windscreen upper edge setting, which is clearly visible in the pictures and does not undergo deformation during an impact. Contact time for t=0 ms, corresponding to the contact of the filmed vehicle and consistent with the time of the crash test and the simulation. At the beginning of the analysis, the results of simulation consistence with the default data proposed by the V-SIM with pictures recorded in the crash test movie are presented below Fig. 4a-f.

It was found that, for the default data, the program does not precisely reconstruct the collision. At time t=50 ms, the simulated car too deeply penetrates the obstacle, Fig. 4b. This phenomenon increases and at time t=100-150 ms, the difference is still bigger, which is clearly noticeable on the upper edge of the windscreen of the simulated car in relation to the image from the crash test, Fig. 4cd.

At time t=200-300 ms, Fig. 4e,f, the program still does not precisely reflect the collision and there continues to be a clear difference in the coverage of the silhouette of the vehicle filmed during a crash test with the simulated one; the edges of the roof at the upper edge of the wind screen do not overlap.

Moreover, it was found during the crash test at time t=47 ms that the vehicle front right wheel stops turning, whereas the front left wheel stops turning at time t=48 ms. The wheels are blocked as a result of progressing deformation of the front body part. As the crash test shows, at time t=69 ms, the wheels of the back axle are raised and they lose contact with the ground. Next, the front right wheel starts turning at time t=117 ms, whereas the left one at time t=121 ms. The rear wheels fall down on the ground at time t=210 ms. However, the V-SIM simulation program does not reconstruct these phenomena automatically for the simulated car. Below, the results obtained of the simulation consistence are presented for the identified parameters with images recorded in the crash test movie Fig. 5a-f.

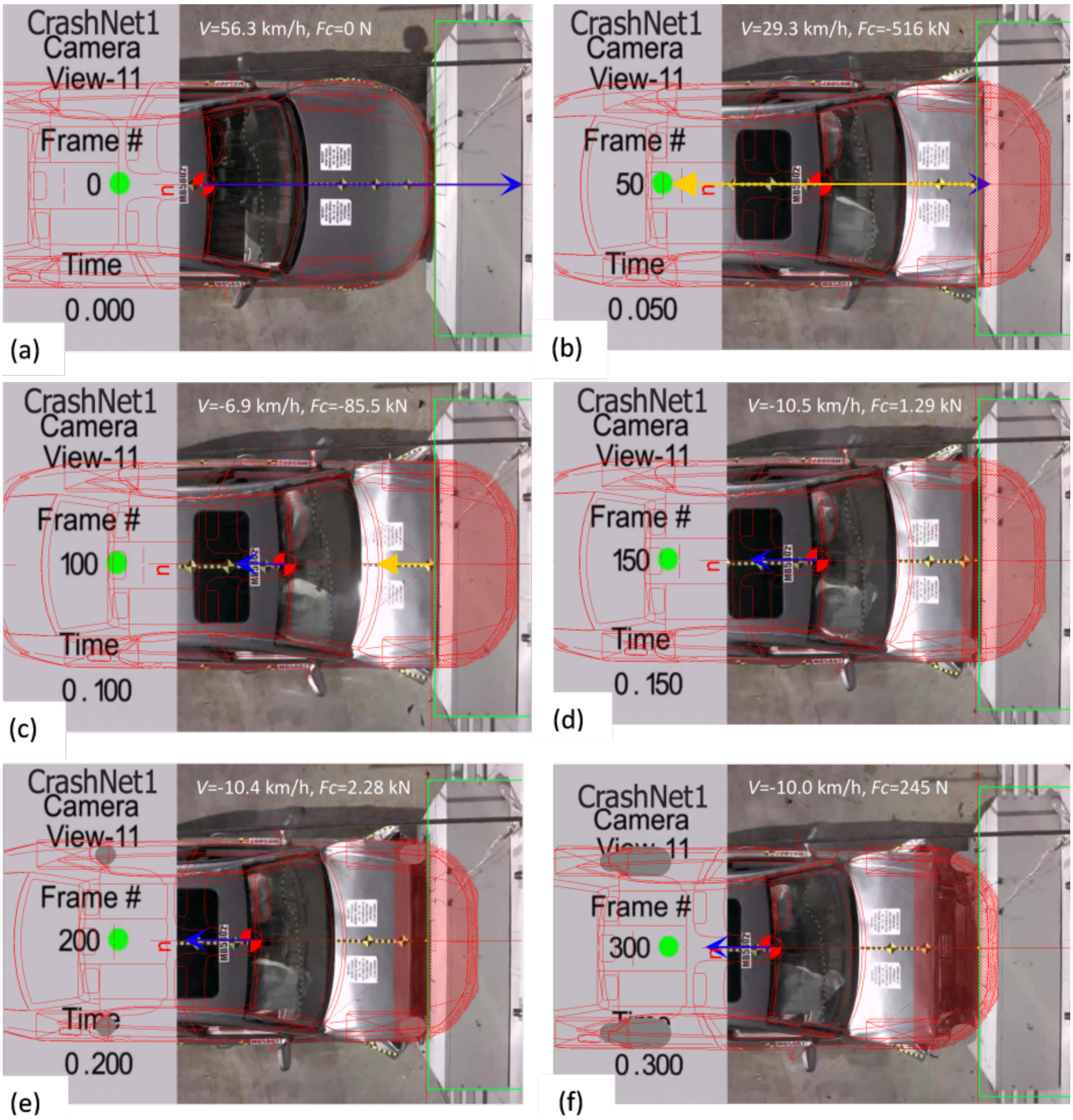


Fig. 4. Comparison of vehicle projections with recorded images for time: t=0 ms (a), t=50 ms (b), t=100 ms (c) and t=150 ms (d), t=200 ms (e) and t=300 ms (f)

In order to show blocking and unblocking of wheels, the V-SIM program operator needs to enter the following tasks: blocking and unblocking of the front left and right wheels at the time provided from the parameters identified from the crash test. Reconstruction of the vehicle rear axle wheel rising during the collision and their falling down on the ground for the times obtained from crash tests is a more complicated task. For this effect, it is necessary to enter an appropriate value of lowering of plane of contact force $\Delta z'$. Moreover, the vehicle simulated in this program has a default value of its body stiffness 730 kN/m^3 in the phases of compression and restitution, which the operator needs to change on the basis of the identified parameters in order to obtain consistence of the simulation with the experiment. Table 1 shows the default data used in the simulation Figs.4a-f and identified data entered into the simulation Figs. 5a-f.

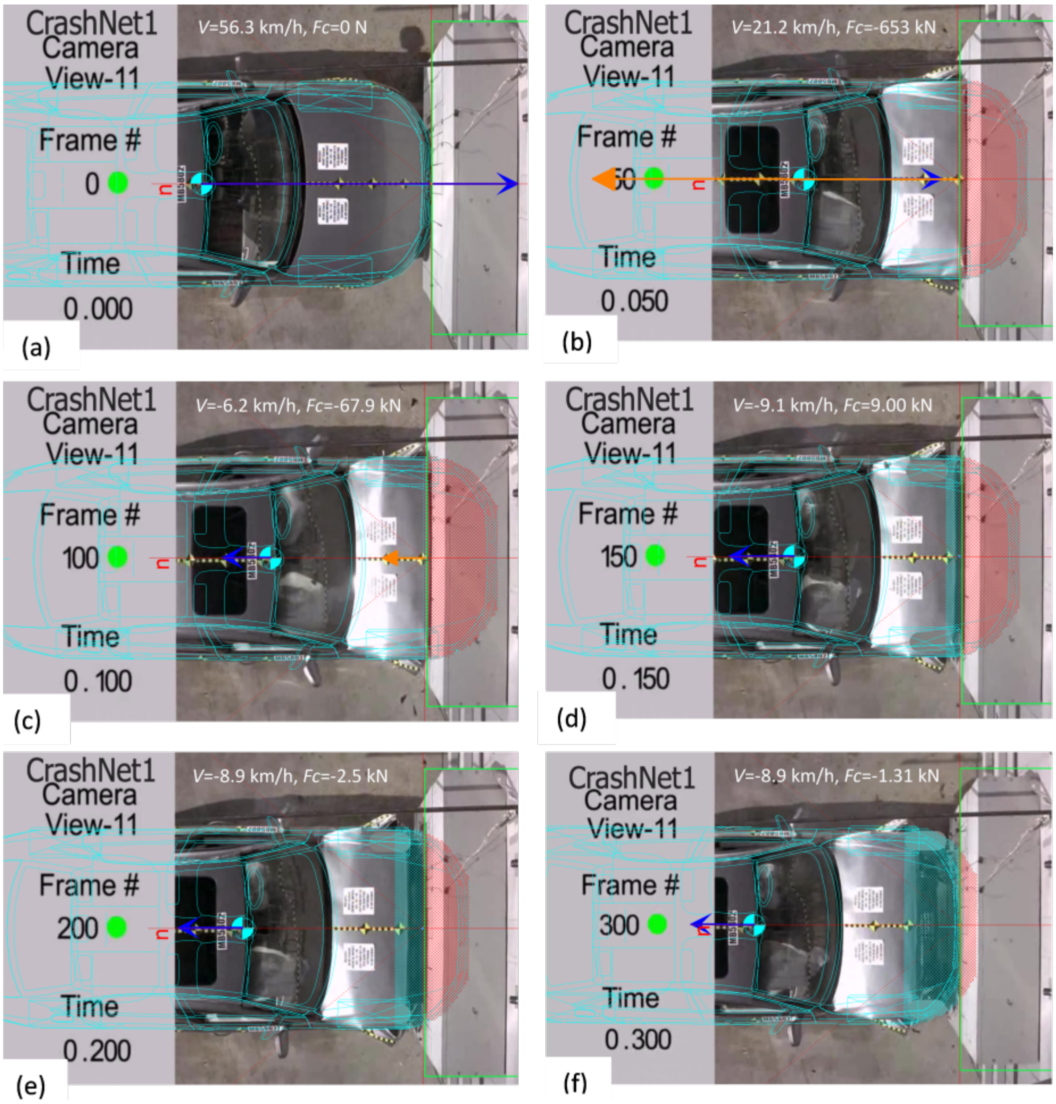


Fig. 5. Comparison of experimental results with the results of simulation obtained for identified parameters for time: t=0 ms (a), t=50 ms (b), t=100 ms (c) and t=150 ms (d), t=200 ms (e) and t=300 ms (f)

Table 1

Values of parameters

Parameter	Default data	Identified data
Slip friction coefficient	0.8	0.8
Adhesive friction coefficient	0.9	0.9
Rolling resistance coefficient	0.015	0.015
Stiffness of the car body for the compression phase	730 kN/m^3	970 kN/m^3
Stiffness of the car body for the restitution phase	730 kN/m^3	600 kN/m^3
Restitution coefficient	0→0.24	0.17
Lowering of plane of contact force $\Delta z'$	0,000 m	-0.210 m
Front axle wheels blocking	doesn't exist	FR 47 ms FL 48 ms
Front axle wheels unblocking	doesn't exist	RR 117 ms RL 121

5. SENSITIVITY OF THE COLLISION COURSE SIMULATION TO THE DATA TO BE ENTERED

Below Fig. 6, there are time histories obtained for cars' displacements and velocities, in a simulation performed on the basis of default parameters, without them being changed by the operator and after entering the parameters given in table 1 on the basis of data identified from the crash test.

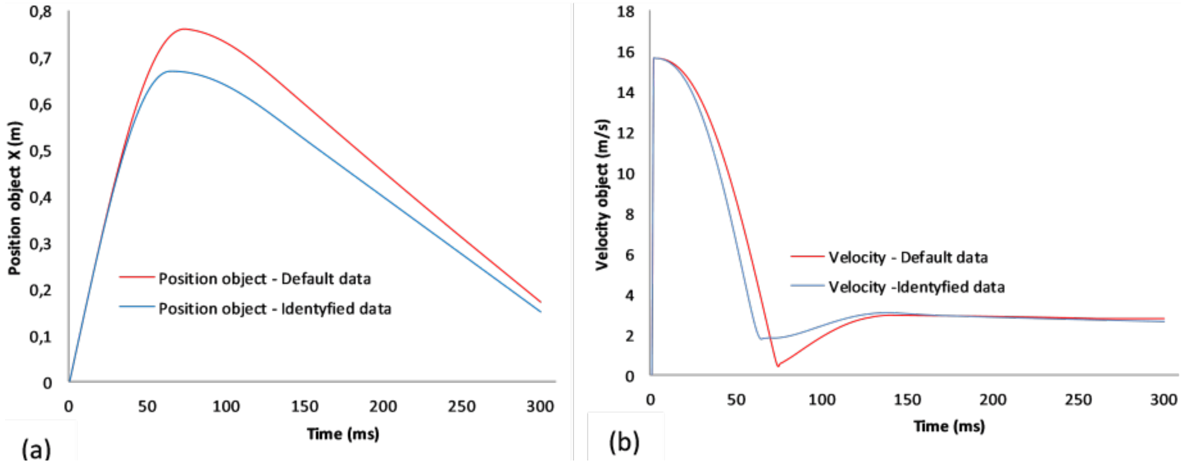
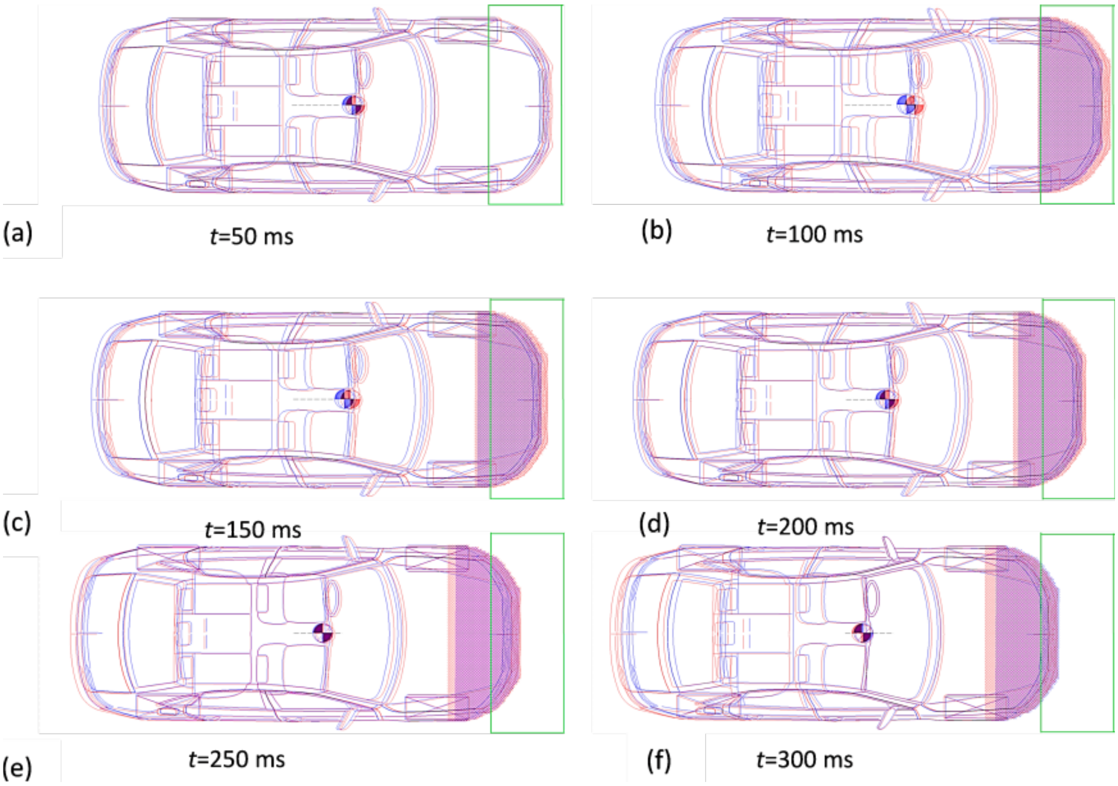


Fig. 6. Time histories of displacements *X* of the object in the global system (a) and linear velocity *V* (b)

Differences in the time histories of displacements and velocities are clearly noticeable for the default and identified parameters. Only in the initial phase of the collision, until time t=40 ms, were the vehicle positions consistent in the simulations. Further, the car position error in the simulation with default data increases and, at time t=75 ms, it reaches the highest value ΔX=0.099 m Fig. 6a. Below, there are differences in the positions of the vehicle body vector silhouettes during a collision, for default parameters and those identified from the crash test Fig. 7a-f. In the simulation with the use of default parameters, although the position difference decreases, after the above-given time $t=75$, the car does not reach position consistence for time t=300 Fig. 7f. However, full consistence of the vehicle displacements during a collision was obtained in the simulation for parameters identified from a crash test Figs. 5e-f. For default parameters, the impact velocity in the compression phase is too high due to the low stiffness of the car body, whereas, in the restitution phase, it is just the reverse: the velocity is too small because of the very high stiffness of the car body Fig. 6b. Therefore, the vehicle does not reach a position that is consistent with the experiment. Thus, a practical conclusion can be formulated that if a simulation performed in the verification of dynamic damage by the SDC method is to be appropriate, experimental parameters from a crash test need to be identified and used in the simulation.

5. CONCLUSIONS AND DISCUSSION

In conclusion, it can be said that precise reconstruction of a collision is not possible for default parameters offered by the V-SIM program. This is caused by nonlinear phenomena that should be taken into consideration by an expert in the identification of appropriate input data. An expert should take into account differences in the body stiffness of cars, which depends on the body structure reinforcement elements (e.g. front wheels suspension, beam of the bumper and cross members) as well as those that increase the car stiffness during deformation upon contact with a wall. The car body stiffness for the compression phase has been increased to 970 kN/m^3 to decrease the body deformation depth. After the compression phase t=66 ms, the vehicle speed is close to zero; therefore, a restitution factor has been reduced to 0.17. In the restitution phase, however, only a small amount of energy is released. After changing the parameters given in Table 1, the same depth deformations of the simulated vehicle were obtained as those of the real vehicle filmed.


(a) *t*=50 ms (b) *t*=100 ms

(c) *t*=150 ms (d) *t*=200 ms

(e) *t*=250 ms (f) *t*=300 ms

Fig. 7. Vehicle positions obtained for V=56.3 km/h and six time instances: t=50 ms (a), t=100 ms (b), t=150 ms (c) and t=200 ms (d) t=250 ms (e) and t=300 ms (f) - the blue vector styling represents the simulation results for the data identified, and the red one - the results for the default data in V-SIM4

It is also very important to change the application point of force F_C. The program used for calculation of the model does not automatically detect the moment when the car rear axle wheels detach from the ground during a collision; therefore, if this happened, it needs to be entered manually. Similarly, the program does not automatically detect blocking and unblocking of the front axle wheels during a collision in the phases of compression and restitution. In order to achieve this effect, the lowering of the plane of contact force by $\Delta z'$ -0.21 m was introduced and the front wheels were blocked, the right one during t=47 ms and the left one during t=48 ms, and unblocked, respectively, at t=117 ms and t=121 ms. This information can be obtained by an expert through an analysis of crash tests in order to estimate the time of such occurrences.

Therefore, an expert who uses the SDC method for the verification of an insurance claim needs to be aware of the necessity to modify the default parameters proposed by the program, according to the experimental data. Otherwise, inappropriate simulation results will be accepted as correct and the verification result of an insurance claim by the SDC method will be wrong as well. This, in turn, will directly affect the legal proceedings.

The research also showed that the V-SIM program should be developed to apply a collision model that considers the body zones with different stiffness and automatic wheel blocking detection in the function of the body deformation depth.

In order to support the decision process of insurance claim verification by the SDC method, it is recommended to use the program developed by the author that is operated by Microsoft Excel [30].

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