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## VERIFICATION OF ROAD ACCIDENT SIMULATION CREATED WITH THE USE OF PC-CRASH SOFTWARE

**Summary.** The paper discusses an example of PC-Crash software usage for road accident reconstruction. Only a segment of the software capabilities is presented, together with a comparison of the visualized 3D simulation with the actual collision video record.

**Keywords:** PC-Crash, road accident reconstruction, road accident visualization, vehicles collision

### 1. INTRODUCTION

Traffic is inseparably connected to road accidents. The amount of road accidents per million citizens and the related mortality rates in Poland are among the highest in the EU. There is an obvious need to carry out any possible actions that may lead to a decrease in these numbers. The effectiveness of these actions depends, for example, on the adequate assessment of collision reasons.

The appropriate assessment of accident causes is vastly important in terms of determining criminal responsibility and damage compensation.

This paper presents a comparison between a simulation of a road accident based on trails left at the scene, as prepared by the author using PC-Crash software, and the actual course of a crash recorded by a car video recorder placed in a motor vehicle not involved in the respective accident (the recording vehicle was moving behind one of the colliding vehicles).

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## 2. ROAD ACCIDENT RECONSTRUCTION

The main task of reconstruction is to recreate the course of an accident in order to recognize the causes of a crash. First of all, one must conclude and calculate the vectors and values of velocity affecting the colliding vehicles. These conclusions can be made based on simulations and reconstructions.

Impact simulation depends on appropriately calculating the parameters characterizing vehicle movement in the first moment after impact. These mathematical operations are based on data describing the moment just before impact.

Reconstruction is an inversion of simulation. One can say that, during simulation, time runs forward, as opposed to reconstruction, where time goes backward.

The vectors and values of velocity at the start of collision can be determined, based on calculations derived from the law of momentum:

$$V_1 = \frac{m_1 \cdot V_1' \cdot \sin(\alpha_2 - \alpha_1') + m_2 \cdot V_2' \cdot \sin(\alpha_2 - \alpha_2')}{m_1 \cdot \sin(\alpha_2 - \alpha_1)} \quad (1)$$

$$V_2 = \frac{m_1 \cdot V_1' \cdot \sin(\alpha_1' - \alpha_1) + m_2 \cdot V_2' \cdot \sin(\alpha_2' - \alpha_1)}{m_2 \cdot \sin(\alpha_2 - \alpha_1)} \quad (2)$$

$$\sin(\alpha_2 - \alpha_1) \neq 0,$$

or based on calculations derived from the law of angular momentum:

$$S_x = \frac{x_{2c} \cdot J_{1c} \cdot \Delta\omega_1 + x_{1c} \cdot J_{2c} \cdot \Delta\omega_2}{x_{2c} \cdot y_{1c} - x_{1c} \cdot y_{2c}} \quad (3)$$

$$S_y = \frac{y_{1c} \cdot J_{2c} \cdot \Delta\omega_2 + y_{2c} \cdot J_{1c} \cdot \Delta\omega_1}{x_{2c} \cdot y_{1c} - x_{1c} \cdot y_{2c}} \quad (4)$$

where  $V_1, V_2$  are the values of velocity at the start of collision;  $V_1', V_2'$  are the values of velocity at the start of post-collision movement;  $m_1, m_2$  represent the mass of the vehicles;  $\alpha$  represents the angle of velocity vectors;  $S_x$  is the impulse component in the 'x' direction of the accepted coordinates system;  $S_y$  is the impulse component in the 'y' direction of the accepted coordinates system;  $\Delta\omega_1, \Delta\omega_2$  represent the gain of angular velocity caused by the accident [1/s];  $J_c$  is the moment of vehicle inertia in relation to the vertical axis pierced by the vehicle's centre of mass; and  $x_c, y_c$  are the centres of the mass coordinates in relation to 'z'.

The values of velocity at the start of the post-collision movement are as follows:

$$V_{1c}' = \frac{S_y \cdot \cos \alpha_1 - S_x \cdot \sin \alpha_1}{m_1 \cdot \sin(\alpha_1' - \alpha_1)} \quad (5)$$

$$V_{2c}' = \frac{S_x \cdot \sin \alpha_2 - S_y \cdot \cos \alpha_2}{m_2 \cdot \sin(\alpha_2' - \alpha_2)} \quad (6)$$

The values of velocity at the start of collision are as follows:

$$V_{1c} = \frac{S_y \cdot \cos \alpha_1' - S_x \cdot \sin \alpha_1'}{m_1 \cdot \sin(\alpha_1' - \alpha_1)} \tag{7}$$

$$V_{2c} = \frac{S_x \cdot \sin \alpha_2' - S_y \cdot \cos \alpha_2'}{m_2 \cdot \sin(\alpha_2' - \alpha_2)} \tag{8}$$

There is a number of simplified models that allow us to calculate the linear and angular velocity of a vehicle at the start of its slipping movement. These models can be used until the movement distance of the centre of mass and the variations in the longitudinal axis rotation angle are known during the whole motion.

The Marquard model is an example of these above-mentioned simplified models. It was created for two-wheel vehicles, in which adequate coefficients are set by averaging the calculation results in relation to the time of the motion. These coefficients allow us to perform a reconstruction based on simplified formulas with reasonably good approximation, based on the law of kinetic energy and work balance.

For this study, estimating post-collision movement parameters is based on the Marquard model (full slide movement):

$$V_c' = \sqrt{2 \cdot k_s \cdot \mu_s \cdot g \cdot S + V_k^2} \tag{9}$$

$$\omega' = \text{sgn}(\Delta\varphi) \sqrt{k_\varphi \cdot \mu_s \cdot g \cdot |\Delta\varphi| \cdot \frac{L}{i^2} + \omega_k^2} \tag{10}$$

$$k_s = 0,17 \cdot x^3 - 0,488 \cdot x^2 - 0,03 \cdot x + 1$$

$$k_\varphi = 0,328 \cdot x^3 - 0,772 \cdot x^2 + 1,072 \cdot x$$

$$x = |\Delta\varphi| \frac{L}{2 \cdot S}$$

where  $V_c'$  represents the values of linear velocity in the centre of mass at the start of the post-collision movement [m/s];  $\omega'$  is the angular velocity value at the end of the impact [1/s];  $\mu_s$  is the slide traction coefficient;  $S$  is the length of the mass centre movement [m];  $V_k$  represents the values of linear velocity in the centre of mass at the end of the post-collision movement [m/s];  $g$  is the gravitational constant;  $L$  is the axis gauge [m];  $i_c$  is the vehicle's inertia radius [m];  $\Delta\varphi$  is the total rotation angle in the post-collision movement [rad]; and  $k_s, k_\varphi$  are Marquard's coefficients.

The Marquard model allows us to estimate the velocity at the beginning of the post-collision movement. It can be used in a situation when all wheels are blocked or no wheel can roll. In reality, one will often confront the situation where only one or some of the wheels will be blocked (e.g., as the cause of post-impact structural damage or deformities).

The Burgard model [1] allows us to calculate a vehicle's movement parameters at the moment just after the end of the impact by considering the impulse vector direction and the breaking force depending on the wheel damage.

The value of the linear and angular velocities in the centre of mass at the start of the post-collision movement can be calculated with the use of the following:

$$V_p' = \sqrt{2 \cdot a' \cdot s + V_k^2} \quad (11)$$

$$\omega_p' = \sqrt{\frac{m \cdot g \cdot \omega_r \cdot l}{J} \cdot |\Delta\varphi| \cdot \text{sgn}(\Delta\varphi)} \quad (12)$$

although:  $a' = \mu_s \cdot g \cdot [f_h + (1 - f_h) \cdot \sin \varphi_m]$   
 ( $a'$  represents the effective delay of the post-collision movement)

where  $V_p'$  represents the values of linear velocity in the centre of mass at the start of the post-collision movement [m/s];  $\omega_p'$  is the angular velocity value at the end of the impact [1/s];  $\mu_s$  is the coefficient of slide traction;  $S$  is the length of the mass centre movement [m];  $V_k$  represents the values of linear velocity in the centre of mass at the end of the post-collision movement [m/s];  $m$  is the mass of the vehicle [kg];  $g$  is the gravitational constant;  $f_h$  is the breaking force partition coefficient, whose value includes the amount of force and the nature of the braking by the wheels;  $\omega_r$  is the rotation resistance coefficient;  $l$  is the axis gauge [m];  $J_c$  is the moment of vehicle inertia in relation to the vertical axis, pierced by the vehicle's centre of mass [kgm<sup>2</sup>]; and  $\Delta\varphi$  is the total rotation angle in the post-collision movement [rad].

In the case of unblocked front wheels, their angle of rotation from the longitudinal position may be essential. The precise analysis of such a case can only be conducted by calculating the configuration of unilinear derived functions of movement. Such analysis allows us to conduct post-collision movement parameters by considering geometrical changes of the vehicle, especially, the wheels' dislocation caused by deformations.

### 3. PC-CRASH SOFTWARE FOR RECONSTRUCTION CALCULATIONS

Currently, a wide variety of software is available for use in reconstructing vehicle crashes and the dynamics of movement calculations on a broad scale, such as PC-Crash, V-SIM, VirtualCRASH, CARAT and HVE [3]. One of the most popular in Poland is PC-Crash (DSD PhD Steffan Datentechnik, Austria).

PC-Crash software has been designed for carrying out mathematical calculations for the purpose of reconstructing road accidents. The software allows us to simulate the course of action in almost all eventualities, due to the integration of numerous modules, in particular, vehicle databases, vehicles' dynamic models, crashes and multichunk arrangements, graphic modules and 3D animation sequences. It specifically enables the simulation of movement and collision between two vehicles (e.g., single- or double-track vehicles), and between vehicles and environmental objects (e.g., trees, walls), foundations (e.g., when a vehicle turns around, debris falling from scarps or trenches), and biomechanical objects (e.g., pedestrians, passenger movements). The software also facilitates time and space analysis of accident, which is essential for assessing the correctness of participants' actions in the moments before an event.

PC-Crash allow us to simulate the course of action in general case, from the beginnings of endangerment through the pre-collision, collision and post-collision movements until the movement arrest. The software provides three accident models:

- Kudlich-Slibar (classic or Newtonian)
- Rigidness, using multichunk arrangements modelling
- Reticular, external coating, represented by a deforming net

Simulation is the base method of analysis. The Kudlich-Slibar model is used for simulation in which the post-collision vehicle's movement parameters are calculated, based on data from the moment before impact. The model assumes that collision time is infinitesimal, which is why vehicle movement during impact is neglected. An impact vector is placed in one particular spot and all other external forces (e.g., influence of the road on wheels) are disregarded [4].

#### 4. CASE STUDY

This chapter presents a fact-based crash reconstruction with the use of the Kudlich-Slibar model and PC-Crash software. Data used in this case are taken from court files relating to a particular road accident.

A Seat Leon driver attempted to perform an overtaking manoeuvre in relation to multiple vehicles; however, this individual did not pay regard to the horizontal P-3 traffic sign (unilateral non-transgressing line). During the motion on the lane in the opposite direction, the vehicle collided frontally with a VW Golf III passenger car. At the time of the crash, the Seat Leon was placed beneath a hill peak and in front of a road bend.

The evidence left at the scene is indicated on Figure 1.

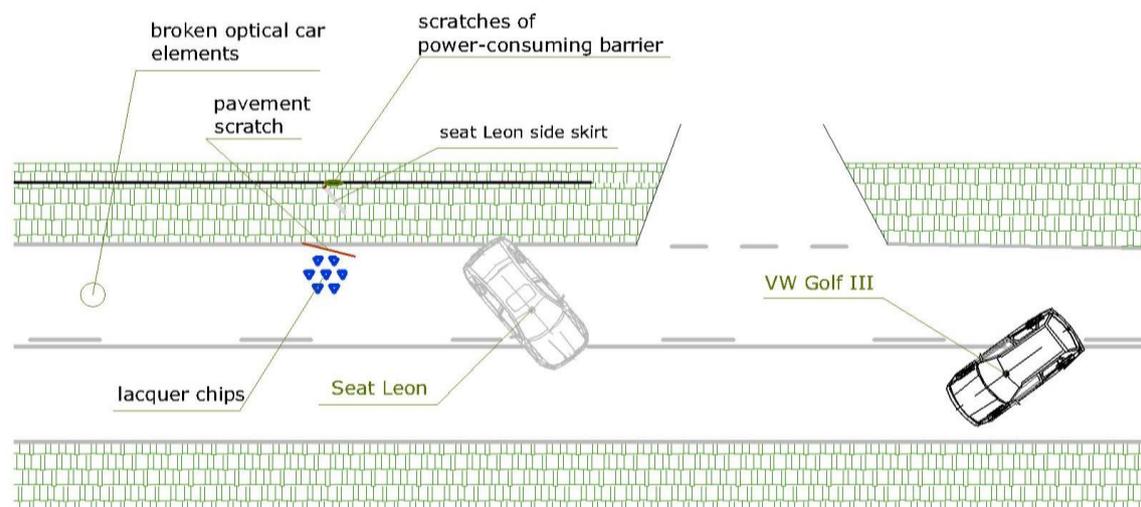


Fig. 1. Scene sketch

The evidence from both vehicles indicates that three events occurred at the time of the accident:

1. Frontal collision between the Seat Leon and the VW Golf III

2. Collision between the Seat Leon's left-posterior corner and the power-consuming barrier
3. Collision between the VW Golf's left-posterior bumper corner and a third car at the level of the posterior-left wheelhouse shell

During the latter impact, the VW Golf's stern could have been lifted by around 0.5 m (Figure 3), with the third vehicle moving in the opposite lane in the appropriate direction.

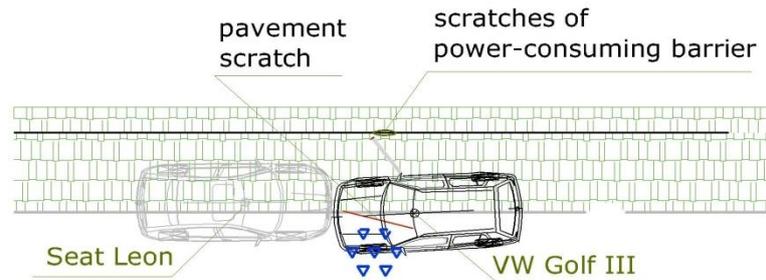


Fig. 2. The placement of the Seat Leon and the VW Golf III at the time of frontal impact



Fig. 3. Relative placement of the VW Golf III and the third vehicle (moving in the opposite lane) at the time of impact

During the impacts, the vehicles sustained significant deformations (the computer software provides the option to modify the geometry of the models). Those modifications are included in the calculations of the post-impact movements (Figures 4-5).



a



b

Fig. 4. The Seat Leon’s geometry shift caused by deformation: a) fact-based photograph of the scene; b) model used in the post-impact movement calculations



a b  
 Fig. 5. The VW Golf’s geometry shift caused by deformation: a) fact-based photograph of the scene; b) model used in the post-impact movement calculations

During the initial simulations, difficulties with accurately recreating the VW Golf’s second impact involving the left-posterior bumper corner occurred, i.e., during the initial simulation, the car rear could not be lifted into the appropriate position. The vehicle that took part in the accident was heavily used. There is a probability that the rear-axis shock absorbers were not working as intended. The PC-Crash software allows the user to define the suspension parameters: after lowering the damping ratio of the rear-axis shock absorbers, the expert witness applied the simulated course, which justified the revealed evidence.

Carrying out these simulations allowed us to calculate the probable crash velocities: VW Golf – 40.0-45.0 km/h; Seat Leon – 83.0-89.0 km/h. The lowest error value of 6.2% (weighted relative error) [4, 7] was determined for the velocities for the VW Golf at 41.0 km/h and the Seat Leon at 85.0 km/h.

Being able to create a 3D animated video of the accident, based on mathematical calculation results, is an essential software requirement. A video of this kind is particularly useful for the accurate evaluation by specialists in other disciplines (e.g., lawyers).

The course of this accident was recorded by video camera in one of the cars in the column overtaken by the Seat Leon.

The figures below present a comparison of the real crash video and the 3D animation of the discussed collision at the time of the accident (Figures 6-8).



a b

Fig. 6. Frontal crash involving the Seat Leon and the VW Golf: a) film frame from the car video recorder; b) 3D view from the simulation



a

b

Fig. 7. Collision of the Seat Leon's left-posterior corner with the power-consuming barrier: a) film frame from the car video recorder; b) 3D view from the simulation



a

b

Fig. 8. Collision of the VW Golf's left-posterior bumper corner with the third car, which was moving in the opposite lane in the appropriate direction: a) film frame from the car video recorder, b) 3D view from the simulation

## 5. CONCLUSIONS

Increasingly complex simulation software is available, which allows for the course of accidents to be recreated, as well as the presentation of results following the arduous and complicated calculation of relevant parameters [5,6]. In the discussed case, the author refers to PC-Crash. An additional option provided by this software is the ability to present the accident as a short, animated movie, which can accurately reflect the real accident.

Progress made in the area of personal computers has enabled programmers to provide increasingly complex calculation algorithms, together with other advanced tools involving, for example, the finite element method and software used by expert witnesses [11,12,13].

Additionally, the actual progress of artificial intelligence (AI) developments has meant that simulation software is more commonly used for complex calculations. Its broad use can be observed, including indirectly in the courts during cases that require the reconstruction of road accidents.

The literature presents many approaches to solving problems in the context of analysing images with AI [14-17]. The authors of AI-related papers have paid particular attention to the analysis of the sensitivity of relevant models [18,19].

On the topic of road accidents, it is noteworthy that a considerable amount of research has taken place on road safety around the world, in which authors have focused on both human and technical aspects in relation to the occurrence and course of road accidents [3,20-22]. One needs to remember that a road accident is always the effect of various factors, such as human, vehicle or environmental factors. It is also important to bear in mind the numerous studies that have led to improvements in the reliability of vehicle elements and their proper diagnostics [23-35].

We hope that, as a result of ongoing technological progress, the increased accessibility of advanced algorithms and relevant international studies will lead to a decrease in the number of road accidents and improvements in their outcomes, or at least allow for their real course of action and causes to be established at an easier stage.

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