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VEHICLES FRONTAL IMPACT ANALYSIS USING COMPUTER SIMULATION AND CRASH TEST

Dragos Sorin Dima* and Dinu Covaciu

Department of Automotive and Transport Engineering, Transilvania University of Brasov, Brasov 500036, Romania

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ABSTRACT−Reconstruction of car accidents is a complex task, with many unknown variables. Among the parameters used to assess the accident severity, in case of a frontal collision between two vehicles, are the change in velocity (delta-v) and the Energy Equivalent Speed (EES). The EES is usually determined based on the deformations. Delta-v can be obtained from the crash pulse recorded with Event Data Recorders, or with crash loggers based on accelerometers, in case of crash tests. In this paper is presented a full scale crash test that involves two vehicles in a frontal collision. The results are obtained using different analysis methods: direct application of a model, processing the measured crash pulse, and computer simulation.

KEY WORDS : Frontal collision, Crash test, Crash pulse, Energy equivalent speed, Delta-v

NOMENCLATURE

EES : energy equivalent speed, m/s
S : momentum, kg·m/s
$S_{ix,y}$: momentum of vehicle *i*, in direction x or y
$m_{ix,y}$: mass of vehicle *i*, direction x/y, kg
$v_{ix,y}$: velocity of vehicle *i*, direction x/y, before impact, m/s
$v'_{ix,y}$: velocity of vehicle *i*, direction x/y, after impact, m/s
SR : speed ratio

1. INTRODUCTION

Crash tests have an important role in assessing the vehicles safety. These are destructive processes, conducted to determine the compatibility of the vehicle with safety standards and in the same time to study the strength and behaviour of the various components in the event of a collision.

Crash tests are configured to conduct studies on:

- Frontal impact: Impact, at a certain speed, with a solid wall or with another vehicle;
- Partial frontal impact (overlap): When only part of the front of a vehicle collides with a barrier or another vehicle;
- Lateral impact: Usually, a vehicle-vehicle impact, when the front of a vehicle collides one side of the other vehicle;
- Rollover: To test the capacity of the structure to resist to his own weight following a dynamic impact;
- Vehicle-pedestrian: Impact between the front of the vehicle and a dummy;
- Vehicle-bicycle: Impact between a car and a two-wheel vehicle;
- Vehicle-lateral barrier: Testing the behaviour of the vehicle body and safety systems, when the vehicle collides with road side protection elements, posts or other obstacles.

A crash test can be also simulated on a computer using specialized software. Simulation helps designers and researchers to optimize the vehicle structure, or the dummies and the barriers used in experiments.

When a vehicle is involved in a collision, there is a deformation of its structure, which reduces its speed until it stops or detaches by the other vehicle or obstacle. The deformation of the sheet metal will produce a low deceleration pulse of the vehicle, while more rigid components, such as the chassis or engine, will cause high amplitude deceleration pulses to be transferred to the rest of the vehicle, and to the occupants. The deceleration series recorded during the impact forms the deceleration curve, known also as the crash pulse. An objective for vehicle manufacturers is to obtain lower decelerations in order to reduce occupant injury. The vehicle crashworthiness involves the identification of technical solutions to control the energy and the crash pulses.

2. METHODOLOGY OF COLLISION ANALYSIS

2.1. Case of a Vehicle-vehicle Impact

The parameters used to describe the crash severity are the change in velocity (delta-v) of the center of gravity of the

Corresponding author: e-mail: d.dima@unitbv.ro

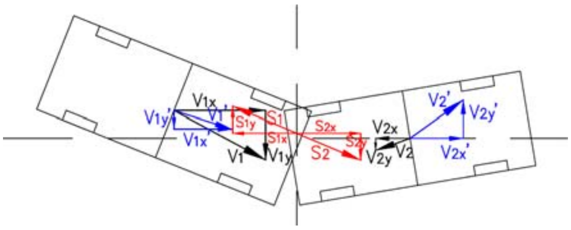

Figure 1. Collision model; S-momentum, v-velocity.

vehicle and the EES (*Energy Equivalent Speed*) value (Robinette *et al*., 1994). EES is a measure of deformation or, more exactly, the kinetic energy converted to thermal energy through deformation, and it was introduced in 1980 by Burg and Zeidler (1980) and Zeidler *et al*. (1985). In a collision without glance-off, such as a barrier impact with 100 % overlap, EES and delta-v are of similar values. When glance-off occurs in an impact (with partial overlap), the EES is higher than the delta-v (Berg *et al*., 1998). In the context of a vehicle crash, delta-v (Δv) specifically refers to the change in velocity during the impact (the difference between the velocity at impact and the residual velocity after energy absorption and interaction with the target vehicle). It depends on the relative impact speed, the respective masses of the vehicles and the coefficient of restitution. Delta-v depends by the relative impact speed, the weights of the vehicles and the coefficient of restitution, and it can be used as a predictor of occupants injury (Bálint *et al*., 2013).

By following the Slibar model (Slibar, 1964; Steffan, 2009), (Figure 1), it is assumed that, after applying a momentum, the movement of the vehicles is decomposed in a translation, followed by a rotation. Then, because there is a crush of metal during the impact, it should be considered the loss of energy, as *deformation energy.*

The principle of momentum conservation:

$$S_{1x} = -S_{2x} \tag{1}$$

$$S_{1y} = -S_{2y} \tag{2}$$

leads to:

$$m_1 \cdot (v_{1x} - v'_{1x}) = -m_2 \cdot (v_{2x} - v'_{2x}) \tag{3}$$

$$m_1 \cdot (v_{1y} - v'_{1y}) = -m_2 \cdot (v_{2y} - v'_{2y}) \tag{4}$$

where m_1, m_2 are the vehicles weights, v_{1x}, v_{1y}, v_{2x}, v_{2y} are the directional velocities of the vehicles before impact, and v'_{1x}, v'_{1y}, v'_{2x}, v'_{2y} are the directional velocities of the vehicles after impact.

For the rotational movement, it can be stated:

$$J_1\omega_1 = r_{1x}S_{1y} - r_{1y}S_{1x} \tag{5}$$

$$J_2\omega_2 = r_{2x}S_{2y} - r_{2y}S_{2x} \tag{6}$$

where ω_1, ω_2 are the rotational speeds, or yaw velocity, r_{1x}, r_{1y}, r_{2x}, r_{2y} are the rotation radiuses of the two vehicles, S_{1x}, S_{1y}, S_{2x}, S_{2y} represent the momentum, as defined in the equations above, and J_1, J_2 are the moments of inertia, of the vertical axis. Similar equations can be written for the end of rotation (with rotational speeds ω'_1, ω'_2), considering these are for the begining of the rotation.

The loss of energy, during collision, including both translation and rotation, is:

$$\Delta E = (E_1 + E_2) - (E_1' + E_2') \tag{7}$$

where (with i being the index of the vehicle):

$$E_i = \frac{1}{2}m_i v_i^2 + \frac{1}{2}J_i\omega_i^2 \text{ with } v_i^2 = v_{ix}^2 + v_{iy}^2 \tag{8}$$

$$E_i' = \frac{1}{2}m_i v_i'^2 + \frac{1}{2}J_i\omega_i'^2 \text{ with } v_i'^2 = v_{ix}'^2 + v_{iy}'^2 \tag{9}$$

and it results:

$$\Delta E = \frac{1}{2}\begin{bmatrix} m_1(v_{1x}^2 - v'^2_{1x}) + m_1(v_{1y}^2 - v'^2_{1y}) + m_2(v_{2x}^2 - v'^2_{2x}) + \\ m_2(v_{2y}^2 - v'^2_{2y}) + J_1(\omega_1^2 - \omega'^2_1) + J_2(\omega_2^2 - \omega'^2_2) \end{bmatrix} \tag{10}$$

With other words, the deformation energy is equal with the kinetic energy before collision, minus the kinetic energy after collision. This deformation energy can be expressed as a kinetic energy by introducing the *EES* (*Energy Equivalent Speed*):

$$\Delta E = \frac{1}{2}m_1 EES_1^2 + \frac{1}{2}m_2 EES_2^2 \tag{11}$$

EES is expressed, like the velocities, in $m \cdot s^{-1}$.

For a single vehicle which is crushed against a fixed, non-deformable barrier, without spin-off motion, the deformation energy is:

$$\Delta E = \frac{1}{2}m_1 v_1^2 = \frac{1}{2}m_1 EES_1^2 \tag{12}$$

The vehicle weight is m_1 and the initial velocity is v_1. Since the vehicle stops after collision, the variation of velocity (delta-v) is equal with the initial velocity v_1.

Delta-v is the change of velocity of the center of gravity of the vehicle, during the impact. This is usually different from the EES. In the particular case when there is no rotation movement, delta-v can be calculated by integration of the vehicle deceleration in the x direction (parallel with the longitudinal axis of the vehicle). In the general case, all the deceleration components should be considered. A control parameter is the *delta-v* versus *EES* ratio, defined as "speed ratio" (Rabek and Sachl, 2001):

$$SR = \frac{\Delta v_i}{EES_i} \tag{13}$$

where Δv is delta-v (the change of speed, during the impact) and i is the index of the vehicle.

The value of SR depends by the collision type and should be: $0.9 < SR < 1.2$ for a collision without glance-off, $0.75 < SR < 0.9$ for an incipient glance-off, and $SR < 0.75$ for a collision with glance-off.

2.2. Crash Pulse

The crash pulse is the deceleration curve during the collision, and is characterized by shape, amplitude and duration. It is used to calculated the changes of velocity and dynamic crush of a vehicle, by integration. The vehicle crash pulse is related to the injuries of occupants, and it should be an objective measure of the severity of occupants injuries (Park and Kan, 2010). Some metrics can be deducted from the crash pulse, including: maximum acceleration, moving average acceleration (used to calculate the *Acceleration Severity Index*) (Gabauer and Gabler, 2005), delta-v, time to zero velocity, displacement, jerk (the acceleration derivative), energy density, energy, power, power density (Huang, 2002).

Delta-v is considered to be a measure of the severity of a traffic collision (Shelby, 2011). It is used, since 1970, in the accident reconstruction, and is estimated also with crash reconstruction programs, like CRASH (*Calspan Reconstruction of Accident Speeds on Highways*). However, delta-v, alone, cannot describe the severity of the crash, since the same change in velocity can be obtained for different time intervals. To date, the commonly used algorithm used to establish the change in velocity of vehicles is CRASH3 (Neades and Smith, 2011), which is implemented in the most used computer software for accident reconstruction.

The crash pulse is measured with Event Data Recorders (EDR) in real road events, and with dedicated data acquisition systems in crash tests. Using analytical methods, based on a crash pulse measured in a particular crash test, can be determined crash pulses of various severities. For this, the shape of the pulse is approximated with well recognized shapes. Examples of shapes used are: haversine ($\sin^2$), sine, square wave, triangular (Varat and Husher, 2003). In other studies, the pulses are parametrized using eigenvalue analysis, and multiple linear regression is used to determine the influence of crash variabled on the pulse (Iraeus and Lindquist, 2015).

The delta-v is obtained from the crash pulse by integration; it is, essentially, the area under the curve of acceleration versus time. Depending by the orientation of the two vehicles, or the vehicle in relation with the fixed obstacle, it can be consider only the acceleration in one direction, or all the acceleration components (x, y, z).

3. EXPERIMENTAL STUDY

3.1. Crash Test

The crash test was conducted following this scenario (Figure 2): a vehicle is accelerated to the speed of 35 km/h and enters in frontal collision with another vehicle, which is stationary. The moving vehicle was towed using a long cable, attached to a truck. Just before the impact the cable was released from the towing vehicle.

The collision phases are shown in Figure 3: pre-impact, impact and post-impact. As it can be seen in the photos, the impact was not with 100 % overlap.

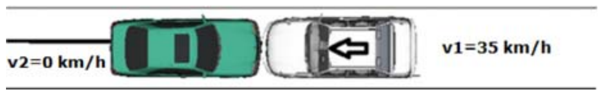

Figure 2. Scenario of a vehicle-vehicle collision.

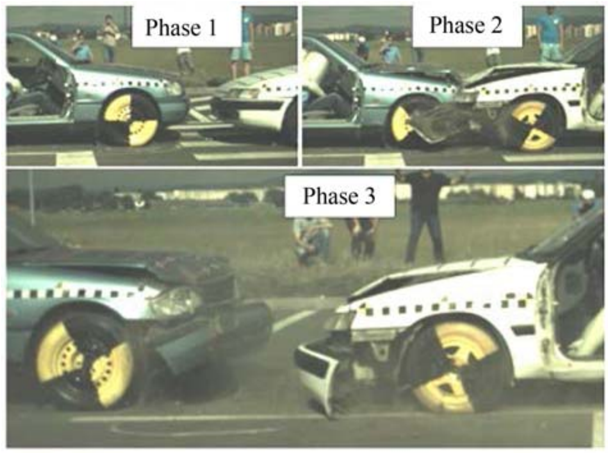

Figure 3. Collision phases.

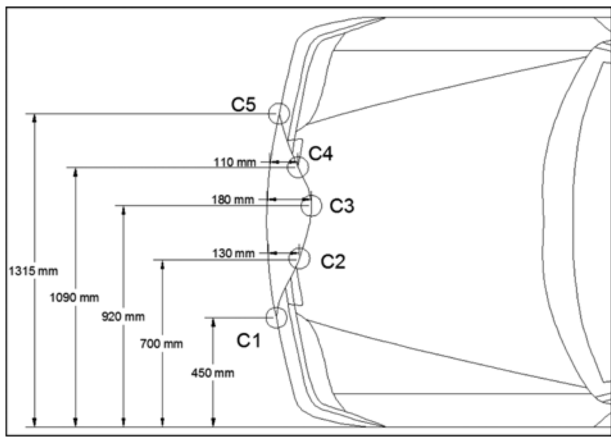

Figure 4. Deformation measured on moving vehicle.

The change in velocity of the vehicle 1, during the impact phase is not equal with the initial speed (like in case of collision with a fixed barrier), because the vehicle is still moving after the two vehicles are separated.

The deformations of the two vehicles are measured using an aerial photography taken after the impact (Figures 4 and 5).

Determination of post-impact vehicle deformations is essential in the reconstruction of accidents, especially for the use of specialized programs. Based on the measured deformations, the collision parameters were estimates using the CRASH3 algorithm, implemented in PC-Crash software. The calculated values for EES are: 17.9 km/h for the moving vehicle, and 13.9 km/h for the stationary vehicle.

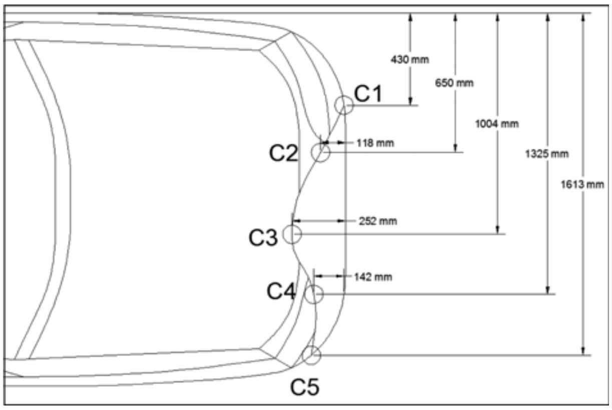

Figure 5. Deformation measured on stationary vehicle.

3.2. Data Acquisition and Processing

Both vehicles were instrumented with data acquisition devices: tri-axial accelerometers and GPS loggers (for speed measurement). The accelerometers had a measuring range of ± 200 g and a bandwidth of 1.6 kHz. The device used is PicDAQ, from DSD (2017): a data acquisition platform for record of dynamic data, where accelerations and angular velocities describe the movement (for vehicle driving performance, braking tests, and vehicle crash tests). The speed is measured and recorded using a GPS logger (Covaciu and Dima, 2017) with a sampling rate of 5 Hz. Data are processed using a dedicated Windows software application (Figure 6 - zero on X-axis is the time of impact).

The speed recorded using GPS receivers is quite accurate, because it is not calculated by derivation of the distance between successive positions, but using the values exported through NMEA 0183 sequences, where the speed is calculated based on Doppler effect. The impact speed is estimated at 34 km/h. The speed drop of about 20 km/h should correspond to the delta-v of the moving vehicle. The acceleration on this diagram is calculated as speed derivative, and is affected by the sampling rate, which is too small (5 Hz), compared to the impact duration. The measured speed will be used as a reference.

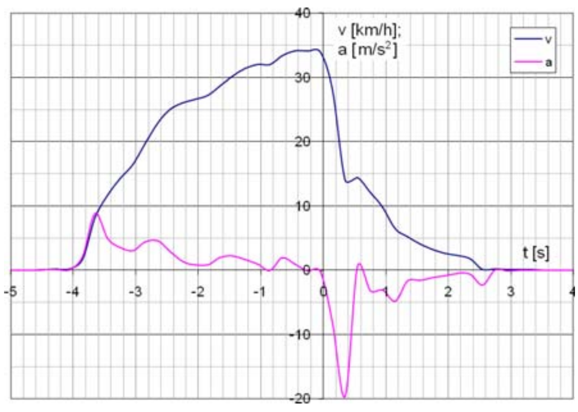

Figure 6. Speed measured with GPS device.

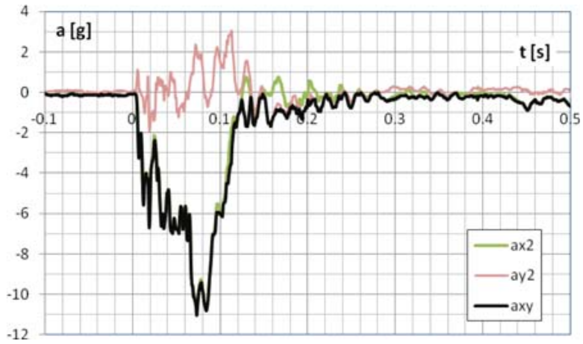

Figure 7. Acceleration measured on the moving vehicle (filter: CFC 60).

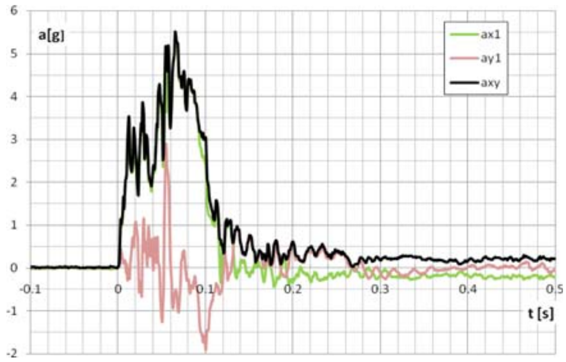

Figure 8. Acceleration measured on the stationary vehicle (filter: CFC 60).

Accelerations, measured with a sampling rate of 1 kHz, are filtered using the CFC 60 filter, as recommended by SAE J211 standard (1995). The longitudinal and lateral accelerations measured on the moving vehicle, and the resultant acceleration, are shown in Figure 7 (where zero on X-axis is the time of impact). The acceleration in Z direction is neglected.

By approximating the shape of the crash pulse with a triangle, the speed variation was determined as 19.5 km/h (the maximum acceleration is considered about 10 g and the pulse length is 110 ms).

For the stationary vehicle, the crash pulse determined using longitudinal and lateral accelerations is presented in Figure 8. The estimated delta-v, by approximating the shape of the pulse with simple geometric figures, was 12.4 km/h. The same result was obtained also by integrating the measured acceleration on the given time interval (the length of the crash pulse). The maximum speed measured with a GPS device was 12 km/h (used just as a reference value, as for the moving vehicle).

4. CALCULATION AND RESULTS

Knowing the final positions of the vehicles, and the impact speeds, the EES values were calculated using the model

Table 1. Input data and results for EES calculation.

Input data:				
Weight of vehicle 1	1100	kg		
Weight of vehicle 2	1900	kg		
Energy lost in collision, veh. 1	14100	J		
Energy lost in collision, veh. 2	14100	J		
Post-collision speed, veh. 1	3	m/s	10.8	km/h
Post-collision speed, veh. 2	3	m/s	10.8	km/h
Angle of post-collision velocity 1	0.017453	radians	1	degree
Angle of post-collision velocity 2	3.141593	radians	180	degrees
Angle of vehicle 1 x axis at stop	0.017453	radians	1	degree
Angle of vehicle 2 x axis at stop	3.054326	radians	175	degrees
Friction coefficient	0.6			
Wheel base, veh. 1	2.62	m		
Wheel base, veh. 2	3.03	m		
Results:				
Impact angle	− 0.00447	radians	− 0.25617	degrees
Energy equivalent speeds:				
EES_1	5.063236	m/s	18.22765	km/h
EES_2	3.852545	m/s	13.86916	km/h
V_{10}	9.528021	m/s	34.30087	km/h
V_{20}	0	m/s	0	km/h

presented above. The input data and results are presented in Table 1.

The computer simulation uses the initial velocities and positions of the vehicles and the EES taken from databases, to obtain the final positions of the vehicles. The initial data are adjusted until the known final positions are obtained. The program used to simulate this crash test was PC-Crash (Figure 9). The best match, of the final positions, was obtained for an initial speed (moving vehicle) of 32.7 km/h and the *Energy Equivalent Speed* values: EES_1 = 18.24 km/h and EES_2 = 13.88 km/h.

The results obtained from acceleration measurement (delta-v), and with two calculation methods (EES) are centralized in Table 2. Delta-v is obtained from the crash pulse, by integration. The CRASH3 algorithm was used with the PC-Crash program, and the calculus of EES based on the presented model was calculated manually and confirmed also with a computer simulation (using also PC-Crash).

Table 2. Delta-v and EES obtained with different methods.

	Δv (crash pulse)	EES (calc.)	EES (CRASH 3)	Speed Ratio
Vehicle 1 (moving)	19.5 km/h	18.2 km/h	17.9 km/h	1.07
Vehicle 2 (stationary)	12.4 km/h	13.8 km/h	13.9 km/h	0.9

The control parameter SR (speed ratio) was calculated using the results obtained from measurement (crash pulse) and calculated EES. These are: $SR_1 = \Delta V_1/EES_1 = 1.07$ for the moving vehicle and $SR_2 = \Delta V_2/EES_2 = 0.9$ for the stationary vehicle. Both values are in the normal range of 0.9 to 1.2, for a collision without glance-off.

The delta-v obtained with the simulation software (as can be seen in Figure 9) is 22.7 km/h for the moving vehicle, and 13.1 km/h for the stationary one. These values are close to those determined from the crash pulses, considering that the shapes of crash pulses were approximated by simplified geometry.

5. CONCLUSION

A crash test with two cars involved in a frontal collision was presented in the paper. The first vehicle was moving, and the other was stationary. The parameters recorded during the crash test were velocity and acceleration of both

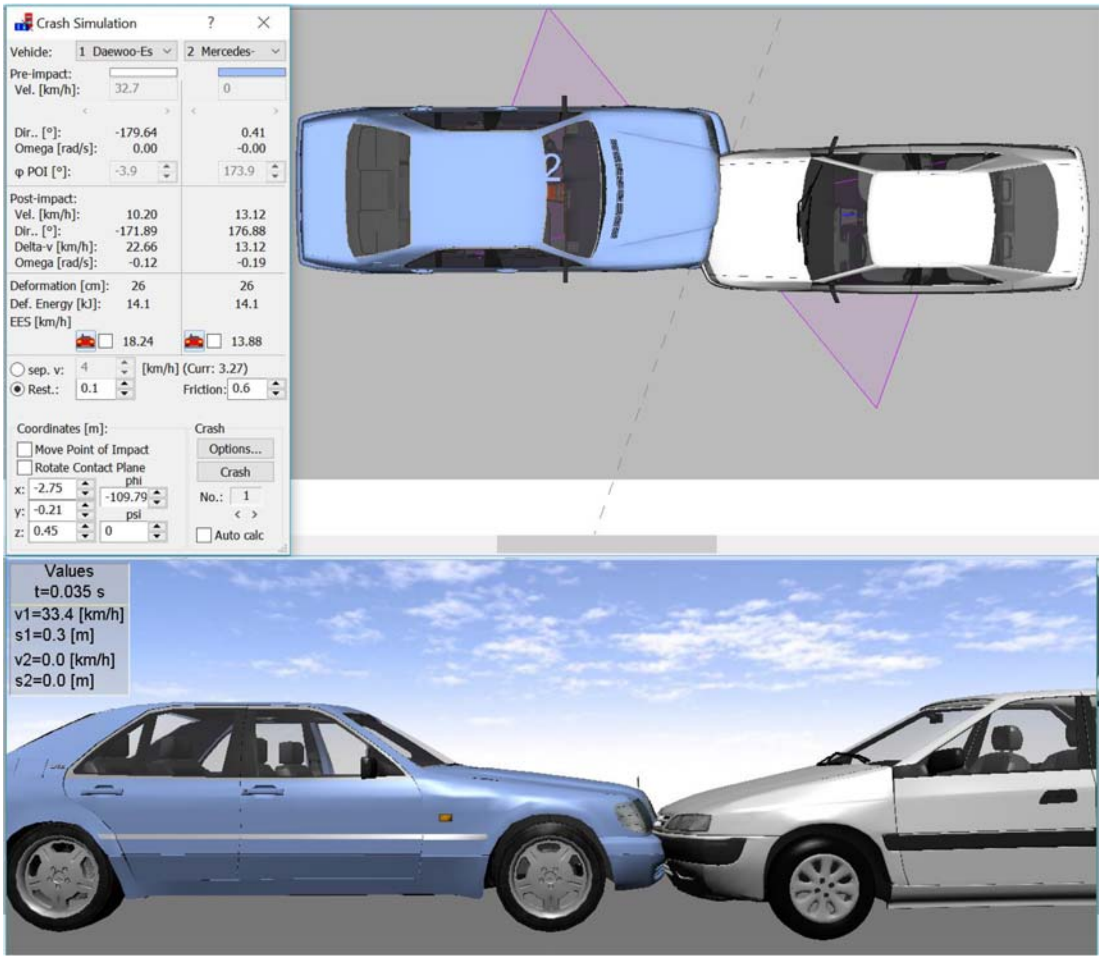

Figure 9. Collision simulation in PC-Crash.

vehicles. Other input data considered were the deformations of the vehicles bodies, measured after collision. Using the measured accelerations, it was determined the crash pulse for each vehicle, and the delta-v parameter was calculated. This parameter is considered to be a measure of the crash severity. In case of a real accident, the crash pulse can be available if the vehicle is equipped with EDR.

In traffic accident reconstruction, a goal is to establish the velocities (that means, speed and direction) of the vehicles before the impact. The input data are, in most cases, the final positions of the vehicles. Using the available data, and estimating other parameters (like, for example, the post-impact speeds), the researcher apply the mathematical model to determine the impact speeds. The EES values can be also estimated. When EES is available from databases, other input parameters, which are, otherwise, adopted, can be calculated. The EES can be estimated also using the CRASH3 algorithm, starting from the measured deformations of the vehicles bodies. These calculations can be done using computer simulation programs.

In this study the calculations were made directly, applying the mathematical model implementd in spreadsheet program, and using the simulation software PC-Crash. The results - initial speeds and EES - were similar. The delta-v, determined from the data recorded during the crash test, is also close to the values given by the simulation software, for both vehicles. The control parameter, SR (speed ratio: the delta-v to EES ratio), was in the recommended range, confirming that the results are correct.

Crash tests, like the one presented in this work, may be useful to the accident reconstruction experts, who can use them as references for real traffic accidents.

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