Analysis of Chosen Aspects of a Two-Car Crash Simulation

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Abstract. The article presents a computer simulation of vehicle collision using the PC-Crash 8.0 software. The simulation results were compared to analytical calculations by the Routh method with the use of the coefficient of restitution for deformations or velocities. Calculations were prepared based on the crash theory. Both the stiffness based and the use mesh based model of a crash was considered. However, the use mesh based model was used, because the stiffness of car bodies in both models was not known.

The analysis concerning the chosen aspects of the consequences of car crash was made, mainly due to the change of both the mass – inertia parameters in the car body and its stiffness. The given simulation was conducted several times in order to specify the change in the after crash values.

Keywords: road accident analysis, simulation, car crash.

1 Introduction

The modelling of a car crash may be considered in different aspects [2]. This paper focuses on a front impact and a side impact crash, as the most frequent in Poland in the period of 15 years (Fig. 1). As a result of the side impact fatalities or several injuries of passengers may occur, as well as widespread damage to the car, following the change in its mass – inertia parameters.

Simulations of an oblique side impact and a frontal oblique impact was conducted using the PC-Crash 8.0. The vehicle model being hit is the Volkswagen Passat 2.0, while striking – the Opel Vectra 2.2 DTI, both from the years of production 2002 – 2005. The collision simulation was prepared at a high equal velocity on an intersection, and on a straight section of single carriageway road. This case reflects the event in which the Volkswagen was struck at the intersection while enforcing the right of way. In the event of a frontal collision the Opel left for the opposite lane.

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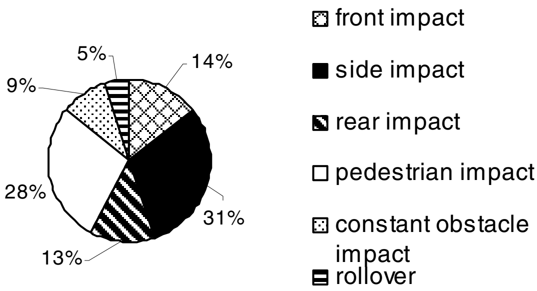

Fig. 1. Proportional participation of the types of impact in the overall number of collisions between 1995 and 2010. Source: own research.

2 Assumptions

The duration time of the simulation was 2 s, of which the time of the impact itself was 0.9 s. Basic assumptions:

- vehicle models are linear, the mass – inertia parameters were adopted according to the producers data, however some were modified for the simulation, the bodies are treated as collections of rectangular elements with constant stiffness;
- the motion takes place on a dry surface with a coefficient of adhesion equal to 0.8;
- the vehicles are moving at velocities: – 50 km/h, Vectra – 80 km/h;
- the initial Volkswagen Passat mass of 1370 kg has been increased by the weight of the driver and passengers equal to 272 kg in accordance with [1], while the initial

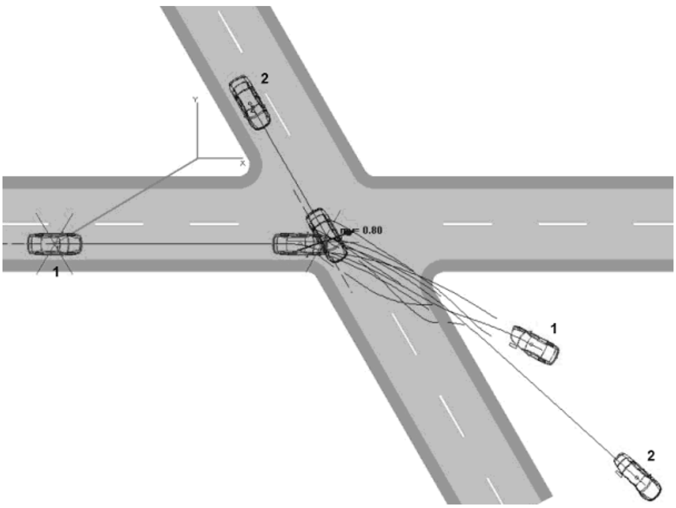

Fig. 2. Location of both cars before and after side impact collision. 1 – Opel, 2 – Volkswagen. Source: PC-Crash.

Opel Vectra mass of 1510 kg has been increased by the weight of the driver and three passengers equal to 272 kg, also in accordance with [1]. No baggage was included;

- according to [1] the height of the centre of mass for the laden vehicle was assumed at 0.56 m for both Opel and Volkswagen;

The assumption that the driver and passengers weighed 68 kg is consistent with the procedures for determining the allowed load of a car described in [1].

In Fig. 2 the location of both cars before and after the side impact collision is shown, whereas in Fig. 3 – before and after the front impact collision.

The main aim of the computer simulation was to conduct cars collision with the defined parameters as well as verification of the simulation results through analytical calculations. Another aim was to check the differences in the simulation results after running it several times. So called "use mesh based impact model" was used. It is a model of impact, where a vehicle body is divided into little polygons and the kinetic energy of impact into the deformation of each polygon.

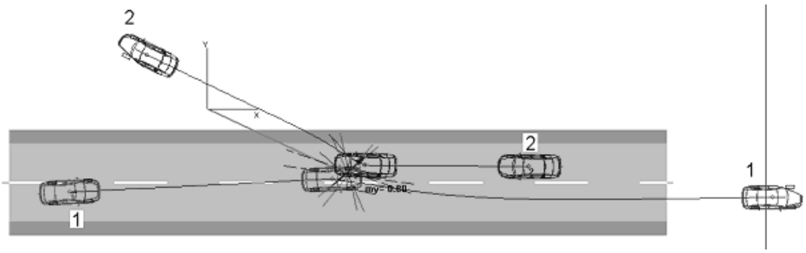

Fig. 3. Location of both cars before and after front impact collision. 1 – Opel, 2 – Volkswagen. Source: PC-Crash.

3 Description of the Simulation and the Selected Elements of PC-Crash Software

In the PC-Crash a vehicle body is treated as a single rigid block [3]. The vehicle body is represented by a rectangular prism of a certain mass, moments of inertia, structural* and torsional rigidity.

The aspect of structural rigidity is taken into account in two ways. In the mesh based impact model the stiffness of the elements, into which the body is divided, is the same for the whole body. The kinetic energy of the impact is transformed into the deformation energy, and the deformed elements are stiffer than non-deformed ones. In the stiffness based impact model the stiffness is described by a linear function. For the calculation of the impact elasticity a coefficient of restitution may be assumed based on the Newton hypothesis, i.e. the ratio of the impulse from the phase of deformations disappearance to the impulse from the phase of increasing deformations.

* Structural stiffness according to [3] is defined on the basis of the depth of deformation associated with the weight of car at rest.

In the PC-Crash the parameter defined as the rigidity of the body is described as a depth of deformations in relation to the weight of the vehicle model. The stiffness of wheel models is half the value specified for the body. In models of passenger cars a quarter of the stiffness of the lower vehicle body is assumed for the roof plate.

A change in the torsional rigidity of the body in PC-Crash 8.0 in terms of closing the gap in the normal thrust of wheels on the road surface was not taken into account, as the vehicle bodies are treated as rigid solids. In addition, the values of the vehicle wheel loads before and after the collision are presented in the crash protocol (Table 1 – 3). It is also assumed that during the simulation the vehicle models move along a flat surface with a specified coefficient of adhesion. It was assumed that in this case the body torsional stiffness is constant.

Table 1. Values of normal reactions of the road on wheels before collision

	Opel Vectra	Volkswagen Passat
Load of wheel 1 [N]	4337	3993
Load of wheel 2 [N]	4337	3993
Load of wheel 3 [N]	4403	4060
Load of wheel 4 [N]	4403	4060

Table 2. Values of normal reactions of the road on wheels after the side impact

	Opel Vectra	Volkswagen Passat
Load of wheel 1 [N]	4483	3991
Load of wheel 2 [N]	4195	3997
Load of wheel 3 [N]	4508	4057
Load of wheel 4 [N]	4220	4063

Table 3. Values of normal reactions of the road on wheels after the front impact

	Opel Vectra	Volkswagen Passat
Load of wheel 1 [N]	4329	3988
Load of wheel 2 [N]	4341	3995
Load of wheel 3 [N]	4396	4056
Load of wheel 4 [N]	4408	4063

The simulations of both collisions were repeated five times to test the repeatability. Table 4 shows the results for each repetition.

The first four simulations were carried out in succession without restoring the initial state, i.e. no return of vehicles to their original positions (to press "stop"). In the event of a side impact in repetitions 2, 3, and 4 there were secondary collisions that took place in the further movement of vehicles after the first collision. Nevertheless, the results of successive iterations differ from the first simulation by about 2 - 5%. All the velocities before and after the collision are different from the assumed (80 and 50 km/h) due to the collision detection option, through which the realism was preserved, i.e. braking just before the collision.

Table 4. The results of five repetitions of the same simulation

car	side impact		front impact	
	Opel Vectra	Volkswagen Passat	Opel Vectra	Volkswagen Passat
simulation 1				
before-crash velocity	76.49 km/h	48.22 km/h	75.23 km/h	45.13 km/h
after-crash velocity	52.93 km/h	63.07 km/h	64.39 km/h	35.59 km/h
simulation 2				
before-crash velocity	78.30 km/h	47.74 km/h	75.28 km/h	45.11 km/h
after-crash velocity	52.87 km/h	63.26 km/h	63.02 km/h	34.37 km/h
simulation 3				
before-crash velocity	79.50 km/h	48.83 km/h	76.96 km/h	46.90 km/h
after-crash velocity	52.74 km/h	63.44 km/h	64.47 km/h	35.80 km/h
simulation 4				
before-crash velocity	80.14 km/h	49.36 km/h	76.95 km/h	46.84 km/h
after-crash velocity	52.72 km/h	63.46 km/h	63.50 km/h	34.89 km/h
simulation 5				
before-crash velocity	76.49 km/h	48.22 km/h	75.23 km/h	45.13 km/h
after-crash velocity	52.93 km/h	63.07 km/h	64.39 km/h	35.59 km/h

The fifth simulation was carried out after resetting the previous, or back to the initial positions of vehicles. The results are equal to the ones of the first simulation. Obtaining consistent results thus involves the need to simulate with starting at the initial position of vehicles.

For further analysis the results of simulation no. 1 were used. Table 5 shows selected parameters of the protocol for the initial and final phase of the collision with the segmentation for the side and front impact. The depth of the body deformation is noticeable, which in the side impact velocity of about 80km/h is 0.34 m for the Volkswagen, bearing in mind the so-called mutual penetration of the body. The front of the striking car (Opel) was strongly deformed and the deformation depth is 0.40 m This shows that for such type of collision and for cars of similar weight and size the depth of deformation is larger for the front of the impacting vehicle (rigid passenger). The confirmation of this can be found in the section on the front impact collision. For a vehicle moving at higher velocities (Vectra) the depth of deformation is greater. It follows that the impact velocity affects the resulting strain, which is consistent with the basic equations of the theory of collisions [6, 7].

The values of the angular velocities around the vertical axes in the initial phase of collision were different from zero. Following the adoption of the centre of mass of vehicles greater than zero, phenomena of roll occur, and the moments of inertia for all

Table 5. The protocol of side and front impact crash. The moments of inertia after the load with passengers are shown in brackets.

	side impact		**front impact**	
car	Opel Vectra	VW Passat	Opel Vectra	VW Passat
VALUES AT THE BEGINNING OF THE CRASH				
before-crash velocity [km/h]	76.49	48.22	75.23	45.13
vehicle angle [deg.]	-1.27	-60.40	2.79	178.61
velocity direction [deg.]	-2.76	278.76	0.61	174.88
angular velocity around z axis [1/s]	-1.11	-0.24	-0.25	-0.90
velocity along z axis [km/h]	0.02	-0.02	-0.77	0.83
angle of lateral tilt [deg.]	-0.02	-0.01	-0.61	0.38
roll angle [deg.]	0.01	0.01	0.54	-0.75
angular velocity around x axis [1/s]	-0.01	-0.05	-0.17	0.18
angular velocity around y axis [1/s]	0.01	0.01	0.20	-0.32
moment of inertia around x axis [kgm^2]	714 (822.98)		661.9 (771.54)	
moment of inertia around y axis [kgm^2]	2379.9 (2743.16)		2206.2 (2571.66)	
moment of inertia around z axis [kgm^2]	2379.9 (2743.16)		2206.2 (2571.66)	
impulse of the impact force [Ns]	13096.46		7396.46	
VALUES AT THE END OF THE CRASH				
after-crash velocity [km/h]	52.93	63.07	64.39	35.59
the change of velocity dv [km/h]	26.46	28.71	14.94	16.22
vehicle angle [deg.]	-1.27	-60.40	2.79	178.61
velocity direction [deg.]	-13.97	332.15	-7.87	156.04
angular velocity around z axis [1/s]	-3.04	1.31	-1.17	-2.16
velocity along z axis [km/h]	0.11	-0.12	-0.47	0.51
angle of lateral tilt [deg.]	-0.02	-0.01	-0.61	0.38
roll angle [deg.]	0.01	0.01	0.54	-0.75
angular velocity around x axis [1/s]	-0.60	1.82	-0.66	-0.61
angular velocity around y axis [1/s]	0.47	-0.09	0.36	-0.00
depth of deformations [m]	0.40	0.34	0.63	0.55
coefficient of restitution k	0.10		0.10	

axes are included [3]. Doubts about certain simulation results are raised by the velocity change in the protocol (dv) that do not correspond to the difference in before- and after-crash velocities for both vehicles. Unfortunately it was not possible to determine how these values were calculated.

4 Verification on the Basis of Analytical Calculations

Calculations were prepared for comparison with the simulation results according to the method for the collision issues including the tangential velocity restitution. The data for the calculation was assumed according to Table 5, however the inputs of tangential and normal velocities were obtained by the transition from the Cartesian coordinate system (Fig. 4) to the natural local coordinate system (tangential and normal, Fig. 5, 6). The velocity vector of the striking vehicle (Opel) had to be projected orthogonally on the axes adopted in accordance with Fig. 5. It was assumed that the velocity vector of the impacted vehicle is parallel to the tangent axis (*t*), and the striking vehicle vector coincides with the normal to the collision (*n*).

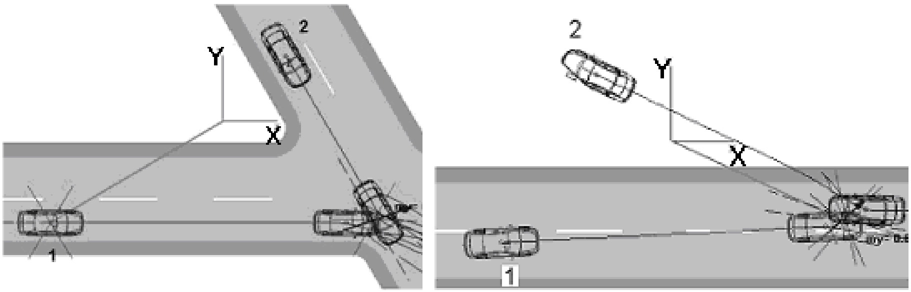

Fig. 4. Coordinate system x-y for side and front impacts. Source: PC-Crash.

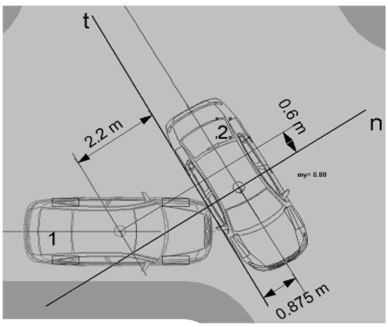

Fig. 5. Location of the local coordinate system for the side impact. Source: PC-Crash.

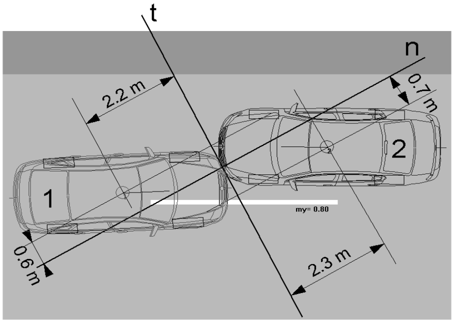

Fig. 6. Location of the local coordinate system for the front impact. Source: PC-Crash.

In the side impact, the angle of the vehicle taken from Table 2 was assumed as the impact angle, since it is measured relative to the x axis in the Cartesian coordinate system x-y. It is also easy to situate the tangential axis (along the edge) of the struck vehicle and the normal axis (perpendicular to the tangent). It is more difficult to realize this for a frontal collision, where the vehicles are positioned almost parallel to the x axis. Using the trigonometry, knowing the distance of the vehicles from the centre of collision (Fig. 6) the angles to the axes x and y can be calculated.

Based on paper [4] concerning the collision theory, a theoretical analysis of the collision issue was performed. The issue of restitution of tangential velocity was taken into account. It was assumed that during the collision, except for the so-called volumetric strains, also non-dilatational strains occur, associated with the stress in the tangential direction occurring on the surfaces of vehicles. By analogy with Newton's hypothesis a formula to determine the coefficient of restitution of tangential velocities [2] is presented.

$$\theta = \frac{w_t^{'}}{w_t} \tag{4.1}$$

The relative tangential velocity in the nonslip collision was described by formula (4.2).

$$w_t^{'} \equiv w_t - \alpha_{tt} S_t - \alpha_{nt} S_n = \theta w_t \tag{4.2}$$

The relative normal velocity

$$w_n - \alpha_{nt} S_t - \alpha_{nn} S_n = -R w_n \tag{4.3}$$

where [4]:

$$\alpha_{tt} = \frac{1}{m_1} + \frac{1}{m_2} + \frac{n_1^2}{I_1} + \frac{n_2^2}{I_2}, \qquad \alpha_{nn} = \frac{1}{m_1} + \frac{1}{m_2} + \frac{t_1^2}{I_1} + \frac{t_2^2}{I_2},$$
$$\alpha_{nt} = \alpha_{tn} \equiv \frac{n_1 t_1}{I_1} - \frac{n_2 t_2}{I_2} \tag{4.4}$$

Equations (4.2) and (4.3) were solved with respect to impulses, which in turn allowed determining the value of the tangential and normal impulses (4.5).

$$S_t = \frac{-(1+R)\alpha_{nt} w_n + (1-\theta)\alpha_{nn} w_t}{\alpha_{nn}\alpha_{tt} - \alpha_{nt}^2}$$
$$S_n = \frac{(1+R)\alpha_{tt} w_n - (1-\theta)\alpha_{nt} w_t}{\alpha_{nn}\alpha_{tt} - \alpha_{nt}^2} \tag{4.5}$$

The solution of this problem for a car crash on rough surfaces requires the knowledge of three factors: the dynamic coefficient of friction f (in the Routh system for the transient impulse $S_t=fS_n$), the coefficient of restitution for normal R and tangential θ velocities. The kinematic state after the collision is described by formulas (4.6).

$$v_{1t}' = v_{1t} - \frac{S_t}{m_1}, \qquad v_{2t}' = v_{2t} + \frac{S_t}{m_2},$$
$$v_{1n}' = v_{1n} + \frac{S_n}{m_1}, \qquad v_{2n}' = v_{2n} - \frac{S_n}{m_2}, \tag{4.6}$$
$$\omega_1' = \omega_1 + \frac{S_t n_1}{m_1 i_1^2} + \frac{S_n t_1}{m_1 i_1^2}, \qquad \omega_2' = \omega_2 + \frac{S_t n_2}{m_2 i_2^2} + \frac{S_n t_2}{m_2 i_2^2}.$$

The results of analytical calculations are shown below. Distances n_1, n_2, t_1, t_2 of both centre of mass to the centre of collision were measured in the PC-Crash with both cars located at the point of a contact position. Using formulas (3.6) a system of six equations with six unknowns was obtained. Those unknowns were sought for the final moment of impact (4.6). In the shear and compression instantaneous velocity formulas [4], the instantaneous values were replaced by the values from the beginning of the collision. Then the coefficients f, R, and θ were so chosen, that the values of after-crash velocities were as close as possible to those obtained in the simulation.

The results of calculations for the side impact:

a) before crash:

$v_{1n} = 10.62\, m/s, v_{1t} = 18.4\, m/s, v_{2n} = 0, v_{2t} = 13.39\, m/s, \omega_1 = -1.11 \frac{1}{s}, \omega_2 = -0.24 \frac{1}{s};$

b) after crash:

$v'_{1n} = 5.09 m/s, v'_{1t} = 15.18\, m/s, v'_{2n} = 5.99\, m/s, v'_{2t} = 16.88\, m/s, \omega'_1 = 1.33 \frac{1}{s}, \omega'_2 = 1.71 \frac{1}{s};$

the whole impulse S=11392 Ns.

With coefficients f=0.58, R=0.01, θ=-0.8, the values of velocities in the final phase of collision were: $v'_1 = 57.66\, km/h, v'_2 = 64.5\, km/h.$

The results of calculations for the front impact:

a) before crash:

$$v_{1n} = 16.68 m/s, v_{1t} = 12.57 m/s, v_{2n} = 10.51 m/s, v_{2t} = 6.82 m/s, \omega_1 = -0.25 \frac{1}{s}, \omega_2 = -0.9 \frac{1}{s};$$

b) after crash:

$$v'_{1n} = 14.31 m/s, v'_{1t} = 10.95 m/s, v'_{2n} = 13.08 m/s, v'_{2t} = 8.59 m/s, \omega'_1 = 1.14 \frac{1}{s}, \omega'_2 = 0.54 \frac{1}{s};$$

the whole impulse S = 5121 Ns.

With coefficients f=0.71, R=0.01, θ=-0.8 the values of velocities in the final phase of collision were: $v'_1 = 64.89\, km/h, v'_2 = 56.35\, km/h.$

As it can be seen from the calculations, the coefficient of restitution of the normal velocities is greater than the default assumed in the PC-Crash (R=0.1). Moreover, the values of the angular velocities of both vehicles are much larger than those given in the protocol of computer simulation. Progressive values of impact velocities in the final phase differ slightly from the results of simulation in the PC-Crash. While the total value of the impulse is smaller by about 1300Ns for the side impact and by 2300 Ns for the front impact than the value obtained in the simulation.

5 Conclusion

The obtained results can be used for further research. The examination of the influence of disturbance in the centre of mass and moments of inertia for different cars and stability examination for so disturbed vehicle may be one aspect of the impact modelling [5].

Both the coefficient of restitution of normal and tangential velocity plays an important role in modelling the collision of vehicles in real conditions. The values of both coefficients depend on the type of collision and the angle of the resultant force of impact. The value of the impact force impulse was considered particularly in the case of the side impact, because in this case it is difficult to determine the point of force application. Besides, it depends on the impact velocity, the masses of colliding vehicles and moments of inertia of cars involved in the collision.

Such qualitative evaluation leads to arbitrary assumptions adopted in the quantitative sense, but with reference to reality.

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