COMPARISON OF SELECTED IMPACT PARAMETERS BY SIDE VEHICLE CRASH TESTS WITH COMPUTATIONAL SOFTWARE RESULTS

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Abstract: Article shows carried out crash tests between front part of moving and side part (cabin for passengers) of stationary vehicle. The goal of the article was to investigate and observe as many impact parameters as possible, which are necessary for correct traffic accident analysis. Authors carried out experiments with impact speeds of impacting vehicle between 36 and 55 kph. Emphasis was put on investigation of post-crash motion, depth of deformations on vehicles and amount of deformation energy as the parameters for accident reconstructionist. The amount of deformation energy has been compared to results for impacting vehicle gained from CRASH3 module calculation in software PC-CRASH ver. 10.2 and also with simulations with the help of simulating software Virtual CRASH ver. 3.0. Sufficient results correlation at comparable tests between those methods has been found.

Keywords: side crash test, impact parameters, energy equivalent speed, deformation energy.

1. Introduction

The issues dealt with in this article fall within forensic science, particularly within traffic accident reconstruction. Experts who within the framework of a complex analysis of a traffic accident often use simulation programs such as PC Crash (2016) and Virtual CRASH (2016) in order to process the actual plot of the accident must always enter only those input parameters that are in a technically acceptable range. For the verification of the collision parameters in particular it is necessary to use the data from the real crash tests performed for such needs. The works (Campbell, 1974), (Strohrer, 1986), (Batista, 2005) (Seiffert, 2007) and (Cichos, 2008) deal in detail with the issue of sought parameters such as force, energy intensity of impact, stiffness of a given part of a vehicle or vehicle deformation depth. These obtained parameters are subsequently used in traffic accident reconstructions. Many authors and publications such as (Burg, 2009), (Branch, 2011), (Huang, 2002) and (Hugemann, 2007) deal with traffic accident reconstruction that aims to find out the cause of an accident.

The work focuses on side crash tests, when a passing vehicle crashes into the side of a stationary vehicle. All the principal world organisations dealing with safety research and vehicle testing (EuroNCAP, 2016; NHTSA, 2016; IIHS, 2016) have included similar impact configurations in their testing programmes. Euro NCAP as the European independent testing authority uses a deformable barrier running at a speed of 50 kph as a “ram” which crashes into the side of a tested vehicle at an angle of 90°. The ram has a weight of 950 kg as well as a front deformable honeycomb panel size of 500 x 1500 mm (height x width). The organisation called National Highway Traffic Safety Administration (NHTSA) tests the side of vehicles by impact at an angle of 90° which is caused by a deformable barrier running at a speed of 61 kph. The ram’s weight is 1507 kg and its front part has a height of 600 mm. Insurance Institute of Highway Safety (IIHS) performs two different vehicle side tests. The first impact test is coincident with the NHTSA organisation if, and only if, a higher moving deformable barrier of at least 760 mm in height is used. This higher barrier corresponds better to higher front parts of vehicle, in particular to SUVs. The second test (performed by NHTSA as well) differs in mutual impact configuration when a tested stationary vehicle is turned at an angle of 27° towards the longitudinal axis of the moving deformable barrier. The barrier has a weight of 1360 kg and crashes at a speed of 61 kph.

The above-mentioned list of performed side crash tests is focused on the research and testing of safety of new vehicles introduced to the market. The possibility of injury to the crew members of these vehicles, who are replaced with dummy figures during testing, is the main sought parameter. The publication (Chan, 1998) focuses on a correlation between the penetration depth of a part of the vehicle body into its interior – DEPTH, the Thoracic Trauma Index TTI and Pelvic Lead. The work (Stolinski, 1998) concentrates on investigation into the possibility of injury to the vehicle crew in case the impact occurs at a side of the vehicle more distant from the passenger position.

During four performed proper crash tests the vehicles were not fitted with dummy figures and the main attention was therefore focused on investigation into the impact parameters of the vehicles themselves. In particular, they include post-impact velocity, post-impact movement (trajectory), post-impact deceleration and subsequent calculation of deformation energy of vehicle collision and its redistribution to individual vehicles. The deformation energy acting on individual vehicles was quantified by energy equivalent speed (EES).

The performed crash tests were carried out using older vehicles more or less affected by bodywork corrosion. Corrosion significantly reduces the stiffness of vehicle bodywork and larger deformations therefore rationally occur at the same parameters. Such deformations would result in more serious injury to the crew of such a vehicle than to the crew of a new vehicle. However, this fact may not be entirely wrong, especially once we realize that for example in Germany the average age of a vehicle is from eight to nine years; nevertheless, in the Czech Republic it already ranges from fourteen to fifteen years.

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The investigation thus aimed to perform crash tests, analyse obtained data and on the basis of this data determine the EES parameter for individual vehicles. It further aimed to compare obtained data with the computational solution carried out using CRASH3 module in PC CRASH version 10.2 simulation program on the basis of comparable vehicle stiffness database and also to apply obtained data and verify it by means of simulation with support of Virtual CRASH version 3.0 simulation program.

2. Methods

In total, four crash tests within an impact speed range of 36 to 55 kph were performed. It was always a collision of the front part of a moving vehicle with the side of a stationary vehicle at an angle of 90°: during crash test no. 3 there was a mutual angle between the vehicles of about 83° whereas during crash test no. 1 the mutual angle between the vehicles was ca. 94°. In two cases (tests no. 1 and 2) the Honda Civic was used as a stationary vehicle. During crash tests no. 3 and no. 4 Skoda Felicia, or Skoda Felicia Combi, was used as a running vehicle. Therefore even from this perspective an appropriate comparison of damage range to vehicles of the same type is possible at different parameters. The performed crash tests were carried out with the participation of an IFE team for the following vehicle impact configurations:

1. A Nissan Almera crashed into the side of a stationary Honda Civic at a speed of ca. 55 kph,
2. A Chrysler Sebring crashed into the side of a stationary Honda Civic at a speed of ca. 43 kph,
3. A Skoda Felicia Combi crashed into the side of a stationary Mercedes Benz at a speed of ca. 50 kph,
4. A Skoda Felicia crashed into the side of a stationary Opel Omega Combi at a speed of ca. 36 kph.

Fig. 1.
Side crash test between Nissan Almera (moving vehicle) and Honda Civic, 3D scan in final position

The determination of deformation energy absorbed by the deformation zones of a vehicle during a collision with an obstacle (or another vehicle) is one of the important parameters in the solution of vehicle collision itself. The entire movement of vehicles during the plot of an accident depends on this amount, particularly the calculation of the driving speed of vehicles just before collision. In an expert's practice the only clue to determining the deformation energy is the range of vehicle damage or the deformation depth of its relevant sections. If we knew the stiffness characteristics of the relevant sections of particular vehicles, we could determine the consumed deformation energy on the basis of a relationship:

$$E_D = \frac{1}{2} \cdot k \cdot x^2 \tag{1}$$

Where; E_D: deformation energy [J], x: deformation depth [m], k: car stiffness [N/m].
Unfortunately, the stiffness characteristics are not commonly available for reconstructionist. In an expert's practice the expert estimate of EES, which expresses kinetic energy of a vehicle proportional to the deformation energy that is needed to reach an appropriate range of permanent deformation. This article should serve for verification of these estimates, while, on the contrary, the consumed deformation energy, or EES of the vehicles, will be determined from the input parameters. During the actual process of determination of the deformation energy during vehicle collision we will proceed from the law of the conservation of energy, therefore the (vehicle) system energy before collision must be equal to the total system energy after collision. In vehicle collision mechanics three types of energy are distinguished:

$$E_P = m \cdot g \cdot h \tag{2}$$

$$E_{K_T} = \frac{1}{2} \cdot m \cdot v^2 \tag{3}$$

$$E_{K_R} = \frac{1}{2} \cdot I \cdot \omega^2 \tag{4}$$

$$E_D = W_D = \frac{1}{2} \cdot m \cdot EES^2 \quad (5)$$

Where; E_P: potential energy [J], E_{KT}: kinetic energy of translation [J], E_{KR}: rotation energy [J], E_D: deformation energy [J] which is determined by performing deformation work W_D, m: vehicle weight [kg], g: acceleration due to gravity value [m/s^2], h: vehicle centre height [m], v: vehicle speed [m/s], ω: vehicle angular velocity [rad/s], I: vehicle moment of inertia [kg.m^2], EES: energy equivalent speed [m/s].

The total energy balance of a vehicle colliding with an obstacle (vehicle) is therefore as follows:

$$\sum_{i=1}^{n} (E_{K_T i} + E_{K_R i} + E_{pi}) = \sum_{i=1}^{n} (E'_{K_T i} + E'_{K_R i} + E'_{Pi}) + \sum_{i=1}^{n} E_{Di} \quad (6)$$

Where; E_{KTi}, E_{KRi}, E_{Pi} :individual components of the i[th] vehicle (obstacle) energy before collision [J], E'_{KTi}, E'_{KRi}, E'_{Pi} :individual components of the i[th] vehicle (obstacle) energy after collision [J], E_{Di}: deformation energy of the i[th] vehicle (obstacle) [J].

From the total energy balance, we are able to determine the total deformation energy consumed for documented permanent vehicle damage cause. For simplification, the components of energy converted into heat energy are not taken in account. In the instance that we know the EES value for one vehicle it is possible from the following two equations - after the mathematical treatment on the basis of known depths of deformation to individual vehicles - to divide the deformation energy expressed for each vehicle in the EES form:

$$E_{Def} = \frac{1}{2} \cdot m_A \cdot EES_A^{\ 2} + \frac{1}{2} \cdot m_B \cdot EES_B^{\ 2} \quad (7)$$

With the use of the following equation we can, after the mathematical treatment and substitution method (7), obtain the division of the total deformation energy into deformation energy components for individual vehicles, for instance, on the basis of known depths of deformation to individual vehicles. For this method the vehicles should have preferably the same or at least similar bodywork stiffness characteristics in the area of collision.

$$\frac{EES_A}{EES_B} = \sqrt{\frac{m_B \cdot x_A}{m_A \cdot x_B}} \quad (8)$$

The data acquired from the performed crash tests was processed by three methods:

I. The determination of EES on the basis of deformation depth: the total deformation energy was calculated from the discovered parameters of vehicle impact and post-impact vehicle movement. This total deformation energy was divided into components for individual vehicles on the basis of known deformation depths. This method for chosen collisions is not entirely appropriate as it is the collision of the front part of the vehicle (with higher stiffness) into the side of the vehicle. It is appropriate to compare even those results achieved by this procedure in order to find out whether there will be any noticeable difference in older vehicles or not,
II. The determination of EES on the basis of stiffness parameters available from CRASH3 software data: when the stated EES values for moving vehicles were acquired from the database of vehicle stiffness parameters available in CRASH3 software, which is a part of PC Crash ver. 10.2 simulation program. Subsequently, on the basis of the known EES value for a moving vehicle and the total deformation energy values of a given collision the EES value of the second (stationary) vehicle was calculated with the help of the equation (7),
III. Vehicle impact simulation with the simulation program support: the data acquired from the performed crash tests were subsequently used for the vehicle impact simulation with the simulation program support. In this case Virtual CRASH ver. 3.0 simulation program was used for traffic accident reconstruction. Simulation of the vehicle impact and post-impact vehicle movement is carried out by means of gradual optimization of the input values. The impact simulation is carried out by means of forward methods, i.e. from the centre to the final position. The program uses for impact solution the so-called impulse-impact model which replaces all the contact forces acting in the deformed profile of the damaged part of the vehicle with a single force resultant passing through so called point of impact. On the basis of the position of the point of impact from the profiles of both vehicles in the moment of maximum deformation depth in a direction of impulse action the energy equivalent speed (EES) values are recalculated from the deformation energy.

3. Results

Individual crash tests and the acquired data, which was subsequently used for the determination of the EES parameter for individual vehicles, are described in this chapter.

3.1. Crash test no. 1 – Nissan Almera x Honda Civic

This crash test was carried out by the collision of a Nissan Almera running at a speed of 55 kph that crashed with its front part into the left side of a stationary Honda Civic. The angle of longitudinal axes of the vehicles was ca. 94°, see fig. 2. The parameters of the vehicles as well as the impact and post-impact movement necessary for the actual solution and calculation of deformation energy are stated in table 1. The breaking of the Nissan was taken into account for the post-impact movement. The post-impact rotation of the Honda vehicle was of an angle of ca. 34°. The post-impact movement of the Honda vehicle was taken as friction (skidding) over the surface (dry, clean asphalt).
In order to calculate the EES value for the Nissan Almera vehicle in CRASH3 program, the input parameters for recalculation chosen were the values from the crash test of a similar vehicle Nissan Sentra model year 1998, test number 2771, carried out by NHTSA.
For simulation the Virtual CRASH version 3 simulation program was used by i.a. Kudlich-Slibar impact model. A certain simplification occurs with this model – all the impact plot is situated in one moment of time and the impact forces are replaced with their resultant passing through the so-called point of impact. The input parameters were:

- Vehicle positions in the moment of the first contact (i.e. Exact point of contact and a mutual angle of rotation of the longitudinal axes of vehicles),
- Vehicle movement speeds just before impact,
- Angular speeds,
- Immediate vehicle weight,
- Size parameters of vehicle (according to the manufacturer),
- Adhesion (just for the conformity of vehicle runs to the final positions – does not affect the impact calculation),
- Deformation depth.

In order to reach conformity the collision parameters were varied:

- Impact point position (x,y,z),
- Restitution coefficient.

It was not necessary to vary the other impact parameters (friction, impact plane direction) as it was an impact completely without slide and therefore with a low impact point speed during collision.

Table 1
Parameters of impact and post impact motion of vehicles - Test no. 1 (author)

Nissan Almera (A) Length: 4340 mm; Width: 1690 mm; Height: 1395 mm	**Honda Civic (B)** Length: 4325 mm; Width: 1695 mm; Height: 1390 mm
Vehicle weight (m_A) = 1050 kg	Vehicle weight (m_B) = 1100 kg
Pre-impact speed (v_A) = 54,8 kph	Pre-impact speed (v_B) = 0 kph
Post-impact trajectory (S'_A) = 3,75 m	Post-impact trajectory (S'_B) = 4 m
Post-impact speed (v'_A) = 25,2 kph	Post-impact speed (v'_B) = 27,6 kph
Deformation depth (x_A) = 0,26 m	Deformation depth (x_B) = 0,25 m
Total deformation energy (E_D) ca. 61 kJ	

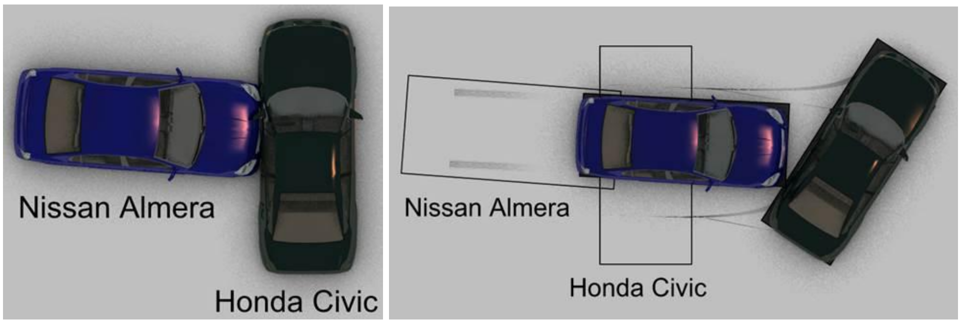

Fig. 2.
Side crash test no. 1, left – impact position, right – final position (Virtual CRASH)

3.2. Crash test no. 2 – Chrysler Sebring x Honda Civic

The crash test was carried out with a Chrysler Sebring vehicle running at a speed of 43 kph, which crashed with its front part into the left side of a stationary Honda Civic vehicle at an angle of 90° (see fig. 3). After the collision of vehicles the anticlockwise rotation of the Honda vehicle at an angle of ca. 90° took place, the vehicles subsequently got mutually wedged with their left sides and this way moved to their final positions.

In the calculation of the EES value for the Chrysler Sebring vehicle in CRASH3 program the input parameters for recalculation chosen were the values from crash test of similar vehicle Chrysler Sebring model year 2007, test number 5886 carried out by NHTSA.

Table 2

Parameters of impact and post impact motion of vehicles - Test no. 2 (author)

Chrysler Sebring (A) Length: 4844 mm; Width: 1792 mm; Height: 1394 mm	**Honda Civic (B)** Length: 4325 mm; Width: 1695 mm; Height: 1390 mm
Vehicle weight (m_A) = 1510 kg	Vehicle weight (m_B) = 1100 kg
Pre-impact speed (v_A) = 43 kph	Pre-impact speed (v_B) = 0 kph
Post-impact rotation (α'_A) = 0 °	Post-impact rotation (α'_B) = 90 °
Post-impact speed (v'_A) = 25 kph	Post-impact speed (v'_B) = 25 kph
Deformation depth (x_A) = 0,10 m	Deformation depth (x_B) = 0,20 m
Total deformation energy (E_D) ca. 44 kJ	

Fig. 3.

Side crash test between Chrysler Sebring (moving vehicle) and Honda Civic (author)

3.3. Crash test no. 3 – Skoda Felicia Combi x Mercedes Benz W210

The Skoda Felicia Combi vehicle crashed with its front part into the right side of Mercedes Benz W210 vehicle at a speed of 50,5 kph. The angle between longitudinal axes of the vehicles during the collision was ca. 83, see fig. 4. After the collision of vehicles, an anticlockwise rotation of the Mercedes Benz vehicle at an angle of ca. 30 ° took place.
In the calculation of the EES value for the Skoda Felicia vehicle in CRASH3 program, the input parameters for recalculation chosen were the values from crash test of similar vehicle Volkswagen Golf II model year 1986, test number 945 carried out by NHTSA.

Table 3

Parameters of impact and post impact motion of vehicles - Test no. 3 (author)

Skoda Felicia Combi (A) Length: 4237 mm; Width: 1635 mm; Height: 1420 mm	**Mercedes Benz W210 (B)** Length: 4818 mm; Width: 1799 mm; Height: 1441 mm
Vehicle weight (m_A) = 900 kg	Vehicle weight (m_B) = 1510 kg
Pre-impact speed (v_A) = 50,5 kph	Pre-impact speed (v_B) = 0 kph
Post-impact trajectory (S'_A) = 1,7 m	Post-impact trajectory (S'_B) = 2,2 m
Post-impact speed (v'_A) = 15 kph	Post-impact speed (v'_B) = 21 kph
Deformation depth (x_A) = 0,26 m	Deformation depth (x_B) = 0,25 m
Total deformation energy (E_D) ca. 53 kJ	

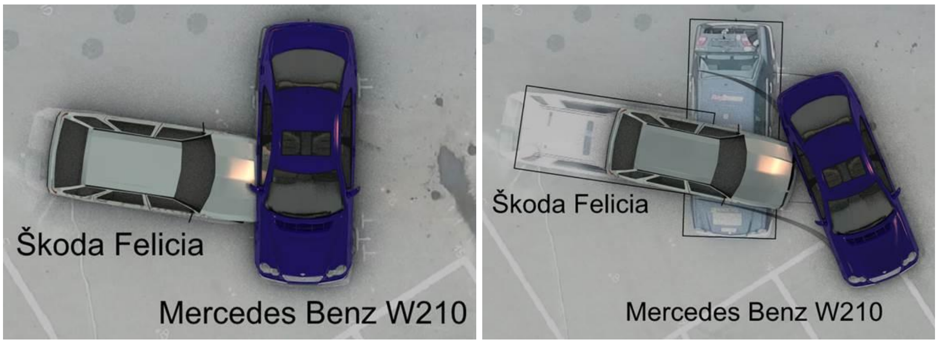

Fig. 4.

Side crash test no. 3, left – impact position, right – final position (Virtual CRASH)

3.4. Crash test no. 4 – Skoda Felicia x Opel Omega Combi

The Skoda Felicia vehicle crashed with its front part into the right side of Opel Omega Combi vehicle at a speed of 36 kph. The angle between longitudinal axes of the vehicles during the collision was ca. 90° (see fig. 4). After the collision of the vehicles no significant rotation of the Opel vehicle took place; it was therefore neglected in the solution of energy balance.

In the calculation of the EES value for the Skoda Felicia vehicle in CRASH3 program the input parameters for recalculation chosen were the values from the crash test of a similar vehicle, the Volkswagen Golf II model year 1986, test number 945 carried out by NHTSA.

Table 4

Parameters of impact and post impact motion of vehicles - *Test 4 (author)*

Skoda Felicia (A) Length: 3883 mm; Width: 1635 mm; Height: 1415 mm	**Opel Omega Combi (B)** Ĺenght: 4898 mm; Width: 1776 mm; Height: 1505 mm
Vehicle weight (m_A) = 925 kg	Vehicle weight (m_B) = 1750 kg
Pre-impact speed (v_A) = 36,3 kph	Pre-impact speed (v_B) = 0 kph
Post-impact trajectory (S'_A) = 1,1 m	Post-impact trajectory (S'_B) = 1,3 m
Post-impact speed (v'_A) = 12 kph	Post-impact speed (v'_B) = 15 kph
Deformation depth (x_A) = 0,20 m	Deformation depth (x_B) = 0,10 m
Total deformation energy (E_D) ca. 26 kJ	

4. Discussion

The achieved results are laid out in a well-arranged way in Table 5. The EES parameter value for individual vehicles was inacceptable accordance with the chosen methods (deviations found in system of kph units). In almost all tests the calculated EES value for moving vehicle was higher in the method II. This phenomenon would correspond with the higher stiffness of the front part of vehicle against the side. Nevertheless, the difference is not too significant as with regard to the condition of bodywork of individual vehicles, particularly with regard to the range and degree of corrosion the stiffness of those parts could be already considerably affected (reduced). Deformations of the same or similar vehicles from particular crash tests are shown and compared in fig. 5 – 7. By means of simulation in Virtual CRASH program a good accordance between calculated parameters and parameters recorded in real crash test was confirmed. It is possible to use further the obtained results in an expert's practice in traffic accident reconstruction, particularly when determining the EES value.

Fig. 5.

Side part of Honda Civic, left – test no. 1 EES cca 27 kph, right – test no. 2 EES cca 25 kph (author)

Fig. 6.

Front part of Skoda Felicia, left – test no. 3 EES cca 28 kph, right – test no. 4 EES cca 23 kph (author)

Fig. 7.
Side part of vehicle, left Mercedes Benz – test no. 3 EES cca 22 kph, right Opel Omega Combi – test no.4 EES cca 10 kph (author)

Table 5
Overview of results according to the selected methods (author)

Test number	Impact speed [kph]	Deformation energy E_D [kJ]	Car	EES [kph]		
				I.	II.	III.
1.	55	61	Nissan	28	31	27
			Honda	27	23	27
2.	43	41	Chrysler	16	19	16
			Honda	26	24	25
3.	50	53	Skoda	28	28	26
			Mercedes Benz	21	21	23
4.	36	26	Skoda	22	24	22
			Opel	11	9	11

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