Let It Crash! Energy Equivalent Speed Determination

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Abstract: Crash analysis including calculation of the impact speed and related determination of deformation energy is one of the main assumptions for the clarification of mostly negligent crimes. In this article were introduced results of two crash tests representing the comparison of the stiffness and technological obsolescence and their influence on the resulted vehicle deformation. Different extent of vehicle deformation was used to demonstrate the limits of selected methods for Energy Equivalent Speed determination as a value which expresses the kinetic energy dissipated by the vehicle during the contact phase.

1 INTRODUCTION

The comprehensive crash analysis includes the impact speed determination and related determination of vehicle energy loss during impact or more precisely the deformation energy expressed by the Energy Equivalent Speed parameter (EES).

Deformation energy determination in EES form is important especially when the availability of objective evidence is limited (Macurová et al, 2019). The methods for crash documentation and analysis are selected by individuals (Vangi, 2019). The accuracy of obtained crash reconstruction results is dependent on the accuracy of the input data.

Current methods for EES determination have some limitations in terms of usability. This article aims to compare the limitation of selected methods for EES determination especially concerning the vehicle age and related differences in vehicle parts stiffness as one of the main parameters influencing the deformation energy determination. (Bradáč, 1999; Coufal, 2014; Semela, 2014). The usability of selected methods will be demonstrated on the determination of the EES parameters of the vehicles after the crash test realised by the Institute of Forensic Engineering, Brno University of Technology. For the EES determination can be used a number of methods, some of these methods will be briefly introduced in the following chapters.

1.1 EES Calculation using PC–Crash (CRASH 3)

The EES determination using software PC–Crash programme CRASH 3 assumed the linear dependence between the force and plastic deformation. One of the main limitations is the one central stiffness characteristics (Macurová et al., 2019). The vehicle database contains US market vehicles, the use in the EU could be limited. The EU market vehicles could have different stiffness (Burg et al, 2017; Coufal, 2014; Görtz, 2018).

1.2 Numerical Modelling (FEM)

Finite elements method used the fully deformable vehicle model and allows comprehensive analysis of the individual impact phases and identification of damaged vehicle parts. The FEM is mainly used for the vehicle components development. Burg (2017) described FEM as sufficient tool for substation of crash testing with a pre-series model. The time-

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consumption, computational requirements, and related costs eliminate the usability of the method in forensic practice (Vangi, 2010; Burg, 2017).

1.3 Energy Raster

The energy raster method is based on the Campbell assumption of the linear impact speed – deformation depth relationship. The method was further developed by W. Röhrich, D. Schapera, D. Vangi, H. Burg and H. Rau (Vangi, 2009, 2010). For the EES estimation is the vehicle front subdivided into energy fields with the deformation in these sectors. Based on the deformation depth in the sectors, the total amount of deformation energy is subtracted. The energy raster usability could be limited for the collision with partial overlapping. The method is suitable for front-end collisions with full overlapping and older vehicles with rectangle shapes (Semela, 2014; Coufal, 2014; Čopiak, 2019; Macurová et al, 2019).

1.4 The Comparison Method

The comparison method is one of the basic and also most often used methods. The deformation of the vehicle is compared with the vehicle with known EES (EES_{etalon}) in the EES catalogue. Vehicles weight differences are considered.

$$EES_{vehicle} = \sqrt{\frac{m_{etalon}}{m_{vehicle}}} \cdot EES_{etalon} \qquad (1)$$

Most of the used catalogues do not contain modern vehicles. The methodology of the catalogue vehicles EES determination is not specified. In the Czechia, the Melegh catalogue is mostly used (Melegh, 2005) or PC-Crash database.

2 CRASH TESTS

The EES determination methods have various limitations (especially concerning the different structures of modern vehicles deformation parts) (Bradáč, 1999; Coufal, 2014; Semela, 2014). Crash tests could serve as a basis for the determination of selected parameters (vehicle stiffness included) for the purpose of crash analysis. To point out the different extent of deformations depending on the deformation elements stiffness, two almost identical crash tests were performed - similar vehicles (the modern vehicle Skoda Rapid and older Skoda Felicia), similar impact speed, and impact scenario (side impact). During the first crash test the modern vehicle hits the side of the older vehicle, the second crash test was reversal – the older vehicle hits the side of the modern vehicle.

Table 1: Vehicle parameters.

parameters	crash test 1		crash test 2	
	Rapid	Felicia	Felicia	Rapid
Manufacture year	2016	1996	1996	2016
Length (mm)	4 304	3 855	3 855	4 304
Width (mm)	1 706	1 635	1 635	1 706
Height (mm)	1 459	1 415	1 415	1 459
Wheelbase (mm)	2 602	2 450	2 450	2 602
Weight (kg)	1 294	931	892	1 294
Impact speed (km/h)	55	0	57	0

Figure 1: Crash tests configuration.

2.1 Crash Test 1

In the first crash test vehicle Skoda Rapid crashed in approximately 55 km/h into the side of the vehicle Skoda Felicia.

Figure 2: Damage correspondence - crash test 1.

Skoda Rapid has significant damage in the area of the front right corner including right headlight and fender, front bumper and bonnet. The headlight and bonnet were damaged due to contact in the area of vehicle Skoda Felicia A-pillar respectively the front edge of the vehicle front door as the area with higher stiffness. The Skoda Rapid bumper was horizontally broken also due to contact with the front edge of the Skoda Felicia front door. On the Skoda Rapid bumper in the area of the right front corner is the imprint of the Skoda Felicia tyre.

Figure 3: Vehicle Skoda Rapid after crash test 1.

Skoda Felicia was significantly damaged on the right side of the vehicle. Due to the vehicle age and related extensive corrosion of the load-bearing parts of vehicle bodywork, the vehicle bodywork collapsed (evident from the damage of the vehicle sill and vehicle floor in the area of the front passenger seat and vehicle roof braking), front door breakage and damage of the front door under A-pillar caused by front bumper reinforcement of the vehicle Rapid.

The entire area of Felicia's B-pillar intruded into the vehicle interior. The vehicle components collapsed and the occupant survival space was impaired (vehicle model has almost no deformation zones). On the right side of the vehicle Felicia is a clear imprint of the vehicle Rapid mask, bonnet edge, and front bumper reinforcement.

Figure 4: Vehicle Skoda Felicia after crash test 1.

The impact force was also transferred to the vehicle's left side – the front fender and door displacement.

Figure 5: Vehicle Skoda Felicia after crash test 1.

2.2 Crash Test 2

In the second crash test vehicle Skoda Felicia crashed at approximately 57 km/h into the side of the vehicle Skoda Rapid.

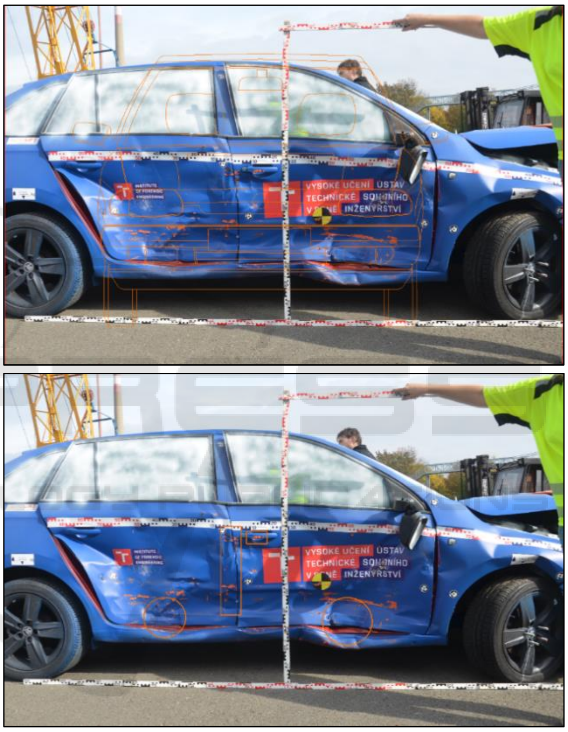

Figure 6: Vehicle Skoda Rapid after crash test 2.

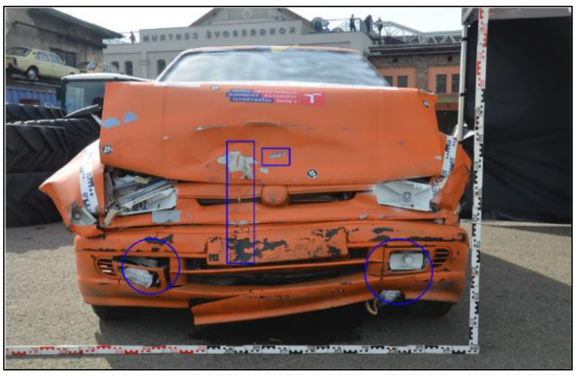

Figure 7: Vehicle Skoda Felicia after crash test 2.

The whole front part of the vehicle Skoda Felicia was damaged –both fenders, front bumper and mask, broken bonnet. Slightly left from the vehicle emblem on the bonnet, mask and bumper is a clear imprint of the vehicle Rapid B-pillar.

On the vehicle Skoda Rapid is damaged the right side in the area of both vehicle doors. The sill and both doors were damaged. There is no significant deformation of the B-pillar and the occupant survival space was not significantly impaired.

2.3 Comparison of the Crash Tests

The Skoda Felicia vehicle damage is significantly extended in comparison with the modern vehicle Skoda Rapid. The vehicle obsolescence is manifested in the vehicle's active and passive safety and also in the construction itself and used materials. The vehicle age has also a negative effect on the properties of some elements. With age increase, the probability of corrosion is higher, which reduces the rigidity and leads to the more extensive deformation of vehicle exterior and interior. The vehicle age increase is also related to the higher probability of serious injuries during a traffic crash.

Table 2: The comparison of vehicle damage.

The vehicle front	
Skoda Rapid	Skoda Felicia
Slight damage on the right front corner including the bonnet, right headlight, and fender, broken front bumper	Flat deformation of vehicle front including the broken bonnet, both fenders, front bumper, damaged mask
The vehicle side	
Skoda Felicia	Skoda Rapid
Extensive corrosion of the load-bearing parts of vehicle bodywork Vehicle bodywork collapsed Damage of the sill and vehicle floor in the area of the front passenger seat, deformation of the vehicle roof, deformation of the B-pillar, and impairment of the occupant survival space	damaged sill and both right doors no significant deformation of the B-pillar, and impairment of the occupant survival space.

3 EES DETERMINATION USING SELECTED METHODS

For the quantification of the EES parameter was used comparison method and PC-Crash CRASH 3 module. PC-Crash is one of the most widely used programs for collision reconstruction worldwide (Richardson et al., 2015) The obtained results were compared with the EES determined using data from crash tests.

3.1 Crash Tests

The crash parts could be divided into following stages: (Coufal, 2014, Daily at al., 2006):

- Collision – two objects interactions with large forces over a short time.
- Compression – the kinetic energy is absorbed and the object is deformed. The compression phase is terminated when a dynamic deformation reaches a maximum.
- Restitution – during the rebound phase is some stored energy turned back into kinetic energy and the object departs with some relative speed.

For the determination of vehicle deformation during crash tests were considered these individual parts of a crash and quantified corresponding energy in these individual crash parts - the plastic deformation energy, the elastic deformation energy, and also the maximum of deformation energy which corresponds with the sum of elastic and plastic deformation energy. The maximum deformation depth at the end of compression was measured using a top-view photo from drones.

3.2 Comparison Method

For the EES determination of the damaged vehicle is necessary to find comparably damaged vehicles with known EES in the EES catalogue. The Skoda Felicia front deformation was compared e.g. with the vehicle Skoda Favorit and Suzuki Swift (Figure 7 and Table 3).

Figure 8: Comparison method.

Table 3: The example of the comparison method.

	m_c [kg]	EES_c [km/h]	m_v [kg]	EES_v [km/h]
Skoda Favorit	870	29	931	28,0
Suzuki Swift	775	29	931	26,5

3.3 PC-Crash (CRASH 3)

PC–Crash programme CRASH 3 use NHTSA vehicle databank, where the comparable vehicle needs to be found for the EES calculation. In the deformation section is necessary to set the measured permanent deformation depth in the constant distance with the maximum 12 sections c_1 to c_n; k-factor and direction of the action force. The weight of the analysed vehicle must be considered, also the impact speed, deformation depth, and maximum speed in which deformation does not occur (b_0) need to be comparable (Semela, 2012, Brach, 2012). For the deformation depth measurement were used data from 3D scanner and also top-view photography from drones. The deformation depth using 3D scan was averaged from 3 sections in the area of maximum deformation depth.

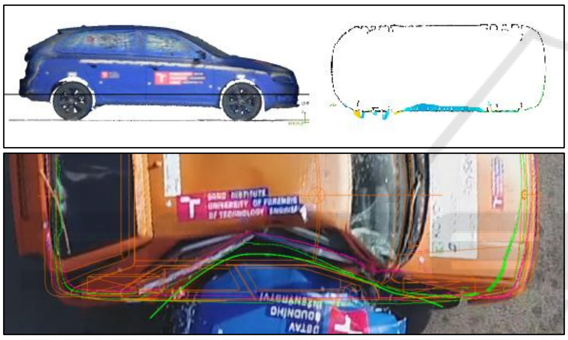

Figure 9: The measurement of deformation depth using 3D scanner.

Software PC–Crash programme CRASH 3 considers one central stiffness characteristic of the whole vehicle front. EES (respectively deformation energy) of the front damaged vehicle was used for the determination of the vehicle side damaged vehicle. For both vehicles is calculated maximum deformation depth X using the average plastic deformation depth X_p and elastic deformation depth X_e.

$$X_E = \frac{X_p \cdot k}{1 - k} \text{ [m]} \tag{2}$$

$$X = X_p + X_E \text{ [m]} \tag{3}$$

For the determination of maximum impact force F_{max} is used the quantified maximum deformation energy E_{D1} of the front damaged vehicle:

$$E_{D1} = E_{DP1} + E_{DE1} \text{ [J]}, \tag{4}$$

where E_{DP} is the plastic deformation energy of vehicle 1:

$$E_{DP1} = \frac{1}{2} \cdot m_1 \cdot EES_1{}^2 \text{ [J]} \tag{5}$$

And E_{DE1} is elastic deformation energy of vehicle 1:

$$E_{DE1} = \frac{E_{DP1} \cdot k^2}{1 - k^2} \text{ [J]} \tag{6}$$

The maximum Impact Force F_{max} could be then determined as:

$$F_{max} = \frac{2 \cdot E_{D1}}{X_1} \text{ [N]} \tag{7}$$

The maximum impact force is equal for both vehicles and could be used for the determination of maximum deformation energy E_{D2} of vehicle two:

$$E_{D2} = \frac{X_2 \cdot F_{max}}{2} \text{ [N]} \tag{8}$$

The elastic deformation energy of vehicle 2 could be then determined as:

$$E_{DE2} = E_{D2} \cdot k^2 \text{ [J]} \tag{9}$$

and the plastic deformation energy of vehicle 2 as:

$$E_{DP2} = E_{D2} - E_{DE2} \text{ [J]} \tag{10}$$

EES of the side damaged vehicle is determined using equation:

$$EES_2 = \sqrt{\frac{2 \cdot E_{DP2}}{m_2}} \text{ [m/s]} \tag{11}$$

4 RESULTS: EES

EES parameter was determined using the comparison method (EES catalogue) and PC-Crash CRASH 3 module. For EES determination in PC–Crash CRASH 3 module is necessary to determine the deformation depth. Two methods of deformation depth measurement were used – measurement from top-view photography and 3D scans. For the measurement of deformation depth from 3D scans were averaged values from three sections (cuts) in the area of maximum deformation. The EES of the vehicle side damaged were determined based on the EES of the crash opponent.

The obtained EES values were compared with the EES determined using data from crash tests. Table 2 illustrates the obtained EES results in relation to the used method. Table 4 illustrates calculated EES using selected methods (comparison methods, a calculation based on the crash test data, PC-Crash, and deformation depth obtained from top-view photography and 3D scanner). The procedure of EES determination using these methods was described in the previous chapter.

Table 4: Determined EES using selected methods.

Crash		Comparison method [km/h]	PC-crash		Crash test [km/h]
			Top-view [km/h]	Scanner [km/h]	
1	Rapid	18-22	14 - 16	14 - 17	13 - 16
	Felicia	26-30	30 - 37	32 - 39	23 - 28
2	Felicia	24-29	28 - 34	31 - 38	25 - 32
	Rapid	19-24	12 - 14	16 - 19	10 - 15

Besides the comparative method, there are significant deviations of determined EES only in the case of the side-damaged Skoda Felicia vehicle. This deviation can be caused by the extent vehicle corrosion, inappropriate selection of stiffness in the PC-Crash software, or distortion of deformation depth measurements. The results can be also influenced by the set speed value b_0.

Resulting EES from the comparison methods is comparable with data obtained from crash tests for the Skoda Felicia vehicle. Usability of the comparison method for the vehicle Skoda Rapid is limited because the used EES catalogue (Melegh, 2005) contains mostly older vehicle models.

5 DISCUSSION

This article aimed to introduce the results of two crash tests representing the comparison of the stiffness and technological obsolescence. On these crash tests were analysed limits of the selected methods for EES determination. The EES value expresses the kinetic energy dissipated by the vehicle during the contact phase i.e energy converted to thermal energy through deformation (Berg, 1998).

Structural behavior and properties differ depending e.g. on the vehicle model. Even similar vehicles (similar weight/length/width) could have different deformation characteristics, especially depending on the vehicle stiffness influenced by the degradation of vehicle bodywork (Abellán-López, 2018; Vangi, 2020).

Realised crash tests of comparable vehicles in similar impact speed only inverted collision scenario (first crash scenario – modern vehicle Skoda Rapid crashed into the side of old vehicle Skoda Felicia, second crash scenario – old vehicle Skoda Felicia crashed into the side of the Skoda Rapid) demonstrate the influence of the vehicle age (and related degradation – corrosion of the bodywork), respectively technological obsolescence (and the related difference in the stiffness) to the resulting extent of the damage. Deformation of Skoda Felicia is significantly more extensive in comparison with the modern vehicle Skoda Rapid. During side impact into the vehicle Skoda Felicia was impaired the occupant survival space.

The EES were determined for all tested vehicles using selected methods - based on the crash test results, using PC–Crash CRASH 3 module and comparison method. The deformation depth was measured using a top view photo from a drone and 3D scans.

The calculated EES values for the frontal damage of vehicle Skoda Felicia are comparable. Used EES catalogue (Melegh, 2005) contains mostly older vehicle models. Used database in the module CRASH 3 in PC-Crash software is applicable primarily on the frontal damage. Top-view photography use for the frontal deformation depth measurement is mostly not affected by significant deviation, because the damage is mostly not covered by other vehicle parts – as vehicle hood (which could be a limitation of the top-view photography usage for deformation depth measurement of the vehicle side deformation).

The EES values determined using comparison with the damage of vehicle with known EES value could be inaccurate for the modern vehicles, as proved by EES values of Skoda Rapid vehicle. The EES catalogues mostly do not contain modern vehicles. The limitation is also the subjectivity of the extent of vehicle damage assessment during the determination of similarly damaged vehicles for comparison.

Determination of the EES using module CRASH 3 in the PC-Crash software is influenced by accessible vehicle and their stiffness. The users have to select a vehicle from the NHTSA databank, US vehicles could have different stiffness in comparison with vehicles in the European market (Macurová, 2019). Coufal (2014) compared EES calculation using correlation diagram, comparison method and CRASH 3. As one of the main limitations author concluded that the different stiffness of individual vehicle parts is not considered, as these methods assume homogeneous rigidity for the front of the vehicle.

Results can be also influenced by the inaccuracy of the deformation depth measurement (Żuchowski, 2015). Deformation depth measurement using a top-view photo is limited especially during vehicle side deformation, where could be the maximum deformation depth covered by vehicle roof or other vehicle parts (Moravcová, 2019). Usability of the 3D scanner could be also limited, it is not possible to document plastic deformation - coverage of deformation by another vehicle part or detachment of vehicle body part as a result of the collision. For elimination of results, distortion could be in some specific cases most appropriate combine several measurement methods. Papić et al. (2017) emphasize the usability of a 3D model (which allows to analyse of deformation depth in individual sections) in combination with crash reconstruction software.

As evidenced by obtained results, the EES parameter could be determined in a relatively wide range. Quantified deformation energy is one of the basic parameters for the crash analysis. Significant inaccuracy in the EES determination could influence determined impact speed. The methods for crash documentation and subsequent analysis need to be used concerning the collision type, deformation character and extent, and vehicle characteristics.

Future research activities will be focused on the analysis of efficiency, usability and accuracy of various methods for documentation and vehicle deformation quantification. Selected methods will be experimentally verified during crash tests and real traffic crashes documentation and their subsequent analysis.

6 CONCLUSIONS

Crash analysis including determination of the impact speed is one of the main assumptions for the clarification of mostly negligent crimes. For crash reconstruction, various simulation models can be used. During crash reconstruction is necessary to considered specifics and limitations of used methods, thus different methods should be used depending on the collision types and specific condition (Hoxha, 2017). The inaccuracy of the input affects the output, to achieve more credible output is necessary to used sophisticated and precise methods which allow to document values corresponding with the real situation Svatý (2020). Precise documentation of crashes (especially brake traces) is crucial for the subsequent crash analysis.

The impact speed determination could be based not only on the crash reconstruction but also obtained from vehicle cameras or Event Data recorders (EDR). Previous studies prove the necessity to verify obtained values. The results distortion could occur e.g. due to significant deformation, the control unit damage, recording algorithm delay, or insufficient recording memory or vehicle skidding (Gwehenberger, 2020). The usability of EDR is currently limited in the EU due to legislation. Therefore, it is still necessary to improve methods for crash documentation and analysis (including EES determination).

The parameters which could serve as a basis for the crash analysis (such as vehicle stiffness) could be obtained from the vehicle crash tests (Dima, 2019). Crash tests are realized by many organizations mostly to ensure vehicle safe design e.g. Insurance Institute for Highway Safety (IIHS), National Highway Traffic Safety Administration (NHTSA), DEKRA, Transport Research Laboratory (TRL), Dynamic Test Center (DTC), Crashtest-service (CTS), etc. The usability of data from commercial crash tests focused on vehicle safety testing or homologation is limited for forensic engineering purposes. Crash tests are mainly realised with the new vehicles that are not affected by material degradation. A number of studies pointed to the differences in the deformation behaviour in relation to the vehicle age or obsolescence. There are also differences in brands or vehicle models (Kullgren, 2010, Görtz, 2018; Covaciu, 2016). For the crash analysis in the forensic engineering is necessary to conducted not only crash tests of new vehicles, but also of older vehicles, which may have different characteristics. For these purposes also data collection from real traffic crashes and the subsequent validation of the calculated data within crash tests could be beneficial. Experimentally obtained data enable improvement and refinement of input values for simulation modelling and crash calculation.

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