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UNCERTAINTY OF DETERMINING THE ENERGY EQUIVALENT SPEED (*EES*) OF A VEHICLE COLLISION BY THE EXPERIMENTAL AND ANALYTICAL METHOD

NIEPEWNOŚĆ W OKREŚLENIU PRĘDKOŚCI *EES* ZDERZENIA SAMOCHODÓW WYZNACZANEJ METODĄ EKSPERYMENTALNO-ANALITYCZNĄ

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Summary

One of the basic ways to estimate vehicle speeds at the reconstruction of vehicle collisions is the use of methods generally referred to as "energy methods", where a relation between the "energy equivalent speed" (*EES*) and the size of permanent vehicle deformation is described. There are several mathematical models used in practice to describe such a relation. Usually, a linear relation between the deformation size (depth) and the energy consumed to cause the deformation ("deformation work") is assumed. In contrast, the deformation itself and the deformation energy are described in various ways. In consequence, different *EES* values may be obtained from the calculations, depending

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on the model used. In the accident reconstruction practice, an increasingly important role is played by the uncertainty and reliability of the analysis results obtained. This article is dedicated to the uncertainty of estimation of the energy equivalent speed (*EES*). The uncertainty calculation results obtained with the use of one of the typical methods of determining it, i.e. the total differential method, have been presented. The calculations were carried out for five analytical models used to determine the deformation work, based on the deformation size, for several real cases of post-impact vehicle deformation. The calculation results have been presented in the form of tables and graphs, thanks to which comparisons between both the *EES* values and the values of their absolute and relative uncertainty could be made. The whole analysis has ended with conclusions concerning the values obtained; they may be a source of information on the uncertainty in determining the *EES* parameter depending on the computation model used.

Keywords: deformation work, energy methods, accident reconstruction, total differential method, uncertainty of *EES*

Streszczenie

Jednym z podstawowych sposobów stosowanych przy rekonstrukcji zderzeń samochodów, wykorzystywanym w celu oszacowania ich prędkości, jest grupa tzw. metod energetycznych. W metodach tych opisuje się związek między prędkością równoważną energii *EES* (z ang. *energy equivalent speed*), a rozmiarem trwałego odkształcenia pojazdu. Istnieje kilka praktycznie wykorzystywanych modeli matematycznych opisujących ten związek. Zazwyczaj zakładają one liniową zależność między wspomnianym rozmiarem (głębokością) deformacji, a energią zużytą na jej powstanie (tzw. pracą deformacji). W różny sposób natomiast opisywana jest sama deformacja oraz energia deformacji. W zależności od zastosowanego modelu możemy otrzymać inne wartości poszukiwanej prędkości *EES*. W praktyce rekonstrukcji wypadków coraz istotniejszą rolę odgrywa niepewność i wiarygodność otrzymanych wyników. Przedmiotem artykułu jest niepewność oszacowania prędkości równoważnej energii *EES.* W pracy zostały przedstawione wyniki obliczeń otrzymane przy użyciu jednej z typowych metod jej określania – metody różniczki zupełnej. Obliczenia zostały wykonane dla pięciu modeli analitycznych wyznaczania pracy deformacji, na podstawie jej rozmiaru, dla kilku rzeczywistych odkształceń pozderzeniowych pojazdów. Wyniki przedstawiono w postaci tabelarycznej oraz wykresów, umożliwiających porównanie zarówno wartości parametru *EES*, jak i wyznaczonych dla niego niepewności bezwzględnych oraz względnych. Całość została podsumowana wnioskami odnoszącymi się do otrzymanych wartości. Mogą one być źródłem informacji na temat niepewności w wyznaczaniu prędkości *EES* w zależności od zastosowanego modelu obliczeniowego.

Słowa kluczowe: praca deformacji, metody energetyczne, rekonstrukcja wypadków, metoda różniczki zupełnej, niepewność *EES*

1. Introduction

In the reconstruction of road accidents where a vehicle collision took place, the "energy methods" are often used to estimate the pre-impact speeds. In particular, the energy equivalent speed (*EES*), i.e. the vehicle speed equivalent to the energy consumed to cause the vehicle deformation, is thus determined. The *EES* value can be calculated from the work done during the vehicle body deformation and this work is estimated from the deformation size.

There are several mathematical models making it possible to determine the deformation work. Therefore, a question arises how the model alone can affect the *EE*S value being calculated. A separate issue is the uncertainty of determining this parameter, arising from the uncertainty of the input data. Both of these issues may be important from the point of view of the correctness of an analysis carried out. The objective of this article is to show and illustrate by selected examples how the type of the analytical model used to estimate the deformation work and the uncertainty of evaluation of the vehicle body deformation can affect the *EES* calculation result and the uncertainty of this result.

2. Calculations and measurement methods

The energy methods are founded on an assumption that all the kinetic energy lost by the vehicle during a collision is "consumed" to deform the vehicle, which may be symbolically written down as follows:

$$E_d \cong \frac{m \cdot (V^2 - V'^2)}{2} = \frac{m \cdot EES^2}{2}, \tag{1}$$

where: E_d – permanent deformation energy; m – vehicle mass; V – pre-impact vehicle velocity; V' – post-impact vehicle velocity.

In the literature dealing with accident reconstruction (e.g. [1, 2, 4, 8]), the difference between squared velocity values $V^2 - V'^2$ is written as squared *EES*, and the *EES* parameter proper is referred to as "energy equivalent speed", i.e. the speed equivalent to the energy consumed to cause the vehicle deformation. *EES* is not identical with the change in the vehicle velocity during the collision (which can be construed straight from equation (1)), although it is directly related to the latter and this relation is used for determining the pre-impact vehicle velocities. The *EES* value determined from equation (1) has the form:

$$EES = \sqrt{\frac{2 \cdot E_d}{m}} \tag{2}$$

Based on empirical tests, a relation between the deformation size and the deformation energy is formulated. Various formal representations of this relation are available (they may be found in the accident reconstruction literature, e.g. [1, 2, 5, 6, 7, 8]). Thus, a relation between the vehicle body deformation and the vehicle velocity at the instant of impact may be obtained, by using the *EES* parameter.

This article presents example calculation results, estimating the values of the *EES* parameter and of its uncertainty, for a few real vehicles subjected to a frontal impact. The calculations were carried out with the use of the total differential method, with the following five analytical methods of determining the nominal Ed or *EES* values being used as models of the process under analysis:

– simplified method;
– Campbell method;

- McHenry method;
- CRASH3 method;
- method employed in the PC-CRASH simulation program.

Details of these methods may be found in the literature [1, 2, 5, 6, 7, 8]; this article is exclusively intended to present the impact of the said methods on determining the uncertainty.

The basic equations on which the above methods are founded have been specified below.

- For the simplified method:

$$E_d = \frac{1}{2} \cdot K \cdot C_{śr}^2 = \frac{1}{2} \cdot w_d \cdot h_d \cdot C_{śr}^2 \cdot k^*, \tag{3}$$

where: K – vehicle body stiffness coefficient; $C_{śr}$ – permanent vehicle deformation depth; w_d – average deformation width; h_d – average deformation height; $k*$ – unit bodywork stiffness coefficient.

- For the Campbell method (considered as the basic one):

$$V = b_0 + b_1 \cdot C_{śr}, \tag{4}$$

where: V – velocity of the vehicle frontally hitting a rigid barrier; b_0 – minimum velocity at which permanent deformation of the vehicle body occurs; b_1 – slope of the straight line $V = V(C_{śr})$.

According to the definition of velocity V, an assumption may be made that it is approximately equal to *EES*.

- For the McHenry method:

$$E_d = w_d \cdot (A \cdot C_{śr} + \frac{B \cdot C_{śr}^2}{2} + G) \text{ and } G = \frac{A^2}{2B}, \tag{5}$$

where: A – coefficient defining the minimum unit threshold force at which plastic deformation takes place ($A = \frac{m \cdot b_0 \cdot b_1}{w_d}$); B – vehicle body stiffness coefficient, which defines the unit longitudinal stiffness ($B = \frac{m \cdot b_1^2}{w_d}$); G – energy of the elastic deformation.

If the above formulas for A, B, and G are substituted to equations (5) and (2) then the Campbell and McHenry methods may be shown to be identical with each other. Since "separate" datasets can be found in the literature for each of them (i.e. recommended values of b_0 and b_1 for the Campbell method and recommended values of coefficients A and B for the McHenry method), these two methods were treated in further calculations as separate from each other.

- For the CRASH3 method:

$$E_d = \frac{w_d}{n-1}\left(\frac{A\alpha}{2} + \frac{B\beta}{6} + (n-1)G\right), \tag{6}$$

where: α, β – constants of deformation at the i^{th} point (see Fig. 1); n – number of the points of measurement of the deformation depth.

This is a modified version of the McHenry method, differing from the latter in the way of representing the deformation. Coefficients α and β have the form:

$$\alpha = C_1 + C_n + 2\sum_{i=2}^{n-1} C_i \qquad \beta = C_1^2 + C_n^2 + 2\sum_{i=2}^{n-1} C_i^2 + \sum_{i=1}^{n-1} C_i C_{i+1} \tag{7}$$

- For the method employed in the PC-CRASH simulation program:

$$E_d = \sum_{i=1}^{i=n-1} w_{ci} \cdot \left[\frac{A}{2}(C_{i+1} + C_i) + \frac{B}{6}\frac{C_{i+1}^3 - C_i^3}{C_{i+1} - C_i} + G\right] \tag{8}$$

where: w_{ci} – width between successive points of measurement of the deformation depth (see Fig. 1) .

In the PC-CRASH program, the CRSH3 method has been employed, except for that the method of entering the deformation profile has been modified to enable the introduction of various w_{ci} values.

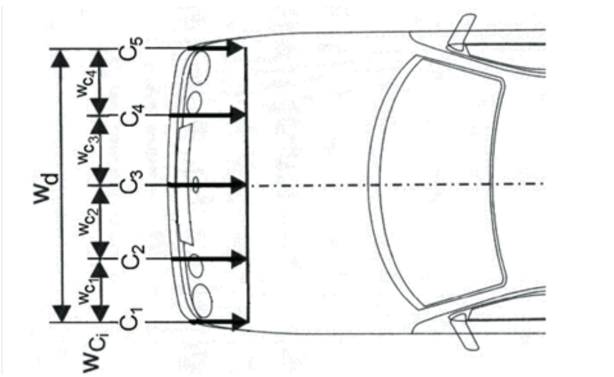

Fig. 1. Schematic diagram illustrating the parameters that define the vehicle body deformation size

A detailed description of the method of measuring the vehicle body deformation and the results of such measurements have been presented in [3]. The deformation size was estimated by measuring its geometrical dimensions at several points as shown in Fig. 1. The average deformation depth was calculated from a formula:

$$C_{śr} = \left(\frac{C_1}{2} + \sum_{i=2}^{i=n-1} C_i + \frac{C_n}{2} \right) / (n-1), \tag{9}$$

where: C_i – deformation depth at the i^{th} measuring point; n – number of the measuring points (equal to 5 or 6 at the measurements carried out).

For the purposes of this article, an assumption was made that the only source of uncertainty was the measurement of the geometrical quantity that described the deformation. The uncertainty was determined with the use of the total differential method, where the total differential was expressed in the following general form:

$$\Delta y = \sum_{i=1}^{n} \left| \frac{\partial y}{\partial x_i} \cdot \Delta x_i \right|, \tag{10}$$

where: Δy – uncertainty of the quantity to be found (ΔEES); Δx_i – uncertainty of the known parameters x_i (C_i); $\partial y/\partial x_i$ – value of the first-order coefficient of sensitivity of y relative to x_i for the nominal value of x_i.

The nominal *EES* values were calculated with the use of formulas (3) to (8) and the first-order total differential method (TDM) was employed for determining the uncertainty. In this work, only the impact of the estimation of vehicle body deformation was investigated; hence, an assumption was made that the uncertainty was exclusively caused by the measurements of the geometrical quantities that described the deformation under analysis.

3. Data used for the calculations

The calculations were carried out for eight example vehicles subjected to frontal collisions, for which the deformation measurement results have been presented in Table 1. For the measurements, a laser distance meter was used. The uncertainty of measurements of geometrical quantities (Δx_i) was assumed as equal to 0.02 m. The values of the other parameters necessary for further calculations have been given in Table 2. In particular, the values of parameters (k^*, b_0, b_1) were assumed on the grounds of literature recommendations [1, 6], appropriately to the vehicle and collision type. The values of coefficients A and B were calculated according to the equations specified above, for the assumed values of b_0 and b_1. Tables 3 and 4 include photographs that illustrate the range of deformations of the vehicles under consideration.

Table 1. Geometrical parameters defining the deformation size for the eight vehicles under consideration

Parameter	Citroen Berlingo	Mercedes Benz C-class	Opel Combo	Opel Vectra
w_d [m]	1.40 ± 0.02	1.35 ± 0.02	1.00 ± 0.02	0.80 ± 0.02
h_d [m]	0.83 ± 0.02	0.89 ± 0.02	0.93 ± 0.02	0.78 ± 0.02
w_{ci} [m]	0.28 ± 0.02	0.27 ± 0.02	0.25 ± 0.02	0.20 ± 0.02
C_1 [m]	0.43 ± 0.02	0.28 ± 0.02	0.65 ± 0.02	0.19 ± 0.02
C_2 [m]	0.37 ± 0.02	0.24 ± 0.02	0.52 ± 0.02	0.23 ± 0.02
C_3 [m]	0.26 ± 0.02	0.26 ± 0.02	0.46 ± 0.02	0.17 ± 0.02
C_4 [m]	0.29 ± 0.02	0.34 ± 0.02	0.28 ± 0.02	0.13 ± 0.02
C_5 [m]	0.24 ± 0.02	0.35 ± 0.02	0.06 ± 0.02	0.10 ± 0.02
C_6 [m]	0.16 ± 0.02	0.34 ± 0.02	–	–
Parameter	**Skoda Octavia**	**Suzuki Splash**	**Toyota Corolla**	**VW Golf IV**
w_d [m]	1.40 ± 0.02	1.50 ± 0.02	1.50 ± 0.02	1.40 ± 0.02
h_d [m]	1.05 ± 0.02	0.76 ± 0.02	0.82 ± 0.02	0.87 ± 0.02
w_{ci} [m]	0.28 ± 0.02	0.30 ± 0.02	0.30 ± 0.02	0.28 ± 0.02
C_1 [m]	0.31 ± 0.02	0.19 ± 0.02	0.36 ± 0.02	0.36 ± 0.02
C_2 [m]	0.26 ± 0.02	0.17 ± 0.02	0.19 ± 0.02	0.31 ± 0.02
C_3 [m]	0.24 ± 0.02	0.20 ± 0.02	0.16 ± 0.02	0.28 ± 0.02
C_4 [m]	0.09 ± 0.02	0.24 ± 0.02	0.15 ± 0.02	0.30 ± 0.02
C_5 [m]	0.05 ± 0.02	0.13 ± 0.02	0.26 ± 0.02	0.31 ± 0.02
C_6 [m]	0 ± 0.02	0.14 ± 0.02	0.02 ± 0.02	0.27 ± 0.02

Table 2. Parameter values assumed for the eight vehicles under consideration

Parameter	Citroen Berlingo	Mercedes Benz C-class	Opel Combo	Opel Vectra
m [kg]	1 225	1 450	1 290	1 270
$k*$ [(N/m)/m^2]	17×10^5	7.65×10^5	17×10^5	11×10^5
$b0$ [m/s]	1.34	3.35	1.34	3.35
$b1$ [(m/s)/m]	23.76	15.84	23.76	15.84
A [N/m]	27 859	56 995	41 072	84 239
B [N/m^2]	493 970	269 491	728 254	398 313
Parameter	**Skoda Octavia**	**Suzuki Splash**	**Toyota Corolla**	**VW Golf IV**
m [kg]	1 275	1 075	1 140	1 185
$k*$ [(N/m)/m^2]	20×10^5	20×10^5	17×10^5	17×10^5
$b0$ [m/s]	3.35	1.34	1.34	1.34
$b1$ [(m/s)/m]	15.84	23.76	23.76	23.76
A [N/m]	48 326	22 818	24 197	26 949
B [N/m^2]	228 503	404 585	429 049	477 841

Table 3. Illustrations showing deformations of the vehicles subjected to frontal collisions

Citroen Berlingo	Mercedes Benz C-class
	
Opel Combo	**Opel Vectra**
	

Table 4. Illustrations showing deformations of the vehicles subjected to frontal collisions (continued)

Skoda Octavia	Suzuki Splash
	
Toyota Corolla	**VW Golf IV**
	

4. Calculation results

The calculation results in the form of nominal *EES* values and of the uncertainty of their estimation, specified as absolute and relative values, have been presented in Table 5 and, as histograms, in Figs. 2 to 4. Fig. 2 shows the nominal *EES* values obtained from the calculations and Figs. 3 and 4 show the *EES* estimation uncertainty in terms of absolute and relative values, respectively.

Table 5. Nominal *EES* values obtained from the calculations, with their estimation uncertainty specified as absolute and relative values

Parameter	Citroen Berlingo	Mercedes Benz C-class	Opel Combo	Opel Vectra
Citroen Berlingo	Simplified	41.9	3.7	8.8
	Campbell	29.6	1.7	5.8
	McHenry	29.6	1.9	6.5
	CRASH3	30.3	0.5	1.8
	PC-CRASH program	30.3	6.2	20.6
Mercedes Benz C-class	Simplified	27.2	2.3	8.5
	Campbell	29.2	1.1	3.9
	McHenry	29.2	1.4	4.7
	CRASH3	29.3	0.7	2.4
	PC-CRASH program	29.3	5.2	17.7
Opel Combo	Simplified	50.4	3.6	7.1
	Campbell	39	1.7	4.4
	McHenry	39	2.1	5.2
	CRASH3	41.7	0.7	1.6
	PC-CRASH program	41.7	6.6	15.8
Opel Vectra	Simplified	14.2	2	14.3
	Campbell	21.8	1.1	5.2
	McHenry	21.8	1.4	7.1
	CRASH3	21.8	0.9	4.3
	PC-CRASH program	21.8	4.7	21.6
Skoda Octavia	Simplified	27.7	3.9	14.2
	Campbell	21.2	1.1	5.4
	McHenry	21.2	1.3	6.1
	CRASH3	21.9	0.8	3.7
	PC-CRASH program	21.9	4.6	20.9
Suzuki Splash	Simplified	29.8	3.9	13.1
	Campbell	20.2	1.7	8.5
	McHenry	20.2	1.9	9.2
	CRASH3	20.5	0.6	3
	PC-CRASH program	20.5	5.4	26.3
Toyota Corolla	Simplified	29.3	3.6	12.4
	Campbell	21.1	1.7	8.1
	McHenry	21.1	1.9	8.8
	CRASH3	21.8	0.6	2.7
	PC-CRASH program	21.8	5.4	24.9
VW Golf IV	Simplified	45.2	3.9	8.5
	Campbell	30.5	1.7	5.6
	McHenry	30.5	1.9	6.3
	CRASH3	30.8	0.5	1.8
	PC-CRASH program	30.8	6.3	20.5

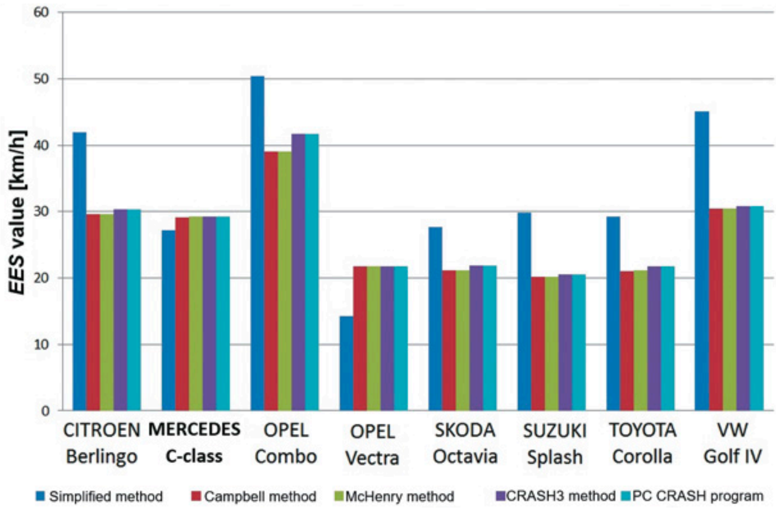

Fig. 2. Nominal *EES* values for the vehicles under consideration

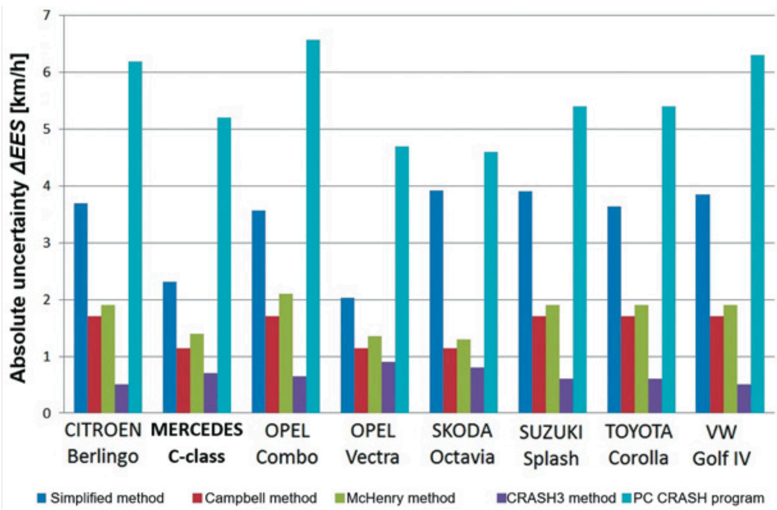

Fig. 3. Absolute uncertainty of the *EES* estimation depending on the method of evaluating the deformation work done during the collision

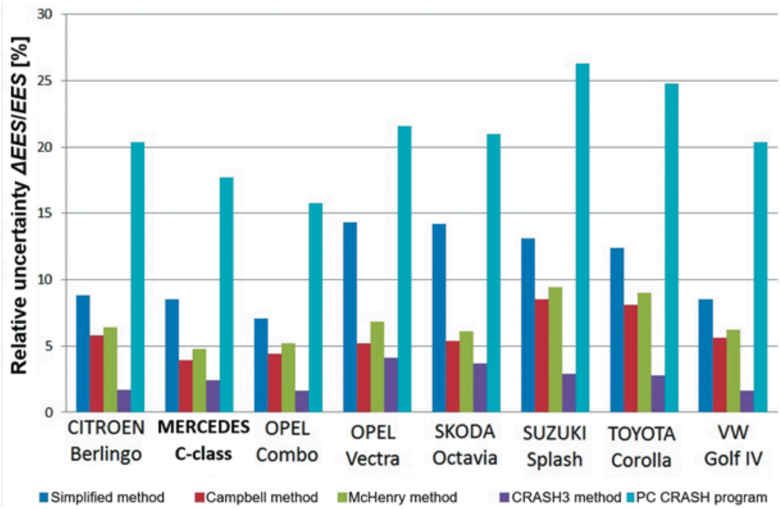

Fig. 4. Relative uncertainty of the *EES* estimation depending on the method of evaluating the deformation work done during the collision

An analysis of the nominal *EES* values shows that the highest values of this parameter were obtained when the simplified method was used. Only for the second and fourth car (Mercedes Benz C-class and Opel Vectra, respectively), the results were lower in comparison with those obtained from the other methods. The differences were quite big, from several to more than ten kilometres per hour (i.e. from 2.1 km/h for Mercedes Benz C-class to 14.3 km/h for Volkswagen Golf IV, as an example). In terms of relative values, the differences ranged from 7.8 % to 31.7 %.

Simultaneously, considerable similarity between the results obtained by the Campbell, McHenry, CRASH3, and PC-CRASH methods may be seen. This becomes clear when the mathematical models used in these methods are analysed. As mentioned previously, the Campbell and McHenry methods are identical to each other and the CRASH3 and PC-CRASH methods derive from the McHenry method, but the deformation profile is represented there in a different way (averaged deformation $C_{śr}$ is used in the McHenry method).The *EES* values in the CRASH3 and PC-CRASH methods are equal to each other because an exactly identical method of defining the vehicle deformation is employed in both of them, with identical w_{ci} values being used in both cases (see Fig. 1).

As regards the results of determining the uncertainty ΔEES, absolute values ranging from about 0.5 km/h to about 7 km/h were obtained, depending on the energy method used, which translated into a range from 2 % to 26 % in terms of relative values. The definitely lowest uncertainty values were obtained for the CRASH3 method (0.5÷0.9) km/h, i.e. (2÷4) %, in terms of absolute and relative values, respectively). The Campbell and McHenry methods are the next in this ranking, with the uncertainty values obtained being close to each other and ranging in both cases from 1.1 km/h to 2 km/h, i.e. from 4 % to 9 % in relative terms. The simplified method yielded uncertainty values from 2.2 km/h to almost 4 km/h from 8 % to 14 %. The uncertainty values were definitely highest for the formula of the PC-CRASH program. In this case, the absolute uncertainty values ranged from about 4.5 km/h to more than 6 km/h, with the relative values varying from 14 % to 26 % (close to 20 % in most cases). The reasons for this high uncertainty should be sought in the form of the mathematical model (equation (8)). The adding operation present in this model and applied to data obtained from individual deformation measuring points results in the summing-up of component uncertainties of deformation measurements. In the other methods under consideration, such an effect does not occur (because of averaging the deformation at determining the deformation energy).

5. Recapitulation and conclusions

Based on a series of example calculations and on actual deformation measurements carried out on post-crash vehicles, a statement may be made that the energy equivalent speed (*EES*) cannot be accurately estimated if the data available are limited to the permanent bodywork deformation values. The energy equivalent speed depends on many factors, especially on the measuring method, measuring instrument, *EES* value determining method, etc. All these factors cause the *EES* value to be burdened with an error, the range of which is defined by the estimation uncertainty discussed herein.

Based on an analysis of the results presented, the following conclusions have been formulated.

- The highest nominal *EES* values are usually obtained when the simplified method is used; for the other methods, these values reach a similar level.
- The lowest uncertainty values, amounting to (2÷4) % in all the cases under analysis, were achieved when the CRASH3 method was used; somewhat higher values, of (9÷14) %, were obtained in the case of using the simplified method.
- The uncertainty reaches the highest values, at a level of about 20 %, when the method employed in the PC-CRASH program is used.
- A relative uncertainty level of 30 % was not reached for any of the *EES* values determined in this work.

It should be stressed here that only the uncertainty related to the measurements of vehicle body deformation was taken into account in the calculations carried out. The impact of the uncertainty of other factors, e.g. bodywork stiffness and values of other coefficients in the mathematical model, was not analysed in this work. Nevertheless, the analysis results and the conclusions presented may be a source of knowledge of the uncertainty arising from a specific EES determination method used.

In the future, an increased interest in the energy methods may be expected. When combined with modern methods of deformation measurements, e.g. three-dimensional scanning together with the use of appropriate computer software, where a verified database of technical parameters of motor vehicles would be available, the energy methods will make it possible to obtain the EES values in a quick way and to reduce the uncertainty of their estimation.

The full text of the article is available in Polish online on the website http://archiwummotoryzacji.pl.

Tekst artykułu w polskiej wersji językowej dostępny jest na stronie http://archiwummotoryzacji.pl.

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