Precision Method of Velocity Determination based on Measurements of Car Body Deformation - Non-linear Method for Intermediate Vehicle Class

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Abstract— **In the research concerning Intermediate NHTSA vehicle class [16] there was presented the application of non-linear description of the b_k coefficient depending on the precrash velocity V_t as a function of generalised body deformation coefficient Cs defined after crash test. The nonlinear relationship includes one independent parameter - vehicle mass. These two parameters - C_s and m- through the surface of the second order describe the value of the crash velocity Vt. Previously used linear model [13, 15, 17] did not allow to achieve the accuracy of velocity determination in the range enabling performing the crash reconstruction based on such model. The non-linear model is more precise. The value of the relative error V_t decreases, what authors present on the plots of the error value as a function of the case number in the database.**

Index Terms—**crash reconstruction velocity, deformation, vehicle, nonlinear method, collision deformation classification.**

I. Introduction

CONTEMPORARILY, the methods of a vehicle crash velocity determination based on body deformation include application of linear models [4, 21, 23,25]. It means that there was assumed a linear relationship between EES velocity [2, 3] - equivalent crash speed which is a measure of kinetic energy lost during the impact [24] - and coefficient Cs [18] representing the averaged value of body deformation (measured at 6 points). Two factors have the main influence on the fact that in a particular case there is obtained a relative error 20-30%. The first reason for such high value is the factor described in PIMOT research, which is based on the random symmetry of the body deformation as far as various vehicle brands are concerned.

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The car body includes asymmetrically placed elements which is a reason for different stiffness at points placed across frontal horizontal line where after the crash deformation parameters C_1-C_6 are measured. Although in the crash experiment the impact is ideally central the pairs of deflection coefficients C_1-C_6 or C_2-C_5 are different. These coefficients refer to the measurements symmetric with reference to the longitudinal axis of the vehicle. The other thing which has bearing on the asymmetry of the values for such pairs is varying elasticity at different points of car body, which after the impact partly returns to its original shape. These two factors generate significant asymmetries in the deformation values for such symmetrically placed points.

Application of the calculation of the average body deformation C_s as weighted arithmetic mean with different weight of each deflection points C_1-C_6 turns out to be more effective in the CRASH method [1]. The authors researched the available database seeking for higher accuracy of the C_s calculation by including more complex weights of each measurement point, however, it brought no improvement. It is the result of the fact that the database includes limited number of vehicles of particular brands. The higher precision would be possible if the crash tests would be repeated for the new database with higher crash velocity spectrum. Whereas, in the case of available database, there test velocities oscillated around three main values. This problem is a result of different aims of the authors of the crash tests and authors of this research. In this case, the purpose was to analyse the nonlinear behaviour of the slope b_k when determining vehicle crash velocity using a function of averaged deformation coefficient C_s. The authors suggest performing crash tests for particular vehicle brands so that it will be possible to calculate more accurate weights of the particular deformation measurement points. Undoubtedly, more complex formula of determination of the averaged deformation will provide decrease of the velocity evaluation error.

The second factor which decreases the precision of the velocity determination is the captured by authors non-linearity of this relationship. Basing on the PIMOT research and the stiffness relationships the authors conclude that the relationship between the vehicle velocity and the averaged deformation coefficient C_s cannot be linear. Undoubtedly, it has even more complex course than included in the article approximation of the slope b_k (as a function of mass m and averaged deformation C_s) by the plane of second order.

More accurate analysis would include higher variability of the slope b_k depending on the ranges of the increasing averaged deformation C_s. The most detailed and precise model describing this relationship would involve using fuzzy logic.

Performing crash tests in order to research the crash reconstruction rather than to certify vehicles would improve the analysis of the particular collision. The authors suggest the possibility to obtain more detailed information about the particular brand which could result in construction of the car body more safe for the passengers during a collision.

Other methods of the vehicle pre-crash speed evaluation are described in [5-15].

II. Database for Calculations of EES

There was described a non-linear method of vehicle test velocity determination using a generalised body deformation coefficient Cs. The method called CRASH 3 [19] is one of energetic methods. Although, the purpose of the crash tests on which the database is based was different than accident reconstruction, it finds good application in the proposed method. In the beginning, the authors analysed series of parameter distributions from the database. The most crucial is the distribution of vehicle test velocities - the histogram of the values V_t (Figure 1).

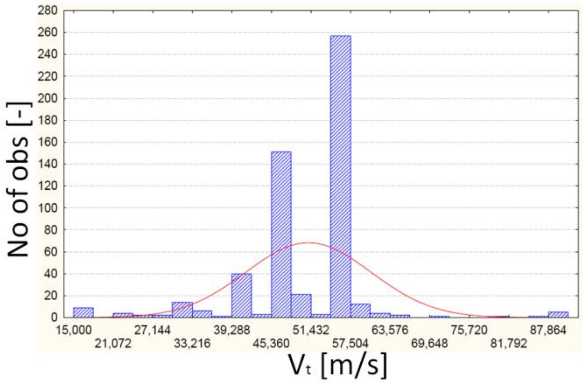

Fig.1. Distribution of test velocities

The values of velocity constitute three main zones and series of significantly smaller zones around them. It most certainly complicates energetic model parameter determination, where the velocity streams should be more fuzzy. It appears that the origin of many points from standing out streams (in this case not excluded from the database) may be correlated with this atypical for research methods and typical for the vehicle certification velocity distribution.

Simultaneously, the experimental method allow using different vehicle brands. Naturally, it hampers obtaining precise calculative results. The crash deformation for each car brand proceeds in different way. The part of the deflection undergoes an elastic return to the original shape. Similarly, different arrangement of the elements inside car body generated differences in coefficients C_1 to C_6 distribution. The authors due those and more complex reasons were not able to define the regular dependences between these coefficients. It would require a research including significantly high number of vehicles of each brand and creating individual method for each of them. Although it would undoubtedly increase the accuracy of the vehicle velocity evaluation it is practically impossible. Hence, there is applied a method including approximations ex. determination of deformation coefficient C_s. The major number of calculations was directed on achieving more precise form of the dependence between the C_s coefficient and C_1 to C_6 coefficients, however there was no valuable results obtained.

The distribution of C_s coefficient is presented in Figure 2. It results from the database that for the similar precrash velocities and Intermediate class vehicle masses there are various values of the C_s coefficients calculated from the parameters C_1 to C_6.

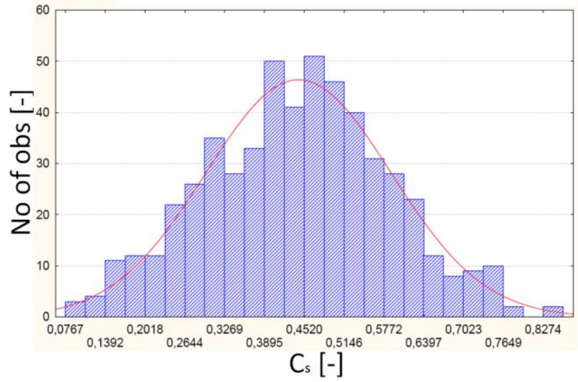

Fig.2. Distribution of Cs coefficient

It follows that the presented calculations are results of averaging by equations and processing of the data. Thus, the obtained accuracies of the velocity V_t determination are not high. Once again, this fact emphasises the importance of the applied, improved method with regard to the linear model, which increases the accuracy significantly. With such constructed database, especially when analysing a particular case the improved precision of velocity determination V_t may have a crucial influence.

III. Calculation Pattern

Hereafter, similarly as in case of Full Size class, there is presented a calculation pattern leading to determination of vehicle velocity EES and the error.

$$A = \frac{m \cdot b_{sg} \cdot b_k}{L_t} \tag{1}$$

$$B = \frac{m \cdot b_k^2}{L_t} \tag{2}$$

$$G = \frac{A^2}{2 \cdot B} \tag{3}$$

where:
m – mass of the vehicle,
b_{sg}= 3.05 [m/s] - elastic collision velocity,
b_k– constant slope of function V_t=f(C_s), equal to 27 [m/s/m],
L_t – width of the deformation zone [m].

Assumed was the following form of the parameters describing deformation:

$$C_s = \frac{\frac{C_1}{2}+C_2+C_3+C_4+C_5+\frac{C_6}{2}}{5} \tag{4}$$

$$\alpha = C1 + C2 + 2 * (C2 + C3 + C4 + C5) \tag{5}$$

$$\beta = C1^2 + C6^2 + 2 * (C2^2 + C3^2 + C4^2 + C5^2) + C1 * C2 + C2 * C3 + C3 * C4 + C4 * C5 + + C5 * C6 \tag{6}$$

From such calculated coefficients there was determined the work of deformation:

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$$W_{def} = \frac{L_t}{5} \cdot \left(\frac{A \cdot \alpha}{2} + \frac{B \cdot \beta}{6} + 5 \cdot G\right) \qquad (7)$$

Next, the value of velocity EES was determined [20, 22]:

$$EES = \sqrt{\frac{2 \cdot W_{def}}{m}} \qquad (8)$$

The relative error of EES determination is calculated due to the following formula:

$$relative\ error = \frac{EES - Vr}{Vr} \qquad (9)$$

where V_r is the real velocity of the vehicle during the crash test.

It was assumed that the collision is central forward and the restitution phase was neglected what allows assuming ideally plastic deformation of the car body during the impact. Assuming the definition of the kinetic restitution coefficient as a negative ratio of the relative velocities - before and after the accident it leads to neglecting of the relative velocity.

Non-linear character of the relationship between the V_t velocity and coefficient C_s and mass of the vehicle is presented in the figure 3. The presentation of this relationship was done twice

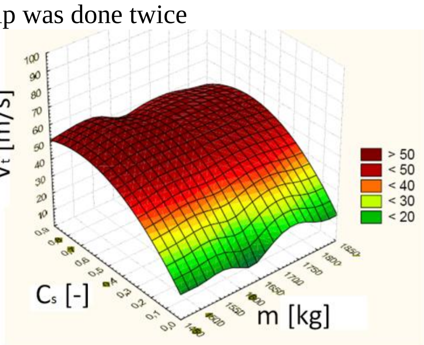

Fig. 3. Relationship between V_t velocity, coefficient C_s and vehicle mass m - method of least squares.

In the figure 3 there is presented the approximation of this relationship using the method of the least squares. Regardless of some visible irregularities in the shape of obtained surface in the Figure there is clearly seen a decreasing tendency of the slope with increasing value of the C_s coefficient. The dependence of this coefficient b_k on the vehicle mass is more complex.

In the Figure 4 there is presented the same relationship in model including approximation with the plane of second order. It does not significantly change the character and shape of the surface.

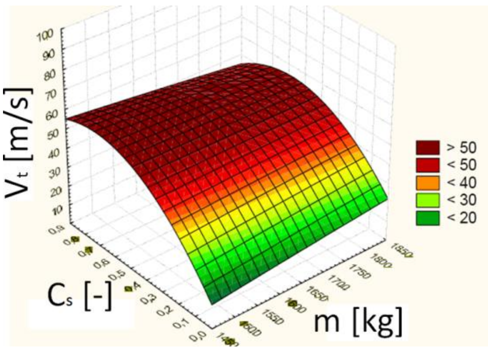

Fig. 4. Relationship between V_t velocity, coefficient C_s and vehicle mass m - plane of second order.

The presented in the Figure 4 dependence became a base to determine non-linear relationship between the b_k and coefficient C_s and vehicle mass.

It is presented in the means of least squares Figure 5 and the plane of second order Figure 6.

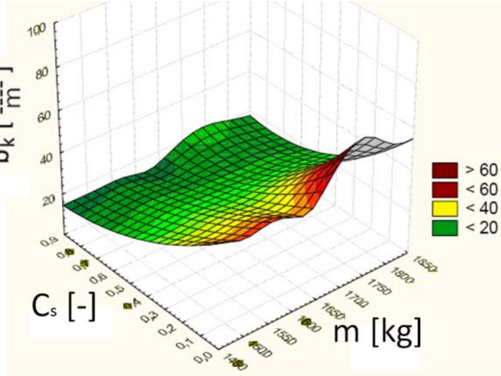

Fig. 5. Relationship between bk coefficient, Cs coefficient and vehicle mass - method of least squares.

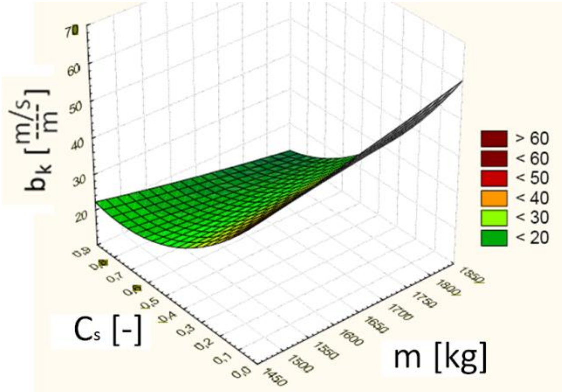

Fig. 6. Relationship between b_k coefficient, C_s coefficient and vehicle mass - plane of second order.

This non-linear model of the b_k coefficient became a reason for using this method.

Basing on the values of b_k coefficient there was calculated, as it was described in previous articles, velocity equivalent - EES and the relative error of V_t determination.

The last two plots present the visible improvement in the accuracy of the vehicle velocity determination. In the figure 7 there is introduced a plot of the precrash velocity determination error due to the linear method, whereas figure 8 presents the same dependence due to non-linear method.

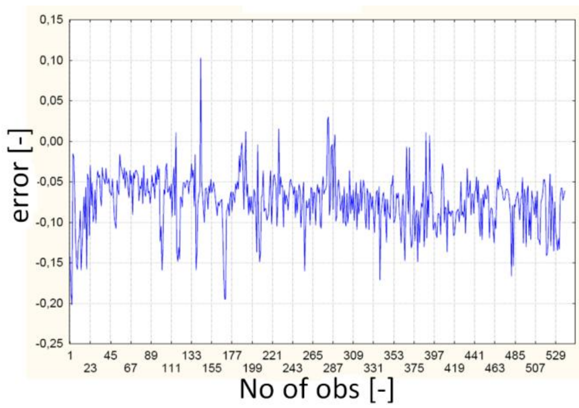

Fig. 7. Velocity determination error - linear method.

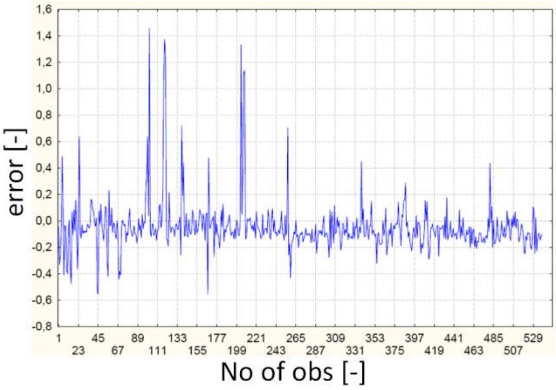

Fig. 8. Velocity determination error - non-linear method.

IV. Exemplary Calculation

The effective depth of plastic deformation is determined as an average at the length of the deformation (Figure 9).

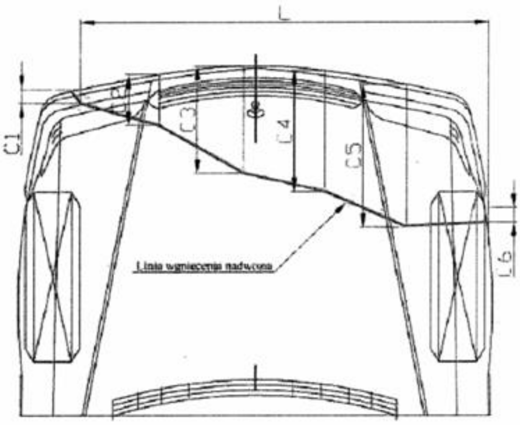

Fig. 9. Measurements of deformation depth.

The determination of the coefficients necessary to perform a crash reconstruction and comparison of the velocity approximation results is illustrated on the following vehicle deformation (Figure 10) example:

Tab. 1. Test parameters.

Vehicle mass m	1586 kg
Crash velocity V_t	47.6 km/h= 13.22 m/s
Velocity corresponding to no plastic deformation	11.0 km/h

The depth of the deformation at 6 points was measured basing on the example and the results are as follows:

Tab. 2. Measurements

Deformation width	**1.502 m**
C1	0.263 m
C2	0.448 m
C3	0.545 m
C4	0.548 m
C5	0.498 m
C6	0.296 m

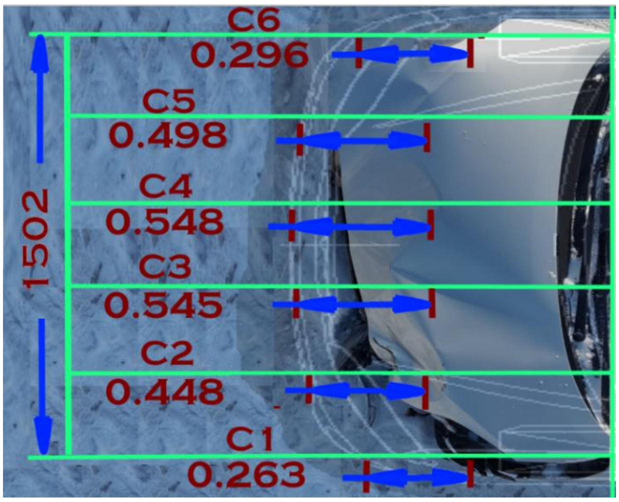

Fig. 10. Measurements of deformation depth.

It enabled calculation of an average deformation coefficient (4):

$$C_s = \frac{\frac{C_1}{2} + \frac{C_n}{2} + \sum_{i=2}^{n-1} C_i}{n-1} = 0.4637\ [m]$$

For the linear method the results are as follows:

$$b_{sg} = 3.05\ [\tfrac{m}{s}]$$

$$linear\ bk = 21.93\ [\tfrac{m}{s}/\text{m}]$$

$$Lt = 1.502\ [m]$$

$$W = 127728{,}4\ [\text{J}]$$

$$EES = 12.313\ [\tfrac{m}{s}]$$

$$linear\ method\ error = 0.06878\ [\text{-}],$$

In case of non-linear model:

$$non-linear\ bk = 25.2114\ [\tfrac{m}{s}/\text{m}],$$

$$non-linear\ W = 161059.5\ [\text{J}],$$

$$non-linear\ EES = 13.82637\ \left[\frac{m}{s}\right],$$

$$non-linear\ metod\ error = 0.045692\ [\text{-}],$$

determining firstly α and β from the relationships (5,6):

$$\alpha = C_1 + C_n + 2\sum_{i=2}^{n-1} C_i = 2.6510\ [m]$$

$$\beta = C_i^2 + C_n^2 + 2\sum_{i=2}^{n-1} C_i^2 + \sum_{i=1}^{n-1} C_i = 3.3298\ [m^2]$$

$A = 75060\ [\frac{N}{m}]$ $An = 86262.5\ [\frac{N}{m}]$

$B = 539867{,}8\ [\frac{N}{m^2}]$ $Bn = 713041.6\ [\frac{N}{m^2}]$

$G = 5217{,}9\ [N]$ $Gn = 5217{,}9\ [N]$

The obtained results differ significantly. Using the non-linear model the result error was decreased essentially. The values are as follows:

- linear method error 7%
- non-linear method error 4%

V. Summary

Further research on the suggested method could modify the applied energy description, as well as, increase the accuracy of vehicle velocity determination by decreasing the error to few percent. The method would be marked with its practical character, possible to apply in real collisions. What is more, it would characterize by low costs and time consumption required for analysis of particular case. The

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authors will seek for obtaining new databases from NHTSA for contemporary crash tests, perhaps including higher number of cases and conducted with higher spectrum of vehicle precrash velocity. It is planned to constantly develop the non-linear model in order to transform it into zonal non-linear model (including the non-linear character in different ranges of the increasing body deformation). It would correspond to the attempt to capture the presented in PIMOT work - the unused relationships of varying body stiffness while the deformation occurs, so that the method of approximation of the theoretical plots (the applied force as a function of the average deformation) could be used as a optimization of the accuracy of the vehicle velocity determination.

In order to improve the results accuracy it is recommended to include higher number of vehicle crash velocities. What is more, it is of particular significance that higher number of tests for each vehicle brand is performed. Each vehicle model should have its own class due to the differences in the construction.

In order to improve the presented method the following aspects should be taken into consideration:

- including asymmetrical impacts
- including cars after tuning

The applied method can be used in programs such as MATLAB or MAPLE. Such model does not require high computational power or high computation time, whereas it can provide a satisfactory convergence of calculation, therefore authors plan on creating a statistical tool that will increase the accuracy of the results.

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