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Determination of Energy Deformation with using NHTSA Stiffness Coefficient

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Abstract*- One of the main problems in appraiser work is to determine what speed the car could have immediately before the accident based only on the collision of car with an obstacle. One of the directions, leading to a solution to this problem is to analyze the energy needed to cause permanent deformation. Since the early 70s, was based on the method, consisting in depth analysis of permanent deformation, which says that the permanent deformation as proportional to the force causing deformation.

Index Terms— **deformation, NHTSA, stiffness coefficient.**

I. INTRODUCTION

One of the main problems in appraiser work is to determine what speed the car could have immediately before the accident based only on the collision of car with an obstacle.

Reconstructing crash with solid obstacle the vehicle or crashing two vehicles to the deal with records of damages which in Poland does not be standardize to principles her preparing.

Searches in world literature show, that it exists many methods of documenting the damages of vehicle and establishing the speed, which caused these damages

The different standards with development of scientific investigations became in USA about discussed problem. One of them served to standardization of ways of processing from the real accidents in aim of improvement of safety of construction of vehicles, different to standardization with crash tests the data as well as the standardizing the methods of analysis of crashes, applied in appraiser practice.

Particular meaning these works took in USA, when then president Lyndon Johnson, touched with fact, that in only 1965 year on roads in USA 50000 men died, affirmed, that" car incidents are among Americans the most frequent cause of death and injuries below 35 year of life". In September 1966 r. signed two momentous laws:

„National Traffic and Motor Vehicle Safety" and

„National Highway Safety".

These acts authorized to creation in 1966 year Federal Motor Vehicle Safety Standards (FMVSS) and National Traffic Safety Agency (NTSA) transformed later in National Highway Traffic Safety Administration (NHTSA). The NHTSA at present time is the largest institution deal with the safety of road movement.

The review of American investigative programs and standards in field of safety of road movement shows on rise of programs marked as:

- VDI - Vehicle Deformation Index [12][13][14],
- CDC - Collision Deformation Classification [15],
- TAD - Traffic Accident Data [16],
- SMAC - The Simulation Model of Automobile Collisions [17],
- CRASH - Calspan Reconstruction of Accident Speeds on the Highway [18] defined at present as Computer Reconstruction of Accident Speeds on the Highway.

In the beginning years 70in Poland - function and still be applied the simplified method of opinion of speed crash, depending on analysis of depth of permanent deformations which tells that permanent deformation is proportional to causing this deformation strength. This affirming brings closer dependence:

$$W_{def} = \frac{1}{2} \cdot b \cdot h \cdot k \cdot f_{tr}^2 \qquad (1)$$

where:
b - width of deformation zone [m],
h - height of deformation zone [m],
f_{tr} - depth of deformation zone [m],
k - stiffness coefficient or energy-consumption [N/mm^2].

In literature [1] the following ranges of the stiffness coefficient can be found:

according to information from 70's [8][18]:

- k=(9,0 – 11)*10^5 N/m^{2}m,when the vehicle strength structure was broken as a result of the deformations,
- k=(2,0 – 4,0)*10^5 N/m^{2}m, when the deformations are located only in the skin plate elements.

according to information from 80's [18]:

when the vehicle strength structure was broken :

- k=(13,5 – 22,6)*10^5 N/m^{2}m for small vehicles,
- k=(9,1 – 13,5)*10^5 N/m^{2}m for medium cars,
- k=(5,2 – 7,2)*10^5 N/m^{2}m for big car.

according to data from [4],

- for cars of beginning XXI age k = (15÷ 9)*10^5 [N/m^{2}m].

Large divergence of this coefficient leads to of vehicles crash test having on investigations aim to specify their value. Investigations these are led in a part of work over safety of traffic and the assurance of safety for passengers of vehicles.

The collision test of vehicle with stiff obstacle on his track is basic investigation. In time of test for the vehicle driving with settled, standardize speed the permanent deformations of elements of vehicle and particularly his body be measured after crash.

It is aim of these investigations:

- in time of colission tests – connection the speed of vehicle in moment of crash with contact deformations his body,

- in time of reconstruction of event the - estimation of approximate speed of vehicle in moment of crash on basis of contact deformations of body.

The following general foundations in track of investigations are accepted:

- rotation in after crash movement characterizes with solid resistance of motion,
- twisting steering wheels are constant (it does not change),
- movement be holds on / after flat surface, adhesion coefficient is constant,

when crash vehicles follows additionally:

- in moment crash the point of contact of vehicles has constant speed,
- do not apply models (programs) to crashes sliding.

II. MODELS

A. Campbell model

Taking into account of following foundations led to rise models called from surnames of their authors. Crash test model proposed by Campbell [2] introduces the proportionality between deformations and speed collision.

$$V = b_0 + b_1 \cdot C \qquad (2)$$

where:
V – collision velocity when the deformation C occurs [m/s],
b_0- limit velocity where the permanent deformation do not occur [m/s],
b_1 – characteristic inclination $[m/ms]$,
C – depth of the permanent deformation [m].

B. McHenry model

On beginning of 70's R. McHenry [3] proposed linear dependence between a force acting on the car and permanent deformations appearing as its acting result. According to McHenry it can be illustrated by equation (3) and graphic (figure 1).

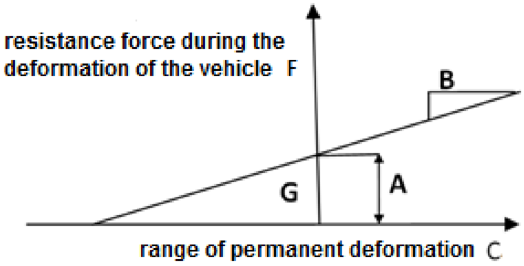

Fig.1 Stiffness model of the vehicle during a collision by McHenry.

$$F = A + B \cdot C \qquad (3)$$

where:
F - unit force of deformation,
A - unit boundary force, after transformation of which it plastic deformation occurs,
B - directional coefficient of linear body model deformation, defining its lengthwise unit stiffness,
C - Permanent body deformation.

The value of the C coefficient is obtained from the measurements of deformation's depth. In the crash test used was procedure of measuring its value in n points, that are evenly disposed on length of the indentation, as shown on the figure 2.

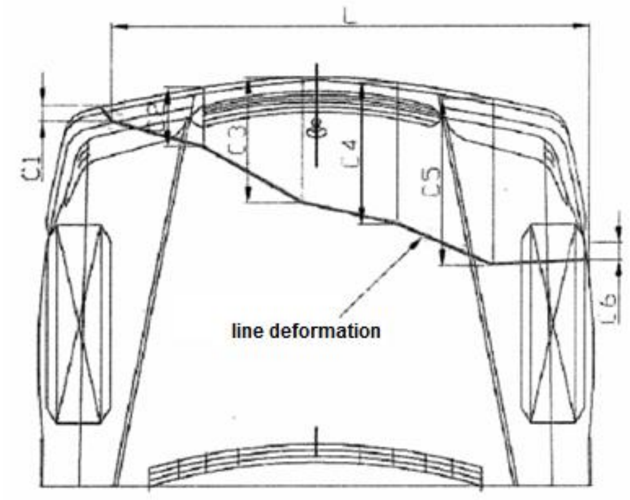

Fig. 2 Method of depth dimensioning of the permanent deformation.

The effective depth of deformation is defined as mean value on the length of indent and can be presented by the following relationship:

$$C_{sr} = \frac{\frac{C_1}{2} + \frac{C_n}{2} + \sum_2^{n-1} C_1}{n-1} \qquad (4)$$

The energy which causes permanent deformation on length L is expressed in the following way:

$$\int_0^L \int_0^C (A + B \cdot C)dcdll = \int_0^L (A \cdot C + B \cdot \frac{C^2}{2} + G)dl \qquad (5)$$

where:
G - integration constant equal,

$$G = \frac{A^2}{2 \cdot B} \qquad (6)$$

L - width of the deformation area [cm].
After integration we obtain:

$$E = A \int_0^L C dl + B \int_0^L \frac{C^2}{2} dl + \frac{A^2}{2 \cdot B} \cdot L \qquad (7)$$

Individual modules of the equation (7) can be defined in the following way:

- $\int_0^L Cdl$ as indent projection’s surface,
- $\int_0^L \frac{C^2}{2} dl$ as moment of the first degree of projection of the indent surface in relation to primary body profile (product of surface of projection and distance of its center of gravity from the first outline of the car body).

It is assumed that all deformation areas have shape of trapeze, it shows figure 3.

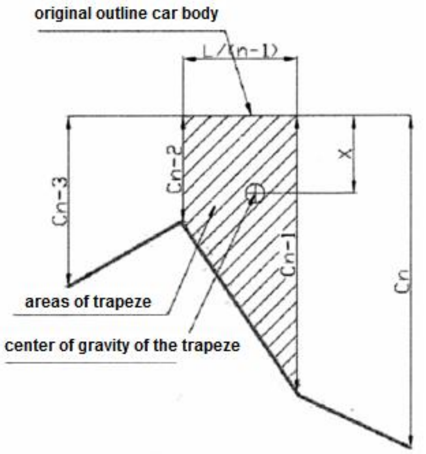

Fig. 3 Method of the determination of the deformed surface gravity center location

The surface of deformation unit is determinate from equal.

$$P = \frac{L}{n-1} \cdot \frac{C_{n-2}+C_{n-1}}{2} \quad (8)$$

While the distance of center of gravity from primary profile of body is obtained from

$$X = \frac{C_{n-2}^2+C_{n-2}+\cdot C_{n-1}+C_{n-1}^2}{3\cdot(C_{n-2}+C_{n-1})} \quad (9)$$

The energy necessary to cause the indentation of the surface *L* and of average depth C_{sr} can be expressed by:

$$E = \frac{L}{n-1} \cdot \left(\frac{A\cdot\alpha_1}{2} + \frac{B\cdot\beta}{2} + (n-1)\cdot G\right) \quad (10)$$

where:

$$\alpha = C_1 + C_n + 2\cdot\sum_{i=2}^{n-1} C_i \quad (10a)$$

$$\beta = C_i^2 + C_n^2 + 2\cdot\sum_{i=2}^{n-1} C_i^2 + \sum_{i=1}^{n-1} C_i \cdot C_{i+1} \quad (10b)$$

In case of symmetrical deformation, the equation takes the form:

$$E = \left|A\cdot C + \left(\frac{B}{2}\right)\cdot C^2 + \frac{A^2}{2\cdot B}\right| \cdot L \quad (11)$$

If then, the energy absorbed by the vehicle for the deformation work is equivalent to the car kinetic energy , that is lost during the crash, then we can to assume, that

$$\frac{m\cdot(\Delta V)^2}{2} = E \quad (12)$$

$$(\Delta V)^2 = \left(\frac{2\cdot A\cdot L}{m}\right)\cdot C + \left(\frac{B\cdot L}{m}\right)\cdot C^2 + \frac{A^2\cdot L}{m\cdot B} \quad (13)$$

$$\Delta V = \sqrt{\frac{B\cdot L}{m}} \cdot \left(C + \frac{A}{B}\right) \quad (14)$$

Therefore, the conclusion is that the border speed of the crash that do not result in permanent deformation and for which the C = 0, has the form:

$$\Delta V_{gr} = b_0 = A \cdot \sqrt{\frac{L}{B\cdot m}} \quad (15)$$

Conducted by NHTSA investigations show, that border speed b_0 contains in range b_0 = 2÷4 m/s = 7,2÷14,4 km/h. Figure 4 presents graph which is speed characteristic in function of depth of body deformation (coefficients b_0 and b_1 correspond to coefficients defined by Campbell).

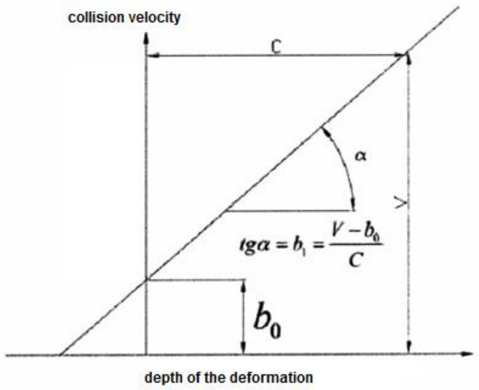

Fig. 4 Campbell dependence of the velocity of the body at the moment of the crash form the depth of the deformation.

Coefficients A, B and G are defined during cars crashes test in such way, that the surface of barrier in which the vehicle hits is perpendicular to longitudinal or transverse vehicle axis. In the case of diagonal crashes, tangent component of friction force contained among barrier and the vehicle increases the stiffness efficiency in direction of main impulse of force.

Coefficients A and B can be found in literature [4,5,6]. Such coefficients in country are propagated also it was showed in table 1. They are brought back to settled size of vehicle mass. However how the mass of similar vehicles results with practice in use is not constant size, which leads to indefinable mistake estimating. According to recommended by NHTSA for groups of vehicles data, both the wheelbase how and the mass be defined in sizes for sure their compartments (tolerated).

Table 1: Values of the coefficients A and B [17]

Parameter		Category				
		Mini	Subcompact	Compact	Intermediate	Van
Wheel base [cm]		205-240	240-258	258-280	280-298	276-330
Track of wheels [cm]		129	138	149	157	171
Length [cm]		405	444	498	540	466
Width [cm]		154	170	184	195	200
Weight [kg]		1000	1386	1610	1928	1952
Hitting the front	A [N/m]	529	454	555	623	671
	B [N/m^2]	32	30	39	23	87
Hitting back	A [N/m]	641	685	718	625	525
	B N/m^2]	26	28	30	9	38
Side impact	A [N/m]	135	245	303	250	-
	B [N/m^2]	26	46	39	34	-

For concrete models of vehicles, it is possible in reports in NHTSA investigations to find the speed of crash, the mass of cars as well as depth of deformation from direct contact in six evenly disposed points of this area. NHTSA reports are accessible in [7]. It is data base including information about crash tests. It contains the vehicles ranked according to manufacturer, the type of, model, of year production. The data base contains picture of the serfs' cars the tests also, they can this the also very helpful materials the servants to estimation of speed of crash.

In enclosed tables of included are values of the speed answering the zero permanent deformation

$$b_0=V_0 \qquad (16)$$

and knowing both mass of the vehicle and length of the deformation area, it is possible to calculate factor of proportionality

$$b_1=\frac{V_{zd}-V_o}{C_{sr}} \qquad (17)$$

C. *Crash3 method*

The **CRASH3** method analyze the deformation of vehicle. It enable assign the EBS parameter (Equivalent Barrier Speed) - the equivalent of European coefficient the EES, on basis of measured contact deformations of vehicle together with division of stiffness of body for different categories of vehicles and different directions of hitting which received in USA universally standard of analysis of crashes. He became applied in two newest European programmers RWD [16] and PC - Crash 7.0 (DSD PhD. Steffan Datentechnik - Linz)

CRASH3 method requires to determinate following coefficients:

- the unitary limit force falling on the area of deformation, after crossing which it comes to plastic deformation of contact zone:

$$A=\frac{mb_0b_1}{L}\ [\mathrm{N/m}] \qquad (18)$$

- coefficient of linear model of permanent deformation / the contact body, defining his unitary longitudinal stiffness:

$$B=\frac{mb_1^2}{L}\quad [\mathrm{N/m^2}] \qquad (19)$$

The distracted on area of deformation body energy was estimated from dependence:

$$E_d=A\cdot\eta+B\cdot\gamma+G\cdot L\ [\mathrm{Nm}] \qquad (20)$$

where:

η - surface of horizontal area throw among original shape of vehicle body and line of contact deformation,

γ - First Moment of Inertia (1st MOI) in relation to defining original line, misshapen with shape of vehicle body and line of contact deformation. Graphic values shows onfigure 5.

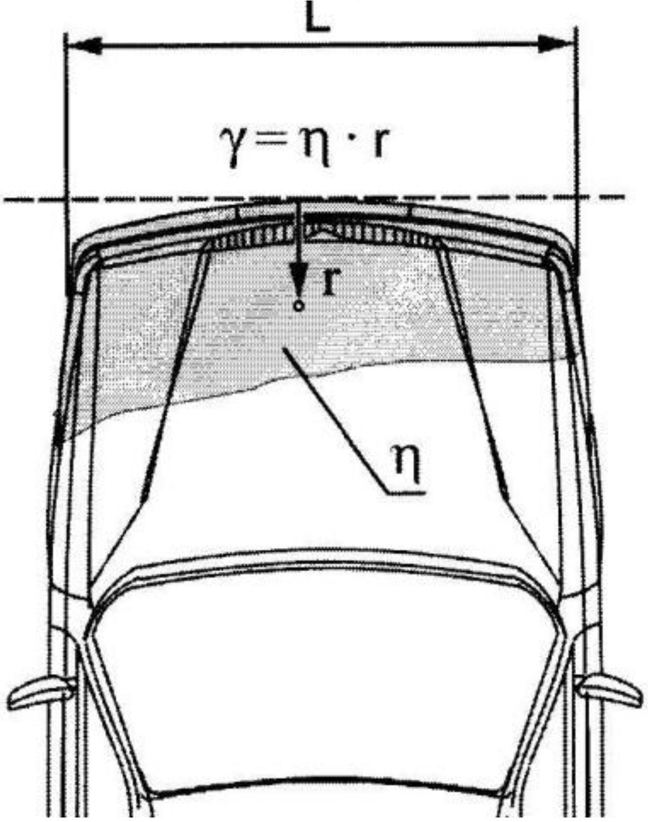

Fig. 5 Graphic sense of parameters η and γ.

EBS parameter, equivalent European EES, was assigned from dependence:

$$\mathbf{EBS}=\sqrt{\frac{2\cdot Ed}{m}}\ \mathbf{[m/s]} \qquad (21)$$

where m is mass of vehicle [kg].

III. EXAMPLE

Establish indispensable coefficients for reconstruction of speed crash. Compare the results of estimating speed of crash on example of damage vehicle for following data:

Length	4,363 [m]
Height	1,391 [m]
Width	1,712 [m]
Wheel base	2,642 [m]
Mass of vehicle	1345 [kg]
Speed of test crash V_{zd}	48,7 [km/h]
Zero speed of deformation V_o	11,0 [km/h]

Depth of damages were measured in support about their showed on drawing picture. They are this:

Width of deformation	1,61[m],
C1	0,347 [m],
C2	0,429 [m],
C3	0,487 [m]
C4	0,490 [m]
C5	0,429 [m]
C6	0,353 [m]

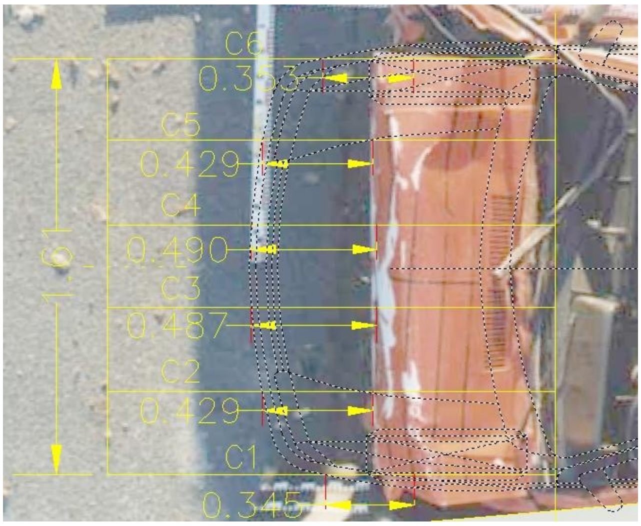

Fig.6 The measurement the depth of damages.

To mark the required coefficients A and the B on basis of investigative practice was accepted $b_0=V_0=$ 11 km/h. Permitted on calculation on length of indent the average of value according to (4).

$$C_{sr} = \frac{\frac{C_1}{2}+\frac{C_n}{2}+\sum_{i=2}^{n-1} C_i}{n-1} = 0{,}437 \text{ [m]}$$

from dependence (17) was assigned:

$$b_1 = \frac{V_{zd}-V_0}{C_{sr}} = 23{,}96 \text{ [m/s]}$$

from dependence (18) assigned unitary limit force of deformation

$$A = \frac{m b_0 b_1}{L} = 611{,}94 \text{ [N/cm]}$$

from dependence (19) determined directed linear coefficient permanent deformation model:

$$B = \frac{m b_1^2}{L} = 47{,}99 \text{ [N/cm}^2\text{]}$$

from dependence (6) assigned unitary elastic energy of deformation

$$G = \frac{A^2}{2 \cdot B} = 3\,901{,}29 \text{ [N]}$$

from dependence (10_ determined stable energy of deformation,

$$E = \frac{L}{n-1} \cdot \left(\frac{A \cdot \alpha_1}{2} + \frac{B \cdot \beta}{2} + (n-1) \cdot G\right) = 123\,867 \text{ [J]}$$

marking previously values α i β rom dependence (10a and 10b)

$$\alpha = C_1 + C_n + 2 \cdot \sum_{i=2}^{n-1} C_i = 4{,}37 \text{ [m]}$$

$$\beta = C_i^2 + C_n^2 + 2 \cdot \sum_{i=2}^{n-1} C_i^2 + \sum_{i=1}^{n-1} C_i \cdot C_{i+1} = 2{,}89 \text{ [m}^2\text{]}$$

Using dependence (12)

$$\frac{m \cdot (\Delta V)^2}{2} = E$$

where substituting for D_v = EBS is possible to delimitate value of this parameter:

EBS = 13,5 [m/s] = 48,7 [km/h]

Results of this test were compared with enumerations presented in publication data [17] is show in table 2.

Parameter	Unit	Calculations by Crash 3	Data according to [17] for calculation	
Leading parameter			weight	wheelbase
Leading size			1386	2,25÷2,80
A	N/cm	611,94	454	555
B	N/cm2	47,99	30	39
EBS	km/h	48,7	40,2	45,2
%	%	100,0	82,4	92,5

Table 2: Results of experiment.

IV. CONCLUSION

Estimation value of EES parameter (the speed is equivalent energy) it is the difficult question of analysis of mechanics crash. In dependence from applied method the calculations the parameter helps in approximate way to mark the collision speed of the vehicle and different time is the valuable supervisory modifier.

It exists published in including picture of the serfs' cars the crash tests catalogues the possibility of delimitation of speed of conflict across utilization the energetic coefficients together with applied protocols.

However the value of the EES parameter on basis of calculations can contain the resulting from non regard the springy deformations mistakes it therefore in this case was it been possible to get approximate value of this parameter . The exact estimation of deformation energy of vehicle has place near using crash tests only, which take into account all kinds of deformations.

In 1974 r. Campbell published article which began the analyzing the process of crashing from energetistic side vehicles. Using crash tests, he put that among speed crash and dependence exists with depth of permanent deformation. He noticed, that absorbed part of energy during crash it gets distracted on elastic deformation.

The parameter the EBS was named the speed the vehicle, near which the kinetic energy was even the energy absorbed on plastic deformations, that is on work of deformation.

The introduced in article example illustrates method of establishing the EBS coefficients indispensable to execution of reconstruction. Received results were compared from literature data. Differences in settled values contained EBS in table 2 appear with accuracy of received methods. Known it is that the older methods were less exact as they based at on different structure of body than the present methods. However the 17% differences permit to measure exact of estimate speed. Should to expect, that lost allowance energy on elastic deformations it will permit on sensible increase exactitude of all methods..”

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