Estimation of driver and passenger injuries during a car crash based on the accident reconstruction method

Przemysław Kubiak, Andrzej Szosland, Jan Awrejcewicz, Bartłomiej Zagrodny

Abstract: In this paper a method of determination of vehicles speed before the collision is presented. Basing on the analyzed data the accelerations during the accident injuries of a driver and passengers have been estimated. The primary objective of this study is to find a precise correlation between the vehicles speed in the early phase of the collision as well as the energy amount responsible for the deformation occurrence. Speed of vehicles during the first phase of the collision has been determined through a comparison of the vehicle kinetic energy and the body deformation. Application of the method of energy equivalent speed (EES) parameter for estimation of the size of destruction yielded more reliable results in comparison to the commonly used standard approaches. This approach has been further extended to estimate more reliable amount of both energy and acceleration transited to the driver and passengers, which allows to control and avoid potential driver/passenger injuries.

Introduction

The primary objective of this study is to look for car crash relationship between the speed of the vehicle in the early phase of the collision, and the energy required to cause the deformation. Speed of vehicles colliding at the beginning phase of the collision is determined by comparing the kinetic energy with the energy of deformation of the body. Based on evaluation methods for parameter EES developed a new method to estimate the size of aiming to obtain more accurate results from both the newly selected coefficients A and B, as well as slope values b_k and unit energy absorbed elastic deformation G. Given the existing methods proposed a new method of computing the value of EES parameter, which is shown below. This new algorithm allows calculate to quite exact values of expected parameter EES for selected ratios of A, B, G, b_k parameters. Additionally, on the basis of the data published in literature [11-13] and pathological report, an attempt was made to estimate a speed range at the moment of collision. Data were taken from a real accident.

1. Modified EES method

For the implementation of the presented method is necessary to determine the stiffness coefficients. For this purpose, carried out were the analysis of the crash tests from NHTSA database. Selected were the head on – collision tests with the vehicles with theoretically non-deformed, rigid barrier. Omitted was the work of deformation of the barrier. Important parameters taken for further calculations are linear and angular velocities which appear immediately after the removal of the shock impulse. The impulse is applied at the geometric centre of mass of deformation area, which is also the centre of the deformation. Assuming that the impact impulse was acting along the longitudinal axis of the vehicle, there was no vehicle rotation in post-collisional motion, and the angle of impact force from the longitudinal axis of the vehicle is $\theta = 0\,°$. The NHTSA database was sorted by the year of the vehicle, vehicle class and type of drive. Selected systematization included division into classes depending on vehicle weight. The juxtaposition is summarized in Table 1

Table 1.1. List of classes of vehicles based on vehicle weight

Mass interval [kg]		**Class of vehicles**
do	900	Mini (City)
900	1250	Small
1250	1480	Compact
1480	1790	Middle
1790	2070	Middle-higher
2070	3500	Luxuries

The breakdown in terms of the type of drive included the distinction between transmission with automatic and manual gearboxes with front and rear axle's drives as well as distinction of the manual and automatic gearboxes with 4WD drive .An important step in the proposed method is to determine the profile of the deformation of the body. Due to suggestef of the improvements of the accuracy of the mentioned method the measurement can be made done in 2, 4 or 6 points. This involves the construction of a car. Measurement of the smaller number of points would be an error due to the structural heterogeneity of the body of the vehicle. Therefore, the length of the deformation area L_t (see Figure 1) should be divided into five equal sections and the depth of indentation in the corresponding six points should be measured. This was achieved as shown in Figure 1.1. The measurement is carried out parallel to the plane of the roadway and the deformed surface is perpendicular to the direction of deflection regardless of the impact force . For the purposes of this article assumed was that the measurements are taken in six points.

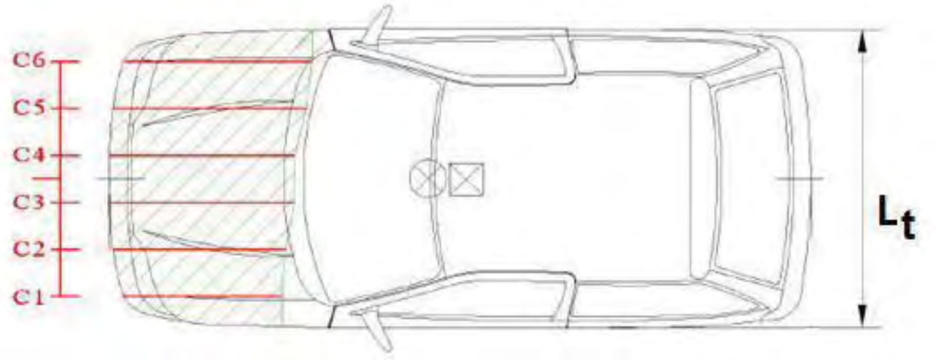

Figure. 1.1. Example of measuring the deformation of the body

Based on these values the C_s parameter is calculated which is the geometric mean of the parameters determining the depth of deformation of C_1-C_6. Calculations are performed in the following manner :

$$C_s = \frac{\frac{C_1}{2} + (C_2 + C_3 + C_4 + C_5) + \frac{C_6}{2}}{5} \quad (1)$$

Assuming that all of these strains will have the shape of trapezoids. For this reason, taking into account the 6 segments in the form of trapezoids the average value is determined basing on the above formula. The calculated value of C_s was used to determine the stiffness constant b_k by the formula:

$$b_k = \frac{V_t - b_{sg}}{C_s} \quad (2)$$

Graphical interpretation of these factors is shown in Figure 1.2.

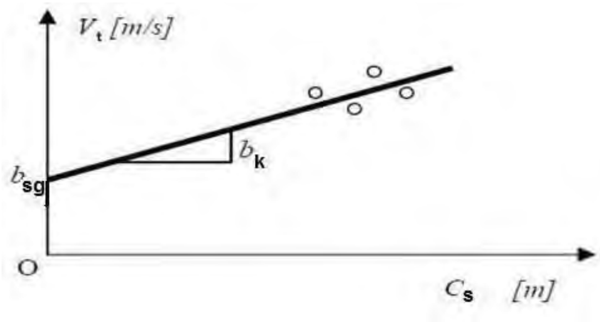

Figure 1.2. Graphical interpretation of the parameters

The value of maximum speed, at which a permanent deformation was established, is adopted as b_{sg} = 11km / h. After determining the parameters of average indentation C_s and b_k it is possible to determine the stiffness parameters A and B:

$$A = \frac{(m_t \cdot b_{sg} \cdot b_k)}{L_t} \tag{3}$$

$$B = \frac{m_t \cdot b_k^2}{L_t} \tag{4}$$

where: m_t – value of the weight of the vehicle [kg] and L_t – width of the deformation [m].

Angular coefficient b_k is indeed determined as plotted , but its value were determined in the work for the classes and the ages of vehicle . Because the values of b_k were established on the basis of more than 30, 000 pending cases, their values can be regarded as highly probable. In this way, determined is the stiffness coefficients for the individual classes of vehicles , which were aligned in accordance with the type of drive. The obtained values were averaged to give the final parameters A, B and G that could be applied for the proposed method. Overview of crash tests demonstrated the feasibility of the difference values of the coefficients for specific vehicles and for the entire class of vehicles. Incorrectly estimated parameters A and B give the false values of the velocity equivalent energy . To avoid this error, the correction factor was proposed. It takes into account the size of the interval (m_{gk}-m_{gp}) , in which there is the weight of the test vehicle:

$$\sigma = \frac{m_t}{m_{gk} - m_{gp}} \tag{5}$$

where: m_t - weight of the test vehicle [kg], m_{gk} - maximum weight boundary of weight range [kg], m_{gp} - minimum weight boundary of weight range [kg].

Therefore, it is proposed for the coefficients A and B to by corrected by a factor of σ and the avaraged values of the variables were adjusted as follows:

$$A_s = \sigma \cdot A \tag{6}$$

$$B_s = \sigma \cdot B \tag{7}$$

G-factor, which is a unit of energy absorbed in the elastic deformation is calculated using the method set out in the proposed coefficients A_s and B_s. It is described by the relationship:

$$G = \frac{{A_s}^2}{2 \cdot B_s} \tag{8}$$

Part of the energy absorbed during a head-on collision is dissipated in the elastic deformation and converted into deformation work. This effect can be seen in correlation illustrating the method of calculating the deformation work W_{def} from damage with a range of deformation L_t:

$$W_{def} = \frac{L_t}{5} \cdot \left(\frac{A_s \cdot \alpha}{2} + \frac{B_s \cdot \beta}{6} + 5 \cdot G\right) \cdot k_e \tag{9}$$

Constant deformation coefficients (α and β) depend on the method of measuring of deformation, i.e. the number of points at which the measurement of deformation was conducted *(C_1-C_2)*. These parameters are calculated using the following algorithms:

$$\alpha = C_1 + C_2 + 2 \cdot (C_2 + C_3 + C_4 + C_5) \quad (10)$$

$$\beta = C_1^2 + C_6^2 + 2 \cdot (C_2^2 + C_3^2 + C_4^2 + C_5^2) + (C_1 \cdot C_2 + C_2 \cdot C_3 + C_3 \cdot C_4 + C_4 \cdot C_5 + C_5 \cdot C_6) \quad (11)$$

The energy of deformation can be adjusted depending on the angle of deviation from the normal plane of dents front of the vehicle. Energy correction factor k_e is calculated using the relationship:

$$k_e = 1 + tg^2\theta \quad (12)$$

Finally, the value of vehicle speed at which the kinetic energy is equal to the energy absorbed to plastic deformation - *EES*, is determined from correlation allowing for the calculation of deformation of the work depending on the geometry of the deformation

$$EES = \sqrt{\frac{2 \cdot W_{def}}{m_p}} \quad (13)$$

The deformation remaining after bouncing from the wall of the vehicle are the result of plastic dissipation of kinetic energy, graphically shown in Figure 1.3. It illustrates the course of the force acting on the barrier during vehicle impact. As can be seen the force reaches a maximum value of about 1000 kN.

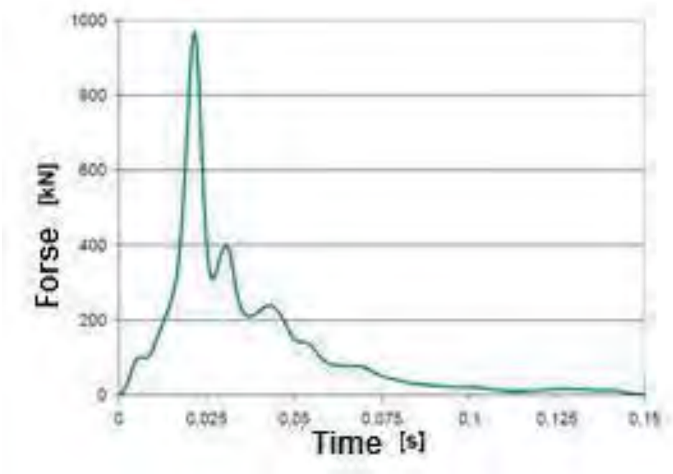

Figure 1.3 The impact force exerted by the vehicle on a rigid barrier at 80 km / h

On the basis of the course of deformation during a collision, the body deformation characteristics obtained in the form of punching force versus the deformation body (Figure 1.3). This can be illustrated in such a way that the initial collision energy is absorbed by the beam front, with the deformation of approximately 100 mm and then by the stringers and gas block.

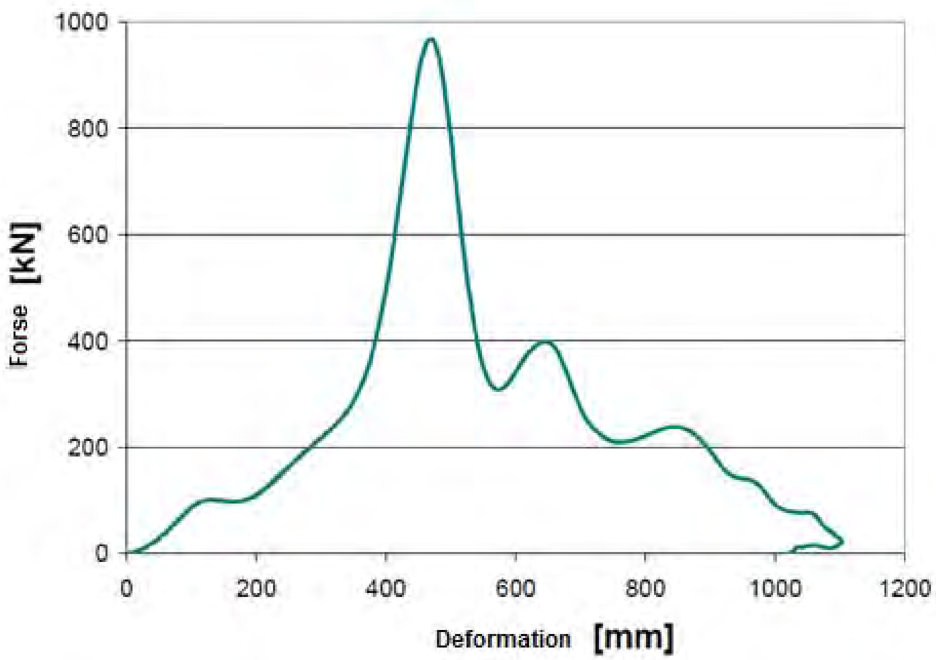

Figure 1.3 Characteristics of deformation vehicle at a speed of 80 km / h

2. Benefits of the proposed method

The different techniques to calculate the parameter EES, which was the essence of Campbell's method are based on the linear relationship between the depth of deformation and strength of the resistance during the deformation of the vehicle. The proposed method adopted similar assumption of linearity of the quantities. In addition it describes the parameters denoted by analogy to the Campbell model with the same symbols, so you can use them directly for comparison. In this model, the implemented linear force acting on the deformable part of the vehicle relative to the width of the front part of the vehicle . Continuing the trajectory parameters F , A, B was estimated per unit width of the deformation. Thus, the relationship that occurs between the average force acting during deformation and permanent deformation Cs coverage takes the following form

$F = A + B \cdot C_s$ (14)

A- strength at which there is no permanent deformation to the formation of , B - body rigidity factor that determines the force necessary to reduce the creation of the individual vehicle , Cs - range of permanent deformation

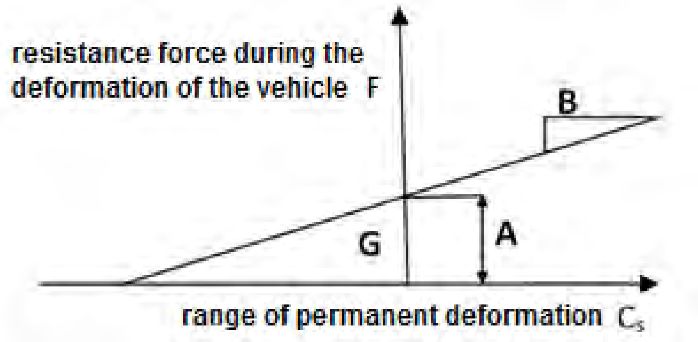

Figure 1.4 The unit force of a head-on impact

Verification of these hypotheses are compatible deformation values defined on the basis of the proposed model with the actual values.This means that the proposed modification can be applied to analysis of actual traffic collisions. However, linking the proposed method with existing methods so far is througt the use of a linear form of equation (1.14) proposed by Campbell.

Example

Vehicle of mini class is driving test at a speed of 80 km / h to hit head-on into a wall experiencing strain indentation of the following depths:C1 = 0.83 [m], C2 = 0.92 [m], C3 = 0.984 [m], C4 = 0.989 [m], C5 = 1.028 [m], C6 = 0.996 [m]For each method, the following results were obtained

Table 1.2 Summary of results

Parameter\Method	Results obtained from crash tests	Results from [10]	Results from the proposed method
C_{Avet} [m]	0,967	0,967	0,967
A$[\frac{N}{m}]$	375	529	460
B$[\frac{N}{m}]$	24	32	37
σ $[-]$	–	-	0,86

$A_s[\frac{N}{cm}]$	–	–	334447
$B_s[\frac{N}{cm^2}]$	–	–	2350174
G [N]	29	44	29
α [m]	9,7	9,7	9,7
β [m2]	14,1	14,1	14,1
k_e	1	1	1
W_{def} [J]	191 786	256 898	238 184
EES $[\frac{km}{h}]$	80,09	92,69	89,25

Table 1.3 Evaluation of the results

	EES [km/h]	Percent of the value from the test	The percentage of error [%]
Benchmark	80,09	-	-
For values from the literature [10]	92,69	1,16	16
For the proposed method	89,25	1,11	11

Comparison of results obtained by the proposed method with the results obtained from the experimental data show that the proposed method provides results more consistent with benchmarks EES_{wz}.

Analysis of the actual vehicle deformation

The setting of the speed is necessary to reconstruct the example of collision allows to estimated the actual damage to the vehicle, characterized by the following data:

Profile crushing C_1= 470 mm, C_2=429 mm, C_3=521 mm, C_4=492 mm, C_5=464 mm, C_6=409 mm

$$C_{Avet} = \frac{\frac{C_1}{2} + \frac{C_6}{2} + (C_2 + C_3 + C_4 + C_5)}{5} = 0,469 \text{ [m]} \tag{15}$$

The value of the parameters A and B are taken from the data calculated from the table below

Table 1.4 Parameters depending on the class of vehicle

		Mini(City)	Small	Compact	Middle	Middle-higher	Luxuries
Weight	kg	Do 900	900-1250	1250-1480	1480-1790	1790-2070	2070-3500
wheelbase	mm	2073	2240	2305	2376	2826	3569
Length	mm	3609	4027	4296	4551	4646	5644
Width	mm	1518	1570	1625	1689	1731	1869
m/s/	b1	24	26	27	27	27	26
N/m	A	460	670	793	927	1017	1100
N/m^2	B	37	60	74	90	94	99
N	G	*29*	*39*	*44*	*51*	*57*	*65*

According to the adopted mass of the vehicle obtained are the following parameters or the class of Small

A= 670$[\frac{N}{m}]$, B= 60$[\frac{N}{m^2}]$, G=39[N]

$$\sigma = \frac{m_t}{m_{mk} - m_{mp}} = 3{,}3\ [-]$$

$$A_s = \sigma \cdot A = 220\ 908\ [\frac{N}{cm}]$$

$$B_s = \sigma \cdot B = 1\ 978\ 286\ [\frac{N}{cm^2}]$$

$$\alpha = C_1 + C_2 + 2 \cdot (C_2 + C_3 + C_4 + C_5) = 4{,}1 \quad [m] \tag{16}$$

$$\beta = C_1^2 + C_6^2 + 2 \cdot (C_2^2 + C_3^2 + C_4^2 + C_5^2) + (C_1 \cdot C_2 + C_2 \cdot C_3 + C_3 \cdot C_4 + C_4 \cdot C_5 + C_5 \cdot C_6) = 2{,}6 \quad [m^2]$$

$$k_e = 1 + tg^2 0 = 1$$

The work of deformation was determined

$$W_{def} = \frac{L_t}{5} \cdot \left(\frac{A_s \cdot \alpha}{2} + \frac{B_s \cdot \beta}{6} + 5 \cdot G\right) \cdot k_e = 417\ 272\ [J] \tag{17}$$

Finally, it was possible to estimate the EES

$$EES = \sqrt{\frac{2 \cdot W_{def}}{m_p}} = 27\ \left[\frac{m}{s}\right] = 97\ [\frac{km}{h}] \tag{18}$$

Analysis of injury.

According to the medical report it is stated that the death of the driver was caused by the trauma of driver's head and cervical spine. There were observed a serious calvarial and base of skull fractures on the left side (frontal and sphenoid bone), intracranial hemorrhage and fracture of the cervical spine (between the vertebrae C4 and C5) in addition to the front longitudinal ligament rupture.

Further analysis of the report indicates that the head of the deceased was struck with a high speed in a barrier, contact occurred primarily in the frontal area as shown by the extensive injuries in frontal and parietal left, left nasolabial fold, cheek and nasal septum, upper lip sore, but only minor, superficial damage of the lower lip, sugillationes in the left fronto-parietal-temporal area and on the face.

In addition, it is stated that the deceased had signs of other chest injuries (including the first right rib fracture) and limb injuries. However, none of these injuries were fatal.

According to publications [11] and [b] basing on these head injuries, defined was that the acceleration / deceleration of the head exceede 80 G and impulse duration was in the range of 30-40 ms.

Based on that information the speed of the driver just before hitting the barrier was estimated in the range from 85 to 113 km/h

Conclusions

The paper presents the method of calculation of the EES, which is based on the parameters estimated from time to rank the NHTSA database. Selected by only testing head-on collisions, and ranked them by the year of manufacture of the vehicle and the type of drive system. This allowed for calculation of he stiffness for different types of vehicles. Analysis of the results of the EES show that the introduction of a correction factor σ used in the algorithm of the proposed method makes it possible to have a much better and closer to reality results than use of other analytical methods. σ coefficient unit corrects values of force and a directional linear boundary deformation model dependent mass. Implementation of this parameter is associated with the fact that the test vehicle weight not only sets belonging to the class of vehicles. The presented algorithm resulted in improved accuracy and standardization of analysis designed to estimate the parameter values EES. The proposed method achieved results similar to those obtained during the crash test, reaching a value only slightly different from the standard. It can be concluded that the proposed method is one of the best methods of analysis.

Presented method for determining a vehicle speed based on the analysis of injuries of persons involved in accidents is not very precise. It should be stressed that the damages during road accidents are affected by many factors such as the vehicle equipment, that is airbags, or fasten seat belts [12].

It is important that for various types of vehicles accelerations during accidents are different (see [13]).

Bibliography

1. Campbell B.J. ,*The Traffic Accident Data Project Scale", Collision Investigation Methodology Symposium*, Warrenton, VA, 1969
2. Campbell K.L, *Energy basis for collision sevrity*, SAE 740565
3. Daily J., Strickland R., Daily J. :Crash analysis with Under-rides and the coefficient restitution, *Institute of Police Technology and Managament's,* 2006
4. Dupiero T. Przypadki szczególnego zastosowania EES, *Rzeczoznawca Samochodowy,* 2002, 7
5. Mackay, G. M., „A Vehicle Deformation Index", U.S. Pilot Study on Road Safety Committee on the Challenges of Modern Society, N.A.T.O. Accident Investigation Workshop, Belgium, June 1970
6. Owsiański R. : *Testy zderzeniowe samochodów osobowych*, *Paragraf na Drodze,* 2006, 11
7. Wach W. , *Amerykańskie standardy analizy zderzeń*, Problemy rekonstrukcji wypadków drogowych VIII Konferencja. Zbiór Referatów (2002), Kraków, 2002
8. Wicher J. :Kilka uwag o wykorzystaniu EES w rekonstrukcji zderzeń samochodu, *Rzeczoznawca Samochodowy* , 2002, 10
9. *Determination of the energy necessary for vehicle deformation in bases of the characteristics of its total deformation,* Instruction for the Tutorial "Introduction to accidents analysis", in Polish
10. *Determination of the value of the scattered energy during body collision.* Tutorial instruction, in Polish
11. K.H. Digges, *Injury Measurements and Criteria*, N.A.T.O. Research & Technology Organisation, RTO MP-20, K2-1 – K2-5, 1998;
12. Siegel JH, Loo GT, McCammon L, Sridhar K, Bents F, Warner M, Schaar R, Davis D, Dischinger PC, Burgess A, Kerns T, Schmidhauser C, Wang SC, Taheri P, MacWilliams J, *Effects Of Delta V And Steering Wheel Intrusions On Airbag Protection Of Brain & Face And Corporeal Injuries In Frontal Motor Vehicle Crashes*, online: http://www.umich.edu/~ciren/newjerse.html (1 XI 2013)
13. Hans-Wolfgang Henn, *Crash Tests and the Head Injury Criterion*, Teaching Mathematics And Its Applications Volume 17, No. 4, 1998.

Andrzej Szosland, Professor: Lodz University of Technology, Department of Vehicles and Fundamentals of Machine Design, Zeromskiego 116 Lodz, Poland (andrzej.szosland@p.lodz.pl).

Przemysław Kubiak, Ph.D.: Lodz University of Technology, Department of Vehicles and Fundamentals of Machine Design, Zeromskiego 116 Lodz, Poland, the author gave a presentation of this paper during one of the conference sessions (przemyslaw.kubiak@p.lodz.pl).

Jan Awrejcewicz, Professor: Lodz University of Technology, Department of Automation, Biomechanics and Mechatronics, Stefanowskiego 1/15 Lodz, Poland (jan.awrejcewicz@p.lodz.pl).

Bartłomiej Zagrodny, Ph.D.: Lodz University of Technology, Department of Automation, Biomechanics and Mechatronics, Stefanowskiego 1/15 Lodz, Poland, the author gave a presentation of this paper during one of the conference sessions (bartlomiej.zagrodny@p.lodz.pl).