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PROBLEM WITH DETERMINING THE VEHICLE IMPACT VELOCITY FOR CAR BODIES BREAKING APART

Summary. This article investigates the impact of a passenger car on a tree, which resulted in the car body breaking apart. A side impact of the car on a tree at high driving speeds is not a standard test in the provisions of the applicable Directives of the European Economic Community, even though the impact poses a serious threat to the driver and the passengers. The threat comes from a deep impaction of the barrier into the body which damages the safety cage. For such impacts, it is very difficult for the vehicle speed to be reconstructed. In practice, expert witnesses and appraisers usually disregard the body-breaking-apart-related energy due to a difficulty in establishing the data for such calculations, which leads to simplifications and speed underestimates. Performing the right simulation of such impacts with accident reconstruction programs without determining the adequate input data for calculations is also impossible to calculate. This paper presents a range of studies and calculations for such incidents and for identifying the input parameters for collision simulations. The approach presented in this article should be used by expert witnesses and researchers. Therefore, this paper provides insights into theory and practice.

1. INTRODUCTION

According to the data reported by the National Council of Road Traffic Safety, in 2020 in Poland, there were 1364 incidents which involved a vehicle's impact on a tree. In those accidents, 384 lives were lost. The data indicate that such impacts cause some of the most dangerous road accident effects, with the highest death rate (28.2 %) [1].

Road collisions are most often reconstructed when commissioned by the public prosecutor or court. Currently, the calculations are made with simulation programs and less frequently with an analytical approach. The opinions of court witnesses trigger legal and economic consequences, as, usually, in the opinion of the court, they are conclusive. Therefore, they should be carefully developed and the results should be corrected.

At present, standard crash tests do not cover a side impact of the vehicle into a barrier, pole or tree at high driving speeds. Thus, in practice, it is very difficult to receive credible data for computer simulations or analytical calculations. The energy required to break the body apart during a crash has

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not yet been verified to identify the input data for the analytical and simulation calculations in the V-SIM program. For that reason, this article focuses on the problems of receiving credible input data for such calculations. That knowledge is not common among property valuators or expert witnesses, and they frequently accept the simplified calculations and simulation results as credible.

A selection of the simulation program is dictated by the expertise requirements and content-wise range. Collisions can be simulated with the Finite Element Method (FEM) or with multibody system dynamics (MBD). Also reduced order dynamic models (ODM) are employed to reduce the calculation time.

Programs using FEM are very rarely used in road accident reconstruction practice despite the possibility of performing precision calculations. This is due to the limited access to vehicle numerical models for the expert and from time-intensive calculations.

For example, in other papers [2, 3], the simulations were run with the use of FEM, a collision with a lamppost with the LS-Dyna program. It was found that the effects of the impact depend not only on the barrier rigidity but also on the sitting on the ground. With that program [4], an impact of the side of the car into a pole was also analysed and a deep impaction of the barrier into the body door was confirmed. Another study [5] involved the use of the ABAQUS/CAE program and also analysed impacts on a pole at high speeds (120-160 km/h).

The next group covers programs modelling the convention of the MBD (e.g. V-SIM programs). However, MBD programs provide simplified models of vehicles and contact between the vehicle and the barrier. As such, they are not as precise as FEM programs. However, they require a short calculation time and a high number of numerical vehicle models in the database. The vehicle's frontal impact into a pole was analysed with MBD programs in other papers [6, 7]. The authors confirmed a high threat to the persons in the vehicle due to deep body deformation. Other papers [8, 9, 10] describe experimental studies of passenger car side collisions.

However, in the analytical approach, in vehicle speed calculations, energy methods have been commonly applied. Such an approach assumes that the effects of the collision are found at the expense of the moving car's kinetic energy loss.

The energy is consumed for friction when moving on the roadway or on another surface, body deformation work, potential energy change, and other circumstances resulting from the collision. As the effects of the collision require energy equivalent to the total work required for such effects to occur, there is an energy balance between the vehicle's loss of kinetic energy and the total work generated by it. In practice, however, the problem is that in the analytical calculations the experts disregard the energy consumed for other circumstances resulting from the accident. Indeed, it concerns the energy (e.g., the energy required for a metal sheet and welds to be broken apart) resulting in the breaking up of the body and a further displacement of its fragments which stop at an essential distance from the barrier. With that in mind, this article considers this problem, which is significant for incident reconstruction.

The remainder of this article has been divided into several sections. Section 2 describes the object of study, outlines the characteristics of V-SIM modelling, and presents the energy balance made. Section 3 offers the calculations of the value of respective works. A method has been proposed to determine the breaking-apart energy for sheet metal and welded connections as a result of the impact, together with specimen preparation. Also, the kinetic energy of the body parts after breaking apart was determined, and the results of the simulation calculations for V-SIM program default data and those identified in experimental studies have been presented. Section 4 presents the key observations and practical conclusions regarding the application of the proposed research and calculation methods, as well as the possibility of applying and the directions of further V-SIM developments.

2. OBJECT OF THE STUDY AND THE VEHICLE MODEL USED IN THE V-SIM PROGRAM

The object of study was a Škoda Superb 1.9 TDI model 2003, the basic technical data of which are provided in Table 1. The vehicle, after the phase of fishtailing on the road, crashed its right side into a tree about 0.5 m in diameter. The tree was adopted as a non-deformable rigid barrier. Due to the impact, the body was broken into two parts, the rear part and the front part, which were thrown in the original direction of the car's motion behind the tree.

Table 1

Parameter values

Parameter	Škoda
Vehicle weight (m)	1465 kg
Weight of the driver and passenger	150 kg
Weight of the front of the vehicle broken apart (m_1)	1065 kg
Weight of the rear of the vehicle broken apart (m_2)	400 kg
Length / width / height of the vehicle	4.803 m / 1.765 m / 1.469 m
Wheelbase	2.803 m
Wheel track	1.515 m

Based on the law of conservation of energy and the accident documentation data, the energy balance has been developed to consider the following factors.

1. E_{pz}: energy loss of the vehicle while fishtailing on the roadside 78.5 m long,
2. $E_{deformation}$: loss of energy for body deformation,
3. E_{zz}: loss of energy for the body metal sheet weld destruction,
4. E_{rb}: loss of energy for the body metal sheet breaking apart,
5. E_{k2}: loss of energy for throwing and rotation of the back of the broken body 18.6 m away,
6. E_{k3}: loss of energy for the displacement of the front of the body broken apart along 13.8 m.

Thus, the energy balance developed from the studies mentioned above can be presented in the form of Equation (1):

$$E_{k1} = E_{pz} + E_{deformation} + E_{zz} + E_{rb} + E_{k2} + E_{k3} \quad (1)$$

V-SIM program [11] modelling, on the other hand, facilitates analysing the impacts between vehicles and vehicles with immovable barriers which occur in the traffic environment designed by the operator. The analysis of the course of the impact and its effects is 3D with a possibility of applying a force model. In the model, the forces between simulation objects develop in a continuous manner from the moment of contact to their separation. The value of the force is determined by the size of the deformation and the stiffness of the simulation objects assumed. Fig. 1 presents the V-SIM rigid area preview offered for a Škoda Superb.

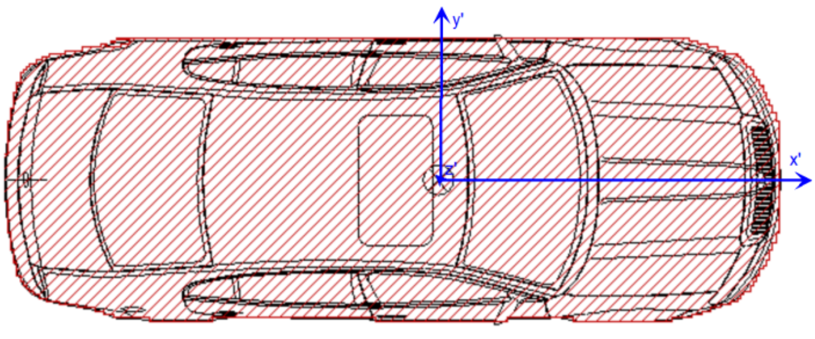

Fig. 1. Vehicle rigid area preview in the V-SIM simulation program

On the other hand, the V-SIM program vehicle model applies the global system of reference, the exes of which are marked *x, y,* and *z*. This system describes the momentary position of the vehicle and of the barriers. In the second system, the determined external forces acting on the vehicle are related to the vehicle, and the system axes are marked *x', y'*, and *z'*. The centre of the system is found at the centre of vehicle weight *C*, and its position is determined by the radius vector r_C (Fig. 2). The model, while considering the rotary movement of the vehicle's four wheels, has ten degrees of freedom.

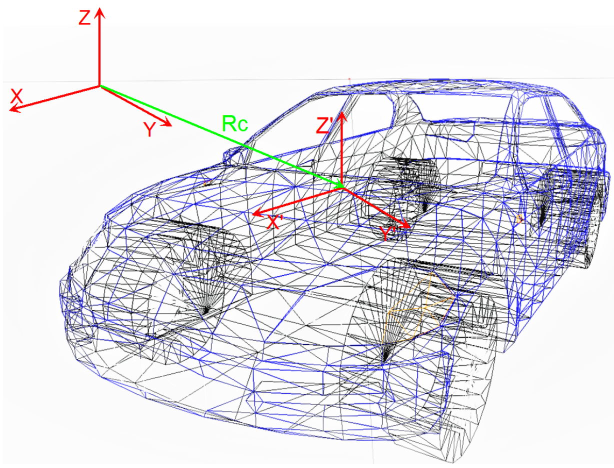

Fig. 2. Vehicle model in the V-SIM program

3. DETERMINING THE TOTAL KINETIC ENERGY OF THE VEHICLE

3.1. Energy prior to a crash into a tree

The kinetic energy of the Škoda before it crashed into the tree was lost due to friction while the car fishtailed along 78.5 m of asphalt and grass. The average value of the coefficient of adhesion (μ = 0.45) was assumed to calculate the value of the work performed from Equation (2), and its value of 559 659 J was received:

$$E_{pz} = \mu \cdot m_C \cdot g \cdot S \tag{2}$$

where: μ = 0.45 – averaged coefficient of adhesion, m_C = gross vehicle weight 1615 kg (vehicle weight of 1465 kg + driver's weight and passenger's weight of 150 kg), g = 9.81 m/s^2 – gravitational acceleration, S = 78.5 m – section of the vehicle fishtailing prior to the crash into a tree.

3.2. Energy of body deformation as a result of a crash into a tree

The value of the energy of deformation of the Škoda body was calculated using a simplified method with geometric deformation parameters (width, height, and depth), as well as the coefficient of unitary stiffness. The data needed to cover the geometric parameters of deformation of the Škoda body were taken from the description of the damage to the vehicle. The body deformation energy was calculated using Equation (3), which yielded a value of 241 920 J:

$$E_{deformation} = \frac{(b_n \cdot h_n \cdot f_n^2)}{2} \cdot k \tag{3}$$

where: b_n = 2.4 m – deformation width, h_n = 0.7 m – deformation height, f_n = 0.4 m – deformation depth, k = 18·10^5 N/m^3 – coefficient of unitary stiffness.

3.3. Energy of the body breaking apart as a result of a crash into a tree

The Škoda body sheet metal strength was determined from tests and experimental studies. This was done by applying a static tensile test for the vehicle sheet metal specimens. The test aims to determine the strength properties of the steel sheet metal required to calculate the kinetic energy required to destroy it.

Static tensile test

The mechanical properties of the steel sheet metal were determined based on a static tensile test compliant with PN-EN 10002-1 (EN ISO 6892-1:2009) [12]. For this test, specimens were taken from the Škoda Superb presented in Fig. 3.

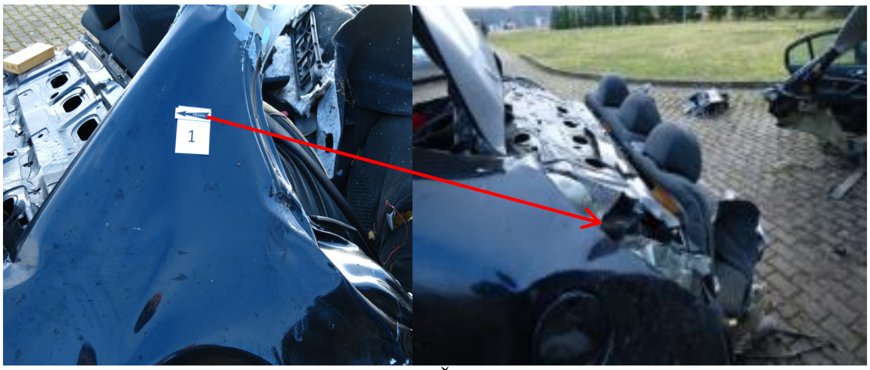

Fig. 3. View of the place of the specimen taken from the Škoda body

Specimen preparation for testing

The tensile tests involved the use of flat specimens cut out from an element of the body which, compliant with the norm, was straightened out with special care. Fig. 4 presents a diagram of the specimen used for mechanical working, with a rectangular cross-section compliant with the above norm.

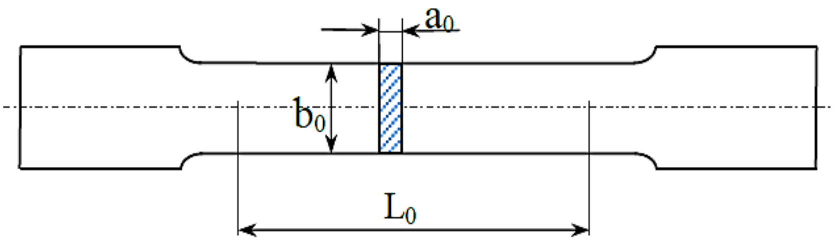

Fig. 4. Specimen after mechanical working with a rectangular cross-section: L_o = measurement length, a_o = specimen thickness, namely the distance between the rolled areas which are not subject to mechanical working, b_o = specimen width

Three specimens were prepared for testing to verify the repeatability of the results. A three-time measurement repeatability was applied. The averaged values of the measurements of the specimen shapes are provided in Table 2. The cross-section area of the specimen prior to loading was calculated according to Equation (4).

Table 2

Measurements of the specimens prepared for breaking

Specimen number	L_0 [mm]	a_0 [mm]	b_0 [mm]	S_0 [mm^2]
1	100	0.8	24	19.2
2	100	0.8	25	20
3	100	0.8	25	20

Testing stand

A static tensile test for the Škoda body steel was performed at ambient temperature (19 °C) with a universal testing machine ZD-20, manufactured by VEB WPM Leipzig, class 1, with a range of 4-200 kN. Fig. 5a presents a photograph of the universal testing machine, and Fig. 5b provides an image of specimen no. 1 mounted in the jaws (prior to and after working).

Testing results

The tensile test provided data on the dependence of the tensile force on absolute elongation $F = f\,(Al)$. The application of coordinate system F-AL for describing the test was not convenient, as a comparison of the results for two different materials would require the application of specimens with the same cross-sections. The coordinate system was used to make the results independent of the specimen's cross-section. In this system, stress (σ) and strain (ε) were described based on the following Equations (4) and (5):

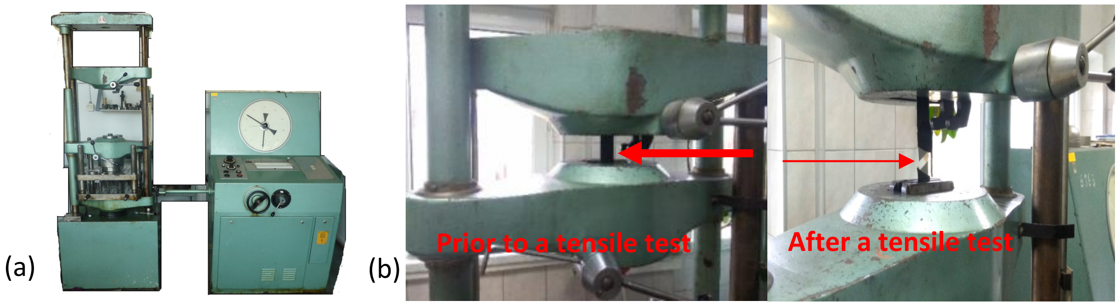

Fig. 5. Photographs of (a) the strength testing stand (ZD-20) and (b) specimen no. 1 mounted in the jaws of the testing machine prior to and after the tensile test

$$\sigma = \frac{F}{S_0}\ [\mathrm{N/mm^2}] \tag{4}$$

$$\varepsilon = \frac{\Delta L}{L_0}\ [-] \tag{5}$$

where: S_0 – initial cross-section area of the specimen, L_0 – initial length of the measurement part of the specimen, F_m corresponds to the maximum force required for specimen strain, and F_u corresponds to the force for which material cohesion loss occurs.

The values of the specimen measurements are given in Table 3.

The tests demonstrated that the mean stresses at which sheet metal gets destroyed as a result of plastic strains based on three tests is R_m = 344 MPa (Table 3).

The value of the stress at the break when the sheet metal is elongated was determined using Equation (6):

$$Rm = \frac{F}{S} \tag{6}$$

where: F – tensile force, S – cross-section area.

Table 3

Values of the measurements of the specimens prepared for a pull test

Specimen no.	L_0 [mm]	a_0 [mm]	b_0 [mm]	So [mm^2]	Fm [kN]	Fu [kN	Rm [MPa]
1	100	0.8	24	19.2	6.8	5.8	354
2	100	0.8	25	20	6.7	6.1	335
3	100	0.8	25	20	6.9	6.0	345

For the calculations, it was assumed that the value of stress for the sheathing and floor sheet metals was R_m = 344 MPa, as well as F and S (see above). For the analysed case, the floorboard thickness corresponded to the sheet metal thickness (g_1 = 1.6 mm), and the floorboard sheet metal breaking apart length was L_1 = 0.63 m. As for the body sheathing, the sheet metal thickness was g_2 = 0.8 mm, and the sheet metal breaking-apart length was L_2 = 1.25 m.

The force value was determined by transforming the dependence of stresses at the break into the following form:

$$F = R_m \cdot S \tag{7}$$

Meanwhile, the cross-section area was calculated as follows:

$$S = g \cdot x \tag{8}$$

For the floor,

$$S_1 = g_1 \cdot x \tag{9}$$

For the body sheathings,

$$S_2 = g_2 \cdot x \tag{10}$$

The sheet metal of the vehicle body did not result in a classic breaking apart as with a static tensile test, a normal and shear stresses occurred on the sheet metal surface. Thus, the minimum cross-section (completely broken apart) was determined by running numerical analyses to find for what value x there are no residual stresses on the other side of the cross-section. For those analyses, two numerical models with x = 0.02 m and x = 0.05 m were built, (see Fig. 6).

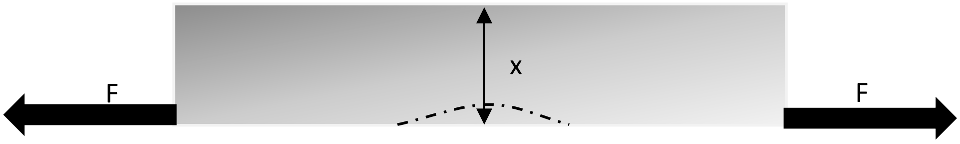

Fig. 6. Diagram showing the depth of residual stresses during the process of sheet metal breaking apart

The values of residual stresses (x) were determined by applying ANSYS software, which is designed to solve problems in the field of structural mechanics [13]. It enables the construction of geometric models and the introduction of loads, as well as the analysis of stress states. For that purpose, a numerical model was developed, the material properties and geometrical parameters of which corresponded to the parameters of the sheet metal studied (Fig. 7). A map of stresses is provided in Fig. 8.

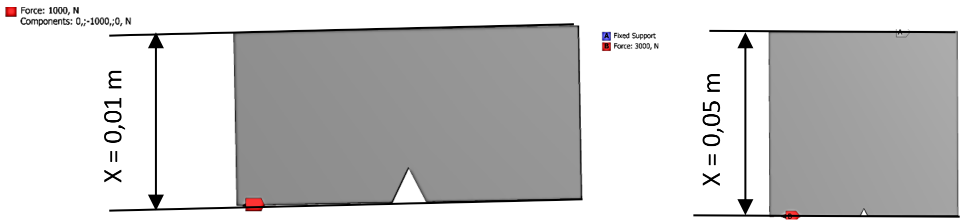

Fig. 7. Numerical model for determining the depth of residual stresses (x)

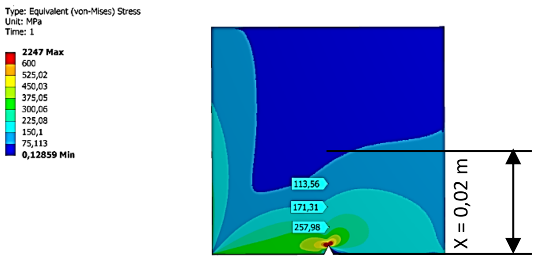

Fig. 8. Map of stresses reduced according to the Huber-Mises hypothesis for the depth of residual stresses (x = 0.02 m)

After the analysis of the results, it was determined that the minimal value of x for which there were no residual stresses on the opposite side from the breaking-apart place was x = 0.02 m, and such value was applied for further analyses. According to the data, for x = 0.02 m, the value of the force required for the breaking apart of the floor was F_1 = 11 008 N, and the force required for body sheathing was F_2 = 5 504 N. Considering the above data, the energy required for the sheet metal to break apart of 13 815 J was calculated using Equation (11):

$$E_{rb} = F_1 \cdot L_1 + F_1 \cdot L_1 \tag{11}$$

For this equation, the data are the same as above.

3.4. Energy of weld damage as a result of the crash into a tree

The weld strength was determined based on experiments using the universal testing machine. The weld testing specimen is presented in Fig. 9, while Fig. 10 provides a view of specimen no. 1 mounted in the jaws prior to and after the strength test of a series of five welds. The strength of a single weld was determined by a test involving five replications; the results of the measurements have been averaged. The following force values (in kN] were recorded for the successive single welds: 5.3, 4.8, 3.8, 3.0, and 3.0. Hence, the value of the average force of F = 4.08 kN resulted in the breaking apart of a single weld and was used for further calculations.

Fig. 9. Specimen prepared to determine the strength of single welds

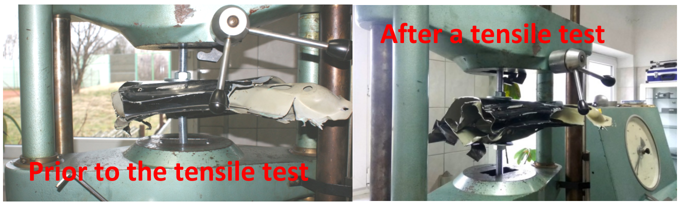

Fig. 10. Specimen no. 1 in the holder of the universal testing machine prior to and after the specimen broke apart

In the tests, the diameter d of the welds was 7 mm. Stresses of R_m = 344 MPa needed to be induced to separate the welded sheet metals. Thus, the energy required to destroy the welds of 5 712 J was calculated from the following Equation (12):

$$E_{zz} = F \cdot d \cdot n \tag{12}$$

where: n = 200 – number of welds destroyed, d = 7 mm – diameter of a single weld.

3.5. Kinetic energy of the broken away rear part of the vehicle

The use of dependence for the transverse projection with a rotation was proposed to estimate the lost energy of the broken away vehicle rear.

It was assumed that the achieved height (h_{max}), according to the accident data, was about 1 m, the angle that the initial velocity makes with the level (α) 12.13 ° and gravitational acceleration (g) 9.81 m/s^2. These values were used to calculate the velocity (V_0) using Equation (13), and the kinetic energy was calculated using Equation (14):

$$v_0 = \sqrt{\frac{h_{max} \cdot 2 \cdot g}{2 \cdot sin^2 \alpha}} \tag{13}$$

$$E_k = \frac{m_2 \cdot v_0^2}{2} \tag{14}$$

Value V_0 = 21.07 m/s was obtained, which for the weight of the body rear (m_2 = 400 kg) gives energy of E_k = 88 770 J.

Further, the analysis provides a calculation of the energy of rotation. First, the value of the moment of inertia was determined, followed by the kinetic energy by applying the following Equations:

$$I = \lim_{\Delta m \to 0} \sum_i r_i^2 \Delta m_i = \int r^2 dm \tag{15}$$

$$E_k = \frac{1}{2} I \omega^2 \tag{16}$$

The weight of the rear vehicle part that broke away was m_2 = 400 kg; considering a radius of r = 0.5 m, the value of the moment of inertia was 100 kg/m^2. The calculations assumed a single complete rotation of the rear body part of 0.5 s of the flight, which gives the energy of rotation of 7895 J. The total energy of the flight of the rear body was E_{k2} = 96 665 J.

3.6. Kinetic energy of the broken away front part of the vehicle

The kinetic energy of the front part of the vehicle after the body broke apart moved along 13.8 m. The above replacement coefficient of adhesion (μ = 0.5) assumed in the analysis was 72 088 J, and it was calculated from the following Equation (17):

$$E_{k3} = \mu \cdot m_1 \cdot g \cdot S \quad (17)$$

where: μ = 0.5 – replacement coefficient of adhesion, m_1 = weight of the front of the vehicle 1065 kg, g = 9.81 m/s^2 – gravitational constant, S = 13.8 m – distance of the displacement of the front of the body.

According to the results of the experiments, the total energy value received from Equation (1) was E_{k1} 989 860 J. For that amount of energy, the initial Škoda velocity was 35.01 m/s (about 126 km/h), and it was calculated using the energy method based on Equation (18):

$$Vo = \sqrt{\frac{2 \cdot Ek1}{mc}} \quad (18)$$

where: E_{k1} = 989 860 J, mc = 1615 kg.

3.7. V-SIM simulation of the crash into a tree

Modelling the collisions of vehicles and traffic in different road conditions and the load transported has been discussed in other papers [e.g. 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25]. However, in this article, simulation calculations were made with the V-SIM program and vector stylings of a Škoda body [26]. First, calculations were done for the default data of the program and then for the data changed based on the data received from the analysis. Differences in reconstructing the collision with the program and conclusions were determined to be applied in practice. Fig. 11 below shows those differences.

The simulations modelled the crash with the right rear side of Škoda driving into a tree at an initial speed of 126 km/h. The analytical calculations demonstrated that after the car crashed into a tree and the body broke apart, the car still had enough kinetic energy to fly with a rotation of its rear part 18.6 m away and a displacement of the front part of 13.8 m. The calculated total energy of those balance components is 168 754 J, which corresponds to the speed of about 52 km/h, which was the car's speed when it broke apart.

The simulation for the default data of the program revealed that the body of the simulated car at 126 km/h did not break apart.

The cause of such atypical crash reconstruction problems was searched for in the V-SIM program, which models the vehicle body as one solid figure with averaged stiffness. It was agreed that the stiffness of the simulated car body must be decreased to such a value that crashing at a speed of 126 km/h results in the body getting broken apart by the tree, after which the car speed would still be 52 km/h. The compliance of the above speeds was recorded after a change in vehicle stiffness from the default value of 718 kN/m^3 to 142 kN/m^3. Fig. 12 shows the time courses in the changes in speed for both cases.

4. CONCLUSIONS AND DISCUSSION

This study has shown that the calculated speed of a car whose body was broken apart as a result of the impact into a barrier requires considering the energy required to break apart the sheet metal, destroy the welds, and displace the fractured parts of the body, both of which were moving in the air and on the ground. Disregarding these phenomena leads to an underestimated impact velocity, which affects the precision of the velocity calculated and which can have legal consequences for the parties to the litigation. The results of the study support the approach presented in the article for the calculations discussed in the cases of collisions of vehicles into a tree or a pole when the body breaks apart.

Moreover, the results demonstrate that when crashing into a tree or a pole and having the body break apart, performing the right simulation with MBD programs based on default data is not possible, and it requires establishing the right input data from the analytical calculations and experimental data presented considering the above phenomena accompanying the body breaking apart. Only then can the simulation calculations be used for further analysis of the accident course and reconstruction.

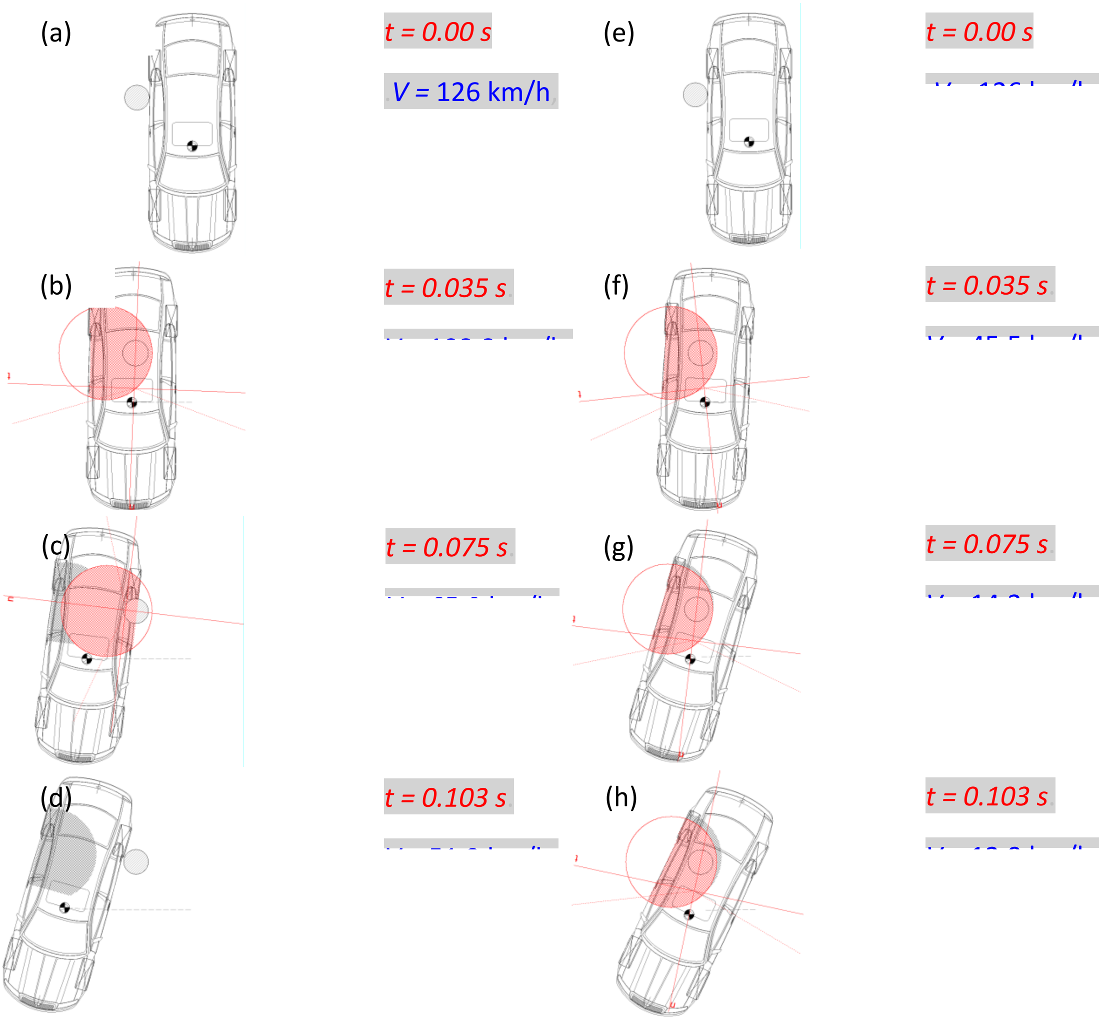

Fig. 11. Comparison of the course of a Škoda crashing into a tree at time: t = 0 s, t = 0.035 s, t = 0.075 s, and t = 0.103 s, for the data changed based on the study performed (a, b, c, d, e) and V-SIM default data (e, f, g, h)

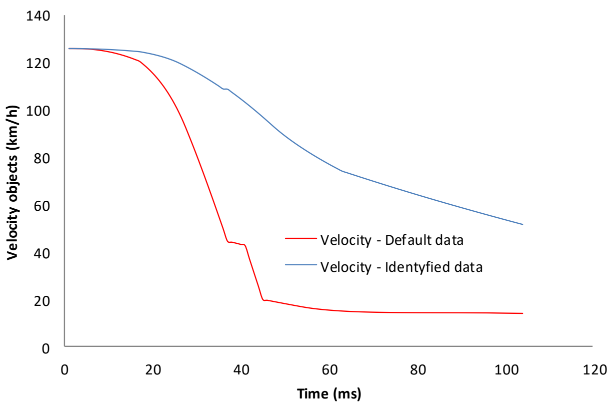

Fig. 12. Comparison of changes in the vehicle's velocity during the impact for default and identified data

The results of this study also demonstrate that MBD program modelling should involve the use of the body of the vehicle divided into zones of different stiffnesses, which would enhance the reconstruction of the course of the incident. Thus, modelling with such programs requires further improvements.

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