THE ANALYSIS OF OCCUPANT MOTION IN FRONTAL BARRIER IMPACT OF A CHASSIS FRAME VEHICLE[1]

Leon Prochowski

Military University of Technology
ul. Gen. S. Kaliskiego 2, 00-908 Warsaw 49, Poland
tel.: +48 22 6837866, fax: +48 22 6837866
e-mail: lprochowski@wat.edu.pl

Karol Zielonka

Automotive Industry Institute PIMOT®
ul. Jagiellońska 55, 03-301 Warsaw, Poland
tel.: +48 22 8111397, fax: +48 22 6755781
e-mail: k.zielonka@pimot.org.pl

Andrzej Żuchowski

Military University of Technology
ul. Gen. S. Kaliskiego 2, 00-908 Warsaw 49, Poland
tel.: +48 22 6837454, fax: +48 22 6839230
e-mail: azuchowski@wat.edu.pl

Abstract

Human body motion during a road accident usually results from the effect of forces of inertia. The analysis of that motion, particularly displacements towards the vehicle interior have significant practical aspect as it facilitates conclusions concerning the mechanisms of danger and injury formation. At the same time, the analysis provides direct indications regarding the improvement of passive safety equipment.

The paper presents the time-space diagrams of motion of dummy's head, neck, torso and hips – the driver of a frame chassis vehicle, identified on the basis of results of the measurements registered in frontal barrier impact and the frame-by-frame analysis of videos recorded during the course of experiment. Courses of these diagrams were associated with acceleration measurement results and forces affecting the parts of the dummy.

The experiment showed the complex nature of the influence on the dummy caused by the forces of inertia after a collision of the vehicle with an barrier, vehicle body motion against the frame, reactions in the safety belts, friction on a seat and contact reaction of the vehicle interior equipment. At the same time, it presented the possibilities of indicating the courses of speed variations and dummy displacement as well as significant limitations of calculation possibilities that result from a fact that the process of the impact on the vehicle interior elements is hard to describe.

Keywords: *transport, road safety, vehicle safety, crash tests, frontal accidents, occupant kinematic*

1. Introduction

A group of passenger cars used for off-road driving, heavy duty operation (forestry, agriculture) and for individual recreation purposes is getting bigger and bigger. As this trend is getting more intensified, the cars are universally improved, become more comfortable, easy to drive and are equipped with more comfort and safety equipment.

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Passenger off-road cars are usually equipped with frame chassis as they can be characterized with high durability and rigidity. The most often, rigid longitudinal frames where longitudinal members go in parallel or almost parallel against the longitudinal vehicle axis. The frame combines all assemblies and systems in one whole and supports a vehicle body. In that type of vehicles, the vehicles bodies are fixed to a frame by means of connectors and brackets. Those type of connections use rubber and metal elements that are designed to reduce dynamic loads in connection area.

The purpose of this paper is to carry out the analysis of motion of a dummy placed on a driver's seat during a collision of a passenger and off-road car with a non-deformable barrier and to show the relation between the dummy motion and the condition of his dynamic loads. The tests were performed on a vehicle with a classic longitudinal frame of high rigidity (frame supporting structure). The analysis results should indicate the sources of extreme dynamic loads affecting the human body and possibilities of improving the protective equipment for passengers of vehicles with frame supporting structures.

2. Test object and measurement preparation

The test was performed on a Tarpan-Honker vehicle. Figure 2.1 presents the view and basic dimensions of the vehicle.

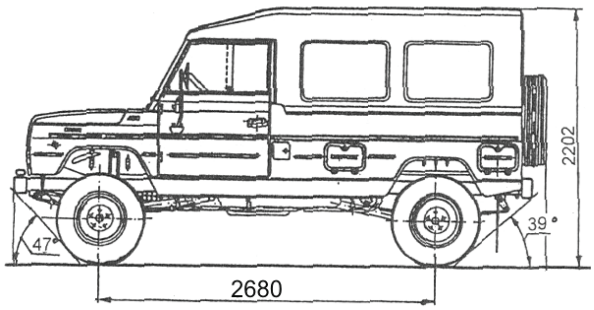


Fig.2.1. Test object and its basic dimensions [1]

The structure of a tested vehicle consists of an independent chassis with a longitudinal frame of a compact structure. The chassis, shown separately in Figure 2.2, is a uniform structure fixed to the frame be means of 9 steel connectors with a rubber insert.

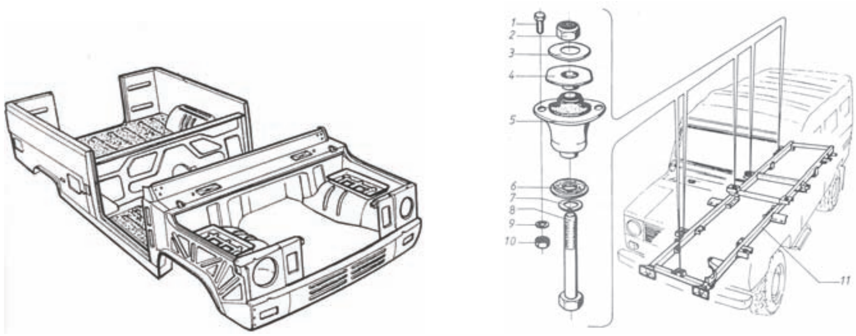


Fig. 2.2. Chassis and its fixing to the longitudinal frame of a vehicle

Passengers on the first row seats are equipped with three-point safety belts with inertial tensioners, their fixing is shown in Fig. 2.4. Belt fixing points belong to the chassis and are not bounded to the seats. A dummy, fastened with the seat belts, was placed in a position typical for a car driver while driving.

The arrangement of the measurement system elements at the stage of preparation of experiment involving a collision of a vehicle with non-deformable barrier (concrete barrier) at the following speeds: 4, 10 and 43 km/h is described below. The experiment was carried out in the in Automotive Industry Institute PIMOT® in Warsaw.

Fig. 2.4. Arrangement of a dummy with sensors during preparation for the tests

A dummy, shown in Fig.2.4, includes the acceleration sensors (head, torso and hips) and crushing force and moment sensors (neck). Figure 2.5 shows initial position and directions of acceleration sensor operation in the head and force sensor and crushing moment (components x, y, z), installed in the neck of the Hybrid III dummy. Obviously, position of the sensors related to the dummy is changed when the dummy relocates in barrier impact test.

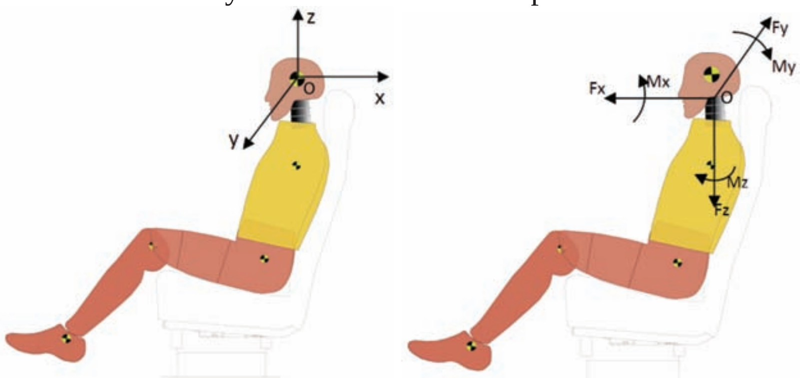


Fig. 2.5. Directions of the acceleration sensor axis in the head and crushing force and moment sensor axis in the neck (initial status)

Results of the measurements using the sensors described above were supplemented with information obtained from two high-speed cameras (500 frames per second). The papers [4, 5] show the influence of barrier impact velocity on the dynamic loads of the dummy in the vehicle (range: 4-43 km/h). While this paper analyzes the test results recorded during frontal collision at the speed of 43km/h.

3. Frame-by-frame analysis of video recordings

Figure 3.1 shows a few frames from the videos recorded by cameras at the following moments:
- before the impact,
- maximum dummy shift forward,
- maximum dummy shift backwards.

The specification shows the following phases of dummy displacement against the vehicle body interior and the process of its deformation (crushing) for three impact velocity values.

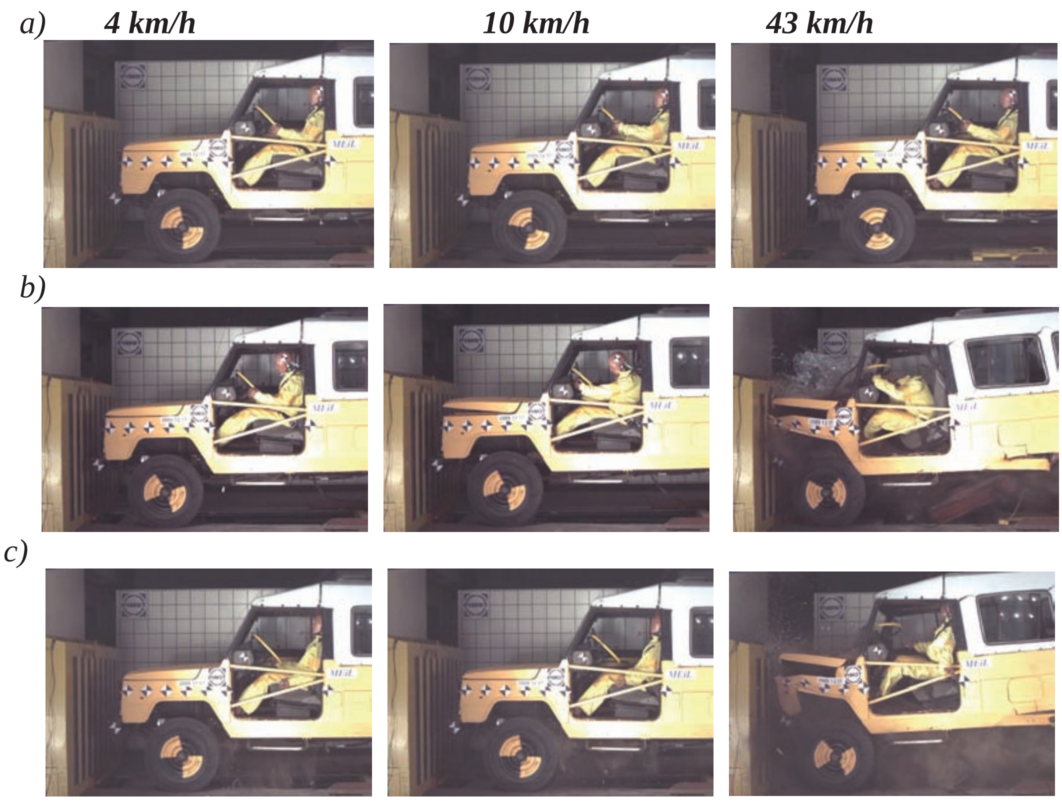


Fig. 3.1. Photos illustrating the dummy displacement and vehicle body deformation in frontal impact barrier test: a – condition before the collision, b – maximum dummy shift forward, c – maximum dummy shift backwards

Dummy motion recorded on the video shows that the safety belt successfully holds the dummy in the seat and the dummy head does not contact the vehicle elements only at small values of the velocity in frontal impact barrier test (4 and 10 km/h). At the impact velocity of 43 km/h the dummy significantly shifts in relation to the seat, hitting the vehicle elements with its head. Table 3.1 specifies characteristic stages, describing further positions of the dummy and the vehicle at a impact velocity 43 km/h. Several illustrations to the description from table 3.1 are shown in Figure 3.2. A detailed dummy motion analysis is given below.

Table 3.1. Further dummy and vehicle positions at a impact velocity 43 km/h

Impact time [ms]	Description
0	Beginning of the vehicle and barrier contact
20	Beginning of the steering wheel shift upwards and towards the windscreen
28	Steering wheel hits the windscreen
36	Beginning of the dummy displacement in relation to the seat under the influence of forces of inertia
56	Maximum driver shift
88	Maximum vehicle front deformation
110	Maximum dummy head shift forward
125	Lifting of the back part of the vehicle and the rear wheel lift-off from the ground
172	The end of the vehicle and the barrier contact , beginning of the return motion
296	Maximum dummy head deflection backwards
397	The rear wheels contact the ground again
552	Repeated extreme head shift forward

Observed steering wheel shifting at the initial stage of the impact results from the displacement of the steering gear which is placed right behind the beam of the front bumper. Therefore, a small deformation of the front part of the vehicle causes the shift of the steering gear backwards and it forces the movement of the steering wheel through the steering shaft, visible on the photos.

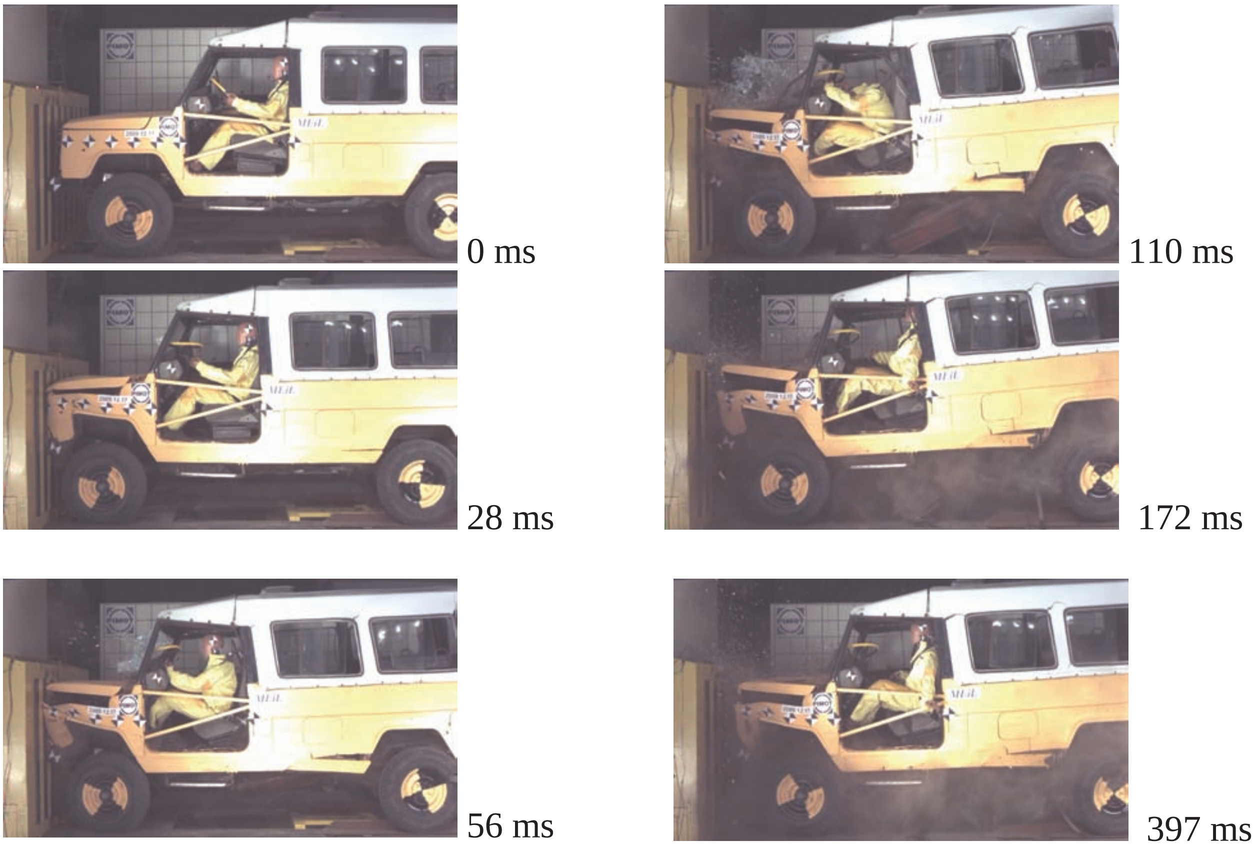


Fig. 3.2 Characteristic stages of the dummy and the vehicle motion in barrier impact at the speed of 43 km/h (numbers next to the video frames indicate current time as in table 3.1).

4. Dummy kinematics durring barrier impact

The dummy displacements, resulting from the forces of inertia after the collision of the vehicle with the barrier, are limited by reactions in the safety belts, friction on the seat and contact reaction of the interior equipment in the vehicle. As shown in Figure 4.1, further stages of the dummy displacement have been prepared on the basis of the frame-by-frame analysis of the video recorded during the experiment. The drawing shows the dummy displacement in relation to the seat, torso deflection and the moment when the head impact at the vehicle elements. The photos, presented on the side, specify A and B dimensions, characteristic for the driver safety, describing the head location against the area of its contact with the dashboard. On the basis of the video analysis, trajectories of motion of particular parts of the dummy in relation to the vehicle, in barrier impact test.

Trajectories in Fig. 4.2 show the displacements of the head, the neck, the torso and the hips in the space-time system, marked with the 10 ms time step on the distance grid in direction of the vehicle motion (longitudinal) and vertical direction. The figure shows the points only with 20 ms interval in order to avoid its excessive concentration. Dimension grid lines are marked every 20 cm, and their beginning is connected with the middle part of the head before the collision. Displacements of the dummy's head and neck are shown in Figure 4.2 are very high. As a result, the dummy hits the vehicle elements with its head, chest and knees (steering column cover, dashboard, Fig. 4.1).

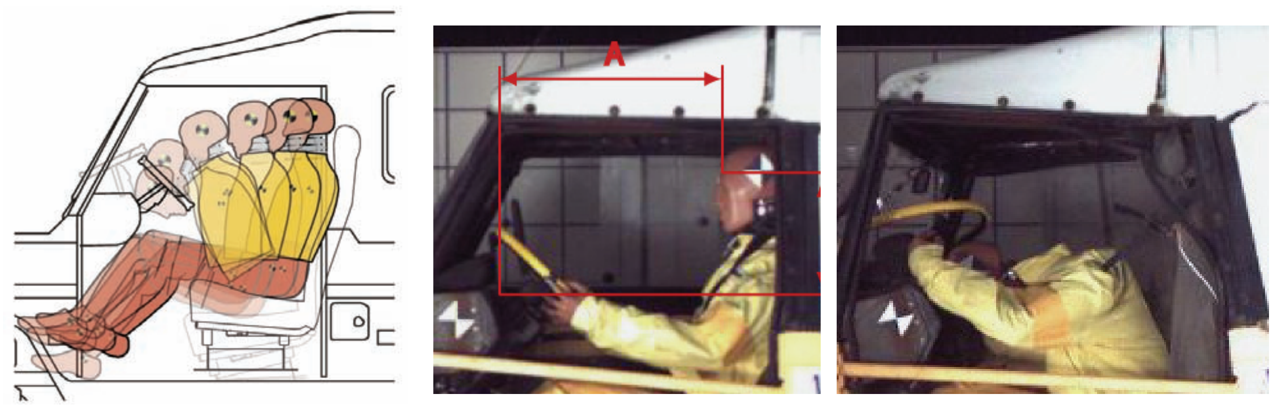


Fig.4.1. Outline of the driver's cab in the Honker and the following stages of the dummy displacement during the experiment; distance between the initial head position and the impact point: A=0,53 m, B=0,25 m

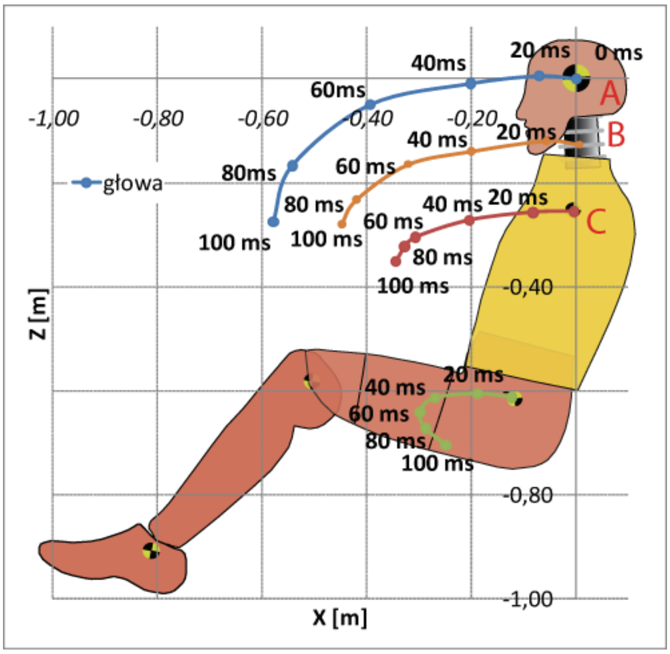


Fig. 4.2. Trajectories of displacement of the characteristic points of the dummy

Table 4.1. Maximum values of displacement along the markers placed on the dummy (direction of the vehicle motion)

Dummy	Longitudinal displacement. m
Head	0.58
Neck	0.46
Torso	0.37
Hips	0.28

Displacements of the dummy's head and neck shown in Figure 4.2 are very high (Table 4.1). The torso shift by almost 0.37 m and the hip shift by 0.28 m also includes the stretching of the safety belts under the pressure of the dummy under the influence of the forces of inertia.

Relations between the linear displacements are supplemented with the information about the angular torso and head displacement. Characteristic angular positions of the head and the torso are shown in Figure 4.3.

a) b)

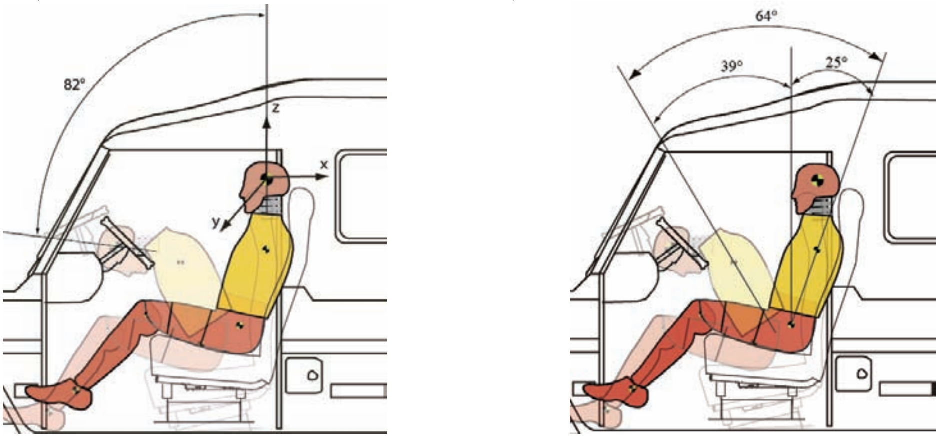


Fig.4.3. Angular displacements of the head (a) and the torso (b); a change of the seat base position resulting from the deformation of the floor along the frame is also shown on the figures

4.2. The analysis of results of the measurements of dynamic loads and displacements of the dummy's head and torso

Marked displacements of the dummy were associated with the course of accident acceleration which was calculated from the components (compare Fig. 2.5), recorded during the experiment

$$a(t) = \sqrt{a_x^2(t) + a_y^2(t) + a_z^2(t)}\,. \tag{1}$$

Using those courses, compiled in one homogeneous scale shown in Figure 4.4, a moment of time was identified when the head and the torso touch the vehicle interior elements.

a) b)

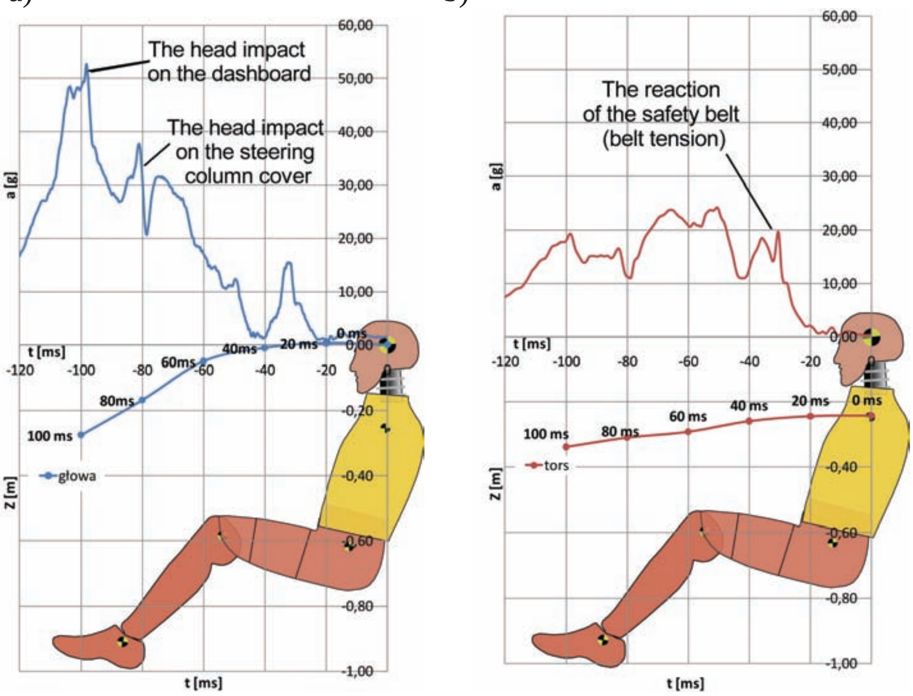


Fig. 4.4. Association of the course of changes of the accident acceleration and the dummy displacement in barrier impact at the speed of 43 km/h; a - the head, b - the torso

It is an important stage for further analysis. Relations between the extreme delay values, recorded during the experiment with displacements of the dummy and its contact with the vehicle interior elements, including the dashboard and the steering column cover also shown. The figure 4.3a shows the moment when the head hits the steering column cover and then it hits the dashboard. While the figure 4.4b shows the moment when the safety belts start to significantly affect the torso, i.e. when the stage of their initial tension is over.

Measured courses of the dummy's head and torso delay were used to define the velocity of their displacement in relation to the vehicle, including the value of velocity of the head when hitting the dashboard. Such information is required to estimate the energy of the head impact on the cab elements and it is important when designing the airbag deployment process. Figure 4.5 compiles recorded components of the head acceleration in directions x,y,z (according to fig. 2.5) and the component a_{Tx} of the torso acceleration. Values of the torso delay increase significantly earlier than the values of the head acceleration. The head continues the pre-impact motion at the initial stage of impact.

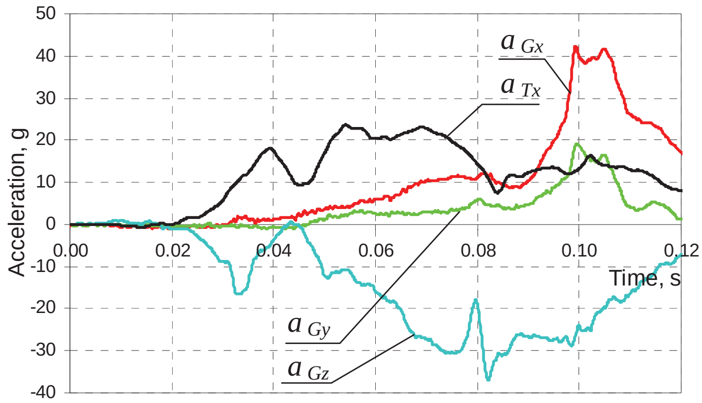


Fig.4.5. Head acceleration realizations, components: a_{Gx}, a_{Gy}, a_{Gz} *and the component* a_{Tx} *of the torso acceleration*

Complex movement of the dummy's head at that moment was reduced to the flat movement (plane O*xz*), in order to make further simplification of calculations. The fact that the head acceleration component a_{Gy} has the values significantly lower than a_{Gx} *i* a_{Gz} has been also taken into account. The effect of omitting the component a_{Gy} is shown in Figure 4.6.

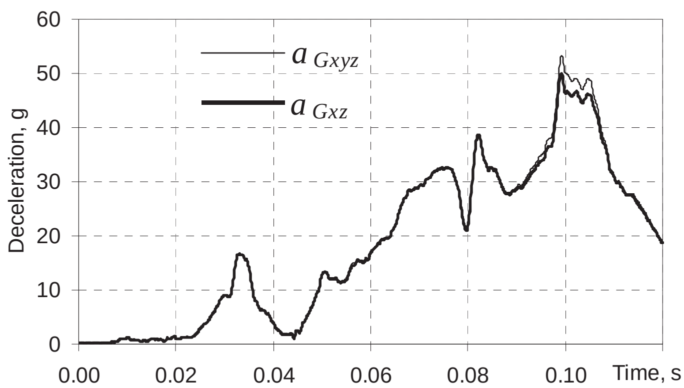


Fig. 4.6. Specification of the head acceleration course calculated in two ways:

$$a_{Gxz}(t) = \sqrt{a_x^2 + a_z^2} \quad \text{and} \quad a_{Gxyz}(t) = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

In order to make further calculations of the head movement in relation to the vehicle and the ground, the identification of variation of the head inclination angle α in time is required. It has been done on the basis of the frame-by-frame analysis of the video recorded during the experiment. Obtained course $\alpha = f(t)$ is shown in Fig. 4.8 and it has been used when calculating the components of:

$a_{XG}(t) = a_x \cdot \cos\alpha - a_z \cdot \sin\alpha$ - horizontal acceleration,

$a_{ZG}(t) = a_x \cdot \sin\alpha + a_z \cdot \cos\alpha$ - vertical acceleration.

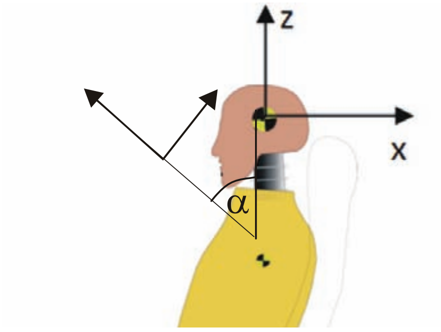


Fig. 4.7. Change of the head sensor axis position

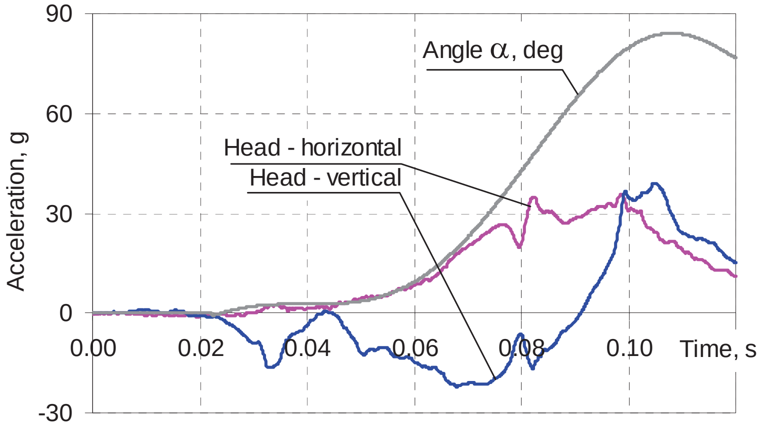


Fig.4.8. Head acceleration component realizations $a_{XG}(t)$, $a_{ZG}(t)$ *and angle* α

After integration of the component $a_{xT}(t)$ of the torso acceleration, the realization of the torso velocity in relation to the ground in horizontal direction was obtained. Similarly after integration of realization $a_{XG}(t)$ and $a_{ZG}(t)$, the realization of the head velocity in relation to the ground in horizontal and vertical directions was obtained. The following settlements were considered in calculations:

- the head hits the dashboard and reflects in about 90-110 ms;
- maximum head acceleration in vertical and horizontal direction, on the basis of the cab dimensions before the experiment, amounts to: A=0.53 m and B=0.25 m (dimensions A and B are given in Figure 4.1).

The head hitting the dashboard significantly interrupts the course of measured acceleration. Therefore, this course can be used for head velocity and displacement calculations is proper only until the moment when the head hits the dashboard i.e. until 90-100 ms.

Figure 4.9 associates the course of variations of the head and torso velocities with the vehicle (cab) speed during collision. The safety belts start to react on the dummy (brake its movement) in about 30 ms from the initial moment of the collision of the vehicle and the barrier. Earlier, the dummy shifts in relation to the seat under the influence of the force of inertia at the impact velocity. In 60-70 ms, the head tilt starts to increase in relation to the torso (information obtained from the video analysis). As a result, the value of the component of the horizontal head velocity decreases rapidly and the value of the vertical component increases (Fig. 4.9). Characteristic velocity values are given in tables 4.2 and 4.3.

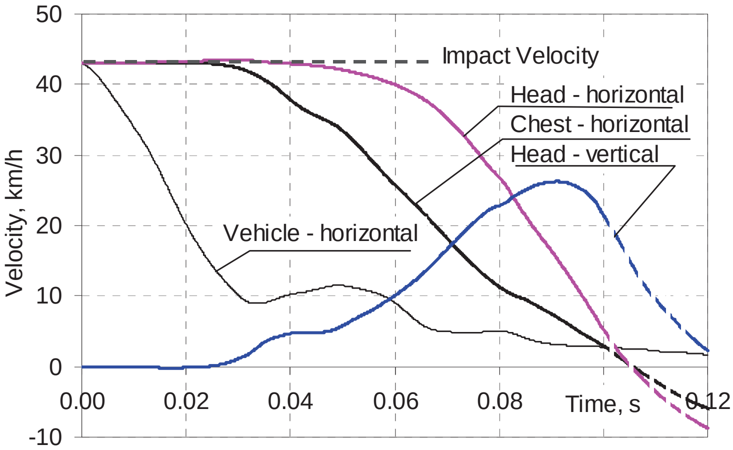
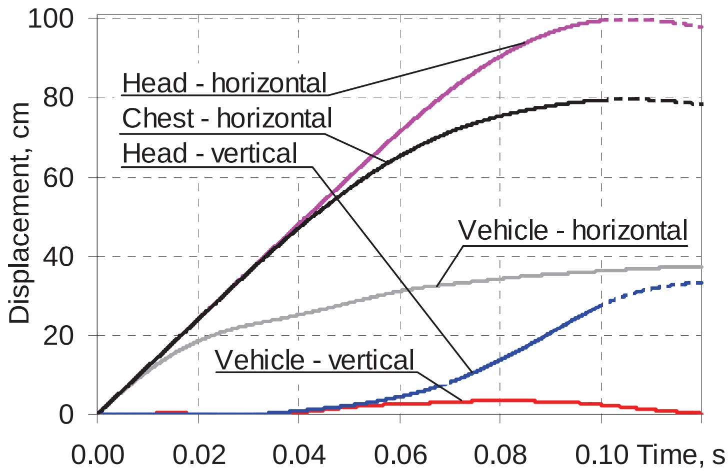


Fig. 4.9. Association of head, torso and cab velocity realization in relation to the ground

After repeated integration of acceleration $a_{XG}(t)$, $a_{ZG}(t)$ and $a_{xT}(t)$, head displacements in vertical and horizontal directions in relation to the ground and torso displacements in horizontal direction (Fig.4.10a) were obtained. Considering the displacement of the cab in horizontal and vertical direction (Fig.4.10a), head and torso displacement in relation to the vehicle were calculated (Fig.4.10b). The results of the displacement calculations are given in tables 4.2 and 4.3.

a)



b)

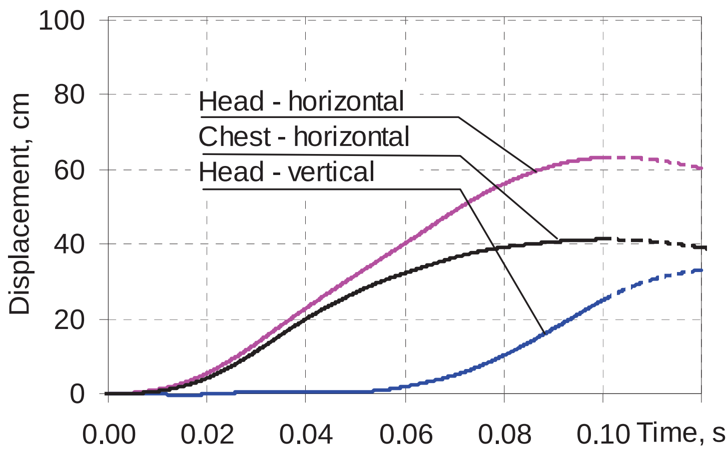


Fig.4.10. Head and chest displacements in relation to the ground (a) and the vehicle (b)

Obtained calculation results indicate that the maximum head displacement in horizontal and vertical directions defined on the basis of integration of acceleration realization is comparable with the values indicated by the vehicle structure, i.e. A=0.53 m and B=0.25m. It provides a basis for positive evaluation of the head velocity and displacement calculations.

Calculations, carried out on the basis of the frame-by-frame analysis of the video recorded during the experiment and calculation based on the integration of acceleration courses are not accurate. It results in a need to provide multiple verification of obtained values of the head velocity and displacements. These values are of basic significance at the stage of selection of the airbag arrangement and size, belt and seat fixing points and selection of belt tension operation time and the front airbag deployment activation time. Improvement of operation of that type of equipment and their effective integration in a particular vehicle requires such analysis.

Table. 4.2. Characteristic values describing the dummy's head movement when the vehicle impact in the barrier

Time [ms]	Description	Head velocity [km/h] in direction		Displacement [m] in relation to the vehicle defined on the basis of: video analysis (Fig.4.2) / integration of the acceleration course	
		horizontal	vertical	horizontal	vertical
31	Beginning of visible reaction of the safety belts (belt tension)	43	3	0.13/0.13	0.01/0.00
51	Maximum lap belt tension force	42	6	0.30/0.31	0.02/0.00
68	Maximum shoulder belt tension force	35	16	0.48//0.48	0.11/0.03
80	The head impact on the dashboard	27	23	0.54//0.56	0.16/0.10
90-100	The head impact on the steering column cover	15-5	26-21	0.58/0.59-0.61	0.28/0.18-0.25

Table. 4.2. Characteristic values describing the dummy's torso movement when the vehicle impact on the barrier

Time [ms]	Description	Torso velocity [km/h]	Displacement defined on the basis of video analysis [m]	Displacement defined on the basis of integration of the acceleration course [m]
31	Beginning of visible reaction of the safety belts (belt tension)	41	0.14	0.13
51	Maximum lap belt tension force	33	0.27	0.27
68	Maximum shoulder belt tension force	17	0.32	0.35

5. Summary

In frontal barrier impact test, the human body is affected by dynamic loads resulting from the sudden vehicle motion braking. The nature of these loads is strictly related to the vehicle structure. Framed structure of the vehicle used in the experiment, without controlled crush areas, generates complex processes that resulted in the vehicle body displacement in relation to the frame by about 0.2 m.

Measured courses of the dummy's head and torso delay were used to define the velocity of their displacement in relation to the vehicle, including the values of the head velocity when it hits the dashboard (about 23 km/h in vertical direction and about 10 km/h in horizontal direction). Such information is required to evaluate the energy of the impact when the head hits the cab elements and it is significant when designing the airbag deployment process. These values are of basic significance at the stage of selection of airbag arrangement and size, belt and seat fixing points and selection of belt pretensioner operation time and the front airbag deployment activation time. In order to improve the operation of that equipment and successfully integrate it in a particular vehicle, such analysis needs to be carried out.

The experiment showed the possibilities of indicating the courses of variation of velocity and displacement of the dummy's parts in relation to the vehicle and significant limitations of that analysis that occur when the dummy's head hits the vehicle interior elements. It resulted in a need to perform the frame-by-frame analysis of the video recorded during the experiment and due to that a verification of obtained head velocity and displacement values was possible.

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