CHILD SAFETY IN A CAR DURING A FRONTAL COLLISION

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Abstract

Road accidents with participation of the children are of particular nature. According to surveys, the older children at the age of 8-12 years are often transported in cars in a wrong way. They are usually fastened with seat belts designed for adult passengers. In order to make the seat belts safe for a child, they should be used together with a booster cushion or a high back booster seat.

This paper presents the test results and analysis of dynamic loads affecting a child in the back seat of a passenger car during a frontal collision. The car body was accelerated to a speed of about 48 km/h and then it was suddenly stopped in a time of about 100 ms. The analysis was carried out on the basis of results of experimental tests performed at the collision station in the Automotive Industry Institute in Warsaw. The attention was paid to the influence of protection device type on the P10 dummy, representing a child at the age of about 10 years. Three child protection options during a collision were considered: the dummy was sitting directly in a car seat, on a booster cushion and on a seat. The dummy was fastened with standard seat belts. Evaluation of the protection device influence on the dummy loads was given in association with the operation of the seat belts. During evaluation, the indexes of biomechanical resistance of a human body to the impact load effects were used. They made the basis for the evaluation of the child injury severity risk.

Keywords*: road transport, vehicle safety, crash tests, child safety, booster seat*

1. Road accidents involving children and their effects

Road accidents are still the most frequent external cause of children's death [10]. In Poland, 2296 children at the age of 0-14 years died in road accidents during the period of 2000-2012. Their number is systematically decreasing, from 265 in 2000 to 89 in 2012 [6, 15]. Considering the changing population of the children at the age of 0-14 years, the fatal injury index per 1 million children amounted to 36.3 in 2000 and it amounted to 15.3 in 2012 and it confirms a significant improvement of the children safety in the road traffic.

Children at the age of up to 14 years mostly die on the roads as the passengers of the passenger cars (about 45% children were killed in the road accidents in EU-15 during 2003-2009 [4, 6], about 52% in Poland during 2010-2012 [15]). In Poland, children at the age of up 14 years make about 8% of victims and 15% injured ones among passengers of the passenger cars [15].

Detailed data on the road accidents involving children is not available in Poland (including places occupied in a car, type of collision, child restrain method). On the basis of the data on the road accidents in the USA [1] Tab. 1 gives the index values specifying a number of severely injured or killed (MAIS3+) per 1000 children occupying the rear seats. It only includes accidents with restrained children. This data confirm that in most accidents older children are worse restrained than the younger ones. Frontal collisions are particularly dangerous for the children at the age of 9-12 years.

The paper [3] finds out, on the basis of the road accident data from the period of 2000-2005, involving children at the age of up to 10 years, transported in cars, that about 61% of all fatal injuries and severe injuries were among the children at the age of 5 to 10 years, 32% among the children at the age of 1-4 years and the remaining 7% at the age of below 1 year. More victims among older children probably results from that fact that they travel by car more frequently but it can also be caused by improper children restraint in a car.

Tab. 1. The number of serious injured or killed (MAIS3+) per 1000 restrained children, according to age and crash type (USA, 1991-2005) [1]

Crash type	4 to 5 years	6 to 8 years	9 to 12 years
Frontal	2.8	4.4	16.0
Side	6.5	4.1	7.7
Rear	7.1	1.2	0.6
Rollover	3.1	6.7	7.1

The above data on the road accidents results in the following findings:
- majority (51-54%) of children at the age of 0-14 years killed in the road accidents were the passengers of the passenger cars,
- older children at the age of about 10 years are in the group of the highest risk,
- frontal collisions are the most dangerous among various types of accidents, they make 10-12% of road accidents but they generate as much as 19-20% fatal injuries [15].

Considering the above, the following part of the paper pays attention to the risk of injury for a child at the age of about 10 years, occupying the rear seat of a car during a frontal collision.

2. Children injuries in cars during road accidents

A child in a car should be transported in a restrain seat adjusted to its figure (weight, height). Seats for small children are fixed to a car seat and are equipped with their own belts for fastening a child. Older children usually use the booster seats designed to adjust the seat belt position on a child's body (Fig. 1).

Fig. 1. Booster cushion and high back booster seat [11]

Data on the child injury in the road accidents in Poland is rarely published. It usually refers to a small number of children at the age of about 10 years and does not include information on a type of collision and child restraint method while driving [7, 12]. These both papers state that head and neck injuries were the most frequent child injuries.

More detailed statistical data on child injuries during road accidents are available in foreign literature. The paper [5] specifies that during a frontal collision the risk of head and stomach injuries (AIS2+) for the children transported on a booster cushion and fastened with seat belts were 20-30% lower than for the children without such a booster cushion. Tab. 2 gives the results of analysis of the children injuries during a frontal collision from the European CREST (*Child*

Restraint Systems for Cars) database [5]. A number of the least serious injuries (AIS3+) of individual parts of the body were associated with various child restraint methods: rearward facing, forward facing devices, booster and safety belt, safety belt only. Serious injuries of younger children transported in car seats mostly refer to the head and the neck. Children seating on a booster cushion and fastened with seat belts also suffered from chest and stomach injuries. Children fastened only in a seat belt mostly suffered from severe stomach and chest injuries. Children in all groups often suffered from limbs fractures.

Tab. 2. CREST accident database: Rearward facing / Forward facing devices / Booster and safety belt / Adult safety belt only (frontal impact, AIS3+) [5]

Number of children	Rearward facing systems	Forward facing systems	Booster + seat belt	Adult safety belt only
	31	144	108	148
Head	5	16	7	8
Neck	0	10	11	6
Chest	0	6	9	18
Abdomen	0	3	9	27
Limbs (*- fractures)	4*	20*	25*	38*

Similar results of the children injury analysis are described in the papers [2, 13]. The paper [13], on the basis of the data on the road accidents in Europe from the period of 1998 to 2008, involving children at the age of 6-12, finds that over 70% of 207 children were transported only in the seat belts and 15% without any restraint. None of the children seating on the high back booster seats suffered from AIS2+ injuries. This injures occurred in:

- 8.7% children restrained in adult seat belt only (13 of 149),
- 18.7% children restrained in booster cushions (3 of 16),
- 24.1% unrestrained children (7 of 29).

Restrained children mostly suffered from stomach, head and upper extremity injuries. In case of side collisions (79 children at the age of 6-12 years), passengers mostly suffered from head injuries.

Data given on Fig. 2 refer to the accidents in Australia in the period of 2003-2005 [2], involving 152 children at the age of 2-8 years. There were 15 to 27 children at that age. Frontal collisions made about 50% of accidents and side collisions made 28%. Seat belts were the only restraint for about 60% of the children at the age of 4-6 years and over 90% of the children at the age of 7-8 years.

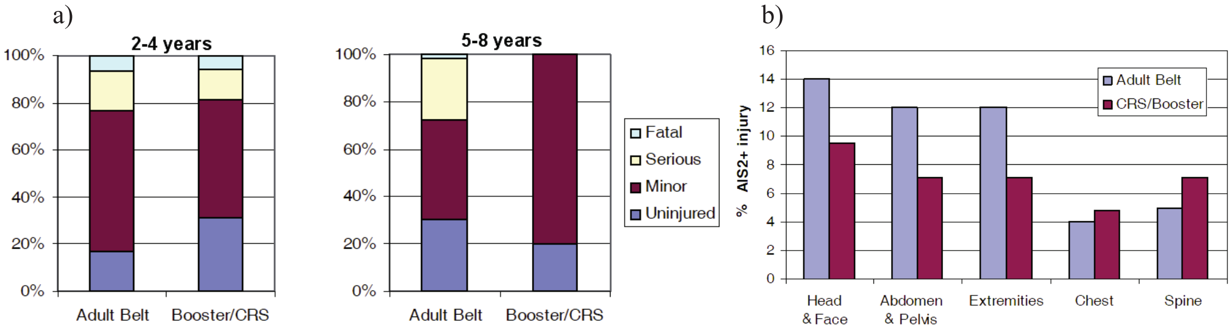


Fig. 2. Relationship between distribution of injury severity, age and restraint (a) and distribution of AIS2+ injuries for different restraint types (b) [2]

Data from the Fig. 2 confirm that the children restrained with CRS/Booster more rarely suffered from injuries than the ones restrained only with a seat belt. Child's head injury was the most frequent one. Younger children suffered from severe internal injuries of the abdominal cavity in frontal collisions were identified, where a lap belt was placed too high and it moved to a stomach resulting in severe injuries [2].

3. Experimental tests of the child dummy loads during frontal collisions

Previous papers [16, 17] present comparative evaluation of loads that affect the passengers occupying the front and the rear seats in a car during a frontal collision. It was found that loads of the dummies in the back seats, including the children at the age of 10 years, are usually several times higher than for the dummies in the front seats.

The evaluation of the influence of restraint equipment on a child load condition during a frontal collision is presented below. The attention was focused on the dummy's head and torso loads P10, representing a child at the age of about 10 years. Evaluation of the protection device influence on the dummy loads was given in association with the operation of the seat belts. The analysis was carried out on the basis of results of experimental tests performed at the collision station AB-554 in the Automotive Industry Institute in Warsaw. The car body was accelerated to a speed of about 48 km/h and then it was suddenly stopped in a time of about 100 ms. The course of the car body delay was in accordance with requirements defined in the Regulations ECE R44, which refers to the tests on the child restraint devices. The maximum car body delay amounted to about 22 g. In the next crash tests, high car body delay repetition was obtained which is crucial for the analysis carried out further on.

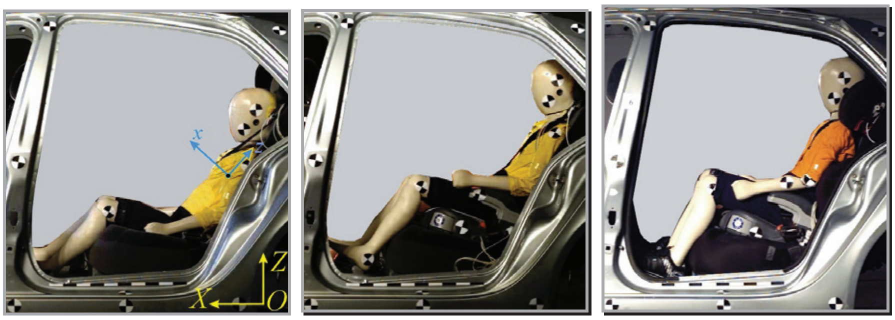
The P10 dummy was seating on the left side of the back seat and was fastened with standard seat belts that were replaced with new ones after each crash test. During the next crash tests (marked as *B, P, F*), the P10 dummy was restrained in different ways (Fig. 3):

B – restrained in adult seat belt only,
P – restrained in booster cushions (for children of 22 to 36 kg),
F – restrained in hi-back booster seat (for children of 15 to 36 kg).

Values measured during the crash tests included:

- forces extending the seat belt band in lap and shoulder sections,
- dummy's head and torso acceleration in three mutually parallel directions.

Crash tests were filmed by means of video cameras designed for fast shooting (1000 frames per seconds).



Test B *Test P* *Test F*

Fig. 3. P10 dummy in a car body

Executions of forces extending the seat belt band were given in Fig. 4. Executions of the force in the shoulder belt (SB) and in the lap belt (LB) were compared separately. The tests B, P and F show various force increase paste in the shoulder belt, while the maximum values of that force and time of occurrence are similar. In case of the force in the lap belt, courses are significantly different: the maximum values and time of occurrence are different. On the basis of the frame-by-frame analysis of the videos, it was found that torso displacement in the direction of driving is the highest when the force in the shoulder belt reaches the maximum value.

In the B test, the dummy is located directly on the back seat, the lap belt band is placed too high over the thighs. The video shows that hip displacement against the back seat is significant during the collision. The lap belt slides from the dummy's thighs and hips to the stomach and further on under the ribs. Internal organs in the stomach and the chest are subject to severe injuries. That effect, the so-called submarining, is visible as a temporary decrease of the force in the lap belt during 85-95 ms (Fig. 4). In the F test, the dummy is placed on the high back booster seat and it is placed more to the front against the backrest of the seat compared to the B and P tests (Fig. 3). That dummy position resulted in a rapid force increase in the lap belt.

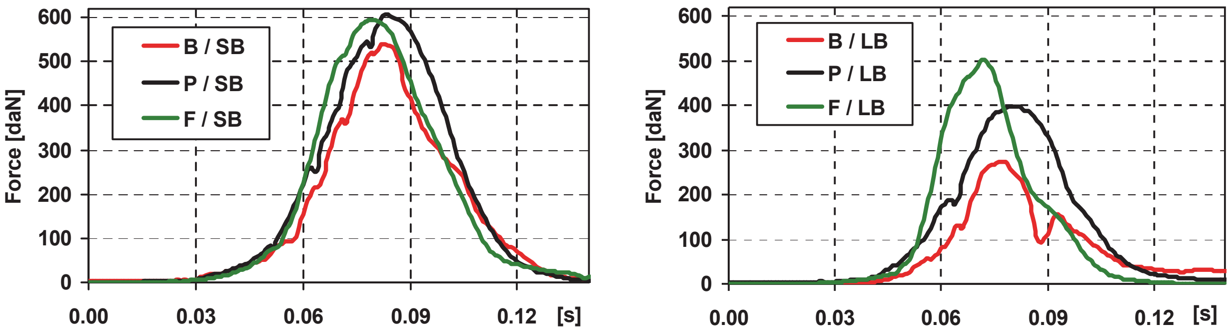


Fig. 4. A course of forces in seat belt (SB – shoulder belt, LB- lap belt)

The resultant values of the dummy's head and torso acceleration are specified on Fig. 5. Their maximum values are several times higher than a car delay (22 g), which is caused by delay in the influence of the seat belt on the dummy (about 30 ms). The maximum values of the resultant torso acceleration are the highest in the test F (high back booster seat), where the force in the lap belt is much higher than in the tests B and P. The maximum values of the resultant head acceleration are the highest in the test B.

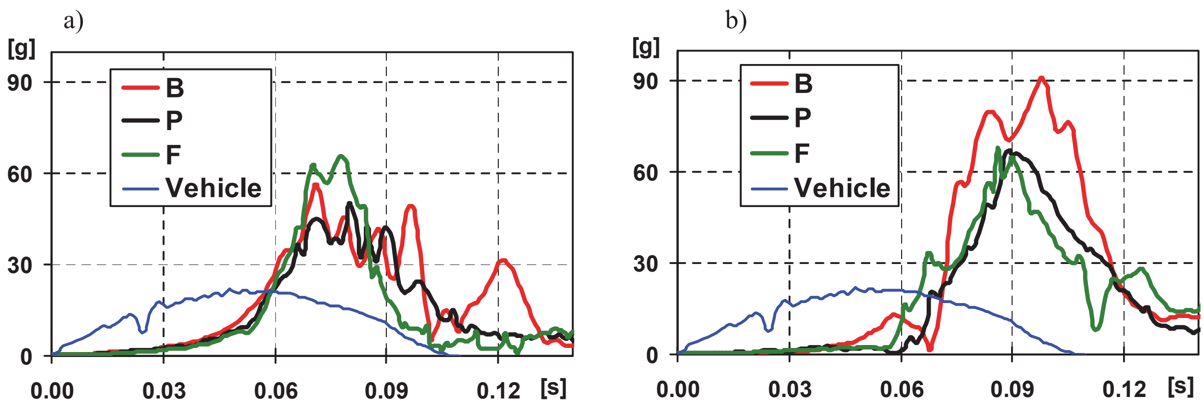


Fig. 5. The resultant values of the dummy's head (a) and torso (b) acceleration in the tests B, P and F

The influence of the restraint device on the dummy motion is much more complex than the above description. More detailed analysis of the kinematics and the dummy's loads in the tests B, P and F will make a subject of a separate paper. Below, the attention is paid to the effects of the restraint device change on dynamic loads of the P10 dummy. For that purpose, the results of the dummy's head and torso acceleration measurement results were used to calculate two injury indexes:

- Head Injury Criterion (HIC_{36}), calculated at time up to 36 ms,
- resultant maximum chest acceleration (C_{Acc}), at time at least 3 ms.

The results of the calculations for HIC_{36} and C_{Acc} indexes are given on Fig. 6. In the test B, where the P10 dummy was seating directly on the rear seat, the value of the HIC_{36} index is several times higher than in the tests P and F. The highest torso acceleration occurred in the test F (63 g). It is higher by 43% than in the test P and higher by 18% in the test B and results from effective operation of the lap belt.

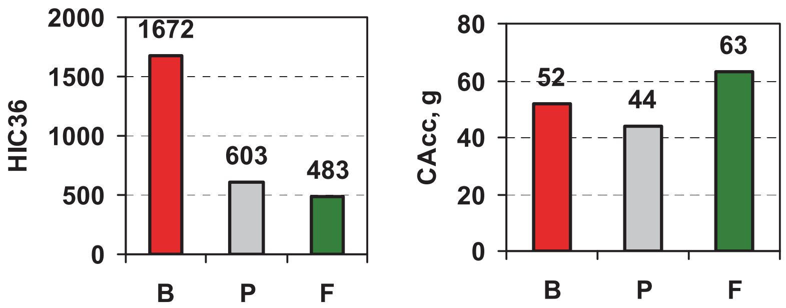


Fig. 6. The results of the calculations for HIC_{36} and C_{Acc}

The methodology described in the paper [16] was applied to evaluate the risk of the dummy's injuries. It is based on relations between the index values HIC_{36} and C_{Acc} and the risk of injuries described by means of a *Abbreviated Injury Scale* (AIS). A probability of severe head and chest injury at the level of AIS4+ is described by the functions [8, 9]:

$$P_{head}(AIS4+) = \{1 + \exp[5.02 - 0.00351 \cdot HIC_{36}]\}^{-1}, \tag{1}$$

$$P_{chest}(AIS4+) = \{1 + \exp[5.55 - 0.0693 \cdot C_{Acc}]\}^{-1}. \tag{2}$$

The risk of death or disability of a person who suffered many injuries is higher than if the injuries apply only to one part of a human body. It includes P_{comb} (*combined injury probability criterion)*, usually expressed in percentage values. Including (1) and (2) we have [8]:

$$P_{comb} = 1 - (1 - P_{head}) \cdot (1 - P_{chest}) = P_{head} + P_{chest} - P_{head} \cdot P_{chest} \ . \tag{3}$$

The results of the calculations are given on Tab. 3. The values of the risk index P_{comb} are the highest in the test B and it is caused by a significant head load. In the test P, the risk of injuries on the level of AIS4+ is 6-times smaller and it is 3 times smaller in the test F.

Tab. 3. A risk of severe head and chest injury at the level of AIS4+ (P10 dummy)

Test	HIC_{36}	C_{Acc}	P_{head} (AIS4+)	P_{chest} (AIS4+)	P_{comb} (AIS4+)
B	1672	52 g	70%	12%	74%
P	603	44 g	5%	8%	12%
F	483	63 g	3%	23%	26%

Obtained results of injury risk calculations were compared to the results previously described in the paper [16]. For that purpose, Fig. 7 associates the index values HIC_{36} and C_{Acc} from the tests B, P and F with values obtained during the analysis of the tests performed by NHTSA [14, 16]. They referred to the child dummy at the age of about 10 years (Hybrid III, 10YO) loads during frontal collision of various passenger cars into a rigid barrier at the speed of 56 km/h. A 10YO child dummy was restrained in high back booster seat. Lines on a diagram indicating injury risk limits AIS4+: 10, 20, 35 and 45% respectively.

Results obtained in the test B, P and F confirm serious influence of the applied type of the child restraint device on the load level and injury risk. The P10 dummy head load in the tests P and F (48 km/h) is lower compared to 10YO dummies (56 km/h), as probably affected by the collision velocity value. In the test B, the load of the P10 dummy seating directly on the back seat is much higher than for the majority of the 10YO dummies seating in the high back booster seats, despite lower collision velocity.

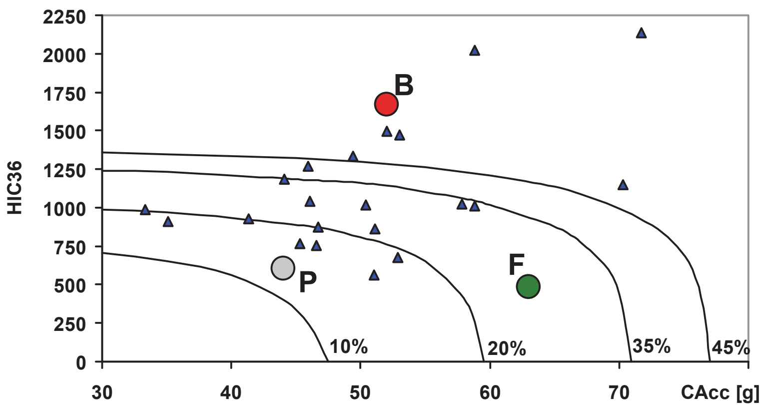


Fig. 7. Association of dummy head and chest loads with AIS4+ injury risk (lines), B, P , F – P10 dummy (48 km/h); ▲ – Hybrid III-10YO (56 km/h)

4. Summary

The number of children killed in road accidents systematically decreases. However, road accidents still remain the major external cause of death for the children at the age of 7-12 years. Car passengers make over a half of the children at the age of 0-14 years killed on the roads.

Older children, 7-12 years old, are usually transported on a booster seat without a backrest or directly on the back seat. During frontal collisions, they are subject to severe head and stomach injuries, particularly in the second case [13].

The restraint device type determines the initial dummy position against the rear seat, its way of displacing against the seat and thus the operation of the seat belt. The laboratory test results given in this paper confirm very high dynamic loads affecting the P10 dummy, seating directly on the rear seat during a frontal collision (test B). Despite the fastened seat belt, the severe head injury risk (AIS4+) amounts to as much as 70%. When the dummy was seating on the booster seat the head injury risk amounted to just 3-5% (tests P and F).

The scope of the child injury risk analysis given in the paper was limited by the P10 dummy measurement abilities and did not include stomach and neck loads that often occur for the children involved in road accidents.

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References

[1] Bidez, M. W., Burke, D. S., King, D., Mergl, K. M., Meyer, S. E., *A Critical Safety Need for Children Ages 9 to 12 in the Rear Seat*, 5th International Conference – Protection of Children in Cars, Munich, Germany 2007.

[2] Brown, J., Bilston, L., McCaskill, M., Henderson, M., *Identification of Injury Mechanisms for Child Occupants aged 2-8 in Motor Vehicle Accidents*, Final Project Report for the Motor Accidents Authority of New South Wales, Australia 2005.

[3] Charlton, J., Koppel, S., Fitzharris, M., Congiu, M., Fildes, B., *Factors that Influence Children's Booster Seat Use,* Monash University Accident Research Centre, Report No. 250, Australia 2006.

[4] Childhood Road Safety, *The European Child Safety Alliance – EuroSafe,* Consumer Safety Institute in the Netherlands 2007.

[5] European Enhanced Vehicle-Safety Committee, *EEVC Working Group 18 Report Child Safety – February 2006,* (www.eevc.org).
[6] European Road Safety Observatory, *Traffic Safety Basic Facts 2011: Children (Aged < 15)*, 2011, (http://ec.europa.eu/transport/road_safety/specialist/index_en.htm).
[7] Goniewicz, M., Wnuk, T., Ostrowski, M., Nogalski, A., Kulesza, Z., *Wypadki komunikacyjne jako przyczyny obrażeń u dzieci*, Zdrowie Publiczne 116(1), pp. 158-161, 2006.
[8] Hackney, J. R., Kahane, C. J., *The New Car Assessment Program: Five Star Rating System and Vehicle Safety Performance Characteristics,* SAE Technical Paper 950888, 1995.
[9] Hong, S., Park, Ch., Morgan, R., Kan, C., Park, S., Bae, H., *A Study of the Rear Seat Occupant Safety using a 10-Year-Old Child Dummy in the New Car Assessment Program,* SAE Technical Paper 2008-01-0511, 2008.
[10] Kułaga, Z., Litwin, M., Wójcik, P., Jakubowska-Winecka, A., Grajda, A., Gurzkowska, B., Napieralska, E., Barwicka, K., Różdżyńska, A., Wiśniewski, T., *Current trends in external causes of children and adolescent mortality in Poland*. Problemy Higieny i Epidemiologii 90(3), pp. 332-341, 2009.
[11] Materiały informacyjne firmy Graco, (http://www.gracobaby.pl).
[12] Stępniewski, W., Rydzewska-Dudek, M., Janica, J., Załuski, J., Niemcunowicz-Janica, A., Ptaszyńska-Sarosiek, I., Dopierała, T., Okłota, M., Szeremeta, M., *Analiza ofiar wypadków drogowych w wieku 0–18 lat w materiale sekcyjnym zakładu medycyny sądowej Akademii Medycznej w Białymstoku w latach 1997-2006,* Roczniki Pomorskiej Akademii Medycznej w Szczecinie, No. 53-2, pp. 50-54, Szczecin 2007.
[13] Visvikis, C., Pitcher, M, Girard, B., Longton, A., Hynd, M., *Literature review, accident analysis and injury mechanisms*, Final Project Report 218744, EPOCh Consortium, 2009.
[14] www.nhtsa.gov.
[15] Wypadki drogowe – Raporty roczne, (http://dlakierowcow.policja.pl).
[16] Żuchowski, A., *Risk of Injury for the Front and Rear Seat Passengers of the Passenger Cars in Frontal Impact,* Journal of KONES Powertrain and Transport, Vol. 19, No. 3, pp. 507-518, 2012.
[17] Żuchowski, A., Prochowski, L., *Analysis of the Influence of the Seat Taken in a Car on the Dynamic Load Affecting People During the Obstacle Impact by the Passenger Car*, *Automotive safety problems,* Vol. 1., Ed. by Stańczyk L.T., Wydawnictwo Politechniki Świętokrzyskiej, pp. 113-126, Kielce, Poland 2012.