

Article citation info:

Żuchowski A. Comparative assessment of the risk of injury to children aged 3 and 10 in a road accident. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2015; 71(1): 133-152, <http://dx.doi.org/10.14669/AM.VOL71.ART9>

COMPARATIVE ASSESSMENT OF THE RISK OF INJURY TO CHILDREN AGED 3 AND 10 IN A ROAD ACCIDENT

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Summary

The article presents results of experimental investigation of the dynamic loads that act on a child carried in a safety seat fixed on the rear seat of a passenger car during a frontal impact of the car against an obstacle. The analysis was done with using the test results published on the Internet by the US National Highway Traffic Safety Administration (NHTSA), covering 12 crash tests where the test car moving with a speed of about 56 km/h frontally hit a rigid flat barrier. The attention was focused on the loads on test dummies representing children aged 3 and 10 years. For all the cars tested, the risk of serious injury (AIS 3) for the child aged 3 years was higher by 5-27 % than that for the ten-year-old one in the test conditions under consideration. It has been found that for the younger child, the greatest danger may arise when the child's head hits its back on the seat backrest in the final phase of the vehicle collision; in contrast, the older child is chiefly exposed to excessive thoracic deflection. The assessment of loads on the test dummies was preceded by an analysis of data collected from the road accidents that occurred in Poland and in the European Union. It has been ascertained that the risk of child's death in a road accident in Poland is comparable for both the age groups under analysis (0-6 years and 7-14 years). However, it is alarming that the value of the rate of hazard to children in Poland is almost twice as high as the EU average.

Keywords: road accidents, crash tests, child safety, child restraint systems

1. Introduction

The road accidents in which children are involved deserve special attention. According to the regulations in force, a child not more than 150 cm tall should be transported in a safety seat or with the use of another child restraint system appropriate for the child's weight and height and being in conformity with applicable technical requirements [20].

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The authors of many publications point out that parents' concern for the safety of their child riding in a car is waning with growing child's age. Older children are often transported without using adequate child restraint systems (safety seats) while the car seats and seat belts are not a sufficiently effective child protection means or even may cause serious injuries to children, chiefly to their abdomen and neck [22]. In Europe, only every third child is adequately protected when travelling by car, according to estimates, and parents too early give up using child safety seats or the like devices and transport even three-year-olds directly on a car seat, fixed by the car seat belt [24, 25]. It has been reported in study [4] that the car seat belt was the only protection means used for about 60 % of children aged 4-6 and for over 90 % of children aged 7-8 years (in Australia). Similarly, results of an analysis of the road accidents that took place in the USA confirm that in most cases the older children are less carefully protected than the younger children are, while frontal collisions are particularly dangerous for children aged 9 to 12 years [2]. The lack of adequate children protection can be clearly seen in the effects of road accidents. It has been highlighted in study [5] that as many as 61 % of all the deaths and serious injuries occurred in children aged 5-10 years, with 32 % and only 7 % having taken place in the 1-4 years and below 1 year age groups, respectively. A more extensive review of works dealing with road accident-related injuries to children and with the methods of protection of children travelling in motor cars was given earlier in [24, 25]. In publications [10, 12], attention was directed to the effects of incorrect use of child safety seats and on the effectiveness of a child safety seat and booster seat when a child aged about 3 years is transported in it. Results of tests carried out with a three-years-old child dummy (3YO dummy) have been given in [9].

The objective of this study was to give a comparative assessment of the risk of injury to children aged 3 and 10 years during a frontal impact of the car against an obstacle. The assessment was based on results of 12 crash tests during which test dummies representing children about 3 and 10 years old (3YO dummy and 10YO dummy, respectively) were placed on the rear car seat. Direct measurement results obtained during the crash tests analysed in this study were downloaded in a digital form from [32]. The assessment of the risk of injury during a crash test was preceded by an analysis of data collected from road accidents in which children of two age groups (0-6 years and 7-14 years) were involved. The work was aimed at identifying the vehicle design and operation factors that are decisive for the loads on vehicle passengers during a road accident and for the necessity of reducing the loads to a minimum. Results of the experimental tests carried out within this scope were given previously in [13, 24-27] and in other author's publications issued in the period from 2006 to 2015.

2. Assessment of the safety of children in road traffic depending on their age, based on road accident data

The intensity and mode of child's participation in road traffic depends on many factors, including child's age. Pursuant to the "Road Traffic Law" Act [20], a child up to 7 years of age may use a public road as a pedestrian exclusively when being under care of a person

aged at least 10 years. A child up to 10 years of age may ride a bicycle exclusively when being under care of an adult and in compliance with the rules and regulations specified for pedestrian traffic, i.e. the child together with its carer should use a sidewalk or pedestrian path and, if having to ride a bicycle on the carriageway, keep close to the left-hand side of the road (to see the oncoming traffic). For unassisted cycling, a bicyclist's licence is required. Such a licence can only be obtained by a person at least 10 years old [21].

In 1995-2012, 4 094 children aged 0-14 years were killed in road accidents in Poland (Fig. 1). This number has been consistently decreasing, from 415 in 1995 to 89 in 2012. It is worth adding here that the total population of children in this age bracket (0-14 years) dropped in Poland from 8.68 million to 5.80 million [29].

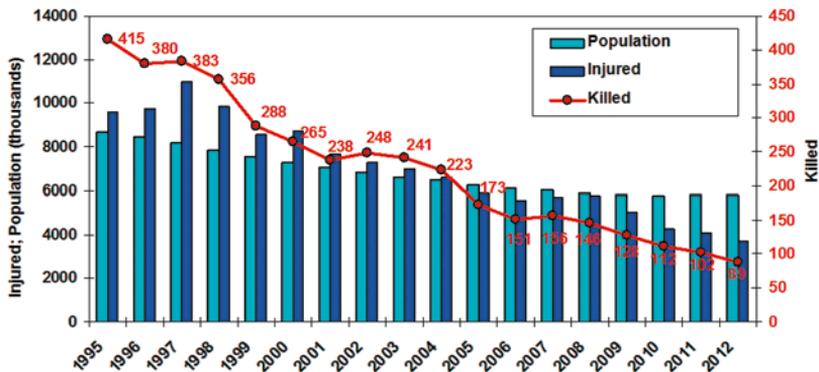


Fig. 1. Children aged 0-14 years being casualties of road accidents in 1995-2012 (based on [29])

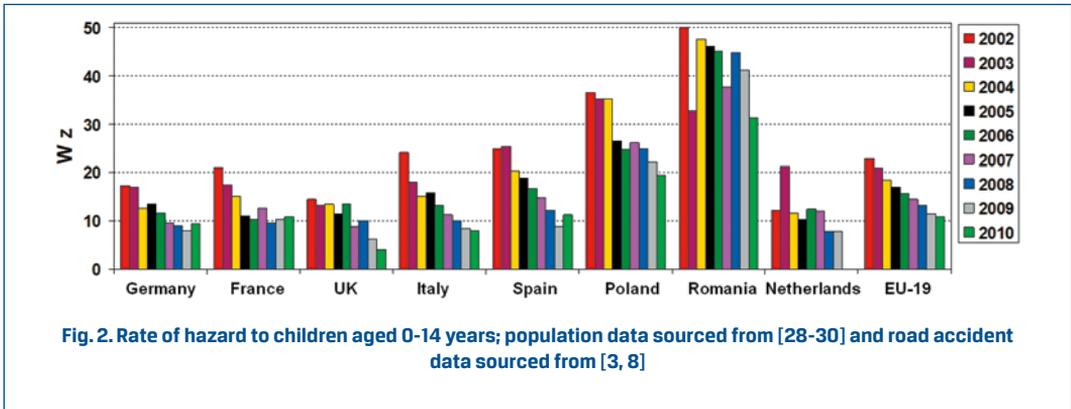
The statistical data about the participation of children in road accidents in Poland were compared with data collected from other EU countries [3, 8]. For the comparison purposes, a rate of hazard to children² (W_z) was calculated:

$$W_z = \frac{\text{number of children (0-14 years) killed in road accidents in the specific year}}{\text{population of children (0-14 years) in millions in the specific year}} \quad (1)$$

Results of calculation of the W_z indicator have been brought together in Fig. 2. Attention was focused on the countries with the greatest population numbers (e.g. Germany with 80.5 million people, Poland with 38.5 million people, or the Netherlands with 16.8 million people). The highest and the lowest values of the W_z indicator were obtained for Romania and the UK, respectively. In 2002-2010, the average value of the W_z indicator decreased from 22.7 to 10.5 in the EU-19 countries and from 35.2 to 19.3 in Poland. Having additionally considered the fact that the values of the W_z indicator in Poland were $W_z = 47.8$ in 1995 and $W_z = 15.3$ in 2012, we can state that the safety of children in road traffic has significantly

² The indicator thus defined is also known as motor vehicle accident-related child mortality rate or MVA-related child mortality rate (translator's note).

improved. Nevertheless, the values of the W_z indicator for Poland are almost twice as high as the corresponding average values of this indicator obtained for the European Union as a whole.



In the years 2008-2012, children up to 14 years of age made about 8 % of the killed and 15 % of the injured among the passengers of motor cars in Poland [29]. The structure of the road accidents with children, by children's age and mode of participation in the road traffic (vehicle driver, passenger, or pedestrian), has been presented and analysed below. For these purposes, data about the accidents with children that occurred in 2008-2012 have been brought together in Table 1. About 50 % percent of the children killed were vehicle passengers; however, information about the vehicles in which the children were transported is unavailable from publication [29]. Based on publications [6, 8], an assumption may be made that most of the vehicles were passenger cars. The data about children aged 0-6 years (seven year groups) and 7-14 years (eight year groups) were presented separately. In the age group of 0-6 years, the accidents predominated where the children were vehicle passengers (i.e. such accidents made about 69 % of the total). The older children (7-14 years of age) were almost equally often vehicle passengers and pedestrians (35 % and 42 %, respectively).

Further on, the attention was focused on child-passengers (the W_z indicator referred to above covered all the children being accident victims, inclusive of drivers/cyclists, passengers, and pedestrians). An answer was sought for a question which age group of the child-passengers is more endangered during a road accident. Differences in the risk of injury (death) may arise from different anthropometric characteristics of younger and older children, which translate into different immunity of their bodies to the effects of impact loads, but also from differences in the effectiveness of various child restraint systems (safety seats) used in both cases.

In this study, the safety indicators often used at the analysis of road accidents were utilized. They included the *accident severity rate* (CW), defined here as follows:

$$CW = \frac{\text{number of child - passengers killed in road accidents in the specific year}}{100 \text{ accidents with child - passengers in the specific year}} \quad (2)$$

Table 1. Children up to 14 years of age being casualties of road accidents in Poland (based on [29]): D – drivers/cyclists; P – passengers; W – pedestrians

Year	Population [million]	Number of accidents				Number of the injured				Number of the killed			
		D	P	W	Total	D	P	W	Total	D	P	W	Total
Children aged 0-6 years													
2008	2.560	45	1027	470	1542	45	1012	470	1527	0	34	15	49
2009	2.631	46	916	401	1363	41	905	387	1333	5	24	14	43
2010	2.721	40	909	318	1267	39	893	314	1246	1	28	5	34
2011	2.827	34	809	356	1199	34	849	360	1243	0	18	14	32
2012	2.845	36	816	298	1150	35	821	336	1192	1	22	8	31
Children aged 7-14 years													
2008	3.302	872	1557	1784	4213	865	1579	1797	4241	18	47	32	97
2009	3.185	843	1372	1489	3704	824	1414	1487	3725	22	36	27	85
2010	3.038	727	1195	1414	3336	713	1222	1405	3340	17	32	29	78
2011	2.992	733	979	1166	2878	730	1176	1265	3171	16	28	26	70
2012	2.952	641	762	1126	2529	632	980	1141	2753	9	23	26	58

as well as the following *rates of hazard*, with the number of child-passengers injured or killed in road accidents in a specific year being taken in comparison with the corresponding population:

$$W_{RP} = \frac{n_{RP}}{N}, \quad W_{ZP} = \frac{n_{ZP}}{N} \tag{3}$$

where: n_{RP} , n_{ZP} – number of the child-passengers injured and killed, respectively, in a specific age group; N – population of children in the same age group, in millions.

Results of calculations of the above indicators, obtained for two age groups of the child-passengers (0-6 years and 7-14 years), have been presented in Fig. 3.

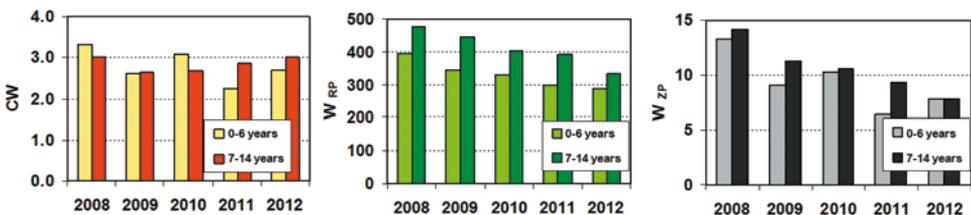


Fig. 3. The severity of accidents and the rates of hazard to child-passengers in Poland (based on [29])

The results of calculations of the severity rates of accidents with children in the age groups under analysis do not give an unequivocal answer to the question formulated previously. In some years, the value of the CW indicator was higher for the group of younger children; in the other years, however, it was higher for the other group. The CW values calculated for the period 2008-2012 are almost identical for both the age groups (2.81 and 2.83 for the younger and older children, respectively). This shows that the risk of death of a child-passenger in result of a road accident does not depend on the child's age.

The W_{RP} indicator values for the older children exceed those for the younger group by about 24 %. Since the number of the injured is usually proportional to the number of accidents, the higher W_{RP} values indicate that the older children more frequently participate in road accidents. This finding is in line with expectations and confirms the conjecture (no data concerning this issue are available) that older children are more frequently transported in motor cars than those of the younger group are. In qualitative terms, the W_{ZP} and W_{RP} values are generally similar to each other, except for the fact that in 2010 and 2012, the W_{ZP} indicator took similar values for the younger and older children.

3. Assessment of the risk of injury to children aged 3 and 10 years, based on laboratory tests

3.1. Objective and scope of the analysis of laboratory test results

The analysis of laboratory test results was undertaken to carry out a comparative assessment of the loads on test dummies representing children aged 3 and 10 years. The loads acting on the child dummies travelling on the rear seat of a passenger car during a frontal collision were examined. The analysis was done with using results of 12 crash tests, published on the Internet by the US *National Highway Traffic Safety Administration* (NHTSA) [32].

During each crash test, a test car moving with a speed of about 56 km/h frontally hit a stationary rigid barrier. The basic specifications of the test cars have been given in Table 2. The cars were grouped according to their body styles (sedan, minivan, van). All the cars were 2005 models, brand-new. The car mass included the mass of the test dummies, i.e. two dummies representing male adults sitting on the front seats and two dummies representing children aged 3 and 10 years placed on the rear seat.

The cars used for the tests differed from each other in their mass, dimensions, and construction of the front crumple zone. The depth of vehicle body deformation after the impact against the barrier, measured at the height of car bumper in the middle of its width ranged from 0.38 m (*Ford Five Hundred*) to 0.65 m (*Chevrolet Uplander*), which confirms significant differences in the construction of the front crumple zone of the cars. The properties of the front crumple zone are decisive for the vehicle deceleration values that occur during the collision [27].

The tests were carried out on test dummies Hybrid III representing children 3 years old and 10 years old, hereinafter referred to as 3YO and 10YO dummies, respectively (Fig. 4). The 3YO dummy was placed on the right-hand side of the rear car seat in a child safety seat (*Evenflo Titan V*) with a five-point harness and a LATCH (*Lower Anchors and Tethers for Children*) system of fastening the safety seat without the car seat belt being used. In the Ford E150 Van car (test V1), the 3YO dummy was placed in the centre of the rear seat. In each of the cars, the 10YO dummy was placed on the left-hand side of the rear seat (behind the driver's seat), on a booster seat (*Graco Turbo Booster Highback*), and it was fixed with a standard seat belt of the car.

Table 2. The cars used for the crash tests (based on [32])

Test symbol	Make	Model	Body style	Mass [kg]	Deformation depth [m]
S1	Chevrolet	Malibu	sedan	1 697	0.51
S2	Suzuki	Verona		1 758	0.53
S3	Pontiac	G6		1 767	0.58
S4	Buick	Lacrosse		1 832	0.63
S5	Ford	Five Hundred		1 924	0.38
S6	Volvo	V70		1 802	0.57
mV1	Toyota	Sienna	minivan	2 165	0.54
mV2	Chevrolet	Uplander		2 243	0.65
mV3	Honda	Odyssey		2 263	0.47
mV4	Chevrolet	TrailBlazer		2 388	0.55
V1	Ford	E150 Van	van	2 675	0.54
V2	Chevrolet	Express		2 721	0.62



Fig. 4. The child safety seat and cushion seat used for restraining the test dummies during the crash tests and the characteristic curves representing the dynamic thoracic deflection of the dummies [15, 16]

In this work, attention was focused on the dynamic loads on dummies' head, neck, and torso. With this objective in view, results of measurements of the following quantities were used, downloaded in a digital form from [32]:

- accelerations of dummy's head and torso;
- forces acting on dummy's neck and moments of such forces;
- thoracic deflection.

3.2. Test dummies and their positioning in the cars

The factors that affect the loads acting on the test dummies during the car impact against the barrier include properties of the protection means used and dummies' dimensions. The overall heights of the 3YO and 10YO dummies are 945 mm and 1 297 mm, respectively, and their heights in a sitting posture are 772 mm and 1 064 mm, respectively. The biggest and smallest differences in dimensions of individual dummies' parts occur in the case of legs and heads, respectively. The mass of the 3YO dummy (16.2 kg) is less than a half of that of the 10YO dummy (35.2 kg), with the biggest differences being observed for the legs and torso. Details on the dimensions and masses of dummies' parts are available from [31]. The two dummies under consideration have different dynamic properties. As an example, Fig. 4 shows the characteristic curves representing the dynamic thoracic deflection of both dummies. Such curves have been determined with the use of a pendulum (with a mass of 1.7 kg for the 3YO dummy and 6.9 kg for the 10YO dummy), which hit the dummy's torso with a velocity of about 6 m/s. The range of the thoracic deflection is about 25 % of dummy's thorax depth.

The cars used for the tests differed from each other in the dimensions of the space provided for passengers sitting on the rear car seat. This space was confined by the preceding seats at the front and by the car seat and child seat backrests at the rear (Fig. 5). In the Suzuki Verona car (test S2), the passenger seat was in its rearmost position; in all the other cars, the front car seats were in their central positions. The values of the distance between dummy's torso and the front seat backrest (dimension CB in Fig. 5) were similar to each other (with the differences usually ranging from 20 mm to 50 mm) and there were only three cars where the CB distance for the 10YO dummy exceeded that for the 3YO dummy. The 3YO dummy's knees were situated farther from the front seat backrest than those of the 10YO dummy were and the difference varied from 40 mm to 120 mm. In the mV2 test, dummies' feet were in contact with the front seat backrest (TB = 0 mm). The initial position of dummies' feet and the way in which dummies' legs come to contact with the front seat backrest during the collision play an important role in shaping the loads on the dummies [13].

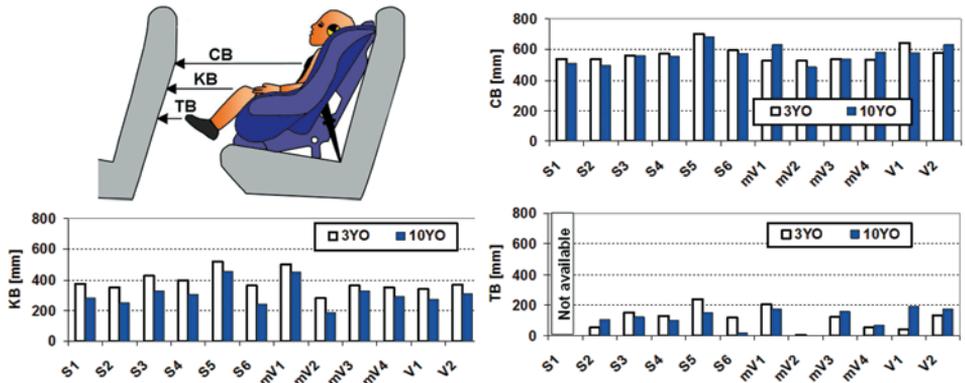


Fig. 5. Dimensions defining the dummy's position in relation to the front seat (based on [16, 32])

During the collision, the dummies moved in relation to the rear car seat within a range determined by the functioning of the protection means used. An example of the dummies' displacements (positions recorded in 50 ms intervals) has been shown in Fig. 6. The forward displacements of the dummies were big; however, none of the dummies hit its head on the front seat backrest in any of the cars.



Fig. 6. Dummies' displacements during the collision in test V1 (based on [32])

3.3. Results of measurements of the loads on the dummies

A preliminary comparative assessment of the loads on the 3YO and 10YO dummies was carried out on the grounds of realizations of individual quantities measured. With this objective in view, the realizations of the following processes were taken for comparisons:

- resultant acceleration of dummy's head and resultant force acting on dummy's neck (Fig. 7);
- resultant acceleration of dummy's torso and thoracic deflection (Fig. 8).

The resultant values were calculated from realizations measured in three mutually perpendicular directions. The realizations were filtered with the use of a CFC 180 filter.

The realizations shown in the graphs in Fig. 7 represent the loads on dummies' heads (curves HA) and necks (curves NF) in two phases of dummies' motion during a collision. The first phase, corresponding to the forward dummy's motion, lasted for the initial period of up to about 0.12 s. The second phase took place when the dummy moved towards the seat backrest. Regardless of the car in which the dummies were seated, the head and neck loads were similar to each other in qualitative terms. In the first phase of dummy's motion, the maximum values of the loads on the head and neck of the 10YO dummy were higher than those measured for the 3YO dummy and this may have been caused not only by the properties of the restraint system used but also by higher mass of the 10YO dummy's head. In the second phase of the motion, the maximum values of the head loads were markedly higher for the 3YO dummy. The strong impact of the back of dummy's head against the child seat backrest indicates heavy elastic strain having developed in the harness that restrains the dummy in its seat, which caused the dummy to be unfavourably thrown back. In addition to this, the backrest of the child safety seat used for transporting the 3YO dummy is far less deformable, which translates into much worse seat backrest capability of cushioning the impact in comparison with the backrest of the booster seat used for restraining the 10YO dummy (cf. Fig. 6).

The resultant acceleration of dummy's torso (curves CA in Fig. 8) was higher for the 10YO dummy, similarly to what was observed for dummy's head. The thoracic deflection (curves CD in Fig. 8) in the 3YO dummy was about 20 mm and made 12-18 % of the thorax depth (132 mm). For the 10YO dummy, the situation was different: in some tests (S1, mV2, mV3, mV4, and V2), the thoracic deflection was about 20 mm (i.e. 12 % of the thorax depth, which was 165 mm) as against about 30-50 mm (18-30 % of the thorax depth) observed in the other tests. Thus, the thoracic deflection was similar in the 3YO dummy and different in the 10YO dummy in the cars under test.

This finding may result from different ways of loading the thorax of the 3YO and 10YO dummies. Namely, the 3YO dummy is fastened to the safety seat with straps (harness) arranged symmetrically on both shoulders, thanks to which the possibility of the thorax deflection is reduced. Conversely, the 10YO dummy is restrained with a seat belt strap placed on the sternum (cf. Fig. 8), which is conducive to thoracic deflection. Since the seat belt strap is placed diagonally in relation to the torso, it may move towards the neck or slip down from the shoulder to the arm during a collision and this may result in an increase or reduction in the thoracic deflection. This disadvantageous functioning of the three-point

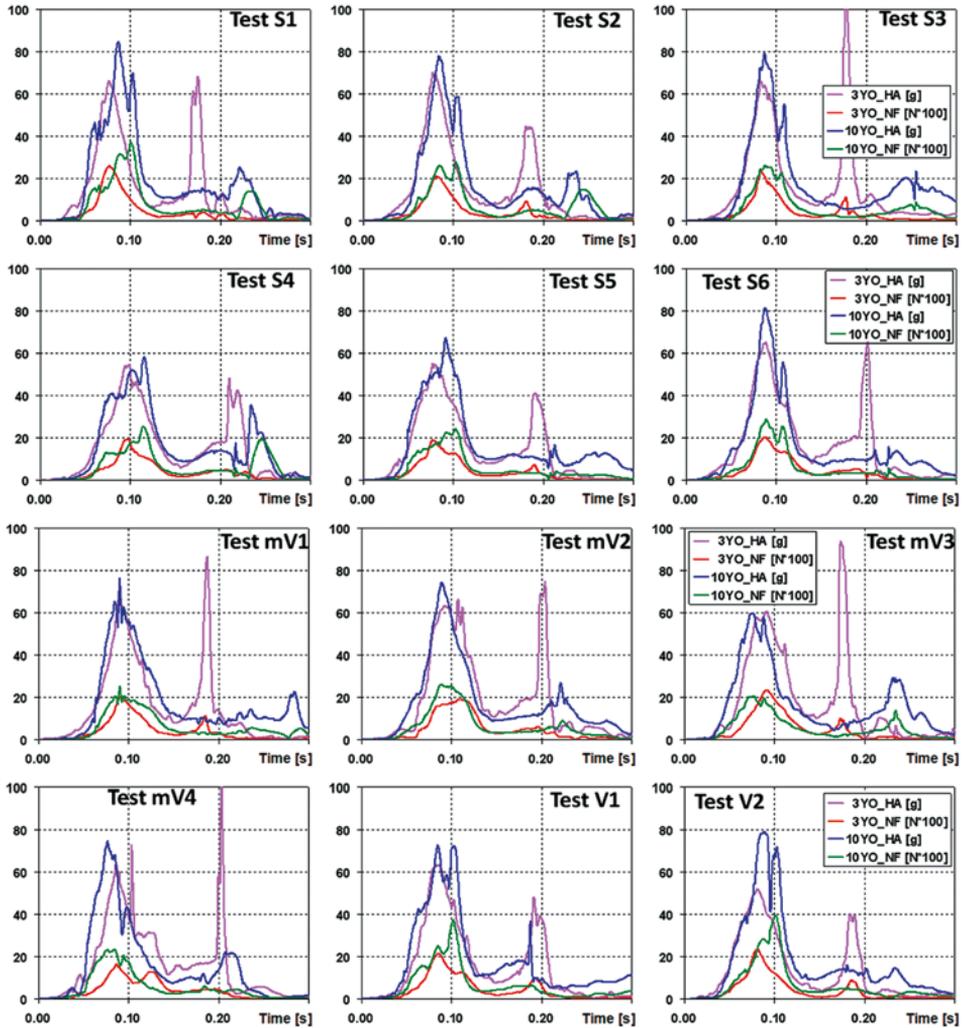


Fig. 7. Resultant accelerations of the head (curves HA) and resultant forces acting on the neck (curves NF) of dummies 3YO and 10YO

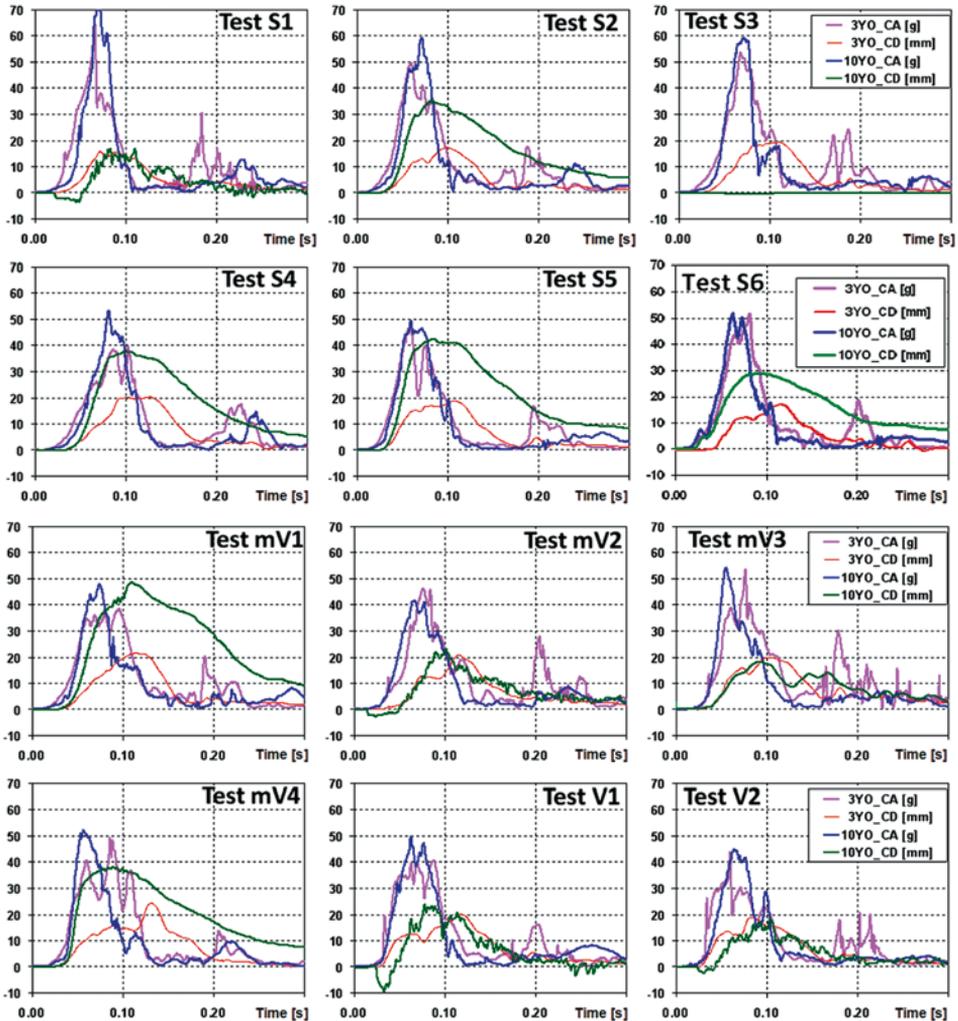


Fig. 8. Resultant accelerations of the thorax (curves CA) and thoracic deflection (curves CD) of dummies 3YO and 10YO (in test S3, the thoracic deflection of the 10YO dummy was not measured)

seat belt was described previously in [25], where it was highlighted that the effectiveness of a seat belt depends on the location of its upper anchorage point. In sedan, minivan, and van cars, the seat belt strap between the shoulder and the upper anchorage point is inclined at various angles, both in the vertical and transverse plane, because this strap runs by the headrest in sedans and it is anchored to a body pillar in minivans and to a beam above the side window. Moreover, the thoracic deflection curve (Fig. 4) shows that the

deflection under a force of about 1 500 N may be within the range of 15-30 mm. In a word, the big differences in the thoracic deflection in the 10YO dummy in individual cars may be explained by the factors pointed out above.

In tests S1, mV2, V1, and V2, the initial values of the thoracic deflection were negative. An explanation for such a finding was sought by analysing the loads on safety belt straps and the video records obtained from high-speed cameras and showing the dummy's movements during the collisions. However, a hypothesis that the negative thoracic deflection might be caused e.g. by the pressure exerted by the seat belt on dummy's abdomen or a thorax side has not been confirmed. Therefore, the results of measurements of the thoracic deflection in the 10YO dummy were afterwards utilized within a limited scope.

3.4. Biomechanical indicators and assessment of the risk of injury to children

It is difficult to give quantitative assessment of differences in the loads on dummies representing children aged 3 years and 10 years on the grounds of the measurement results described above. Therefore, the said results were used to calculate the following four injury indicators (Table 3), described e.g. in [7, 13, 23]:

- HIC_{15} , Head Injury Criterion, calculated for a time interval of up to 15 ms;
- N_{ij} , Normalized Neck Injury Criterion, taking into account the impact of forces (FT and FC, causing tension and compression of the neck) and moments of forces (ME, MF, causing extension or flexion of the neck, i.e. bending the neck backwards or forwards, respectively);
- C_{Acc} , maximum resultant torso acceleration (acting for a period of at least 3 ms);
- C_{max} , maximum thoracic deflection.

The values of these indicators (Table 3) have been determined with taking into account the heaviest loads on the dummies, occurring in almost all the tests in the first phase of dummy's motion, i.e. when the dummies moved forwards. In three tests, the predominating loads occurred in the second phase of dummy's motion, i.e. when the dummy hit its head on the safety seat backrest. The loads were as specified below:

- resultant acceleration of 3YO dummy's head in tests S3 and mV3 (HIC_{15});
- load (moment M_F and force F_C) acting on 10YO dummy's neck in test S4 (N_{ij}).

Any comparative assessment of dynamic loads based on direct comparisons between the values of the above indicators cannot be carried out because the immunity of children to such loads significantly varies with their age. This is also a reason for the fact that the maximum acceptable values of the biomechanical indicators, referred to as *Injury Assessment Reference Values (IARV)* are different for the 3YO and 10YO dummies. These values have been brought together in Table 4, where the critical values of forces F_T and F_C and moments M_F and M_E , used for the calculations of N_{ij} , have been specified as well.

Table 3. Values of the biomechanical indicators

Test symbol	HIC_{15}		N_{ij}		C_{Acc} [g]		C_{max} [mm]	
	3Y0	10Y0	3Y0	10Y0	3Y0	10Y0	3Y0	10Y0
S1	438	705	1.52	1.40	53	70	16	17(-)
S2	514	631	0.91	0.93	49	58	17	35
S3	634*	689	1.01	0.96	52	59	19	-
S4	271	286	0.84	0.93*	38	53	20	38
S5	291	407	0.84	0.80	46	47	19	43
S6	441	725	1.17	1.08	48	50	17	29
mV1	433	459	0.92	0.78	38	47	21	48
mV2	446	589	0.98	1.10	45	41	21	23(-)
mV3	569*	351	1.26	0.86	47	53	20	17
mV4	352	591	0.81	0.91	45	51	24	38
V1	445	486	0.93	0.92	40	46	20	24(-)
V2	257	733	1.35	1.30	34	44	19	19(-)

* - The indicator values calculated for the second phase of dummy's motion (the impact of dummy's head against the safety seat backrest)

(-)- The measurement results assessed as uncertain (see the article text concerning Fig. 8)

Table 4. Injury Assessment Reference Values (IARV) [9, 17, 19]

Dummy	HIC_{15}	N_{ij}	F_T [N]	F_C [N]	M_F [Nm]	M_E [Nm]	C_{Acc} [g]	C_{max} [mm]
Hybrid III 3Y0	570	1.0	2 330	2 130	67	29.3	55	34
Hybrid III 10Y0	700	1.0	3 710	3 390	125	54.8	60	44

In the subsequent analysis, the biomechanical indicator values have been taken in relation to their maximum acceptable (reference) values, with calculating the relative indicators as follows:

$$\gamma_i = \frac{W_i}{W_{dop}} \quad (4)$$

where: W_i - value of a specific indicator (HIC_{15} , N_{ij} , C_{Acc} , C_{max}), given in Table 3;

W_{dop} - maximum acceptable (reference) value of the same indicator, given in Table 4.

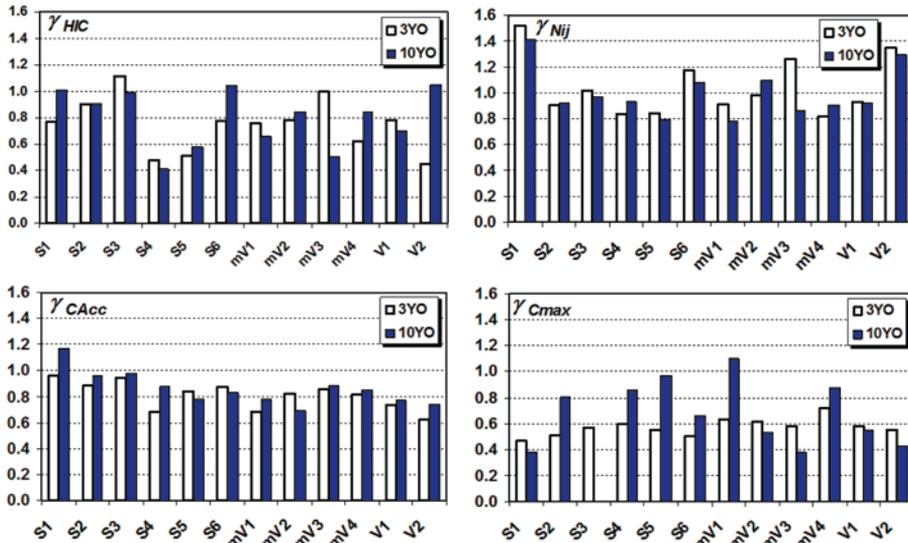


Fig. 9. Results of calculations of the γ_i relative indicators

Results of calculations of the γ_i relative indicators have been brought together in Fig. 9. They lead to the following findings concerning the objective of this work, i.e. relations between the loads on test dummies 3YO and 10YO:

- The biggest differences between the 3YO and 10YO dummies can be seen in γ_{Cmax} and γ_{HIC}
- There were only two tests (S2 and mV4) where the values of all the γ_i relative indicators were higher for the 10YO dummy.
- There were no tests where the values of all the γ_i relative indicators would be higher for the 3YO dummy.

Large scatter can be seen in the γ_i indicator values in individual crash tests, which confirms the fact that the characteristics of passive safety systems in the vehicles under test considerably differ from each other.

The analysis of the γ_i indicators still does not make it possible to give an unequivocal comparative assessment of the loads on the 3YO and 10YO dummies. It is difficult to point out which of the dummies is better protected in a specific car. In many crash tests a situation is encountered that better protection of dummy's head (low γ_{HIC} values) is connected with increased loads on dummy's neck or thorax (high values of N_{ij} , C_{Acc} or C_{max}). Therefore, relations between the calculated biomechanical indicators (Table 3) and the injury risk were used in the further assessment of the loads on the 3YO and 10YO dummies.

This method is based on the relations between values of the HIC_{15} , N_{ij} , C_{Acc} indicators and injury risk, addressed in the *Abbreviated Injury Scale (AIS)* [7, 9, 11, 26]. The risk of moderate (AIS 2) and serious (AIS 3) head, neck, and thorax injury is described with the use of "Injury Risk Curves (IRC)" presented in Fig. 10. The risk of thoracic injury has been given for the C_{Acc} indicator, because the injury risk curves for the 10YO dummy as functions of the C_{max} indicator are unavailable yet (such a dummy was developed as late as in 2003-2005). It is worth explaining here that the possibilities of developing the injury risk curves are very limited. First of all, no experiments with humans can be carried out; on the other hand, the characteristics of corpses used for tests considerably differ from those of living humans and the results of tests with animals, even if reliable, are hardly applicable to humans. Moreover, the experiment costs as well as ethical considerations (experiments with corpses, animal sufferings, etc.) are also important here [18].

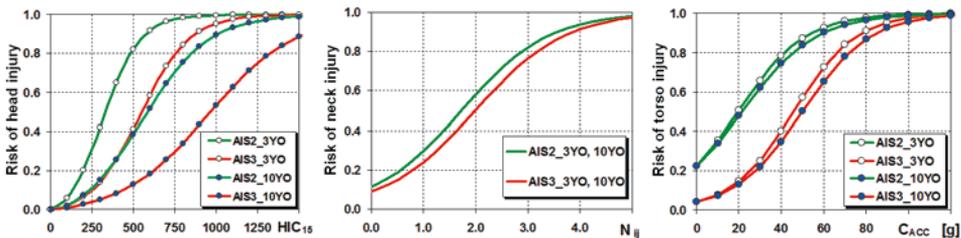


Fig. 10. Functions of the probability of injury (AIS 2 and AIS 3) to the head, neck, and thorax (torso) of the 3YO and 10YO dummies (injury risk curves) [1, 7, 14]

Separate head and torso injury risk curves have been plotted for the 3YO and 10YO dummies due to different anthropometric characteristics of the dummies (Fig. 10). For the neck injury, the risk curves do not depend on the dummy size because different critical values of the forces and moments acting on dummy's neck were taken into account as early as at the calculations of the N_{ij} indicator (Table 4). The neck and thorax injury risk curves do not run through the origin of the coordinate system; therefore, they are inapplicable to the cases with low load values [1]. The injury risk curves reveal different susceptibility of head, neck, and thorax to injuries. The following relations can be seen in the graphs:

- significant differences in the risk of head injury for the 3YO and 10YO dummies;
- small difference between the thorax injury risk curves for the 3YO and 10YO dummies;
- significant differences in the risks of head and thorax injury between the curves for the AIS 2 and AIS 3 injury severity levels;
- small difference in the risk of neck injury between the curves for the AIS 2 and AIS 3 injury severity levels.

The results of calculations of the injury risk for the 3YO and 10YO dummies, obtained with taking into account the indicator values given in Table 3 and the injury risk curves plotted in Fig. 10, have been brought together in Fig. 11. For both the AIS 2 and AIS 3 injury severity levels, the risk of neck and thorax injury was similar in most of the tests for the two dummies. The

risk of thorax injury was 2 to 3 times as high as that of neck injury. Attention is drawn by the results of calculations of the head injury risk. The injury risks considerably differ from each other both between individual crash tests and between the two dummies in the same car. In most of the tests, the risk of moderate (AIS 2) and serious (AIS 3) head injury for the 3YO dummy is higher than that for the 10YO dummy. This is particularly conspicuous in tests S3 and mV3, where the heaviest loads on the head of the 3YO dummy occurred when the dummy's head hit the safety seat backrest (cf. Table 3).

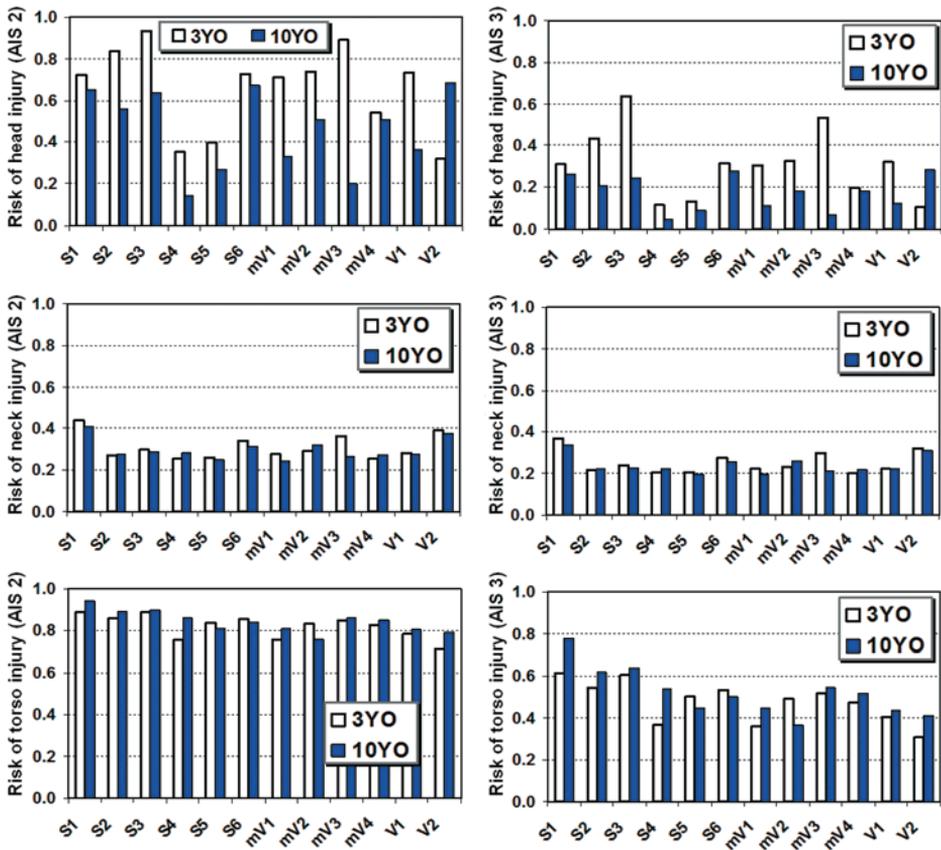


Fig. 11. Risk of injury (AIS 2 and AIS 3) to the head, neck, and thorax (torso) of the 3YO and 10YO dummies

The comparative assessment of loads on the 3YO and 10YO dummies may be more definitive if an indicator denoted by P_{Joint} (Joint Probability of Injury) and representing the overall risk of injury to the dummy is used [11]:

$$P_{Joint} = 1 - (1 - P_{Head}) \cdot (1 - P_{Neck}) \cdot (1 - P_{Chest}) \quad (5)$$

where: P_{Head} , P_{Neck} , P_{Chest} – risk of head, neck, and thorax injury.

Thus, the joint risk of moderate (AIS 2) and serious (AIS 3) injury to the dummies was determined (Fig. 12), based on the injury risk curves and results of measurements of the dynamic loads on individual dummy's parts (head, neck, thorax).

In the test conditions under consideration (frontal impact of the car against a rigid barrier at a speed of 56 km/h), the risk of moderate (AIS 2) injury to the dummies was high (ranging from 0.88 to 0.99). The differences between the risks of injury to the 3YO and 10YO dummies were small (not exceeding 8%), with the P_{Joint} (AIS 2) values being higher for the 3YO dummy in 8 of the 12 tests. The risk of serious (AIS 3) injury to the dummies was more diversified (ranging from 0.55 to 0.89). In 8 of the 12 tests, the P_{Joint} (AIS 3) values were higher for the 3YO dummy (by 5-27%); in two other tests (S4 and V2), the P_{Joint} (AIS 3) values were markedly higher for the 10YO dummy (by 16-18%).

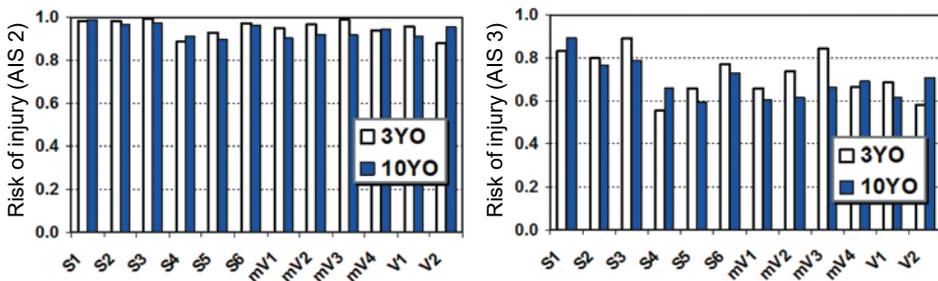


Fig. 12. Joint risk of injury (AIS 2 and AIS 3) to the 3YO and 10YO dummies

The risk assessment results were obtained from crash tests of cars with sedan, minivan, and van body styles. However, no important impact of the properties of the front crumple zone on the observed risk of injury to the dummies placed on the rear car seats was revealed. As an example, the cars used in tests S4 and S5 had different deformation depths (Table 2), but the risks of injury to the 3YO and 10YO dummies in these tests were close to each other. This may indicate that the decisive role in the shaping of the loads on the test dummies is played by the properties of the restraint systems used.

4. Recapitulation

The mode of child's participation in the road traffic is determined by child's age, which is reflected in the regulations that define the use of public roads [20, 21]. The rate of hazard to children in Poland is almost twice as high as the EU average, although the number of children killed in road accidents has dropped more than fourfold during the recent two decades. About 50% of the children killed in road accidents were passengers of motor cars. Analyses of data about road accidents in Poland indicate that the risk of death of child-passengers in a road accident does not depend on their age, but the risk of injury to

child-passengers is higher for older children (Fig. 3), which may be caused by their more frequent travelling.

Results of laboratory tests reveal considerable differences in the loads on dummies travelling in various cars, which may be explained by different properties of the passive safety systems of the cars. Marked differences in the loads on 3YO and 10YO dummies can be seen in the head and neck loads and in the thoracic deflection. It has been ascertained that significant loads on the head and neck of a 3YO dummy may be an effect of the impact of dummy's head against the safety seat backrest in the final phase of the collision. To solve this problem, the safety seat construction must be modified so that the effect of throwing the dummy back towards the seat backrest is reduced. The 10YO dummy, restrained with a standard seat belt, has the belt strap laid on its chest, which may cause significant thoracic deflection (cf. the $\gamma_{C_{max}}$ indicator). The 3YO dummy has the safety harness straps placed on its shoulders, which advantageously reduces the deflection of its thorax.

An unequivocal comparative assessment of the loads on 3YO and 10YO dummies is difficult because the loads on individual dummies' parts (head, neck, thorax) in various cars change in different ways. Therefore, relations between biomechanical indicators and injury risk curves were used in the comparative assessment of the loads and, in consequence, the joint risk of injury (the P_{Joint} indicator) was calculated. In the test conditions under consideration (frontal impact of the car against a rigid barrier at a speed of 56 km/h, child safety seats as described in subsection 3.1), the risk of serious injury (AIS 3) in most of the crash tests was higher for the 3YO dummy (by 5-27 %). This result was obtained with the thorax acceleration (C_{Acc}) being taken into account at the calculations of the risk of injury. The thoracic deflection (C_{max}) could not be taken into account at the calculations of the P_{Joint} indicator because of unavailability of the injury risk curves applicable to the 10YO dummy.

Acknowledgements

The research work was partly done within N N509 559640 Project, funded by the National Science Centre, Poland, in 2011-2013.

The full text of the Article is available in Polish online on the website <http://archiwummotoryzacji.pl>.

Tekst artykułu w polskiej wersji językowej dostępny jest na stronie <http://archiwummotoryzacji.pl>.

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