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SEATBELT IMPACT ON A CHILD DURING A FRONTAL COLLISION

ODDZIAŁYWANIE PASA BEZPIECZEŃSTWA NA DZIECKO PODCZAS ZDERZENIA CZOŁOWEGO

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Summary

The loads on a Hybrid III test dummy representing a child aged about 10 years have been analysed, based on results of crash tests carried out on seven motorcars. During the tests, the dummies were sitting on high-back booster seats, backless booster seats (booster cushions), or directly on the rear car seats and they were fastened with the use of standard car seatbelts. The differences in the seatbelt impact on the child, depending on the child restraint system used, have been pointed out. The analysis was done with using the crash test results published on the Internet by the US National Highway Traffic Safety Administration (NHTSA) and covering the case where the test car moving with a speed of about 56 km/h frontally hit a rigid flat barrier. The relations between dummy's head, neck, thorax, and pelvis loads and the force exerted on the seatbelt have been shown. Attention has been directed to the fact that a child transported without a booster seat has a tendency to slide under the seatbelt, which in consequence may cause injuries to child's abdomen and neck. A question has been examined whether the thoracic deflection can be limited by partial transfer of the load exerted by the seatbelt from dummy's ribs to its shoulder.

Keywords: road accidents, child safety, seat belt, booster seats (backless, high-back)

Streszczenie

Na podstawie wyników testów zderzeniowych siedmiu samochodów przeanalizowano obciążenia manekina Hybrid III, reprezentującego dziecko w wieku około 10 lat. Manekiny podczas badań zapięte były za pomocą standardowego pasa bezpieczeństwa, przy czym siedziały na podstawce

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podwyższającej z oparciem lub bez oparcia oraz bezpośrednio na tylnej kanapie samochodu. Wskazano różnice, spowodowane rodzajem zastosowanego urządzenia ochronnego, w oddziaływaniu pasa bezpieczeństwa na dziecko. Wykorzystano wyniki testów zderzeniowych udostępnione w Internecie przez National Highway Traffic Safety Administration (USA), w których samochód jadący z prędkością około 56 km/h uderzał czołowo w sztywną, płaską barierę. Pokazano relacje pomiędzy obciążeniami głowy, szyi, klatki piersiowej i miednicy manekina a siłą działającą na pas bezpieczeństwa. Zwrócono uwagę, że dziecko bez podstawki podwyższającej wysuwa się spod pasa bezpieczeństwa, który może powodować obrażenia brzucha i szyi dziecka. Rozważono, czy ugięcie klatki piersiowej może być ograniczone przez częściowe przeniesienie obciążenia od pasa z żeber na bark manekina.

Słowa kluczowe: wypadki drogowe, bezpieczeństwo dziecka, pas bezpieczeństwa, podstawki podwyższające (bez oparcia, z oparciem)

1. Introduction

Children aged 6-10 years are too big for being transported in a child safety seat with integrated safety belts (harness) and too small for riding directly on a car seat, fastened with a car seatbelt designed for adults. The requirements applicable to child restraint systems have been specified in UN ECE Regulation No. 44 [13], where five "mass groups" of such systems are distinguished. For children belonging to mass groups II (15-25 kg) and III (22-36 kg), booster seats (Fig. 1c) may be used, either of the high-back or backless type (with the latter, also referred to as booster cushions, being acceptable for mass group III only). Although the booster seats are easy to use, many parents too early cease using them. Contrary to the regulations, about 50 % of children aged six and almost 90 % of children aged ten are fastened with standard seatbelts only [7, 25]. Meanwhile, the failure to use a booster seat results in incorrect positioning of the seatbelt on child's body (Fig. 1a, left), which will reduce the effectiveness of seatbelt operation (due to slipping off the shoulder) or even may cause injuries to child's abdomen or neck [12, 17, 25]. The seatbelt strap should be placed on the sternum body and the clavicle (Fig. 1a, right). In the study reported in [12], almost a half of the 41 booster seats under examination (26 high-back booster seats and 15 booster cushions) were found not to ensure the correct positioning of seatbelt strap on the hips, thorax, and shoulder of a six-year-old child. For 15 out of the 26 high-back booster seats and for 5 out of the 15 booster cushions, the lap seatbelt portion was placed on the abdomen rather than on hips.

Fig. 1b depicts the seatbelt strap positioning in relation to the silhouette of a child sitting directly on the rear car seat, determined for about 30 passenger cars. The drawings represent a 95th percentile boy aged 10 years (solid line) and a 5th percentile girl aged 6 years (dashed line). It can be seen here that when a booster seat is not used, the seatbelt strap is in many cases situated too close to child's neck or too far from it. Fig. 1b shows that in some cars, the use of a booster seat may improve the seatbelt position in relation to a smaller child or worsen this position in the case of a bigger child, especially in SUVs.

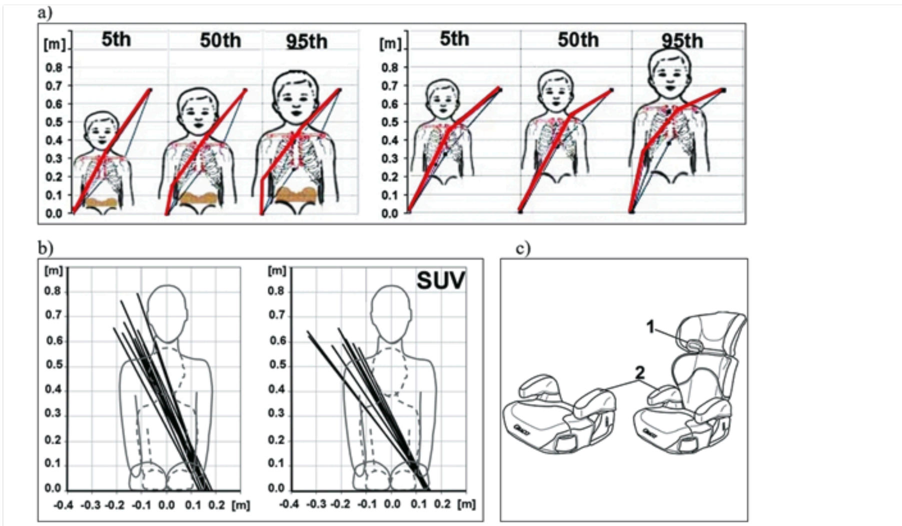

Fig. 1. Positioning of the shoulder belt on child's torso: a) six-year-old child without a booster seat and sitting on a booster seat [2]; b) children aged 6 and 10 years in small passenger cars and in SUVs [3]; c) booster cushion (P) and high-back booster seat (PO) [8]; 1 – seatbelt guide; 2 – armrests

Normally, motorcar seatbelts are designed for adults, but attempts are also made to adapt them for children. As an example, the influence of changes in the location of the upper seatbelt anchorage point on the displacements and dynamic loads of a P10 test dummy representing a child aged about 10 years (with a mass of about 32 kg) was examined in the works described in [11, 22]. It has been found that a lowering of the upper seatbelt anchorage point leads to a reduction in the head and torso accelerations but results in a rotation of dummy's torso in the culminating phase of the vehicle collision. This indicates a danger that the child may slip out from under the shoulder seatbelt portion. The seatbelt position in relation to child's body also depends on the seat cushion and back angles. Based on tests carried out with a model of a test dummy representing a child aged about 6 years, it has been stated in [9] that the head and neck loads and the thoracic deflection may be reduced by optimization of the seat back angle and of the positioning of the seatbelt strap in relation to child's torso.

Children are usually transported on rear car seats. The loads on vehicle passengers, including children, occupying rear car seats during a frontal collision are in most cases many times as high as those on the driver, who is protected with an airbag and seatbelts with tensioners and load limiters [21, 26, 27]. Fig. 2 shows various injury indicators determined for an M50 (Hybrid III) dummy (50th percentile adult male) occupying the driver's seat and for a 10YO dummy (ten-year-old child, with a mass of 35.2 kg, 1.3 m tall) sitting on a high-back booster seat on the rear car seat behind the driver. The following indicators have been presented here (described in e.g. [19, 20]):

- HIC_{36} (Head Injury Criterion);
- N_{ij} (Neck Injury Criterion);
- C_{Acc} (maximum resultant torso acceleration (acting for at least 3 ms));
- C_{max} (maximum thoracic deflection);
- V_C (Viscous Criterion of the thoracic injury).

These data are results of crash tests carried out on 20 passenger cars manufactured in 2005-2006, with masses ranging from 1 600 kg to 2 700 kg (sedan, minivan, van, SUV, and pickup) [28]. In the tests, the test vehicles moving with a speed of about 56 km/h frontally hit a rigid flat barrier. All the vehicles were provided with a driver's airbag. Both the dummies were fastened with seatbelts; in some of the test vehicles, the driver's seatbelt was provided with a tensioner.

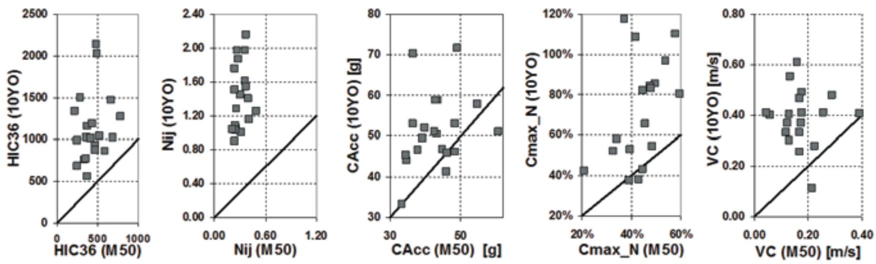

Fig. 2. Comparison of the injury indicator values determined for the driver (M50) and the child-passenger (10YO) occupying the rear vehicle seat; the straight lines represent the relation 1:1 [27]

The acceptable injury indicator values have been brought together in Table 1, where the critical values of forces F_T and F_C as well as moments M_F and M_E taken to calculate the N_{ij} indicator values have been specified as well. The acceptable values of indicators HIC_{36}, N_{ij}, C_{Acc}, and VC are identical for dummies M50 and 10YO, thanks to which the values of these indicators for both dummies may be directly compared with each other. The coefficient λ given in Table 1 tells how many times the value of an indicator determined for dummy 10YO is higher than that determined for dummy M50. Since the acceptable thoracic deflection values C_{dop} depend on the dummy size, the following indicator has been used in this case for the comparisons:

$$C_{max\_N} = \frac{C_{max}}{C_{dop}} \cdot 100\%, \tag{1}$$

i.e. the maximum thoracic deflection value C_{max} has been referred to the acceptable thoracic deflection value applicable to the specific dummy size.

Table 1. Acceptable injury indicator values [6, 14]

Dummy	HIC_{36}	N_{ij}	F_T [N]	F_C [N]	M_F [Nm]	M_E [Nm]	C_{Acc} [g]	C_{dop} [mm]	VC [m/s]
M50	1 000	1.0	6 806	6 160	310	135	60	63	1.0
10YO			3 710	3 390	125	54.8		44	
λ	1.5-6.3	2.6-7.3	–	–	–	–	0.8-1.9	0.9-3.2*	0.5-9.3

* Determined for the indicator C_{max_N} defined by equation (1)

To evaluate the injuries to road accident victims, a six-point Abbreviated Injury Scale (AIS) has been adopted, where specific scores define the injury severity level, with the higher scores representing the greater threat to life. For the injuries with severity corresponding to or exceeding a specific level, e.g. AIS 3, a notation such as AIS 3+ is used. In the work described in [24], it was estimated on the grounds of crash tests with 12 motorcars frontally hitting a rigid flat barrier with a speed of about 56 km/h that the risk of a serious injury (AIS 3) to a ten-year-old child travelling in the vehicle on a high-back booster seat was lower by 5-27 % than such a risk to a child aged three years transported in a child safety seat. However, attention was drawn to the fact that the older child may be exposed in such conditions to an excessive thoracic deflection, caused by the impact of the seatbelt. On the other hand, it has been stated in [22] that even small changes in the initial seatbelt position in relation to child's body may affect the way how the body moves during the collision and, in consequence, the resulting risk of injury.

The objective of this work was to assess the seatbelt operation and the loads on a Hybrid III 10YO dummy representing a ten-year-old child, placed on a high-back or backless booster seat (Fig. 1c) or directly on the rear car seat. This study is an extension of the analysis of results of measurements carried out at the Automotive Industry Institute (PIMOT) in Warsaw [25]. Now, the scope of the measurements taken into account has been considerably widened to cover the loads on dummy's head, neck, shoulder, thorax (including thoracic deflection), hips, and legs.

2. Objects tested and scope of the analysis

The dynamic loads on Hybrid III 10YO dummies placed on rear seats in seven motorcars were examined. The test vehicles moving with a speed of about 56 km/h frontally hit a rigid flat barrier, situated perpendicularly to the direction of vehicle motion (Fig. 3). The analysis was done with using the test results published on the Internet by the US National Highway Traffic Safety Administration (NHTSA) [28]. The data on the test vehicles and on the seating of the test dummies have been given in Table 2. Some results of the crash tests can be found in [6].

The cars used for the tests differed from each other in their masses, dimensions, and constructions of the front crumple zone. The depth of vehicle body deformation after the impact against the barrier, measured at the height of the car bumper in the middle of its width ranged from 0.42 m (Nissan Xterra) to 0.64 m (Chevrolet Silverado). The properties of the front crumple zone of the cars were decisive for the vehicle deceleration values that occurred during the collision (Fig. 3).

Table 2. Data on the test vehicles and on the seating of the Hybrid III 10YO dummies [28]

<table>
<tr><th>Test symbol</th><th>Make, model</th><th>Model year</th><th>Body style</th><th>Mass [kg]</th><th>Deformation depth [m]</th><th>Seated on the right side</th><th>Seated on the left side</th></tr>
<tr><td>A</td><td>Honda Ridgeline</td><td>2006</td><td>pickup</td><td>2 301</td><td>0.56</td><td>PO*</td><td rowspan="6">PO</td></tr>
<tr><td>B</td><td>Pontiac Montana</td><td>2005</td><td>minivan</td><td>2 234</td><td>0.55</td><td rowspan="3">P</td></tr>
<tr><td>C</td><td>Nissan Titan</td><td>2005</td><td>pickup</td><td>2 671</td><td>0.51</td></tr>
<tr><td>D</td><td>Chevrolet Silverado</td><td>2005</td><td>pickup</td><td>2 674</td><td>0.64</td></tr>
<tr><td>E</td><td>Nissan Xterra</td><td>2005</td><td>SUV</td><td>2 167</td><td>0.42</td><td rowspan="3">BP</td></tr>
<tr><td>F</td><td>Mercedes ML350</td><td>2006</td><td>SUV</td><td>2 431</td><td>0.55</td></tr>
<tr><td>G</td><td>Volkswagen Jetta</td><td>2005</td><td>sedan</td><td>1 719</td><td>0.43</td><td>–</td></tr>
</table>

* PO – high-back booster seat; P – backless booster seat; BP – no booster seat

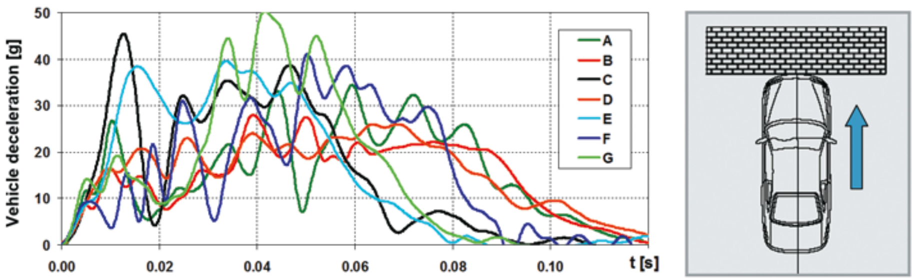

Fig. 3. Vehicle decelerations during the impact against the barrier in tests A-G (56 km/h)

In tests A-F, a 10YO dummy was sitting on a high-back booster seat (PO) on the left side of the rear car seat. On the right side, an identical dummy was sitting on a backless booster seat (P) or directly on the rear car seat (BP). In test A, both dummies were sitting on high-back booster seats, while test G was carried out with only one dummy, placed directly on the rear car seat (BP). The booster seat armrests (part 2 in Fig. 1c) were set in their upper positions.

Example seating of the test dummies in the cars has been presented in Fig. 4 (for tests C and F). In all the cars, both the front seats were set in their central positions. The distances from dummy's chest and knees to the front seat (CB and KB, respectively) and from dummy's head and hip to vehicle door (HW and AD, respectively) have been brought together in Fig. 5. These distances show that the dummy restraint systems used (P, PO, or BP) have an impact on the dimensions of the free space around the dummy and on the dummy's situation in relation to the seatbelt anchorage points. The dummies sitting on a high-back booster seat are situated more frontwards in relation to the rear seat backrest. In test C, the difference between the HW dimensions measured for variants P and PO was as big as 11 cm, because in the PO variant, this dimension was measured from dummy's head to the window glass rather than to the doorframe, as it was in variant P (cf. Fig. 4). Conversely, the type of the restraint system used did not considerably affect the AD distance, except for test E, where this distance was 18 cm and 26 cm for variants BP and PO, respectively. Dummies' feet were not in contact with the front seat backrests and the distance between the feet and the front seat backrest was the shortest (below 10 cm) in tests B and F and the longest (25-27 cm) in tests A and C.

The loads on dummies' heads, necks, shoulders, thoraxes, hips, and legs were analysed. For this job to be done, results of measurements of the following quantities were used, downloaded in digital form from [28]:

- head, thorax, and hips (pelvis) accelerations;
- forces and moments of forces acting on the neck;
- forces acting on the shoulder (clavicle) and thighs;
- thoracic deflection;
- tensile forces in the lap and shoulder seatbelt straps.

Fig. 4. The 10YO dummies in the vehicles used for tests C (top row) and F (bottom row) [28]

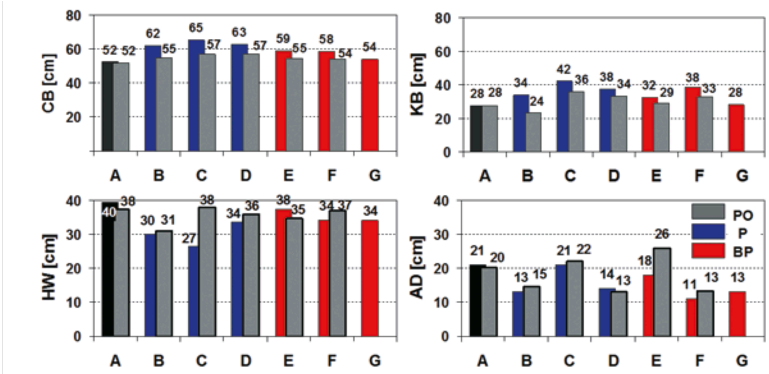

Fig. 5. Distances from the dummy to the front seat (CB and KB) and from the dummy to vehicle door (HW and AD) in the vehicles used for tests A-G

The values of the resultant acceleration a and force F, used for the further analysis, were calculated from the components measured in three mutually perpendicular directions (X, Y, Z):

$$a(t) = \sqrt{a_X^2(t) + a_Y^2(t) + a_Z^2(t)}, \quad F(t) = \sqrt{F_X^2(t) + F_Y^2(t) + F_Z^2(t)} \tag{2}$$

In quantitative terms, the dynamic loads on vehicle occupants were assessed with the use of the injury indicators mentioned in Section 1. The loads on the dummies were also analysed with using video records obtained from high-speed cameras installed in the test vehicles and results of measurements of seatbelt strap movements in relation to the upper seatbelt anchorage point (cf. Fig. 9).

3. Head and neck loads

About 60 % of the AIS 2+ injuries to children aged 8-12 years consist of head injuries (according to data on the road accidents that occurred in the USA in 1998-2007) [5]. The injuries of this kind are often caused by head impacts against vehicle interior components. In frontal collision crash tests, where the test vehicle hits a rigid obstacle with a speed of up to 56 km/h, the seatbelt limits the movement of a child-passenger on the rear car seat and the child does not hit its head on the front seat backrest [22, 24, 25, 27]. In the work reported in [18], it happened in only one out of the 77 crash tests that dummy's head struck the front seat backrest (48 km/h, dummy placed on a backless booster seat). However, the sudden stopping of the torso by a seatbelt and significant tilting of the head in relation to the torso (due to the absence of an airbag) conduces to a growth in the neck loads. According to [21, 27], the head and neck injury indicators HIC_{36} and N_{ij} for the passengers travelling on rear car seats are many times as high as those for the front seat occupants, who are additionally protected by airbags (cf. Fig. 2). The risk of severe injuries (AIS 4+)

to the head of a child aged about 10 years sitting on the rear car seat on a high-back booster seat, resulting from such loads, reached 90 % (it ranged from 10 % to 60 % in 15 out of the 20 vehicles under test), while it did not exceed 10 % (2-5 % in 13 of the 20 vehicles) for an adult male (M50) occupying the driver's seat [26].

The realizations of loads on the head and neck of a 10YO dummy in tests B, C, E, and F have been presented in Fig. 6. In test B, the realizations of loads on a 10YO dummy for variants P and PO were very similar to each other. In test C, the loads on the head and neck of the dummy on a high-back booster seat (PO) were higher than those for the dummy on a booster cushion (P). In test E, the loads measured for the dummy placed on a high-back booster seat (PO) were lower in comparison with those for the dummy sitting directly on the car seat (BP). In test F, where the seatbelts were provided with tensioners, the dummy sitting directly on the car seat (BP) hit the back of its head on the rear seat backrest, at the instant of about 0.2 s.

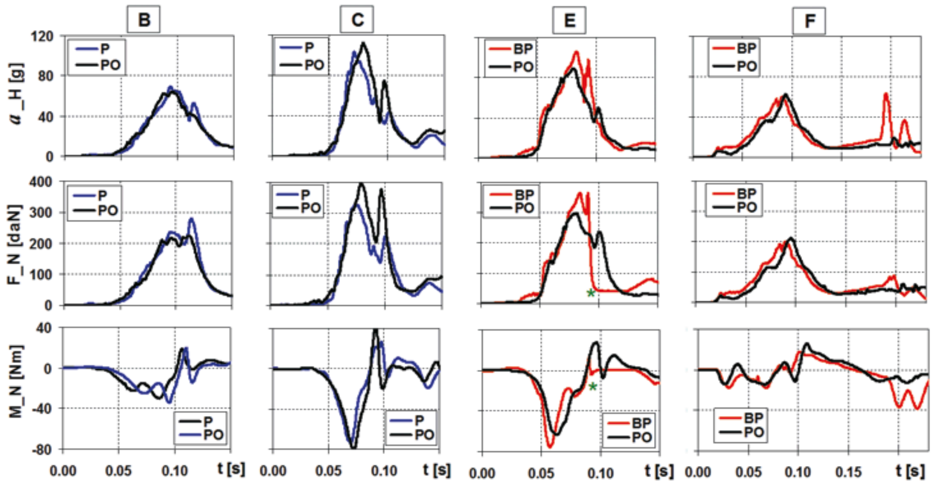

Fig. 6. Resultant head acceleration (a_H), resultant force on the neck (F_N), and moment (M_N) of the force acting on the neck in the sagittal plane (tests B, C, E, and F);

(* in test E, the neck load values recorded in the period 0.09-013 s are dubious; nevertheless, this part of the realization has no impact on the N_{ij} indicator value)

The neck loads result from the inertial forces acting on the head; therefore, the realizations of the head acceleration and of the forces acting on the neck are similar to each other in qualitative terms. An analysis of the video records shows that for all the variants examined (PO, P, BP), dummy's head was significantly tilted frontwards (Fig. 7) and it hit its chin on the sternum, which has been reflected in the a_H and F_N curves as the modal value in the period 0.10-0.11 s (Fig. 6). In the work reported in [16], where a smaller dummy (6YO) was used for the tests, attention was drawn to the fact that the significant neck load values might be explained by excessive rigidity of dummy's spine in comparison with that of the real child's spine. In test F, where the seatbelts were provided with tensioners, the heads of the 10YO dummies were also significantly tilted but without hitting the chest. The advantageous effect of seatbelt tensioner operation, as regards the reduction in head and neck loads, was also confirmed in tests carried out with the use of a 6YO dummy [4].

Fig. 7. Maximum tilt of dummy's head for variants PO, P, and BP (tests A, C, and E)

The head and neck injury indicator values have been presented in Fig. 8. The HIC_{36} values of 500, 1 000, and 2 000 indicate the risk of severe (AIS 4) head injuries estimated at 4 %, 18 %, and 88 %, respectively. The N_{ij} values of 1, 2, and 3 indicate the risk of severe (AIS 4) neck injuries estimated at 18 %, 43 %, and 70 %, respectively [6, 20, 23].

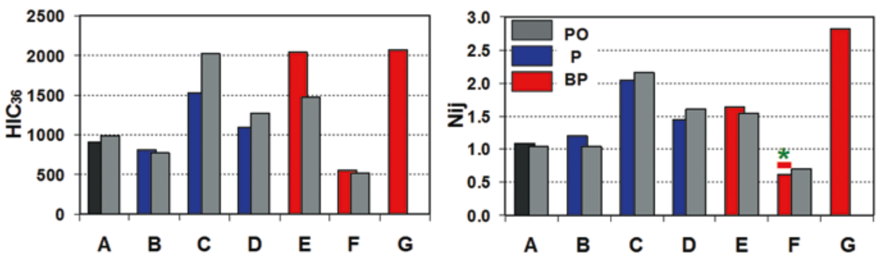

Fig. 8. HIC_{36} and N_{ij} values determined for the 10YO dummies in tests A-G

(* for comments on the N_{ij} indicator values in test F see the text below)

In test A, where both dummies were placed on high-back booster seats (PO), similar values of both the HIC_{36} and N_{ij} indicator were obtained. The highest head and neck loads were observed for variant BP (tests E and G) and the loads had the lowest values in test F (thanks to the seatbelt tensioner operation). In test F, variant BP, N_{ij} = 0.62 occurred when the dummy was tilted frontwards and N_{ij} = 0.81 was recorded when the dummy hit the back of its head on the rear seat backrest (cf. the a_H and M_N curves at the instant of 0.2 s in Fig. 6). Based on the HIC_{36} and N_{ij} values determined in tests C and D, a statement may be made that a change in the child position in relation to the seatbelt strap, caused by the booster seat backrest, may result in an increase in the head and neck loads. The head injury indicator values observed for variants P and PO differed from each other by up to 32 % (in test C); the corresponding maximum difference in the neck injury indicator values was 12 % (in test D). On the other hand, much bigger differences between the values of these indicators were observed to occur between individual vehicles under test. As an example, the HIC_{36} value for the PO variant in test C was 2.6 times as high as that in test B.

Dangerous loads on child's neck also occur at lower speeds of the vehicle impact against a barrier. In the work presented in [18], taken here as an example, the injury indicator for the neck of a 10YO dummy was N_{ij} = 0.62-1.42, with $N_{ij} > 1$ being observed in 21 out of the 40 crash tests (for variants BP and P).

4. Seatbelt impact on the shoulder and thorax

Furthermore, the way of transmitting the seatbelt strap force onto the 10YO dummy's torso was examined for variants P, PO, and BP. With this objective in view, the loads on dummy's shoulder (clavicle) and thorax in the vehicles used for tests B-G were analysed. The inertial force acting on the child-passenger during a frontal collision is chiefly counterbalanced by the forces developing in the seatbelt strap and, to a smaller extent, by the friction between the dummy and the seat and by the impact of dummy's legs against the front vehicle seat. The force stretching the shoulder belt is transmitted onto passenger's body through the shoulder and thorax. An excessive seatbelt pressure on the thorax has an adverse effect because it results in raised thoracic deflection. Below, a question will be examined whether the thoracic deflection can be reduced by partial transfer of the load exerted by the shoulder belt from dummy's ribs to its shoulder (forces F_X and F_Z in Fig. 9). The booster seat causes the child to be elevated in relation to the rear car seat cushion and the booster seat backrest shifts the child frontwards in relation to the rear car seat backrest. Thus, the type of the child restraint system used and the location of the upper seatbelt anchorage point have an impact on the seatbelt strap positioning on child's body [25] and thus on the loads on child's shoulder and thorax. The correct positioning of the seatbelt strap on child's shoulder should be ensured by a seatbelt guide provided in the booster seat backrest (cf. Fig. 1c). Based on an analysis of video records of the test, however, it was found that the seatbelt strap slipped out of the guide at an instant of about 0.11 s in tests B and C and about 0.08 s in test F; in tests D and E, the seatbelt strap remained in the guide in the booster seat backrest.

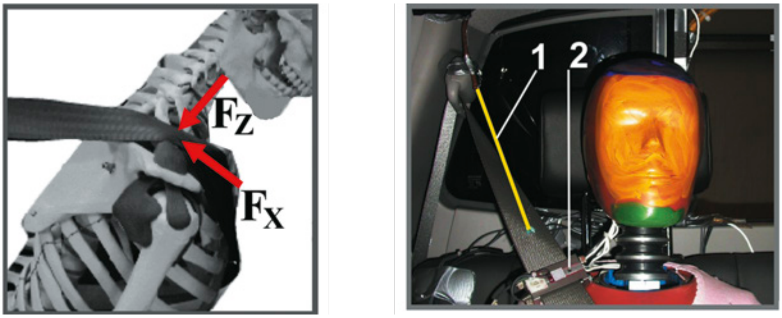

Fig. 9. Position of the shoulder belt strap on dummy's shoulder and thorax and method of measuring the seatbelt strap displacement: 1 – cable of the seatbelt strap displacement transducer; 2 – SB force transducer on the shoulder belt strap [15, 28]

The displacements of the 10YO dummies determined for variants P and PO have been shown in Fig. 10. The instant of 0 ms corresponds to the initial position of the test dummy and the instant of 110 ms corresponds to the maximum displacement of dummy's head. For both variants, large displacements of the dummies in relation to the rear car seat and significant tilts of dummies' heads and torsos can be seen.

The results of measurements of dummies' loads in tests B-F have been brought together in Fig. 11. The results presented include the tensile force in the shoulder belt strap (SB), forces F_X and F_Z acting on dummy's shoulder (cf. Fig. 9), as well as thoracic deflection (C) and acceleration (a_C). The fine lines in the SB force graphs represent the belt strap displacement in relation to the upper seatbelt anchorage point (cf. Fig. 9), in millimetres. The seatbelt strap displacement is an effect of the strap coming out from the retractor before being blocked by the latter and of the strap elasticity. In test F, the seatbelts were provided with tensioners; therefore, the strap displacement was not measured in this case. In tests B, D, and E, the seatbelt strap displacement was 110-160 mm, as against 70 mm in test C. Test C was also unique because of the fact that it was the only test in which the seatbelt broke away the armrests of both booster seats (part 2 in Fig. 1c) on the seatbelt buckle side, at the instant of about 0.07 s. Moreover, the vehicle used for test C (Nissan Titan) reached the highest deceleration in the initial phase of the collision process (cf. Fig. 3) and the loads on dummies' heads and necks were the highest in this case, among those determined for variants P and PO (Fig. 8).

Fig. 10. Displacements of the 10YO dummies in test C at the instants of 0 ms, 80 ms, and 110 ms (based on a video record published in [28]):

a) dummy on a backless booster seat; b) dummy on a high-back booster seat

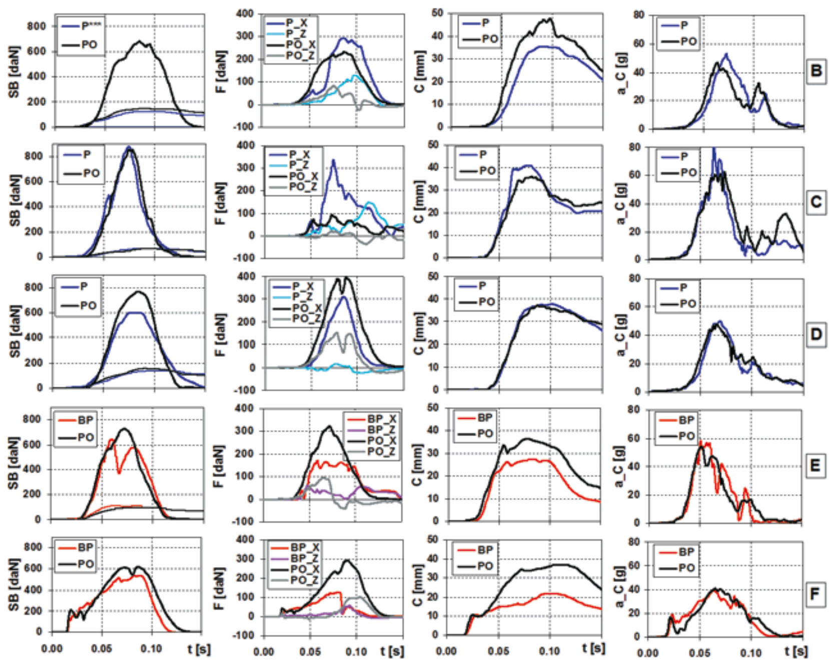

Fig. 11. Shoulder and thorax loads on the 10YO dummies in the vehicles used in tests B-F:

P – backless booster seat; PO – high-back booster seat; BP – no booster seat;

(*** in test B, force SB was not measured for variant P)

The type of the child restraint system used has an impact on the load on the seatbelt on the one hand and on dummy's shoulder and thorax on the other hand. In tests D, E, and F, forces SB in the seatbelts reached higher values for variant PO. In test F, seatbelt tensioners tightened the shoulder belt with a force of about 200 daN within 15 ms. In all the tests, the F_X component of the force applied to dummy's shoulder was 2-3 times as high as the F_Z component. The factors that are conducive to growth in the F_Z component include the tilting of the torso and the upward movement of dummy's arms (e.g. in test C, variant P, see Fig. 10). The partial transfer of the load exerted by the shoulder belt from dummy's ribs to the shoulder reduced the thoracic deflection only in test B, variant P (Fig. 11). In test C, force F_X for variant P was more than 3 times as high as that for variant PO, but the thoracic deflection was also bigger for variant P. In test D, on the other hand, the shoulder load was higher for variant PO, but the thoracic deflection was almost identical for variants P and PO. The fact that the relations between the shoulder and rib loads did not remain the same indicates a possible impact of other factors that can considerably affect the loads on the dummy, e.g. the location of the upper seatbelt anchorage point, which has not been described in [28].

The thoracic loads were assessed on the grounds of three indicators (C_{Acc}, C_{max}, and VC), the values of which have been brought together in Fig. 12. In tests B, C, and D, the thoracic acceleration (C_{Acc}) was lower by 5-14 % for variant PO than that for variant P. In tests E and F, the maximum thoracic acceleration values were similar to each other for both the variants under test (PO and BP), with the thoracic deflection being much bigger for variant PO. Except for test C, whose specific features have been described in the previous part of this article, the VC indicator values for variant PO exceeded those for variants P and BP in all the other tests.

The C_{Acc} and C_{max} indicator values determined for variant PO in individual vehicles differed from each other by no more than 30 %, with the C_{max} indicator value being almost identical (36-37 mm) in tests C-F.

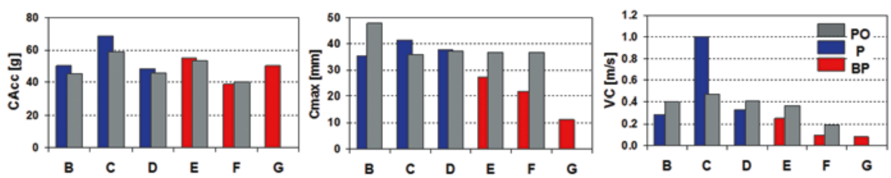

Fig. 12. Thoracic injury indicator values determined for the 10YO dummies in tests B-G

Attention is attracted by low values of the C_{max} and VS indicators for variant BP (tests E, F, and G). The forces on dummy's shoulder measured for variant BP were quite low, too (Fig. 11). This resulted from the fact that the seatbelt strap undesirably slipped off the thorax, to be then caught under dummy's arm. Such a situation has been illustrated in Fig. 13 (with the dummy used for test G having been shown because of better quality of the video record in comparison with that obtained in test E).

Fig. 13. Seatbelt position on the 10YO dummy in test G (based on [28])

The displacements of a dummy sitting directly on a rear car seat clearly show the degree of risk related to the use of such a solution as a child restraint system. The low-sitting dummy slips out from under the lap belt (this is often referred to as "submarining"), which results in a temporary reduction in force LB (stretching the lap belt strap, see Fig. 14). The shoulder belt slips from the shoulder to the neck, which poses a serious hazard to child's life [1, 17]. In consequence, the shoulder and thorax transmit only a small part of the shoulder belt force to the dummy: the values of forces F_X and F_Z and the thoracic deflection are very low (Fig. 14). Conversely, the values of indicators HIC_{36} and N_{ij} in test G reached the highest level (Fig. 8). A strong impact of the back of dummy's head against the rear car seat backrest was also observed, at the instant of about 0.17 s (see F_N and M_N in Fig. 14).

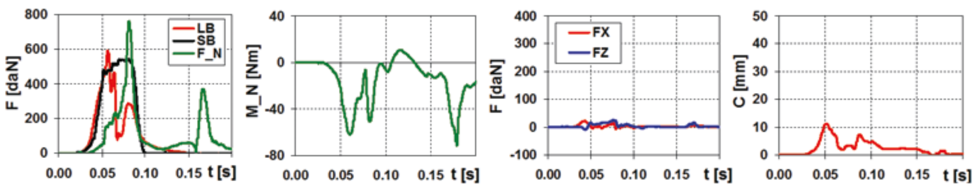

Fig. 14. Loads on the 10YO dummy in test G (variant BP):
LB, SB – forces in the lap and shoulder belts, respectively; F_N – resultant force on dummy's neck; M_N – moment of the force acting on dummy's neck in the sagittal plane; F_X, F_Z – forces on dummy's shoulder; C – thoracic deflection

The hazards to which children are exposed when transported directly on the rear car seat have been confirmed by the test results published in [18]. In crash tests carried out with the use of motor vehicles manufactured in the years 2005-2011 (at impact speeds of 40 km/h, 48 km/h, and 56 km/h) and 10YO dummies sitting directly on the rear car seat (variant BP, 29 tests) and on a backless booster seat (variant P, 48 tests):

- the shoulder seatbelt strap slipped from the shoulder to the neck in 86 % of tests BP and in 31 % of tests P;
- the lap seatbelt strap slipped from the hips to the abdomen in 59 % of tests BP and in 29 % of tests P.

The higher impact speeds were conducive to the undesirable seatbelt slipping off the shoulder and hips.

The measurement results were then used, like in [10], where the thoracic loads on a P3 dummy (a child aged 3 years, with a mass of 15 kg) were analysed, to assess the relations between the seatbelt and dummy loads. With this objective in view, the values of the tensile force in the shoulder belt strap SB were paired in Fig. 15 with the injury indicator values obtained from tests B-G. For variant P0, a proportional relationship can be seen between force SB and indicators HIC_{36}, N_{ij}, and C_{Acc} (the straight lines in the graphs). No trend of this kind can be observed for indicators C_{max} and VC. Therefore, the information about seatbelt loads should not be taken as a criterion of assessment of child restraint systems.

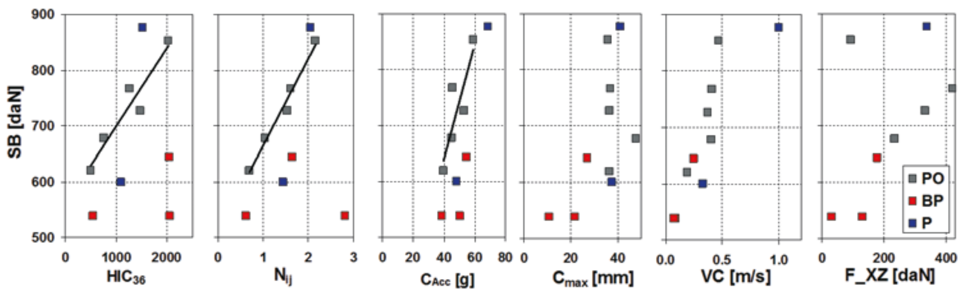

Fig. 15. The pairing of values of the tensile force in the shoulder belt strap SB with the head, neck, and thorax injury indicator values and with the maximum value of the resultant force F_XZ on dummy's shoulder

5. Seatbelt impact on the hips

The seatbelt transmits the inertial force acting on the dummy (35.2 kg) and booster seat (2.0 kg for the seat cushion and 1.2 kg for the seat backrest). In variants P0, P, and BP, the positions of the lap belt differ from each other (details on the belt positions on the dummy are not available from [28]). This has an impact on the value of the tensile force in the lap belt strap [25]. The realizations of the tensile force LB in the lap belt strap (Fig. 16), measured in the seatbelt strap stretch between the lower anchorage point and the booster seat, had lower values in the case of variant P0 in comparison with those for variant P. In variant P0, dummy's knees were closer to the preceding seat backrest (cf. distance KB in Fig. 5), but they did not hit the preceding seat in any of the tests. The realizations denoted by FF in Fig. 16 (the mean value of the forces acting on the left and right thigh) reflect the stretching of dummy's legs with the forces of inertia. Regardless of the type of the child restraint system used, the impact of dummy's feet against the backrest of the preceding seat only slightly reduced the growth in force FF, which translated into an insignificant reduction in the lap belt load.

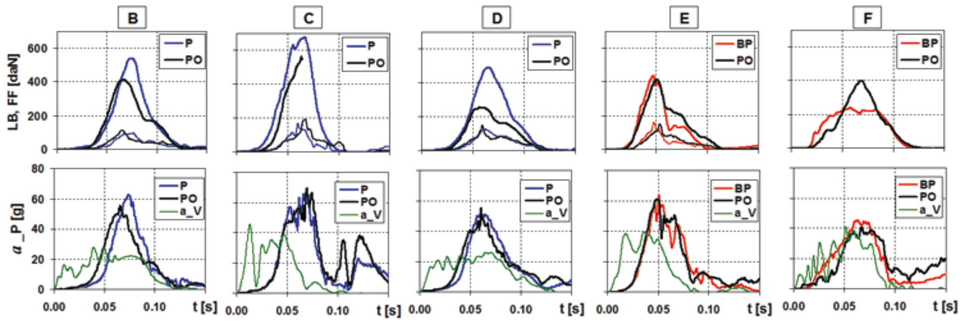

Fig. 16. Forces acting on the lap belt (LB) and thighs (FF, fine lines), resultant pelvis acceleration (a_P), and vehicle deceleration (a_V) in tests B-F (in test C, variant PO, the LB force measuring system failed at the instant of about 0.07 s)

The highest lap belt and pelvis loads occurred in test C, where the armrests in both booster seats were broken on the seatbelt buckle side, at the instant of about 0.07 s. For variant PO, the lowest value of force LB was recorded in test D, where the strongest pressure was simultaneously exerted by the seatbelt on the upper part of dummy's torso (cf. the values of forces SB, F_X, and F_Z in Fig. 11). In tests B and F, the values of the resultant acceleration of dummy's pelvis (hips) were lower for variant PO. The realizations of pelvis acceleration a_P reached much higher values than the vehicle deceleration values (a_V in Fig. 16). This unfavourable situation was caused by a delay in the operation of the seatbelt retractor lock and by the elasticity of the belt strap. In test F, where the seatbelts were provided with tensioners, the pelvis acceleration had the lowest values, approximately equal to those of a_V, which confirmed the effectivity of restraining dummy's hips movements in relation to the seat.

In test E, the lap belt of the dummy sitting directly on the car seat (variant BP) slipped from dummy's thighs and hips onto the abdomen, similarly to what happened in test G (Fig. 13 and 14). This effect manifested itself in a reduction in the lap belt force at the instant of about 0.06 s. In test F, the tensioner acting on the shoulder belt (cf. SB in Fig. 11) caused the lap belt to be stretched as well, but force LB in variant PO increased with a lower rate than it did in variant BP. This could result from the seatbelt strap friction against the booster seat, which reduced the stretching of the lap belt by the tensioner. In spite of these differences, the lap belt did not slip onto dummy's abdomen in any of the two variants (PO and BP) of test F, which confirmed the favourable effect of tensioner operation.

6. Recapitulation

Like in publication [25], where results of tests carried out at the Automotive Industry Institute (PIMOT) in Warsaw have been presented, it has been confirmed here that the use of a seatbelt designed for adults as the only child restraint system should never be considered a satisfactory solution because the position of such a seatbelt on child's body is incorrect, as the belt of this type may slip out of the shoulder and hips onto the neck and abdomen of the child. The load on child's thorax would be then reduced, but instead, the neck and abdomen would be thus exposed to a danger [17] and the head loads would increase (see tests E and G).

The loads on a child travelling on the rear car seat are many times as high as those acting on the driver (Fig. 2). The analysis carried out shows that they may depend to a greater extent on the vehicle-related factors (characteristics of the crumple zone, vehicle seat, and seatbelts, including the arrangement of seatbelt anchorage points) than on the type of the child restraint system used.

The seatbelt should act on child-passenger's hips, sternum, and shoulder; however, many child restraint systems do not ensure the seatbelts to be correctly positioned in relation to the hips and torso [3, 12]. Firm seatbelt pressure on the sternum (ribs) results in excessive deflection of ribs and unfavourable increase in the rate of deformation of the thoracic organs (the VC indicator). Therefore, a question was considered during the analysis of the test results whether the thoracic deflection can be reduced by partial transfer of the seatbelt load from the ribs to the shoulder of the dummy. A situation of this kind occurred in only one of the seven tests (test B). Due to the lack of detailed data on the seatbelt position in relation to the dummy, the mechanism of such an effect of seatbelt operation has not been shown in this work. However, an assumption may be made that the seatbelt pressure may be partly transferred from the thorax to the shoulder by such a seatbelt operation that would facilitate a slight torso tilt, e.g. immobilizing of the hips by tightening the lap seatbelt.

The seatbelt position in relation to child-passenger's body is influenced by the backrest of the booster seat. The child on a high-back booster seat is shifted frontwards in relation to the rear car seat backrest. This enables the placing of legs in a more comfortable position (with the knees bent) and the pushing of hips closer to the seat backrest, which improves the operation of the lap seatbelt. The appropriate positioning of the seatbelt strap and easy displacement of the strap so that it is tightened uniformly and as quickly as possible should be ensured by the seatbelt guides provided in the booster seat and its backrest. The tests revealed incorrect operation of these parts, i.e. slipping of the seatbelt strap out of the guide and excessive strap friction against the booster seat, which hampered the quick stretching of the lap belt by the tensioner (test F).

The tensile force in the seatbelt strap depends not only on the inertial force acting on the child but also on the seatbelt strap positioning on child's body [25]. Therefore, the seatbelt load is not always proportional to the load on the dummy (Fig. 15) and it should not be taken as a criterion of assessment of child restraint systems.

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