ANALYSING THE RESULTS OF RESEARCH ON THE INFLUENCE OF THE POSITION OF A SEAT BELT ON THE MOVEMENTS AND DYNAMIC LOADS OF CHILD'S HEAD AND TORSO DURING A BUS IMPACT AGAINST AN OBSTACLE

LEON PROCHOWSKI[1], MICHAŁ FITAS[2], KAROL ZIELONKA[3]

Military University of Technology, Automotive Industry Institute (PIMOT)

Summary

The dynamic loads acting during a road accident on a child passenger of a bus depend not only on the vehicle construction but also on the properties of the personal protection system used. In motor coaches, the personal protection system basically consists of a seat with a seat belt. The positioning of the seat belt strap in relation to passenger's body depends on the arrangement of the belt-to-seat anchorage points and passenger's anthropometric characteristics.

At this work, we explored the dynamic effects exerted on the body of a child occupying a bus seat during a road accident. For this issue to be tackled, a series of crash tests were prepared that constituted a physical model of a frontal impact of a bus against an obstacle. The tests were carried out with the use of seats where the position of a seat belt on a P10 test dummy (representing a child aged 9–12 years with a mass of 32 kg) could be adjusted. In this paper, results of the crash tests have been presented, which show the influence of changes in the positioning of the seat belt strap in relation to child passenger's torso on the movements of, and on the values of the dynamic loads acting on, the child's head and torso. Such changes have an impact on the longitudinal head and torso movements that take place in the limited space between bus seats.

The analysis of the test results has shown the fact that the standard seat belt inadequately matches the anthropometric characteristics of children; the hazards that may arise from that have also been pointed out. Simultaneously, the analysis has offered a basis for improving the system of personal protection of bus passengers.

Keywords: safety of children, bus seats, dynamic loads of head

[1] Military University of Technology, Faculty of Mechanical Engineering, ul. Gen. S. Kaliskiego 2, 00 908 Warsaw, Poland
Automotive Industry Institute, Vehicle Safety Laboratory, ul. Jagiellońska 55, 03 301 Warsaw, Poland
e-mail: lprochowski@wat.edu.pl

[2] Automotive Industry Institute, Vehicle Safety Laboratory, ul. Jagiellońska 55, 03 301 Warsaw, Poland,
e-mail: m.fitas@pimot.org.pl

[3] Automotive Industry Institute, Vehicle Safety Laboratory, ul. Jagiellońska 55, 03 301 Warsaw, Poland
e-mail: k.zielonka@pimot.org.pl, tel. +48 22 7777 141

1. Introduction

The bus seat should be provided with a personal protection system that would match the dimensions of the seat occupant. The seat construction has an impact on the keeping of a straight position of a child occupying the seat when riding on the bus and affects the position of the seat belt strap, especially of its shoulder portion, in relation to the torso. However, attention is drawn in many publications, e.g. [1, 3, 4, 6, 8], to substantial imperfections of the system of personal protection of children occupying bus seats. This particularly applies to the impossibility of adjusting the position of the seat belt strap to the anthropometric characteristics of bus passengers, especially children [3, 4, 9, 11].

The conclusions drawn from that inspired numerous attempts to develop three-point seat belt systems integrated with bus seats where the position of the shoulder belt portion could be adjusted to the height of the child occupying the seat [3, 4]. One of the proposed systems of positioning the shoulder portion of a three-point seat belt, described in [3, 4], has been shown in Fig. 1. Such a system provides a possibility of adjusting the position of the shoulder belt portion to passenger's height but it causes the bus seat construction to be much more complicated.

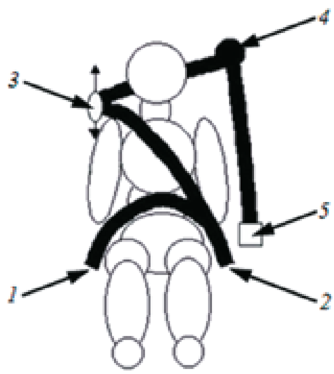


Fig. 1. Example of a system to adjust the position of the shoulder portion of a three-point seat belt: 1, 2 – lap belt portion anchorage points; 3 – guide providing adjustability of the seat belt anchorage height; 4 – shoulder belt portion anchorage point; 5 – retractor

This work was undertaken to analyse the influence of changes in the position of the seat belt strap on the movements and dynamic loads of child passenger's body during a road accident. The analysis was based on measurement results obtained from a series of crash tests carried out with the use of bus seats appropriately prepared. The scope of the analysis covered the loads of child's head and torso. The results of this research work give grounds for assessing the hazard and the possibilities of improving the safety of children as bus passengers. Simultaneously, they lead to evaluating the effectiveness of the modifications often proposed at present to bus seat belts.

The changes in the seat belt strap position were defined in relation to the torso of a child placed on a motor coach seat, in a way as shown in Fig. 2 and in Table 1.

2. Experimental tests

Within this work, experimental tests were prepared as physical simulations of a frontal impact of a bus against an obstacle. The velocity of bus impact against the obstacle was 29.5 km/h. The tests were carried out in compliance with provisions of UN ECE Regulation No. 80 [7], which define the required time history of the dynamic input that should be applied to the seat with a test dummy placed on it; simultaneously, this time history may correspond to the impact characteristics of the front part of a bus superstructure. During the tests, the course of which has been described in [8], a P10 test dummy was used, whose anthropometric characteristics corresponded to those of a child aged 9–12 years with a mass of 32 kg.

Fig. 2 shows the dimensions P_g and P_d, which define the change in the seat belt strap position on the child dummy during two variants of the experimental tests. At test variant 1, the child dummy was placed on a standard bus seat. At test variant 2, the standard bus seat was modified so that the seat belt strap position on dummy's torso could be changed according to the dimensions specified in Table 1. The scatter of the values given in the Table represents the measurement results obtained from two repetitions of the same test variant. A new set of bus seats was prepared for each test variant.

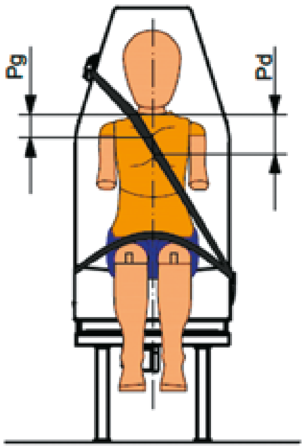


Fig. 2. Position of the seat belt strap on the torso of the P10 test dummy

Table 1. Dimensions defining the position of the seat belt strap on the torso of the child dummy

Dimension	Variant 1 [mm]	Variant 2 [mm]
P_g	30–35	75–80
P_d	115–120	155–160

P_g – distance from the neck to the upper edge of the seat belt strap
P_d – distance from the neck to the lower edge of the seat belt strap

Fig. 3 shows the coordinate systems adopted to describe the test results and transducer locations in the P10 dummy. The $O_GX'Y'Z'$ coordinate system was fixed to the seat base and was treated as a reference system when describing the movements of dummy's solids. In addition to this, local coordinate systems O_LXYZ were adopted as situated at the acceleration transducer mounting points. The transducers were used to measure accelerations of dummy's head and torso. The transducers applied made it possible to measure the three mutually perpendicular components of the said vector values. Moreover, a gyroscopic transducer of angular velocity was used to measure the movements of dummy's head around the O_LY axis.

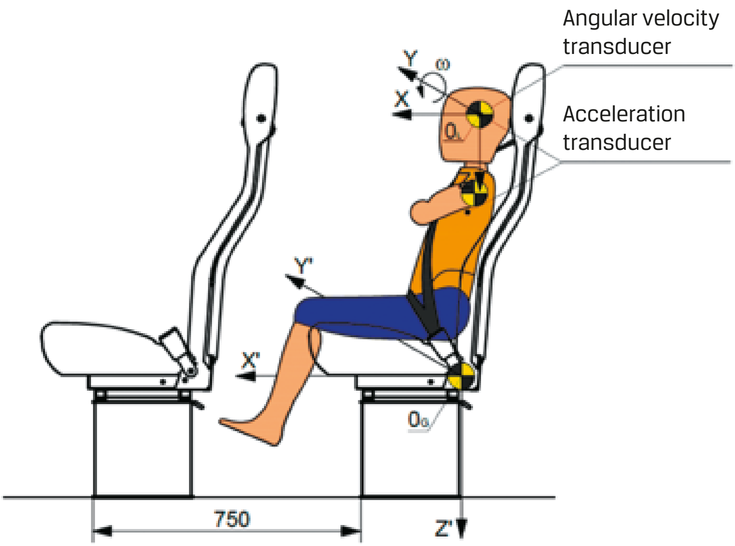


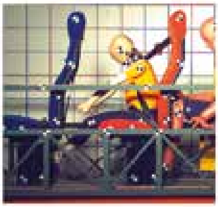
Fig. 3. Coordinate systems (time t = 0) and transducer locations in the P10 dummy

Example frames selected from video records of the experiments (covering both test variants) have been presented in Table 2. This facilitates the preliminary assessment of movements of the upper part of the dummy at successive test variants. The "2.1" and "2.2" test variant symbols have been used to identify successive repetitions of the test variant 2.

Table 2. Selected frames from video records of the experiments

	Variant 1	Variant 2.1	Variant 2.2
Time 0,00 s			

Table 2. Selected frames from video records of the experiments cont.

Time 0,10 s			
Time 0,15 s			
Time 0,20 s			

Based on a frame-by-frame analysis of the video records, successive positions (in 0.01 s intervals) of markers stuck on the dummy were identified. The head and torso trajectories thus determined (Figs. 4 and 5) made a basis for a general assessment of the influence of the seat belt strap position on dummy's movement and on the resulting hazards. A few important details about this movement have been presented in subsequent parts of this paper.

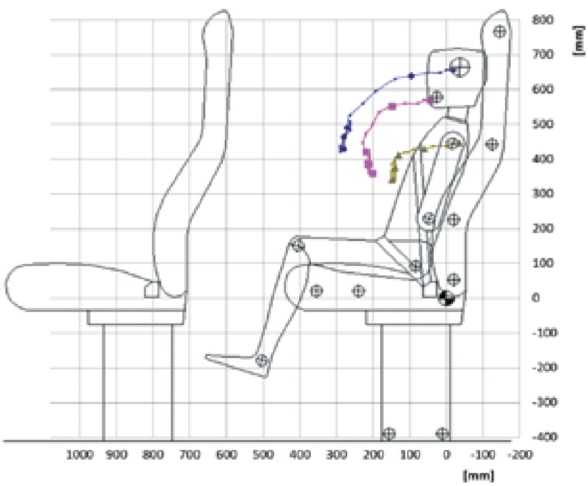


Fig. 4. Trajectories of characteristic points of the P10 dummy (example taken from test variant 1); successive positions of these points have been marked for 0.01 s (10 ms) steps (normal dots) and for 0.05 s (50 ms) steps (bold dots)

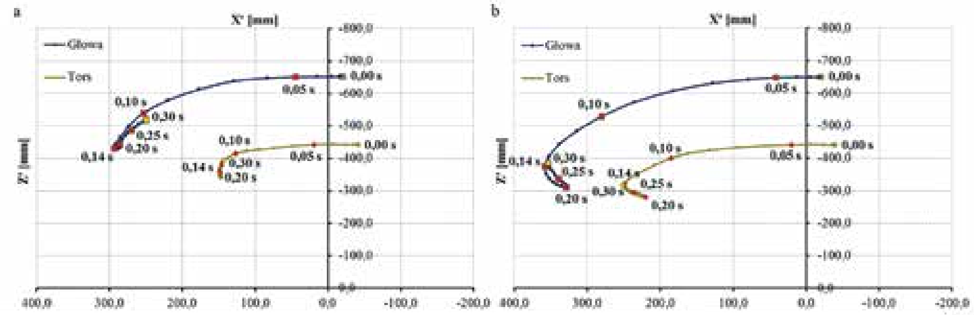


Fig. 5. Trajectories of characteristic points determined by a frame-by-frame analysis: a – variant 1; b – variant 2

Results of the frame-by-frame analysis of the video records showed that the lowering of the shoulder portion of the seat belt (see Table 1) significantly affected the child's head and torso movements during the simulated road accident:

- The head displacement reached its maximum at an instant of 0.14 s at both variants of the seat belt strap position.
- At variant 2, the longitudinal and vertical displacements of child's head exceeded those measured for the standard seat (variant 1) by about 65 mm, which translates into increased risk of injury because the child may hit its head on its knees.
- At variant 2, the longitudinal displacements of dummy's torso exceeded those observed at variant 1 by about 100 mm.
- At an instant of about 0.10 s, the rate of increase in the longitudinal displacement of child's head was reduced with simultaneous increase in the vertical displacement. This means that the head tilt angle rapidly increased in this accident phase, which caused the lower jaw to be pressed against the thorax and the cervical spine to be stretched.

In spite of increased head and torso displacements observed when the seat belt was in its lower position at test variant 2, the child's head did not hit the structure of the preceding seat. At neither of the variants, the pressure exerted by the seat belt on child's torso caused the torso to be thrown back and to hit during the backward movement on the seat backrest.

3. Scatter of the measurement results obtained when repeating the experiment

A success in the experiments as described above depends to a decisive degree on the careful preparation of the tests and on the repeating of exactly identical positioning of the seats and positioning of the seat belt and dummy on the seat. Therefore, many factors were checked before starting the measurements, including the conformity of dummy's position with its reference standard.

Figs. 6 and 7 show an example scatter of the results of head and torso acceleration measurements, observed when repeating variant 2 of the experiment (cf. Table 2). In these illustrations, curves $a_X(t)$, $a_Y(t)$, $a_Z(t)$ represent realizations of acceleration components in the local coordinate system (fine lines); the heavy lines show averaged values obtained from variants 2.1 and 2.2. The curves representing the values recorded for variants 2.1 and 2.2 have been plotted as fine red and green lines, respectively. Fig. 6 shows the head acceleration vs. time curves obtained with the use of CFC600 filtration and, additionally, CFC60 filtration, i.e. with the use of low-pass filters with limit frequencies of 1 000 Hz and 100 Hz, respectively. The CFC600 filtration has been stipulated in UN ECE Regulation No. 80 [7]. Fig. 7 shows torso acceleration vs. time curves after CFC180 and, additionally, CFC60 filtration. The limit frequency of the CFC180 filter is 300 Hz; the use of such a filter has also been stipulated in [7]. The CFC60 filtration was used in both cases additionally to remove the high-frequency components, a significant part of which consists of noise caused by the fact that the course of the experiment has the nature of an impact (with accompanying wave processes, wire vibrations, etc.).

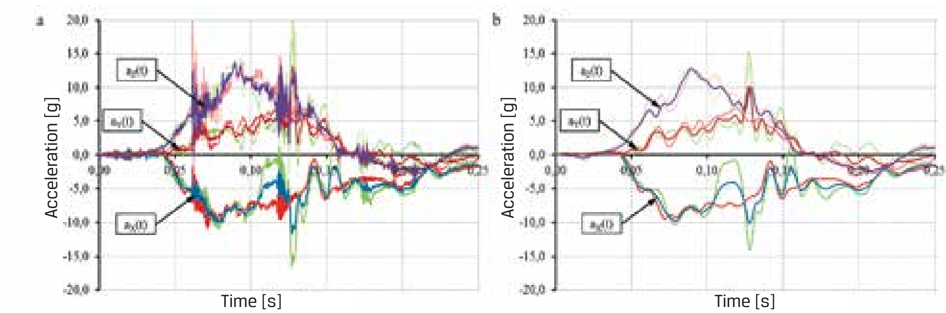


Fig. 6. Scatter of the results of measurements of head acceleration components in the local coordinate system, observed when repeating variant 2 of the experiment:
a – CFC600 filtration; b – CFC60 filtration

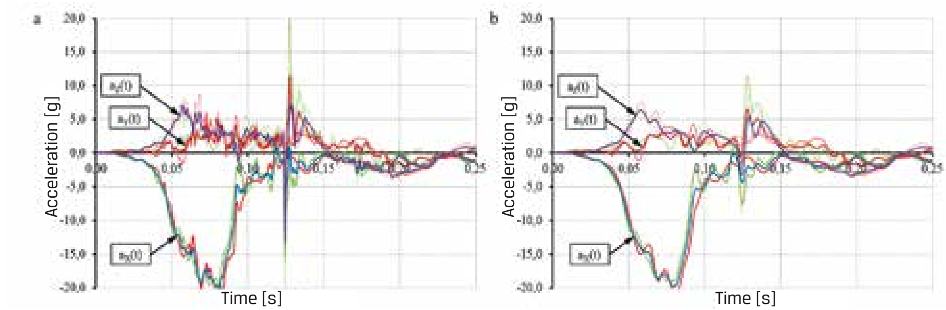


Fig. 7. Scatter of the results of measurements of torso acceleration components in the local coordinate system, observed when repeating variant 2 of the experiment:
a – CFC180 filtration; b – CFC60 filtration

To estimate the scatter of the measurement results obtained when repeating the experiment (cf. Figs. 6 and 7), the average value at individual time instants and the mean values of the standard deviation were calculated. The calculations were made for both filtration types and for three time intervals, i.e. 0.05–0.10 s, 0.10–0.15 s, and 0.15–0.20 s. The calculation results have been presented in Table 3. The additional CFC60 filtration virtually does not affect the profile of the averaged realization of acceleration (cf. the a and b graphs in Figs. 6 and 7). The scatter results, too, almost do not depend of the filtration used. The largest scatter of the head and torso acceleration values occurred (regardless of the filtration type used) in the time interval 0.10–0.15 s, i.e. in the phase when the dummy's motion was slowed down by the seat belt reaction (cf. the trajectories shown in Figs. 4 and 5).

Table 3. Values of the scatter of results of the head and torso acceleration measurements carried out when repeating variant 2 of the experiment

Direction	Time interval	Head [g]		Torso [g]	
		CFC600	CFC60	CFC180	CFC60
X	0.05–0.10 s	0.60	0.49	1.24	1.13
Y		0.64	0.58	0.81	0.71
Z		1.11	0.91	0.75	0.56
X	0.10–0.15 s	1.86	1.80	1.07	0.90
Y		1.47	1.24	1.43	1.07
Z		1.40	1.07	1.51	1.27
X	0.15–0.20 s	0.93	0.92	0.32	0.27
Y		0.78	0.75	0.69	0.66
Z		0.47	0.27	0.37	0.32

4. Acceleration measurement results with an analysis

The measurement results, obtained with the use of a measuring system meeting the requirements of ISO 6487 [5], made it possible to determine the accelerations of the head and torso centres and the angular velocity of the head during its tilting movement. They were used to evaluate the dynamic loads of child's head and torso and the effects of changes in the position of the shoulder portion of the seat belt strap in relation to the child's torso.

Fig. 8 shows time histories of the resultant head acceleration $a(t)$ and its two components, i.e.:

- $a_X(t)$, which reached the highest values and had a decisive impact on $a(t)$;
- $a_Y(t)$, which indicates the presence of a lateral head movement, or in other words the fact that the head moved in a direction perpendicular to the longitudinal symmetry plane of the bus during the frontal (longitudinal) impact of the bus against an obstacle.

The time history of the resultant head acceleration was calculated from components of the acceleration vector:

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

In Fig. 8, lines with different thicknesses were used to identify the curves obtained from the CFC600 and CFC60 filtration (fine lines and heavy lines, respectively).

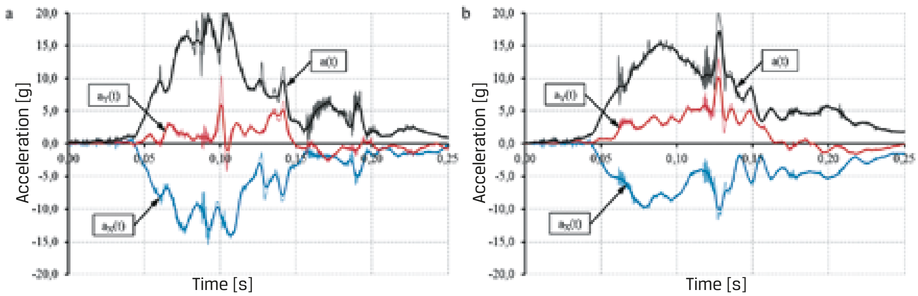


Fig. 8. Time histories of the resultant head acceleration and acceleration vector components in the direction of the OLX and OLY axes: a – variant 1; b – variant 2

Based on the measurement results, the average head acceleration values were calculated for the time interval 0.05–0.15 s and the calculation results have been specified in Table 4. The time interval was defined as the one when the highest dynamic loads occurred during the dummy's tilting movement.

Table 4. Average head acceleration values calculated for the time interval 0.05–0.15 s

Quantity	Variant 1 [g]	Variant 2 [g]	Change in the absolute value after lowering the seat belt strap position
$a_X(t)$	-8.30	-6.35	Reduction by 24 %
$a_Y(t)$	1.95	3.90	Growth by 100 %

The following findings may be formulated on the grounds of the curves brought together in Fig. 8 and the values given in Table 4:

- The lowering of the seat belt strap position had a favourable impact on the resultant child's head acceleration, causing a reduction in this acceleration observed in the time interval 0.05–0.15 s.
- The absolute value of the average longitudinal acceleration component $a_X(t)$ was reduced by 24%.
- The lowering of the seat belt strap position resulted in an unfavourable growth in the value of the lateral acceleration component $a_Y(t)$ at variant 2 of the experiment, which indicated that a dangerous lateral movement of the head occurred during the test.

- The average value of the lateral acceleration component $a_Y(t)$ grew by 100% after the lowering of the seat belt strap position, which means a significant increase in the risk that the passenger would hit his head on the side of the vehicle body or on the passenger sitting beside him/her.

Fig. 9 shows time histories of the resultant torso acceleration and its two components $a_X(t)$ and $a_Y(t)$ (solid lines). Curves representing time histories of the $a_{XX'}(t)$ and $a_{YY'}(t)$ acceleration components (heavy dashed lines), obtained by projecting the vector of acceleration of the centre of torso mass onto axes O_GX' and O_GY' of the global coordinate system fixed to the seat base (cf. Fig. 3), have also been plotted in the graphs. The values of the local components of the torso acceleration vector, which are necessary for these calculations, have been shown in Fig. 7 and the varying values of the torso tilt and rotation angles were determined from an analysis of the video records of the experiment [8].

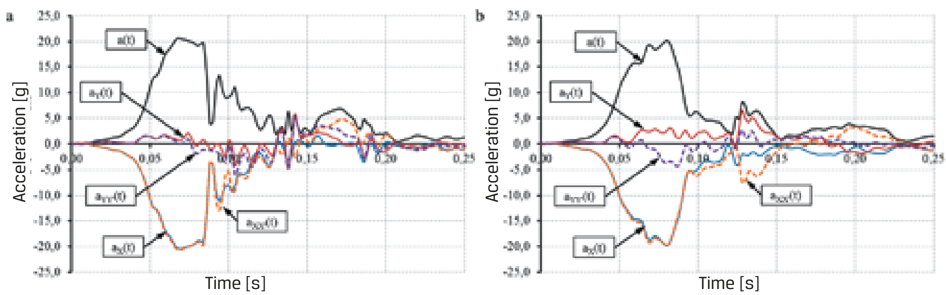


Fig. 9. Time histories of the resultant torso acceleration as well as global and local acceleration vector components in the longitudinal and lateral direction (CFC60 filtration): a – variant 1; b – variant 2

Table 5 shows results of calculations of the average torso acceleration values for the time interval 0.05–0.15 s.

Table 5. Average torso acceleration values calculated for the time interval 0.05–0.15 s

Quantity	Variant 1 [g]	Variant 2 [g]	Change in the absolute value after lowering the seat belt strap position
$a_X(t)$	-8.90	-8.10	Reduction by 9%
$a_Y(t)$	0.07	2.20	Growth exceeding 30×

An analysis of results of the torso acceleration measurements, inclusive of the curves presented in Fig. 9 and the figures given in Table 5, provides grounds for the following findings to be formulated:

- The curves shown in Fig. 9 as time histories of the resultant torso acceleration $a(t)$ and its component $a_X(t)$ were similar for both test variants; however, the $a(t)$ and $a_X(t)$ values determined for the lower seat belt strap position were somewhat lower, especially in the period from 0.09 s to 0.12 s.

- For the lower seat belt strap position (variant 2), the lateral acceleration component values $a_Y(t)$ were higher than those determined for the standard bus seat.
- The lowering of the seat belt strap position caused the average value of the $a_X(t)$ component to be reduced by 9% (Table 5); however, the average value of $a_Y(t)$ simultaneously increased more than thirtyfold.
- The difference between the values of $a_X(t)$ and $a_{XX'}(t)$ shows the impact of the torso tilt angle on the longitudinal accelerations; this impact was markedly stronger in the case of the lower seat belt strap position, especially for t > 0.12 s.
- The difference between the values of $a_Y(t)$ and $a_{YY'}(t)$ confirms that significant rotation of the torso took place during the longitudinal torso movement; the torso rotation angle grew when the seat belt was placed in the lower position and this angle was most clearly visible in the culminating phase of the impact process, which was analysed in [8].

The resultant acceleration vs. time curves presented in Figs. 8 and 9 may also be considered as representing the unit dynamic load acting on child's head and torso due to the inertia force F_B:

$$a = \frac{F_B}{m_G} \tag{2}$$

where: m_G – the mass the acceleration of which is a.

Hence, the analysis of acceleration values is simultaneously a description of the loads the child is subject to during a road accident.

The time histories of head and torso acceleration (cf. Fig. 8 and 9) were used to calculate the *Head Injury Criterion* (HIC) [2, 10] and the *Thorax Acceptability Criterion* (ThAC) [6].

The HIC indicator was calculated without introducing any limitations regarding the length of the time interval that was taken into account:

$$HIC = max\left\{\left[\frac{1}{(t_2-t_1)}\int_{t_1}^{t_2} a(t)\,dt\right]^{2,5} \cdot (t_2 - t_1)\right\} \tag{3}$$

where: $a(t)$ – resultant head acceleration [g];

t_2–t_1 – time interval within which the acceleration values are taken into account.

At the tests examined (where the impact velocity was 29.5 km/h), dummy's head did not strike any vehicle components; therefore, the calculated HIC values were low (Table 6). The calculations were made with using acceleration vs. time curves subjected to the CFC600 filtration. The additional CFC60 filtration only slightly affected the HIC indicator calculation results and the value of this indicator was then reduced by about 4–5% in comparison with that obtained from the curves subjected to the CFC600 filtration. The lowering of the seat belt strap position resulted in a reduction of the HIC indicator value by about 10%.

Table 6. HIC value calculation results

Variant	HIC value	t_1 [s]	t_2 [s]
Variant 1	50.6	0.055	0.143
Variant 2.1	45.9	0.056	0.139
variant 2.2	44.2	0.058	0.151

The ThAC indicator is determined from the extreme torso acceleration values, the time history of which is filtered in compliance with [7]. The measurement results showed that the extreme acceleration values obtained at both test variants were lower by about 30% than the limit of 30 g adopted as the maximum acceptable value of the thorax injury indicator.

5. Head tilt angle measurement results

The measurement and calculation results described previously indicated that differences occurred in the head movements in result of changes in the position of the seat belt strap on dummy's torso. Fig. 10 shows the time history of the child's head tilt angle (angle of rotation around the O_LY axis), determined by integration of the angular velocity of the head movement. When the position of the shoulder portion of the seat belt strap was lowered, the longitudinal displacement of dummy's head (cf. Fig. 5) and the head tilt angle increased to reach values higher by more than 30 % than those recorded for the standard seat belt position. At test variant 2, the head tilt angle came to a value of almost 90 °, which must be considered very high. The growth in the head tilt angle translates into increasing dynamic loads of the cervical spine. An important risk factor is also the length of the period when the extreme values of the head tilt angle occur. At test variant 1, the time of duration of this period was about 0.135 s, while it was extended to more than 0.205 s at test variant 2 (cf. Table 2, Fig. 5, and Fig. 10). When this time elapsed, dummy's head began to move

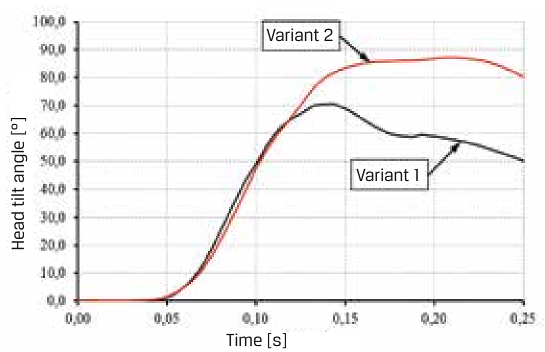


Fig. 10. Time histories of the head tilt angle

back and the neck load declined. In the case of the lower position of the seat belt strap, the time of increase in the head tilt angle was longer by almost 40 % than that recorded at the standard position of the seat belt strap.

6. Recapitulation

The research carried out has revealed some important desirable and undesirable effects of changing, as often proposed, the position of the shoulder portion of the seat belt strap in relation to the centre of the torso of a child travelling on a motor coach seat. The desirable effects include, above all, moving the belt strap away from child's neck, as well as lowering the values of head and torso accelerations, chiefly of their longitudinal components, by 24 % and 9 %, respectively. One of the effects of the examined change in the seat belt positioning is a reduction in the HIC indicator value by 10 %. The child restrained on the bus seat with a seat belt adjusted to the lower position can move within a wider range in comparison with that of the sharp and violent movement that would take place in the case of restraining the child on a standard bus seat. However, the growth in the extreme head tilt angle values to almost 90 ° at test variant 2 and the appearance of marked lateral head and torso movements at the lower seat belt position must be considered an alarming finding.

In spite of larger displacements of child dummy's head and torso, observed when the seat belt was in its lower position, the dummy's head did not hit the structure of the preceding seat.

The measurement and calculation results presented in Figs. 5–9 and in Tables 3–5 have shown that the influence of lowering the position of the shoulder portion of the seat belt strap on reduction in the risk of injury to a child travelling on a bus seat is not unequivocally desirable. At the same time, they have enabled quantitative evaluation of some hazards that would arise from a change in the seat belt position. Such hazards may manifest themselves in an increase in the longitudinal head and torso displacements by 65 mm and 100 mm, respectively, significant head tilt angles (of up to 90 °), and marked trend of the torso to rotate during the longitudinal movement in the culminating phase of the impact process, which indicates the risk that the child may slip out from below the shoulder portion of the seat belt.

The research work has confirmed that the proposed modifications to the personal protection systems provided at vehicle seats can be hardly assessed as producing unequivocally desirable effects in the protection of children from accident hazards. There is a need for further research and for the establishing of substantive foundations for such standards and regulations that would bring about an improvement in the system of personal protection of children travelling on bus seats.

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