ORIGINAL ARTICLE

Experimental and modelling research on coach passengers' safety in frontal impacts

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Abstract

Road traffic accidents involving coaches do not happen very often, but they are very dangerous because they affect a large number of passengers. Coaches (or intercity buses) are not equipped with safety belt harnesses. Valid regulations do not impose any obligation on coach manufacturers to provide intercity buses with either two- or three-point safety belts. This fact may result from the unawareness of risks and injuries that might befall the passengers with no safety belts during accidents. That is the reason why this work aims to compare the aftermath of coach accidents with no safety belts and the ones with safety belts. A detailed aim of this research is to analyse the results of dynamic loads during a frontal impact exerted on coach passengers travelling with and without (two- and three-point) safety belts. This objective was achieved by performing experimental studies and modelling which focused on the process of dynamic load transfer on the human body during a traffic accident. The research was conducted parallel on an adult and a child. The equivalent of a 50th percentile male was a hybrid III dummy (M50), whereas a child at the age of about 10 was represented by a P10 dummy. A numerical model was generated and verified in experimental testing in the scope of kinematics. Also, the comparison of the recorded courses of forces, acceleration, and moments was conducted. The results obtained from the tests were analyzed regarding the injury criteria for head, neck, and thorax. It was observed that both for the two-point safety system and the lack of safety belts, there were high values of acceleration recorded in the centre of gravity of the head. On the basis of the investigations conducted, it was ascertained that only a three-point safety belt system ensures the satisfaction of all injury criteria within admissible standards both in the case of criteria defined in the rules no. 80 and the rules no. 94 determined by the United Nations Economic Commission for Europe. It is the three-point safety belt system which should be obligatory in all intercity buses.

Keywords Experimental investigation · Security systems · Traffic accident · Madymo · Multibody · Safety belts

1 Introduction

1.1 Premises for undertaking the investigations

Nowadays, coaches are one of the most popular means of public transport in Poland and all over the world. In 2019, in Poland, this means of transport carried the total of 459.9 million of passengers. However, in spite of this enormous popularity, the improvements within the scope of travelling safety are small. The most dangerous are frontal impacts which result in the highest number of fatalities. That is the reason why this work focuses on this type of impact. The operation of safety devices during an accident consists essentially in the conveyance (onto the human body) of loads which do not exceed strictly defined criteria and are exerted on appropriate places. Such forces are conveyed through the

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interaction with seats, safety belts, and air bags. The seats on the coaches are standardized and often not provided with any safety belts or the possibility of adjustment of the seat-back or headrest. On the basis of the so-far knowledge of the genesis of injuries, it can be deduced that the public transport should be equipped with passive safety systems, such as two-point or three-point safety belts. Both experimental and modelling investigations presented in this paper show what happens to the passengers of public transport in the case of lack of safety belts and in the case of their application.

1.2 Previous state of research

Many researchers have undertaken investigations in the broad scope of safety in car, bus, and coach traffic [1, 2]. Zhigang Li et al. [3] conducted studies which assessed the safety in school buses. The detailed analysis encompassed the injury criteria of the neck section of the spine in children. The tests showed that the application of the sole hip belt is not sufficient and it is advisable to use three-point safety belts. Karekla et al. [4] analyzed the impact of acceleration on the passengers travelling on the city bus. They analysed activities such as going upstairs and downstairs in double-decker buses. Bolte et al. [5] performed modelling tests in which they assessed the use of two-point and three-point safety belts. Their work implied that such belts might not be effective during a lateral impact and overturning of the vehicle. Elias et al. [6, 7] conducted crash tests on real objects and several sled tests. Those tests aimed to evaluate the applied safety belts during a frontal impact. Özcanli et al. [8] carried out investigations evaluating foam lining on the internal side walls of the coach with a view to the improvement of passengers' safety during the overturning (rolling) of the coach. The studies conducted by Prochowski's team et al. [9, 10] analyzed the influence of dynamic loads caused by the forces of inertia and the forces exerted by three-point safety belts. The analysis of the incidence of the neck section trauma has been discussed also in many publications concerned with the safety in traffic accidents. Joszko et al. [11] carried out investigations evaluating the risk of neck injury in racing drivers who use the Hans system. Whereas, Sybilski and Malachowski [12] carried out numerical analysis a disabled driver with additional equipment designed for his safety and convenience.The occupant responses during the bus accidents have been also analysed in other research publications [13, 14]. Analysis of head, cervical spine, thoracic, and leg trauma is a topic that is widely discussed in the scientific world not only in crash tests of cars [15, 16] or intercity buses [17–19] but also e.g., in the military industry. Gzik and Burkacki et al. [20, 21] conducted simulation tests in which they determined the level of head and cervical spine injuries during an explosion under a military vehicle. Safety in military vehicles in terms of soldier

trauma is also mentioned in publication [22] and comfort at work [23]. Research works also are interesting, in which the operator safety of underground machines and devices is analysed. In these investigations, head and spine injuries are studied because the operator is exposed to rock mass movements [24]. To correctly determine traumatic criteria in biomechanical analysis, it is necessary to correctly formulate numerical models of anatomical parts of the human body [25]. A literature review refers to many works in which numerical models are dedicated to dynamic analyses [26, 27]. In most of them, the selection of appropriate properties of materials to absorb energy is important stage of dynamic modelling [28, 29].

However, the literature review does not show any works which would thoroughly analyze the injury criteria for coach passengers during a frontal impact. The present day legal regulations concerning the provision of coaches with safety systems are regulated by Directive 2005/40/WE of the European Parliament and Council of 7 September 2005. This Directive requires that each tourist coach should be equipped with two-point safety belts. In accordance with the above-mentioned Directive, both static and dynamic tests are conducted to check the safety of the seat belts in the scope of their strength and the method of their attachment to the seat. Within the framework of the static tests, test loads are exerted on particular sections of the safety belts, as can be seen in Fig. 1 [30].

The dynamic tests consist in the mounting of the seats on the coach floor or on a testing platform according to the requirements of the rules no. 80 determined by the United Nations Economic Commission for Europe. This test is divided into two stages. In the first phase, a dummy is not secured by means of safety belts, whereas in the second phase, it is attached with safety belts. The dummy used in the tests is 50th percentile hybrid III. The dynamic test consisted in making the seats with dummies gather speed up to a velocity of 32 km/h and then braking the whole system with
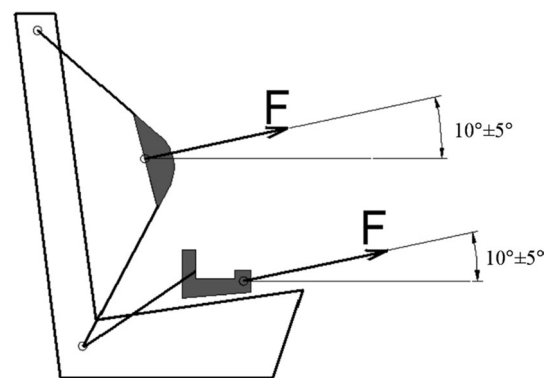

Fig. 1 Application of test loads [30]

a deceleration defined in the rules. The seat is considered safe when it meets the requirements determined in Table 1.

The present day EU directives impose the obligation on the manufacturers of coaches to equip them with two-point safety belts, whereas the safest solution seems to be the application of three-point safety belts. That is the reason why on the grounds of the literature review, it was decided that this work should aim at the recognition of the impact of dynamic loads on coach passengers during a frontal impact with the application of two-point and three-point safety belts. All above information enabled the authors to formulate the correct model for analyzing the safety of bus passengers. All data collected from the literature allowed to simulate the real conditions of the bus frontal collision accident in the MADYMO software (TASS International—a Siemens business, Helmond, The Netherlands).

2 Testing methodology

Within the framework of this work, experimental tests were conducted parallel to modelling tests. These two methods were joined as a common way to achieve a better state of knowledge of the processes and possibilities of minimization of dynamic loads exerted on coach passengers during a traffic accident. On the basis of the experimental tests conducted, mechanical parameters of a real object were identified. Such parameters enabled the determination of boundary conditions necessary for the construction of a numerical model. In addition to that, the experimental tests made it possible to record the courses of deceleration in characteristic points of the vehicle (floor) and the dummy (head, thorax, and pelvis) as well as to identify the values of forces exerted on lower limbs during an impact. The data collected were used for the determination of trauma criteria and the verification of the numerical models developed in this research.

During the investigations conducted, an attempt was made to recognise the influence of dynamic loads on the vehicle passengers in the case of application of two-point and three-point safety belts. To do that, the analysis encompassed the courses and extreme values of dynamic loads acting on the coach passengers during a traffic accident. The analysis was conducted parallel for experimental investigations and modelling tests, for both an adult and a child. During a frontal impact, the load exerted on the person travelling on the coach was determined in accordance with the applied protection devices (PD). The results obtained enabled the definition of the relationship between the two-point or three-point safety belts systems and the occurrence of injuries during a traffic accident. On the grounds of the conducted investigations, it may be concluded which of the safety systems poses the highest risk for the adult or child. The experimental and modelling tests were performed jointly by a team of researchers from the Industrial Institute of Motorization (PIMOT) in Warsaw having experience in the scope of experimental testing and by a team of researchers from the Silesian University of Technology highly competent in the field of modelling and computational simulations.

3 Investigations conducted at testing stations

Experimental testing was conducted at the Industrial Institute of Motorization (PIMOT) using unique equipment, namely a sled testing station for crash tests, a device for testing seats as well as dummies hybrid II (M95), hybrid III (M50), and child's dummy P10. The experimental investigations consisted in the performance of frontal impact crash tests of a physical model of the coach with dummies sitting in the seats. The investigations encompassed the analysis of the influence of the safety belts system on the level of loads exerted on the passengers during a traffic accident. During frontal impact crash tests, the measurements were made of the values and courses of extreme dynamic loads acting on the coach passengers.

3.1 Object of investigations

The physical model of the coach (Fig. 2) which had been prepared for the tests had a front seat and two rows of seats on which dummy hybrid III representing a 50th percentile man (M50) and the dummy of a 10-year-old child (P10) were placed. Crash tests were conducted in which, among other things, the type of safety belts system was changed. During testing, both dummies were fastened to the seats by means of

Table 1 Requirements for seat safety [30]

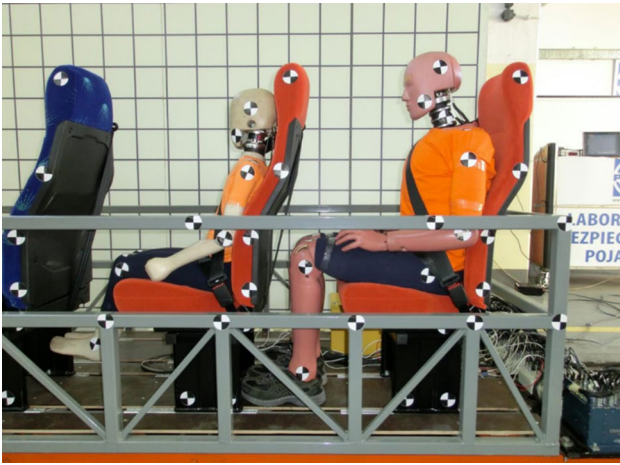| Requirements	Admissible values
Displacement of the dummy's trunk and head forwards in relation to an ancillary seat	< 1.6 m
Head injury criterion (HIC)	< 500
Thorax acceptability criterion (ThAC)	< 30 g except for intervals shorter than 3 ms
Femur acceptability criterion (FAC)	< 10 kN, value 8 kN is not exceeded in intervals longer than 20 ms

Fig. 2 Dummies in the coach physical model

standard safety belts. The upper point of the belts attachment was not changed and their original position was retained. After each crash trial, all elements of the safety belts were replaced even if they were not damaged.

The position of the dummies in relation to the seats and the position of the safety belts in relation to the dummies (see Fig. 3) were described by providing characteristic dimensions (see Table 2) defining the space around the dummies.

3.2 Testing station

The coach model was placed on a sled of the sled testing station (device AB-554), which is presented in Fig. 4. The sled was accelerated using rubber cables up to a velocity of 48 km/h. The desired course of deceleration was obtained by means of a special brake (see Fig. 4). It consists of some rods (mandrels) fixed to the sled. The rods are completed with

Fig. 3 Dimensions describing the dummy position in relation to the seat and safety belt: (**a**) front view M50, (**b**) front view P10, (**c**) side view
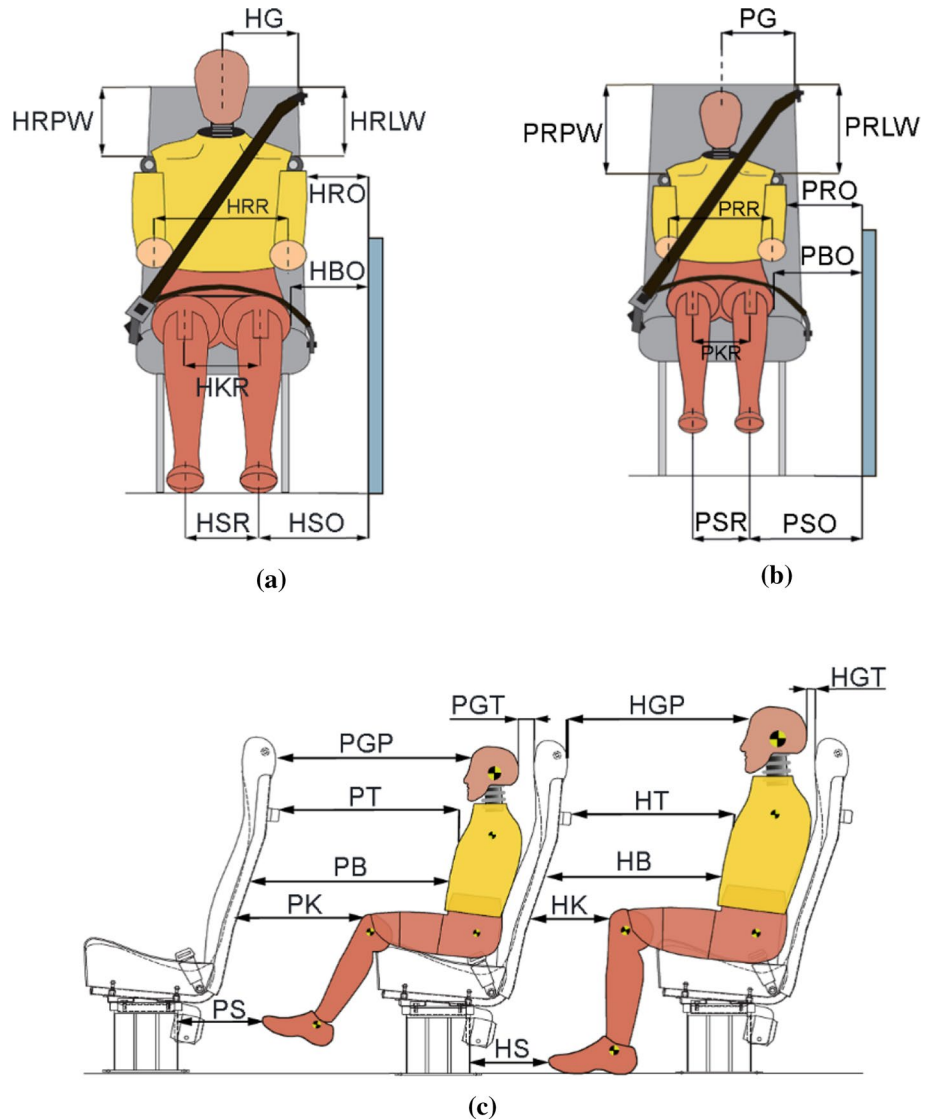
Table 2 Distances describing the position of the dummies

Specimen	Front view		Side view	
	Symbol	Distance (mm)	Symbol	Distance (mm)
M50 dummy	HG	100	HGT	220
	HBPW	225	HGP	350
	HBLW	225	HT	430
	HBR	50	HB	490
	HRR	205	HK	100
	HRO	40	HS	295–300
	HBO	85		
	HKR	175		
	HSR	245		
	HSO	155		
P10 dummy	PG	90–100	PGT	0
	PBPW	330	PGP	515
	PBLW	330	PT	540–545
	PBR	70	PB	575–580
	PRR	282	PK	255
	PRO	105	PS	40
	PBO	150		
	PKR	140		
	PSR	85		
	PSO	250		

Fig. 4 Device AB-554 used for dynamic tests—a view from the sled track (the track made at the PIMOT)

'olive-shaped' steel knobs attached at the end and polyurethane sleeves placed in tubes fixed to the ground. The effect of the sled braking occurs as a result of forcing the 'olive-shaped' knobs through the polyurethane sleeves.

3.3 Characteristics of the coach deceleration

The course of the coachwork deceleration was in compliance with the requirements of the rules no. 80 determined by the United Nations Economic Commission for Europe, which refer to the testing of coach seats. Figure 5 presents the course of deceleration of the coachwork occurring in the direction of the coach movement. As required by the simulation studies, the characteristics of the coachwork deceleration were filtered through a CFC60 filter, i.e., a low-pass filter of a cut-off frequency of 100 Hz. During the modelling calculations, the same time step was adopted as for the recording of the results during experimental testing ($dt = 0.0001$ s).

4 Numerical model generation

Examples of the positions of dummies are shown in Fig. 6. The positions are described by characteristic dimensions which define the space around the dummies. The above-mentioned dimensions were measured on a real-life object and taken into consideration in the model. The way of the dummy's sitting is one of the factors deciding on its behaviour during the test. The arrangement of the dummy's legs is of importance to the movement of the hips and thus affects the influence of the hip belt. The angle of the thigh and shank inclination results, among other things, from the seat height, its length and space in front of the dummy (see Fig. 3). The modelling process adopted mass and geometrical parameters of passengers corresponding to the features and dimensions of the dummy of an adult—hybrid III and the dummy of a child—P10.

4.1 Model, algorithm, and software programme

A numerical model was formulated in the MADYMO software programme, which uses the methodology of the dynamics of multibody systems. This method consists in the copying or modelling of an object using a chain of rigid bodies joined by means of kinematics pairs. Both the bodies and the kinematic joints are determined by a series of physical parameters enabling the solving of motion equations of the whole system. Individual rigid bodies are described by means of the following parameters: mass, moments of inertia and the position of the centre of gravity. As for kinematic pairs, it is defined which bodies are joined with a given kinematic pair. Also, their location in relation to the reference coordinate system is determined. The position of a local coordinate system of individual rigid bodies in relation to the global coordinate system is described by means of a general Eq. (1) where X_i is the matrix of the coordinates of the position vector, r_i is the matrix of the coordinates of the vector joining the beginnings of both coordinate systems, A_i is the matrix of direction cosines, x_i is the matrix of the coordinates of the vector of local displacement of the coordinate system.

Fig. 5 Characteristics of the coachwork deceleration during experimental tests at the PIMOT
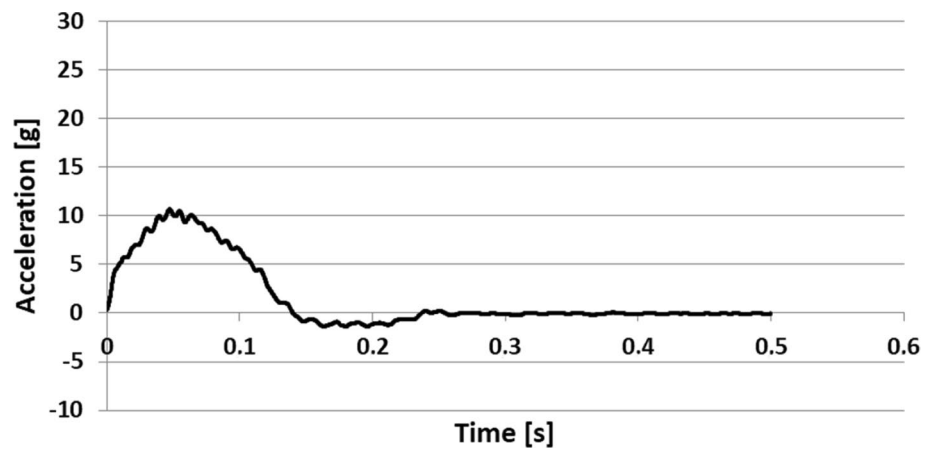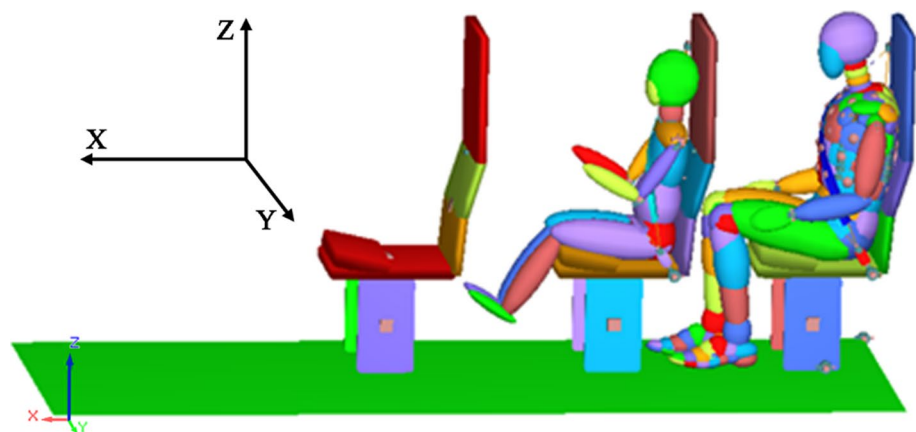

Fig. 6 Models of dummies with seats

$$\underline{X}i = \underline{r}_i + \underline{A}_i\underline{x}_i. \tag{1}$$

The numerical model for the solution to the general equation of motion (2) uses a modified single-phase Euler's method with a constant time step t_s.

$$\mathbf{M}\ddot{x}_t + \mathbf{C}\dot{x}_t + \mathbf{K}x_t = \mathbf{P}_t, \tag{2}$$

where **M** mass matrix, **K** rigidity matrix, $\mathbf{P}_t$ matrix defining external loads applied to the system, **C** matrix defining damping of the system. This matrix is usually adopted in the form of the so-called proportional damping (depending on **K** and **M** matrixes). x_t displacement.

The MADYMO is a software programme dedicated to the generation of dynamic numerical models for the automotive industry. That is the reason why this programme has a library of dummies which are used in crash tests. This facilitates the modelling process greatly. In addition, it is possible to work on each dummy available in the software library and to modify its individual elements depending on the objectives of investigations.

4.2 Determination of numerical model parameters

The numerical model, which was formulated in the above-described software programme, is presented in Fig. 6. The seats are modelled by means of five rigid bodies mapping the seat and the seatback.

These bodies were joined with one another by taking back all degrees of freedom, whereas the seatback was connected with the seat by means of a rotational kinematic pair of a limited angle of rotation. The model takes into account the floor and the first row of seats. The stiffness of the seat foam was described using force in the displacement function and was determined at a testing station at the Industrial Institute of Motorization (see Fig. 7). The foam stiffness was determined on a servohydraulic material testing machine (MTS MiniBionix I, Model 858, Eden Prairie, MN, USA) with a 28 kN force sensor. The test consisted of testing the foam of the chair with a 10 cm diameter drill at a speed of 650 mm/min. The model adopted a coordinate system corresponding with the coordinate system in the real-life object.
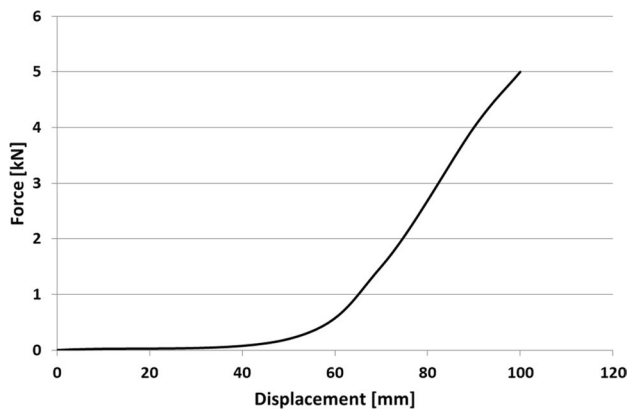
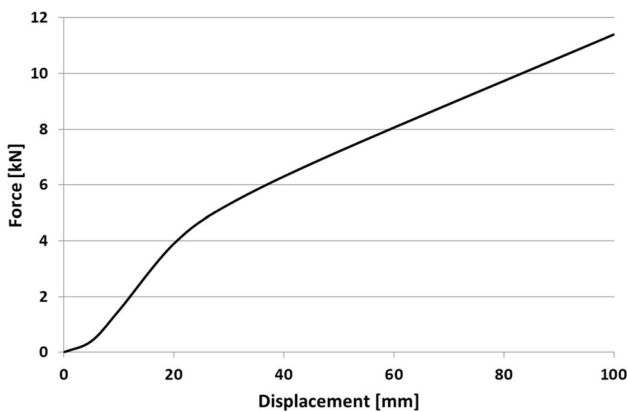**Fig. 7** Characteristics of the seat stiffness (acc. to the PIMOT)

Fig. 8 Force–displacement characteristics of the safety belt

The dummies were seated on the coach seats in accordance with the requirements of the rules no. 80 determined by the United Nations Economic Commission for Europe.

Figure 7 shows the characteristics of the seat stiffness which were adopted for the lower part of the seat (the so-called "nest").
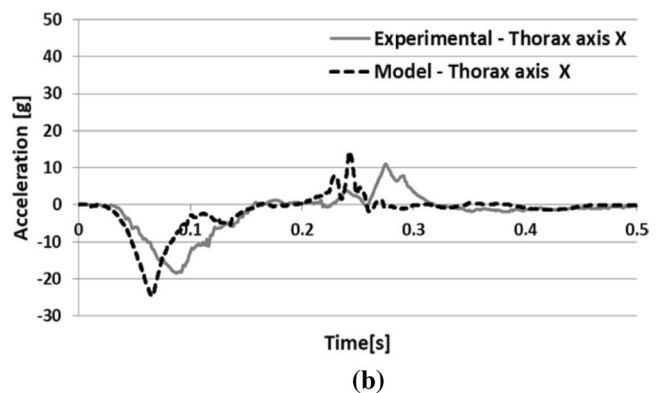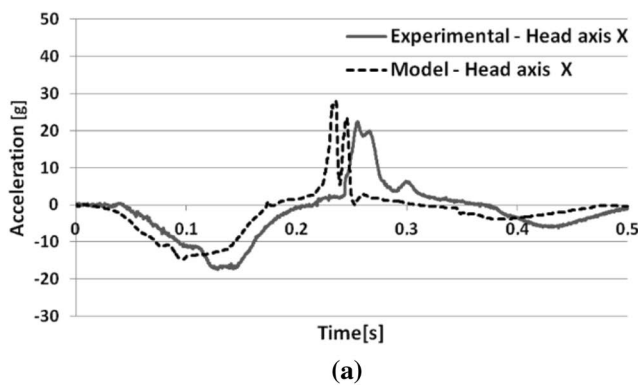
In modelling tests, similarly to experimental tests, the child's dummy was seated in the second row of the coach seats. Each dummy was secured with three-point safety belts. The force–displacement characteristics describing material properties of the safety belt are presented in Fig. 8. The force–displacement characteristics of the belt were determined on the MTS Bionix endurance machine equipped with a 28 kN force sensor. The test was carried out in accordance with the requirements of ECE/UN regulation 16. The test speed was 100 mm/min. The length of the strip sample section between the machine clamps was 200 mm.

5 Model verification

The verification of the model was conducted on the basis of a qualitative comparison of the data obtained in the experiment with the results of a numerical simulation. In the case of the adult dummy (M50), the assessment encompassed the courses of acceleration recorded for the head and thorax (Fig. 9a, b) as well as the values of forces and torques obtained for the neck section (Fig. 10a, b).

A P10 dummy was used both in the simulation and the experiment. Unfortunately, the dummies of this type were equipped only with the accelerometers in the gravity centre of the head and thorax. As a result, the verification of the model was conducted on the basis of the acceleration courses recorded for the head and thorax (Fig. 11a, b).

Moreover, the comparison of the kinematics of the dummies was made in subsequent time moments (Fig. 12). On the grounds of the conducted qualitative analysis, it was ascertained that both the recorded initial signals and the kinematics of the model proved a good correlation between the model and the real-life test carried out at the Industrial Institute of Motorization (PIMOT). As can be observed in the charts of the analysis conducted, there is a time shift of the courses of values obtained from the mathematical model in relation to the results obtained in experimental tests. The
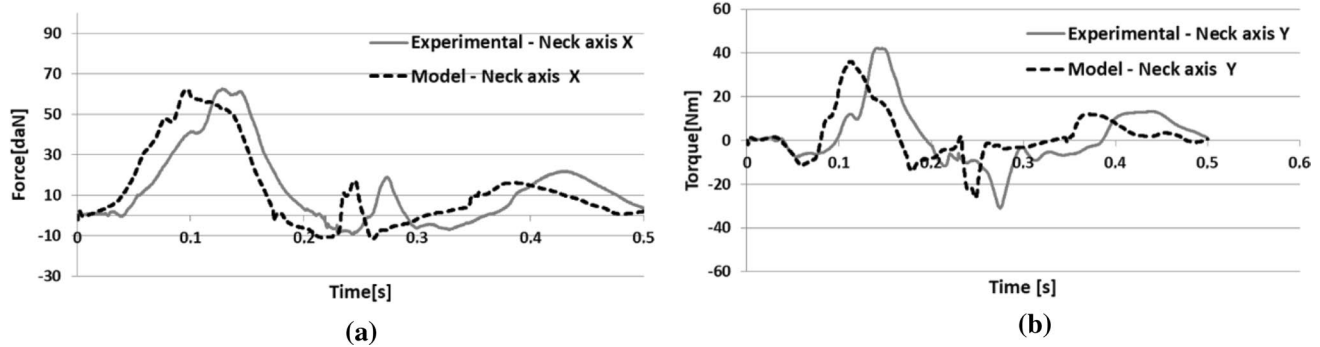

(a)

(b)

Fig. 9 Acceleration, axis *X*, dummy M50: (**a**) head, (**b**) thorax

Fig. 10 Dummy M50: (**a**) force in the neck section—axis *X*, (**b**) torque in the neck section in relation to axis *Y*
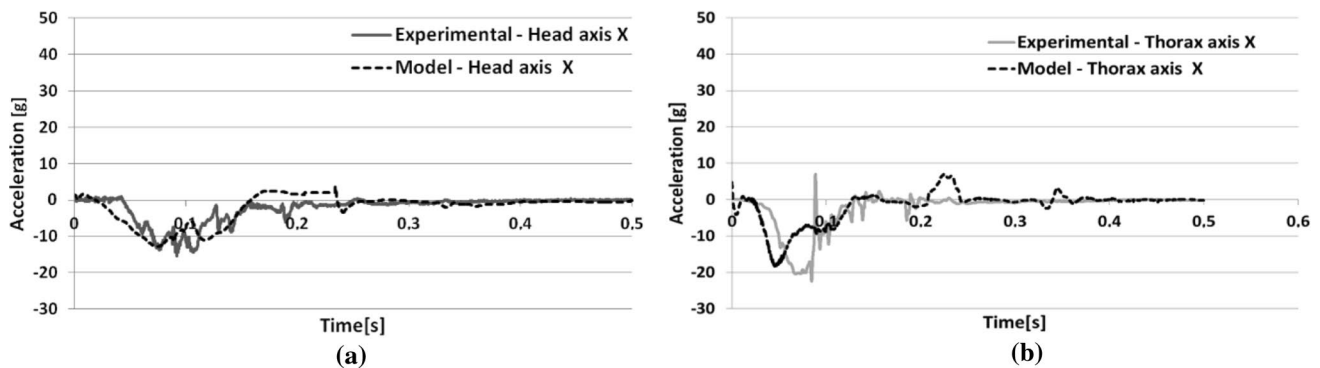

Fig. 11 Acceleration, axis *X*, dummy P10: (**a**) head, (**b**) thorax

above-mentioned shifts result from the way of making measurements of acceleration values recorded during the experiment and modelling tests.

During the experiment, the accelerometer measuring the acceleration of the whole structure was placed on the floor. The recorded acceleration was transmitted onto the dummy through a series of structural elements which provided some kind of damping of the signal coming from the floor onto the dummy. In spite of the above-mentioned time shift, the results of the verification may be deemed correct due to the fact that maximum acceleration values and forces values correspond to one another with great accuracy.

6 Numerical simulations

6.1 Selection of computational variants

The correct verification of the model made it possible to conduct numerical simulations for different variants of wearing the safety belt. In the first variant (W1), the dummies were fastened by means of three-point safety belts, whereas in the second variant (W2), using two-point safety belts. In the reference variant (W3), no safety belts were

used. Numerical simulations were performed at a kinematic input function. Input data for the simulations were obtained from experimental tests performed at a testing station at the Industrial Institute of Motorization (PIMOT). For the purposes of the simulation, the characteristics of deceleration obtained from the tests were filtered using filter CFC60. To perform the simulation, the same time step was adopted, i.e., $dt = 0.0001$ s, which was used for smoothing the characteristics. At the initial moment (time $t = 0$ s), it was assumed that all objects of the model were moving at the same initial velocity V_0, corresponding to the initial conditions of the tests. The conducted simulations enabled the determination of the kinematics of the dummies in particular variants of computations. In addition to that, in each case, biomechanical indices were calculated, such as: head injury criterion (HIC) HIC15 and HIC36, neck injury criterion (NIJ), NCF, NCE, NTF, NTE, viscous injury response index (VC) and thoracic trauma index (TTI) 3-ms CLIP—defined as a value of maximum acceleration in an interval not shorter than 3 ms. In the first computational variant (W1) (see Fig. 13), the dummies were fastened with three-point safety belts.

In the second computational variant (W2), the dummies were secured with two-point safety belts (Fig. 14a). In the
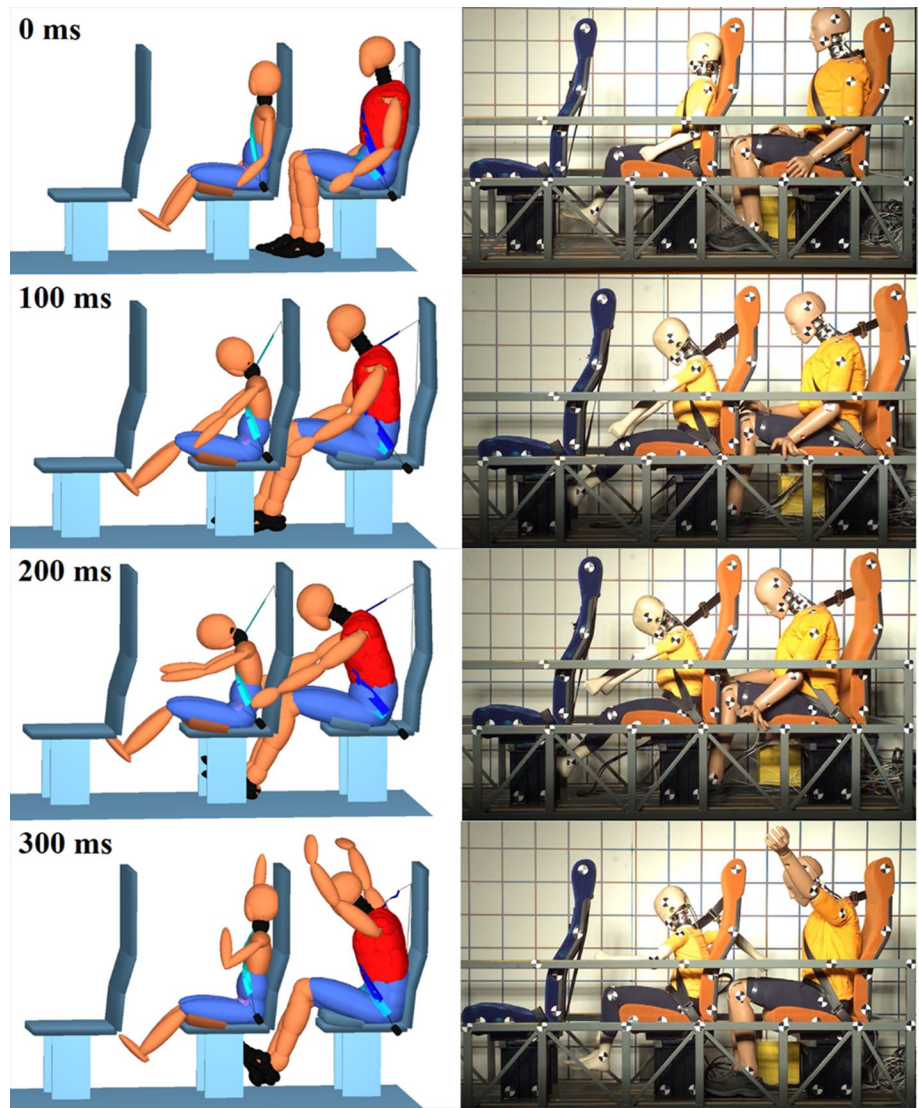
Fig. 12 Kinematics of the dummies

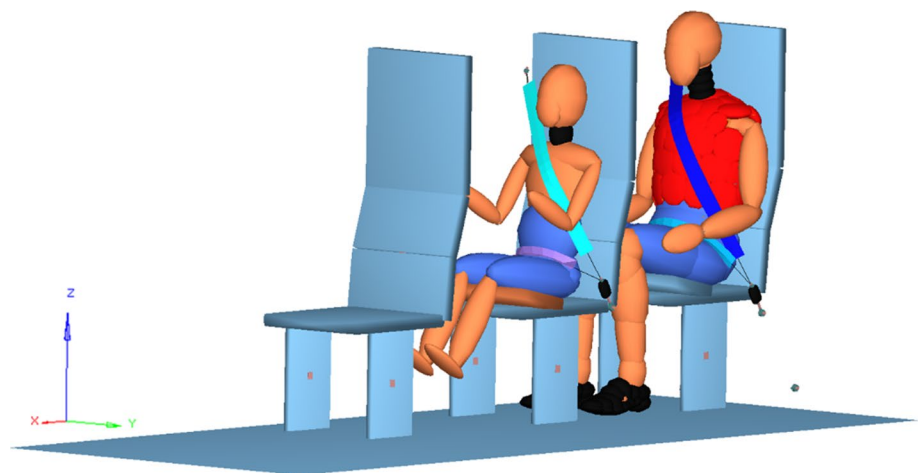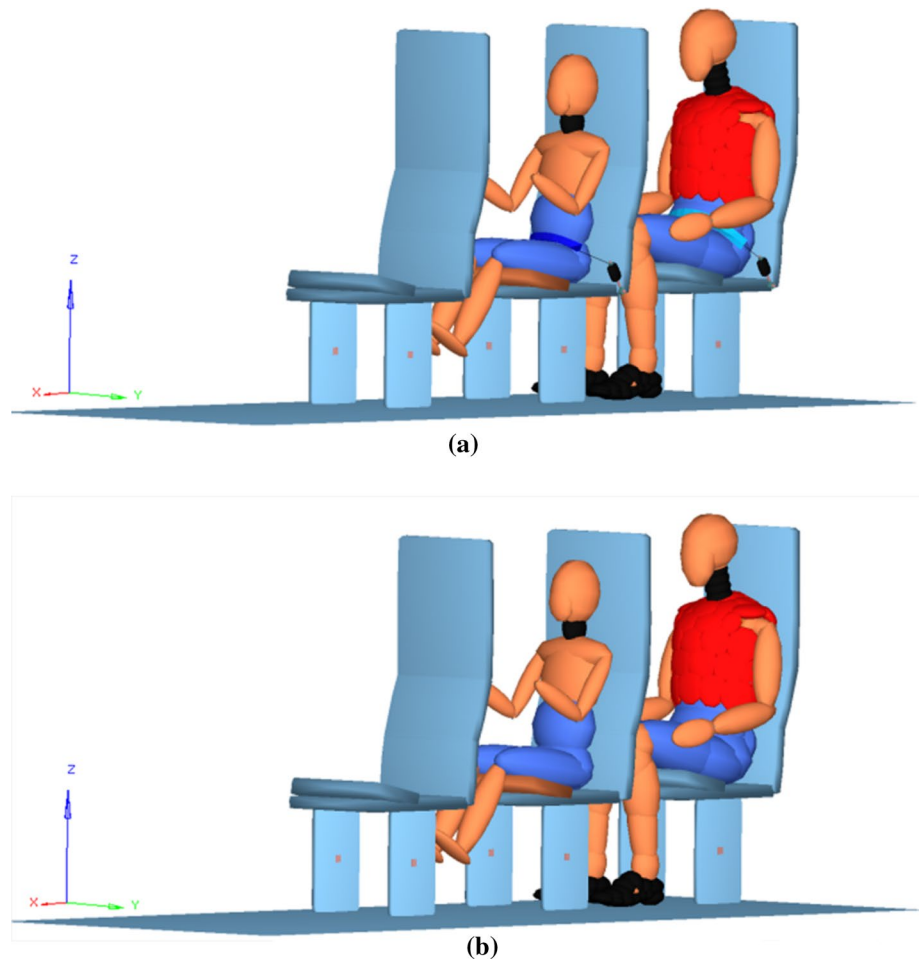**Fig. 13** Computational variant W1—three-point safety belts

Fig. 14 Computational: (**a**) variant W2—two-point safety belts, (**b**) variant W3—no safety belts

(a)

(b)

last variant selected for the analysis, there were no safety belts at all (Fig. 14b).

6.2 Simulation results

On the basis of the conducted numerical simulations, it was possible to verify if the criteria of biomechanical injuries were met for the dummy with measuring instruments, in accordance with the rules no. 80, Supplement 1, determined by the United Nations Economic Commission for Europe. The above-mentioned criteria refer to the following:

K1: forward movement of the dummy's head or any part of its trunk does not occur above the vertical transverse plane located at a height of 1.6 m from point R,

K2: head injury criterion (HIC) is lower than 500,

K3: thorax acceptability criterion (ThAC) is lower than 30 g, except for the intervals lasting shorter than 3 ms ($g = 9.81$ m/s^2),

K4: femur acceptability criterion (FAC) is lower than 10 kN, and value 8 kN is not exceeded in intervals longer than 20 ms.

Table 3 shows the comparison of individual values of the criteria for different variants of simulations (W1, W2, and W3).

Table 3 Criteria values

Criterion	Limit	W1		W2		W3	
		M50	P10	M50	P10	M50	P10
K1 (m)	<1.6	0.26	0.17	0.33	0.39	0.44	0.76
K2 (HIC)	<500	253	101	**2618**	**606**	**9230**	**14,600**
K3 (ThAC) (g)	<30	28	22	**72**	**40**	**63**	**158**
K4 (FAC) (kN)	<10	1.2	0.1	9	0.26	**16**	0.6

Bold values indicate exceeded limits

Apart from the parameters defined in the rules no. 80 by the United Nations Economic Commission for Europe, additional parameters were determined concerning the criteria of neck trauma. They are defined as a maximum tensile force (K5), compressive force (K6) and a maximum moment in relation to axis *Y*. In addition to that, the criterion of thoracic injury was determined, which is defined as the value of the thorax compression (K8—ThCC—thoracic compression criterion) and the criterion of soft tissues injury (K9—VC—viscous criterion). The above-mentioned criteria were not listed in the rules no. 80 determined by the United Nations Economic Commission for Europe and as a result no admissible value limits for such criteria were defined therein. Due to this fact, it was decided to adopt the limits determined in the rules no. 94 by the United Nations Economic Commission for Europe, which refer to the homologation of vehicles with a view to the security and protection of people travelling in/on a vehicle in the case of a frontal impact. The above-named rules apply to the vehicles of M1 category of an admissible total weight under 2.5*t*. Since an old type of dummy P10 was used in experimental tests, the same type was implemented into the numerical model. However, this model of the dummy was not equipped with sensors enabling the determination of the above-mentioned injury criteria. Individual injury criteria are compared in Table 4 below.

On the grounds of the conducted numerical analysis, it was observed that both the system of two-point safety belts (W2) and the variant without safety belts (W3) showed high values of acceleration recorded in the head's gravity centre for both dummies, M50 and P10. In the case of variant W3, acceleration of the head of dummy M50 amounted to 466 g, whereas for dummy P10 it equalled 1160 g. This level of acceleration recorded in the center of gravity of the head gives the risk of injury at AIS level 6 [31, 32]. In variant W2, acceleration of the head of dummy M50 amounted to 321 g, while for dummy P10 it was equal to 76 g. In this calculation variant (W2) for the M50 dummy, the scale of injury also reaches the AIS 6 level, while for the P10 dummy, the acceleration value is within the probability of occurrence of concussion [31]. In the W1 variant, the recorded acceleration

values were respectively for the M50 dummy 45 g and the P10 dummy 27 g. For the recorded acceleration values in the W1 variant, no injuries should occur because these values are below all limits [31]. The obtained acceleration values translate into the values of the head injury criterion (K2). In the case of variant W3, it could be expected that the head injury criterion was going to achieve the highest values, namely it equalled 9230 for dummy M50, whereas it amounted to 14,600 for dummy P10. In variant W2, the values of the head injury criterion also exceeded admissible values and equalled 2618 for dummy M50 and 606 for dummy P10. A similar situation was observed in the case of the thorax acceptability criterion (ThAC). The highest values of the criterion were recorded for variant W3 and equalled 60 g for dummy M50 and 158 g for dummy P10. In variant W2, i.e. for the two-point safety belts, the following values were recorded for the thorax acceptability criterion (ThAC): 72 g in the case of dummy M50 and 40 g in the case of dummy P10. In both W3 and W2 variants, the values of admissible criteria of head injury and thoracic trauma were exceeded in relation to the permissible standard. It was only in the case of variant W1, i.e. three-point safety belts, that all injury criteria were well within admissible standards, both for the criteria defined in the rules no. 80 by the United Nations Economic Commission for Europe and additional criteria which were taken from the rules no. 94 by the United Nations Economic Commission for Europe (see Table 1).

7 Discussion

The computational variants analysed in this work referred to different safety belts systems which are used in vehicles serving the purpose of transporting of more than eight people, excluding the driver. The simulation of a traffic accident was performed in conditions of a frontal impact. Simultaneously, the analysis encompassed dynamic loads exerted on the coach passengers sitting in typical coach seats. On the basis of the results obtained from numerical simulations, it was observed that a type of applied safety belt system

Table 4 Additional values of criteria

Criterion	Limit	W1		W2		W3	
		M50	P10	M50	P10	M50	P10
K5 neck tension	1.1 kN (60 ms) 2.9 kN (35 ms) 3.3 kN (0 ms)	1.56	–	**7.9**	–	**18.8**	–
K6 neck shear	1.1 kN (> 45 ms) 1.5 kN (25–35 ms) 3.1 kN (0 ms)	0.92	–	**15.7**	–	**25.3**	–
K7 neck moment	57 (Nm)	56.7	–	**886**	–	**990**	–
K8 ThCC	42 (mm)	30	–	–	–	–	–
K9 VC	1.0 (m/s)	0.21	–	0.026	–	0.035	–

Bold values indicate exceeded limits

(three-point or two-point one) has a considerable influence on the coach passengers' safety. This fact can be proven by the values of injury criteria, which either come near boundary values or considerably exceed admissible values (W2 and W3). Only in the case of variant W1, i.e. three-point safety belts, all analysed injury criteria are within permissible limits. This project particularly focused on maximum values of loads which affected the dummy's head, neck, and trunk at the moment when the head hit the seatback located in front of the dummy as a result of the coach's frontal impact against an obstacle. The results obtained from modelling and experimental tests undoubtedly show that the use of two-point safety belts is not sufficient. The values of injury criteria for the passengers are in this case similar to the injury criteria values obtained for the simulation without safety belts (W3). This fact was confirmed by high values of acceleration recorded especially in the head's centre of gravity as well as the values of forces and moments recorded in the neck section of the spine. In authors' opinion, only a three-point safety belt system makes it possible that all injury criteria of passengers during a coach frontal impact fall within permissible standards both for the criteria defined in the rules no. 80 and additional criteria in the rules no. 94 determined by the United Nations Economic Commission for Europe. The authors of the publication also see the need to extend the current injury criteria and to include them in the legal norms listed above. On the basis of carried research, it can be seen that taking into account the injury criteria specified in the above-mentioned regulations is insufficient. In future, research authors would like to extend research including impact of rotational acceleration, which largely affects the level of injuries in traffic accidents. The impact of rotational acceleration on the level of injury is raised in many publications, which are presented in the work by Fernandes et al. [31]. The investigations carried out within the scope of this research may contribute to the alteration of legal regulations concerning the provision of coaches with adequate passive safety systems.

Compliance with ethical standards

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