ANALYSIS OF THE INFLUENCE OF THE CAR IMPACT VELOCITY ON THE LOADS OF THE DUMMIES IN THE FRONT AND REAR SEATS

ANALIZA WPŁYWU PRĘDKOŚCI UDERZENIA SAMOCHODU W PRZESZKODĘ NA OBCIĄŻENIA MANEKINÓW NA PRZEDNICH I TYLNYCH FOTELACH

ANDRZEJ ŻUCHOWSKI[1]
Military University of Technology

Summary

It was considered an influence of the velocity, at which the passenger car hits into the obstacle on the dynamic loads of the dummies in the front and back seats. For this purpose, the results of 28 crash tests published on the Internet by the *National Highway Traffic Safety Administration (U.S.A.)* were used. The crash tests of 14 models of the cars were conducted at two values of the impact velocity, at which the cars hits into a barrier (40 and 56 km/h, as well as 48 and 56 km/h). It was shown an influence of the impact velocity on the car deceleration and their deformation specification. It was paid attention to the loads of a driver and a passenger in the front seats (dummies representing a 5-centile men and 5-centile woman) and the passengers in the back seats (dummies representing a 5-centile woman and a 6-year-old child). During an evaluation of the dummy loads were employed the indicators of biomechanical impedance of the human body in respect of the effects of the impact loads related to the head, neck and chest. It was determined that an increase of the velocity at the moment of hitting into an obstacle from 40 km/h up to 56 km/h results in the increase in the risk of serious injury (AIS3+) of the 5-centile woman from 30÷60% to 35÷90%. Increasing the velocity at which a car hits an obstacle from 48 km/h up to 56 km/h results in the increase in the risk of severe injury of the 50-centile woman from 25÷40% to 30÷55%. It was emphasised that the effectiveness of the airbag may depend on the impact velocity, at which car hits the obstacle.

Keywords: road accidents, crash tests, impact speed, loads of dummies, risk of injury

[1] Military University of Technology, Faculty of Mechanical Engineering, ul. Gen. Witolda Urbanowicza 2, 00 908 Warszawa, Poland; e-mail: andrzej.zuchowski@wat.edu.pl

Streszczenie

Rozważono wpływ prędkości uderzenia samochodu osobowego w przeszkodę na obciążenia dynamiczne manekinów na przednich i tylnych fotelach. W tym celu wykorzystano wyniki 28 testów zderzeniowych, udostępnione w Internecie przez *National Highway Traffic Safety Administration (USA)*. Testy zderzeniowe 14 modeli samochodów prowadzone były przy dwóch wartościach prędkości uderzenia samochodu w barierę (40 i 56 km/h oraz 48 i 56 km/h). Pokazano wpływ prędkości zderzenia na opóźnienie samochodów i ich charakterystykę deformacji. Uwagę zwrócono na obciążenia kierowcy i pasażera na przednich fotelach (manekiny reprezentujące 50-centylowego mężczyznę oraz 5-centylową kobietę) oraz pasażerów na tylnych fotelach (manekiny reprezentujące 5-centylową kobietę oraz 6-letnie dziecko). Podczas oceny obciążeń manekinów wykorzystano wskaźniki biomechanicznej odporności ciała człowieka na skutki obciążeń udarowych, dotyczące głowy, szyi i klatki piersiowej. Na ich podstawie określono ryzyko obrażeń osób jadących. Ustalono, że zwiększenie prędkości uderzenia samochodu w przeszkodę z 40 do 56 km/h zwiększa ryzyko poważnych obrażeń (AIS3+) 5-centylowej kobiety z 30÷60% do 35÷90%. Zwiększenie prędkości uderzenia samochodu w przeszkodę z 48 do 56 km/h zwiększa ryzyko poważnych obrażeń 50-centylowego mężczyzny z 25÷40% do 30÷55%. Zwrócono uwagę, że skuteczność działania poduszki gazowej może zależeć od prędkości uderzenia samochodu w przeszkodę.

Słowa kluczowe: wypadki drogowe, testy zderzeniowe, prędkość uderzenia, obciążenia manekinów, ryzyko obrażeń

1. Introduction

A velocity has a significant impact on the risk of a traffic accident and its effects. During a collision occurs a rapid change of the car velocity and the higher the velocity, the most severe injuries are experienced by the accident participants. In the description of the injuries a six-degree scale called AIS (Abbreviated Injury Scale) is often used, where specific kinds of injuries were assigned a certain level, expressed as a number (Table 1). While considering the injuries that include a concerned degree and the higher ones, the AIS3+ notation is used. The MAIS (Maximum AIS) scale is used to describe the condition of the injured with multiple injuries [12]. A correlation between the injury degree and a death risk resulting from those injuries is determined inter alia in [21].

In Poland the persons injured in the traffic accidents are divided into the slightly and severely injured and fatal injuries (a severely injured person is a person who experienced damage to health during a period that lasts for more than 7 days). A share of the fatal injuries was circa of 7.5%, and the severely injured 24.1% among the total number of the injured persons (killed and injured) during the traffic accidents in Poland over the years 2005-2016 [15]. In Table 1 is presented a structure of the injuries of the persons injured in the traffic accidents in the U.S.A. in 2005 [14]. The AIS3+ injuries were taken into account in it although in the traffic accidents prevail the minor and moderate injuries (AIS1 and AIS2). The costs related to the traffic accidents victims are strictly connected with the injury degree. In Table 1 are also specified the relative costs of the wounded victim in the U.S.A. (from the following years: 1994, 2000 and 2010), depending on the injury degree (for a fatality was assumed a value of 100). A unit cost of the victim of the fatal road accident in Poland is approx. 1.5÷2,0 million PLN, of the severely injured person is of 2.21 million PLN, and the slightly injured person - 0.019 million PLN (the unit cost of the fatality is here lower than of the severely injured person) [6, 23]. The more decreased impact velocity, the lower severity of the injuries and thus the costs of the road accident. For instance, in the research papers [1, 16] were estimated the economic benefits resulting from an implementation of the Autonomous Emergency Braking System (AEB) and the Tire Pressure Monitoring System (TPMS) to the cars. A knowledge related to the influence of the impact velocity on the injuries of the persons involved in the accidents is important when you estimate the accident risk (determination of the velocity limits on the roads) and organise the road accident rescue system [2, 18].

Table 1. The injuries in the road accidents and the relative costs of the injured [3, 4, 13, 14]

Degree of injuries	**Severity of injuries**	**Share [%]**	**Relative costs of the injured victim**		
		[14]	**(1994) [3]**	**(2000) [4]**	**(2010) [13]**
AIS1	Minor		0.38	0.31	0.3
AIS2	Moderate		4.68	4.58	4.7
AIS3	Serious	56	16.55	9.16	10.5
AIS4	Severe	23	41.82	21.53	26.6
AIS5	Critical	16	87.91	71.24	59.3
AIS6	Maximum	5	100	100	100

On the basis of the analysis of the data on the traffic accidents, statistical models are developed, making it possible to assess the impact of the impact velocity on the risk of injury of the occupants of the vehicle [2, 16, 18]. For example, in Fig. 1 are determined the models related to the road accidents in the U.S.A. from the years 1994-2000 (those models are a subject of a change as the safety systems are improved in the subsequent car generations). In Fig. 1a are shown the functions describing an influence of the change in car velocity during the collision (*Delta_V*) on the MAIS3+ injury risk during the different types of the collisions (side, frontal and back) [2]. A value of the *Delta_V* decides about a deceleration value during the collision and therefore about a value of the inertia forces, which act on the car and its occupants [19]. The most tragic are the effects of the side impact of the car on the side of the sitting occupants (*Near Side*). For instance, at the *Delta_V*=40 km/h the injury risk MAIS3+ is of 60%. During the frontal and far side collision (the occupants seat on the opposite side of the car) the MAIS3+ risk is approx. 20%. In Fig. 1b are specified the functions that describe an impact of the *Delta_V* on the injury risk of the occupants, from the MAIS2 to the MAIS6 (the different collision types are considered) [16].

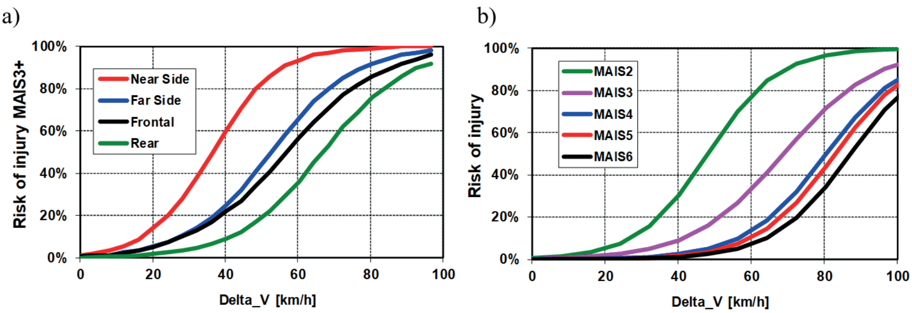

Fig. 1. The influence of the change in car velocity during the collision on the injury risk [2, 16]

In the research paper [19], on the basis of the results of several hundred crash tests [24], the functions that connect the injury risk and the velocity of the car frontal collision with the rigid barrier (cars from the years 2000-2010). On the basis of the head and torso (chest) injuries was determined that an increase of the velocity from 40 km/h to 56 km/h escalates the risk of severe injuries (AIS4+) of a driver and a passenger in the front seats from 4-7% to 8-13%. A goal of this paper is the evaluation of the influence of the car impact velocity upon hitting into the obstacle on the head and torso acceleration, the forces and moments acting on the neck and a chest deflection of the dummies. The analysis considered the loads of the dummies in the front and back seats, showing them in a connection with an operation of the safety belts and the airbag. The goal of this paper is oriented towards an identification of the factors (collision velocity, but also a driver's and passenger's position and the place occupied by them in the car), that decide about the injuries of the participants of the road accident.

2. Selection of the crash tests for the analysis

The evaluation of the influence of the car impact velocity while hitting into the obstacle on the loads of the car occupants was conducted on the basis of the crash tests, published on the Internet by the *National Highway Traffic Safety Administration* (NHTSA, U.S.A.). The results of the tests carried out by the NHTSA were taken in the digital form from [24]. Among the several hundred available crush tests, for the analysis conducted according to the goal of this research paper were selected those, in which the same dummies in the same cars were studies at the different impact velocity into the barrier. The following criteria of the car similarity were taken into account: make and model, bodywork type, manufacturing year, weight and dimensions, engine capacity and position, gearbox type, drive type, seat and dummy arrangement and a tension force of the seat belt pretensioner. As a consequence, the results of the 14 pairs of the new cars from the years 2001-2006 were considered. The above-mentioned cars were summarized in Table 2 according to their bodywork type (hatchback, sedan, van, SUV). The tests related to the frontal collision with the rigid barrier, excluding the T6 and T7 tests, during which the car experienced a collision with the deformable barrier. A difference in the car weights in each pair usually did not exceed 3%, and in the case of two pairs of the cars (T10 and T11) was of 8÷9%. In three other pairs (T8, T9, T14) the cars had different gearboxes (manual, automated) or a number of the drive axles. The similarity of the properties of the frontal crumple zone of the cars was confirmed on the basis of the deformation specifications (compare Fig. 3), drawn up in the manner described in [22].

In the front seats of the cars were the Hybrid III F5 and M50 (the 5-centile woman and the 50-centile man) dummies. The rated values of the car impact velocities upon hitting into the barrier was of 40 and 56 km in the T1÷T7 tests (F5 dummies), and 48 and 56 km/h in the T8÷T14 tests (M50 dummies). The dummies in the front seats were protected by the airbags and their seat belts were fastened (with pretensioners). The belt pretensioners in the respective car models tensioned the belt webbing with a strength from 0.6 kN up to 3.1 kN (compare Fig. 8), whereas in the concerned car pair the values of those both forces were comparable (difference below 10%). In the back seats (on the right and left side – P3 and P4 seats) in the T2 and T5 tests were the 6YO dummies (representing a 6-year-old child), and in the T3, T6 and T7 tests the F5 dummies (in the T3 test, the F5 dummy was only on the seat on the left side). The 6YO dummies were placed in the child safety seats (compare Fig. 10) and fastened with the seat belt (without any pretensioners). The 6YO dummies in the same seats in each car were in the same seats, so the observed differences in loads of the dummies result from a change in impact velocity.

Table 2. The data about the cars and dummies in the front seats (V – impact velocity)

Test no.	V [km/h]	Body type, model year	Weight [kg]	Test no.	V [km/h]	Body type, model year	Weight [kg]
Cars with the F5 dummies				**Cars with the F5 dummies**			
T1	40.3	Hatchback, 2006	1675	T8	47.1	Sedan, 2001	1347
	56.1		1696		56.8		1341
T2	40.3	Sedan, 2005	1752	T9	47.3	Sedan, 2001	1702
	56.5		1758		56.2		1691
T3	40.3	Sedan, 2006	1801	T10	47.8	Sedan, 2004	1794
	56.9		1802		57.1		1635
T4	40.1	Sedan, 2005	2034	T11	47.6	Sedan, 2004	1842
	55.8		2034		56.5		1693
T5	39.0	Van, 2005	2268	T12	47.4	Sedan, 2001	1866
	56.0		2259		56.5		1914
T6*	40.1	SUV, 2005	1771	T13	47.8	SUV, 2003	2301
	56.6		1768		56.2		2271
T7*	40.3	SUV, 2005	1774	T14	47.6	SUV, 2004	2369
	56.5		1774		56.6		2367

* – deformable barrier

The displacements and loads of the dummy during the car collision with the obstacle significantly depend on the initial position of the dummy [9]. Therefore, at the stage of a selection of the crash tests to be analysed it was verified if the dummies in the respective car pairs are similarly arranged in the seats. For this purpose, the distances between the dummy and the car cabin elements marked in Fig. 2 were compared. In the individual car pairs with the F5 dummies the differences of these distances do not exceed 15 mm (tests conducted in the *PMG Technologies*, Canada).

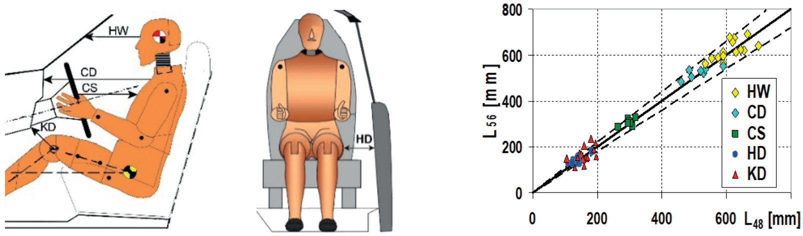

Fig. 2. The dimensions describing a position of the dummy in the car – the dotted lines on the graph determine an interval of ±10% (on the basis of [24])

The crushed test with the M50 dummies were carried out in the different laboratories (in the U.S.A. and Canada), therefore the differences in the arrangement of the M50 dummies during the tests at 48 and 56 km/h are larger than in the case of the F5 dummies. In Fig. 2 were associated the values of the HW, CD, CS, HD and KD distances of the M50 dummies in the cars (in the front seats) studied at 48 km/h (L_{48}) and 56 km/h (L_{56}). The differences between the HW, CD, CS dimensions in the car studied at 48 and 56 km/h were not greater than 10%. The front seats in the cars with the M50 dummies were set in the central position, and the seats with the F5 dummies were shifted forward. As a result, the CS distance of the F5 dummy torso from a steering wheel was lower (183÷270 mm) than the F50 dummy (265÷326 mm). The CS distance is important, e.g. due to effectiveness of the airbag, what will be described further.

3. Influence of the impact velocity on the deceleration of the car and dummies

The severe injuries of a man in the car are usually an effect of the human body impact on the cabin elements. The seat belt and airbag limit the body displacements however they constitute the source of the inertia force, which may cause the dangerous displacements and impacts of the internal organs. They are the more dangerous, the greater car deceleration (acceleration) value and its duration. The increase of the impact velocity of the car upon hitting into the obstacle certainly results in an increase of its deceleration in spite of an increasing deformation of the frontal crumple zone that is a stopping distance. A depth of the deformation of the frontal crumple zone depends also on the car rigidity in the contact site with the obstacle, in that on the arrangement of the assemblies of the drive system and the engine peripherals in the engine compartment, car weight and the obstacle properties [22].

In Figure 3a were given the performances of the car decelerations from the T1 and T6 tests, at the impact velocity upon hitting into the barrier of 40 and 56 km/h (car kinetic energy at 56 km/h is two times greater that at 40 km/h). They are characterized by the dynamic changes of the value, whereby the maximum car deceleration value in the T1 test (hatchback, rigid barrier) at 40 km/h is of 30 g, and at 56 km/h reaches 40 g. In the T6 test (SUV, deformable barrier) it is of 24 g and 35 g, respectively. A duration of the deceleration at both velocity values is similar (deformation phase up to circa 0.07 s and restitution phase is of 0.07÷0.10 s), what confirms that the $Delta\_V$ parameter (Fig. 1) decides about the car deceleration value during the collision. The properties of the crumple zone are usually described by the deformation characteristic, which presents a correlation between the bodywork crushing force and the deformation of the frontal crumple zone [22]. An example from Figure 3b confirms a similarity of the deformation specification of the car pairs in the T1 and T6 tests, so the loads of the dummies were evaluated in the same cars, what is of key importance for the paper goal.

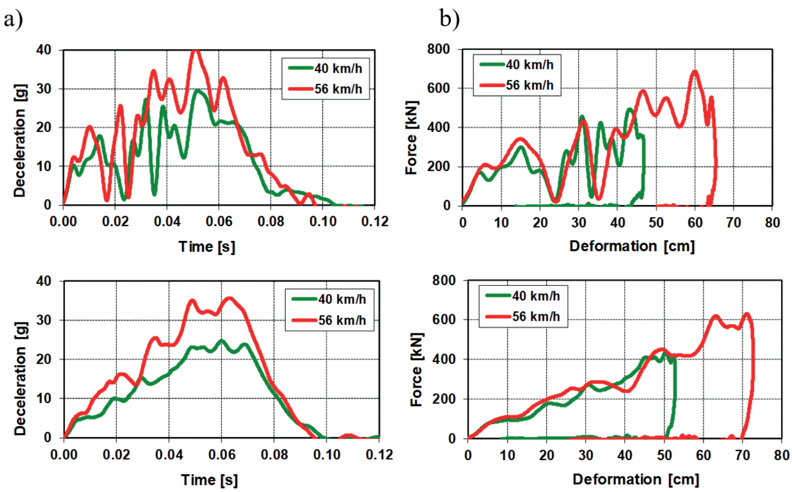

Fig. 3. The performances of the car decelerations and deformation characteristics (T1 and T6 tests)

The deceleration that only partially acts on the occupants (dummies) depends on the car deceleration. An effect of the seat belts and airbag, which restrict a displacement of the body in respect of the car is of a decisive importance. For instance, in Fig. 4 is summarised a performance of the car longitudinal deceleration (acts in a direction of a travel) and an accident deceleration of the head and torso of the dummies (F5) in the driver's seat and in the back seat behind the driver's seat (P4 place), at the impact velocity upon hitting into the barrier of 40 and 56 km/h (T6 tests).

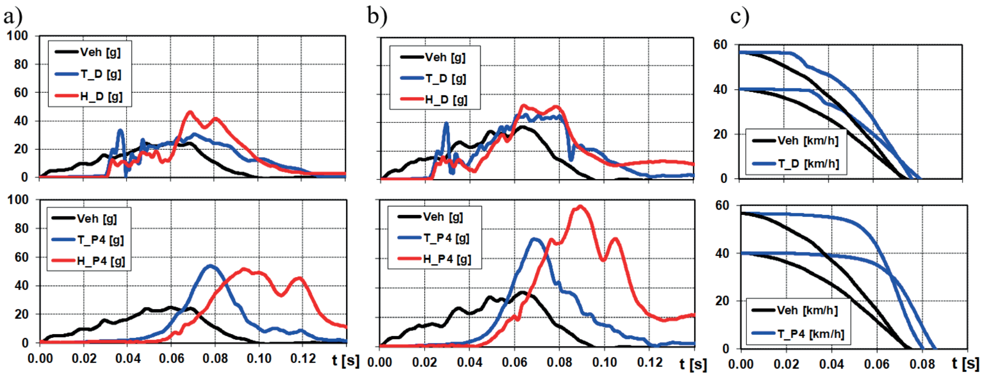

Fig. 4. The performances of the deceleration that acts on the car (Veh), torso (T) and head (H) of the F5 dummy in the driver's seat (D) and in the back seat (P4) in the T6 tests; a) velocity 40 km/h, b) velocity 56 km/h, c) performances of the car velocity and dummy torso

The maximum value of the car velocity ("*Veh*" lines) is significantly lower than the dummy deceleration, in particular in the back seat. It is a delay effect of the seat belt – until the belt webbing is not tensioned, the dummies move in respect of the seats with an initial velocity although the car already decelerates upon hitting into the barrier. This status is illustrated appropriately the performances of the car and dummy torso velocities, shown in Fig. 4c (they were determined by integration of the deceleration performance). The dummy in the driver's seat (D) is here protected by the seat belt with the pretensioners therefore its decelerated motion begins explicitly earlier than the displacement of the dummy in the back seat (P4), where there is no pretensioner.

As a result, the deceleration values of the dummy torso and head in the driver's seat are significantly lower than in case of the dummy in the back seat. In the example given in Fig. 4 an increase of the impact velocity from 40 km/h to 56 km/h (increase by 40%) resulted in an increase of the maximum deceleration value:

- of the car: from 25 g to 37 g (increase by 48%);
- of the torso: of the driver from 33 g to 46 g (increase by 39%), of the P4 passenger from 54 g to 73 g (increase by 35%);
- of the head: of the driver from 46 g to 52 g (increase by 13%), of the P4 passenger from 52 g to 94 g (increase by 81%).

4. Analysis of the injury criteria

In the further conducted evaluation of the influence of the car impact velocity upon hitting into an obstacle on the dummy loads the measurement results of the following parameters were used: head and chest (torso) acceleration, forces and moments of forces acting on the head and a deflection of the chest. The injury criteria were calculated on their basis:

- HIC_{15}, *Head Injury Criterion*, calculated for a time interval of up to 15 ms;
- N_{ij}, *Neck Injury Criterion*;
- C_{Acc}, maximum resultant torso acceleration [g], acting for at least 3 ms;
- C_{max}, maximum thoracic deflection [mm].

HIC_{15} indicator is calculated on the basis of the acceleration of the head and time of the acceleration [5, 11]:

$$HIC_{15} = \max\left[\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} a_G(t)dt\right]^{2,5} \cdot (t_2 - t_1) \tag{1}$$

where:

$a_H(t)$ – resultant acceleration of the centre of the head [g];

$\Delta t = t_2 - t_1$ – length of time [s] with the highest values of $a_H(t)$, $\Delta t \leq 15$ s.

The resultant acceleration of the head and torso was calculated on the basis of the performances, measured in three, mutually perpendicular directions. The values of the N_{ij} criterion were calculated from a correlation [5, 11]:

$$Nij = \frac{F_z}{F_{zc}} + \frac{M_{OCy}}{M_{yc}} \tag{2}$$

where:

F_z, M_{OCy} – axial force (F_T, F_C – tension, compression) and corrected moment of bending the neck towards the axis Oy (M_E, M_F – flexion, extension),

F_{zc}, M_{yc} – critical values of forces F_T and F_C and moments M_E and M_F.

The limit values of the criteria and the loads of the neck from the correlation (2), were specified in Table 3.

Table 3. The limit values of the criteria and the loads of the neck [5, 11, 17]

Dummy	HIC_{15}	N_{ij}	F_T [N]	F_C [N]	M_F [Nm]	M_E [Nm]	C_{Acc} [g]	C_{max} [mm]
M50	700	1,0	6806	6160	310	135	60	63
F5			4287	3880	155	67		52
6YO			3080	2820	96	42		40

The values of HIC_{15}, N_{ij}, C_{Acc} and C_{max} criteria in the impact velocity function were illustrated in Fig. 5. The lines in the graphs connect the points related to the dummies from the concerned car pair studied at two impact velocity upon hitting into the barrier (at the velocity of 40 and 56 km/h during the tests with the F5 and 6YO dummies and at the velocities of 48 and 56 km/h during the tests with the M50 dummies). It was confirmed that the loads of the F5 dummies in the front seats, where are the airbags and the seat belts with the pretensioners, are usually lower than in dummies in the back seats [21] (compare also Fig. 4).

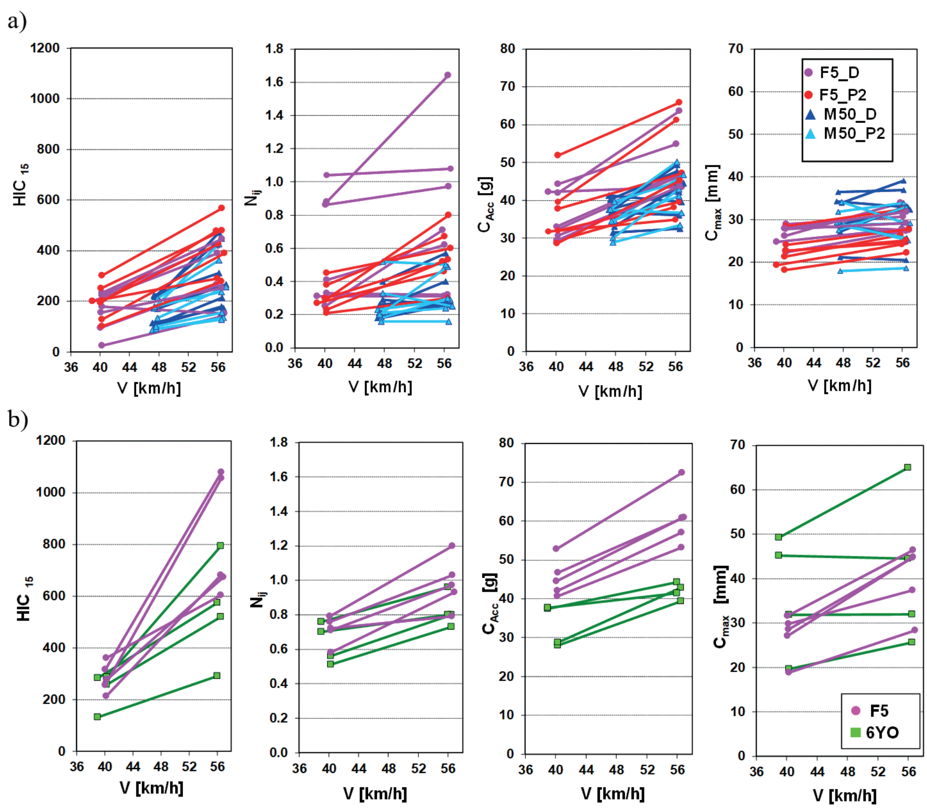

Fig. 5. The values of the injury criteria in the function of the impact velocity;
a) the F5 and M50 dummies in the driver's seat (D) and in the front seat next to the driver (P2)
b) the F5 and 6YO in the back seats

In a majority of the car pairs there are higher values at the greater impact velocity. Referring the values of the injury criteria (Fig. 5) to their limit values (Table 3) it was determined that the limit values of the criteria for the M50 dummies in the front seats were not exceeded in any test. A change of the impact velocity from 48 km/h to 56 km/h in the tests with the M50 dummies had the greater influence on increasing the head load. In the case of the F5 and 6YO dummies, the limit values of the criterion:

- HIC_{15} were exceeded only at the velocity of 56 km/h in the case of three among nine dummies in the back seats (F5 and 6YO);
- N_{ij} were exceeded at the velocity of 40 km/h in the case of one among seven F5 dummies in the driver's seat, and at the velocity of 56 km/h in the case of two among seven F5 dummies in the driver's seat and in the case of two among five F5 dummies in the back seats;

- C_{Acc} were exceeded only at the velocity of 56 km/h in the case of three among nine F5 dummies in the front seats and in the case of three among five F5 dummies in the back seats;
- C_{max} were exceeded both at the velocity of 40 and 56 km/h in the case of two among four 6YO dummies in the back seats.

It captures attention that in some cars the values of the criteria did not increase but decreased at the greater impact velocity. It refers in particular to the chest deflection (C_{max}) of the M50 dummies. The chest deflection results from interacting of the belt webbing and airbag. A value of the pressure force, as well as a place of its application, e.g. an initial arrangement and a manner of the webbing movement in respect of the dummy is also of importance (compare Fig. 10). Furthermore, a specification of the dynamic chest deflection is heavily non-linear. For example, upon loading the chest of the M50 dummy by a force of approx. 4 kN its deflection increases from circa 15 mm up to 35 mm, at the small increase of the pressure force [8].

5. Influence of the impact velocity on a risk of the driver's and passengers' injuries

An evaluation of the relations between an injury severity and values of the mechanical loads that cause the give injuries constitutes an important problem in the injury biomechanics. Thanks to being aware of such relations we have a possibility to connect the results of the crush tests, in which the dummy loads are measures with the injuries, which may occur in humans during the road accident. The risk functions stated in Fig. 6 were used for the risk evaluation. The function of the head injury risk is the same for the M50 and F5 dummies. The function of the neck injury risk is the same for all dummies, because the N_{ij} criterion is calculated while using the limit values of the forces and moments acting on the neck, which are different for the individual dummies (compare Table 3). The function of the chest injury risk due to C_{Acc} is the same for all dummies.

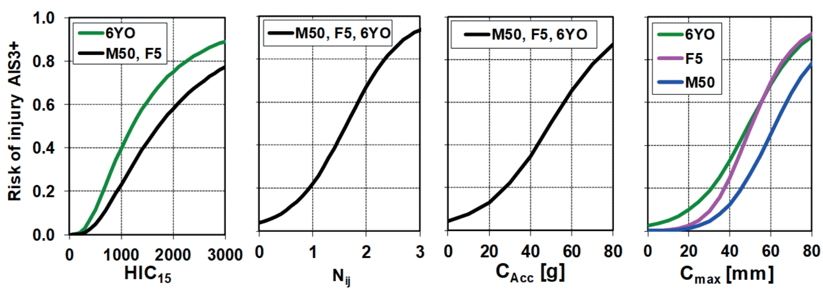

Fig. 6. The functions of the injury risk (AIS3+) of the head, neck and torso of the M50, F5 and 6YO dummies [7, 10]

On the basis of the values of the HIC_{15}, N_{ij}, C_{Acc} and C_{max} criteria (Fig. 5) and the function of the injury risk (Fig. 6), the AIS3+ injury risk of the head, neck and chest, P_{HIC15}, P_{Nij}, P_{CAcc} and P_{Cmax} respectively was calculated. The risk of the driver's head injuries ($PHIC15$) does not exceed 4% and a passenger in the front seat 7%, regardless of the dummy type and impact velocity. The risk of the neck injury ($PNij$) of the M50 dummies is of 5÷11% at both velocity values (48 and 56 km/h). The values of the injury risk of the F5 dummy neck are explicitly higher and are of 6÷24% at the velocity of 40 km/h and 7÷50% at the velocity of 56 km/h. The risk of the chest injury, considering the acceleration ($PCAcc$), is a few times higher than this resulting from a deflection ($PCmax$). In the case of the F5 dummies in the front seats:

- the P_{CAcc} risk is of 21÷41% at the velocity of 40 km/h and 40÷70% at the velocity of 56 km/h;
- the P_{Cmax} risk is of 2÷8% at the velocity of 40 km/h and 3÷14% at the velocity of 56 km/h.

For the M50 dummies in the front seats:

- the P_{CAcc} risk is of 21÷37% at the velocity of 48 km/h and 25÷50% at the velocity of 56 km/h;
- the P_{Cmax} risk is of 1÷9% at the velocity of 48 km/h and 1÷11% at the velocity of 56 km/h.

The injury risk of the passengers in the back seats is higher than in the front seats. The risk of the head injury P_{HIC15} at the velocity of 40 km/h does not exceed 3%, and at the velocity of 56 km/h is of 8÷28%. The risk of the neck injury P_{Nij} is of 10÷16% at the velocity of 40 km/h and 16÷30% at the velocity of 56 km/h. The highest values of the injury risk of the dummies in the back seats relate to the chest. For the F5 dummy, they result from the chest deceleration: PCAcc is of 20÷54% at the velocity of 40 km/h and 34÷80% at the velocity of 56 km/h. In one the tests (T5, 56 km/h) a deflection of the 6YO dummy chest is even of 65 mm, what results in the 76% of the serious injuries.

The risk of death or disability of the person, who experienced multiple injuries is higher than if the injuries related only to one part of the body. It is considered in the P_{Joint} (*Joint Probability of Injury*) indicator, which expresses the total injury risk [7]:

$$P_{\text{Joint}} = 1 - (1 - P_{HIC_{15}}) \cdot (1 - P_{Nij}) \cdot (1 - P_{Chest}) \tag{3}$$

A higher value of the P_{CAcc} and P_{Cmax} (P_{Cmax} was used only in respect of the 6YO dummy, as for the F5 and M50 dummies always was $P_{CAcc} > P_{Cmax}$) was assumed as the chest injury risk P_{Chest}. The results of the calculations of the serious injuries P_{Joint} (AIS3+) in respect of the persons in the front seats (D and P2) in the T1-T14 tests were specified in Fig. 7a, and of the passengers in the back seats (P3 and P4) in Fig. 7b (F5 dummies in the T3, T6 and T7 tests and the 6YO dummy in the tests T2 and T5). The values of the injury risk related to the occupants in the front seats at the impact velocity of 56 km/h are comparable here with the data from the actual road accidents (Fig. 1a).

An influence of the change in car impact velocity upon hitting into the obstacle on the injury risk is different in the respective cars. For instance, an increase of the impact velocity from 40 km/h to 56 km/h increases a risk of the serious injuries (AIS3+) of 5-centile woman in the driver's seat by 3% in the T5 tests, by 18% in the T1, T2, T6 tests and by 36% in the T7 tests. While an increase of the impact velocity from 48 km/h to 56 km/h does not change a risk of the severe injuries of 50-centile men in the driver's seat in the T8, T12, T14 tests and results in an increase of this risk by 15-19% in the T10 and T13 tests.

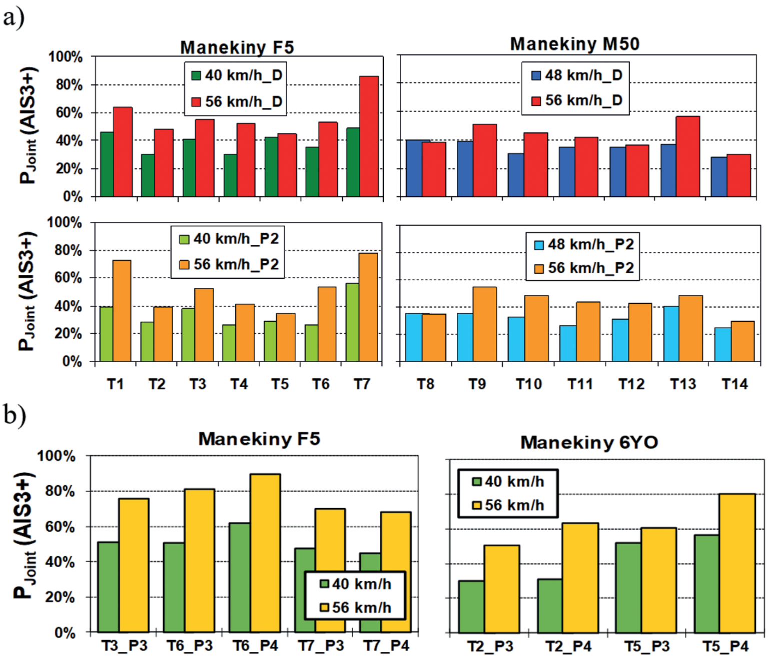

Fig. 7. Influence of the impact velocity on the AIS3+ risk injury;
a) of the driver (D) and the passenger (P2), b) passengers in the back seats (P3 and P4)

6. Influence of the impact velocity on the dummy displacement

A movement of the torso is restricted by the airbag and seat belt, whereby the higher effectiveness of the seat belt, the earlier it is tensioned. In Fig. 8 was given the performances of the webbing tensile force that was tensioned by the pretensioner. At the velocity of 56 km/h the pretensioners tensioned the belt webbing earlier than at 40 km/h as at the higher impact velocity the car reaches quickly a threshold deceleration value used by the pretensioner controller. The different operating time of the pretensioners is visible in particular in the cars from the T6 tests, which hit into the deformable barrier, and the car deceleration increased more slowly than while hitting into the rigid barrier (compare Fig. 3).

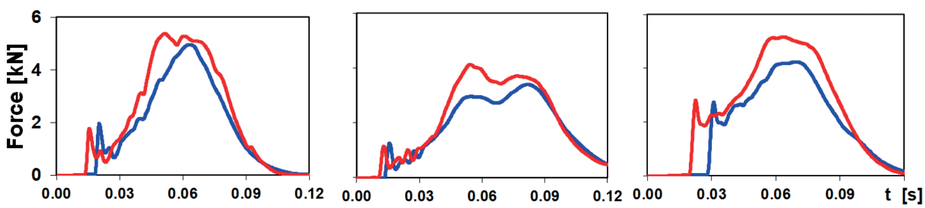

Fig. 8. The performances of the tensile force of the driver's seat belt webbing (the F5 dummy) in the T1, T2 and T6 tests

An important role in shaping the head, neck and torso loads of the dummy plays a velocity of inflating and deflating the airbag. The following parameters are also of importance: a head velocity and its inclination and an airbag inflation status upon a contact with the dummy and a place, in which the head has a contact with the airbag. These factors depend on the dummy size and its arrangement in the seat. An interaction of the airbag on the F5 and M50 dummies is different because the head of the F5 dummy is closer to the steering wheel that the head of the M50 dummy (by circa 100 mm; a seat with the F5 dummy was in the extreme frontal position). Moreover, the heads of the F5 and M50 dummies are at the different height and their weight is of 3.7 kg and 4.5 kg, respectively. The effectiveness of the airbag may also depend on the car impact velocity upon hitting into the obstacle. In Fig. 9 was shown a position of the dummy head (driver) in respect of the airbag in the following phases (from the left):

- a beginning of a contact with the airbag,
- a maximum forward displacement of the head,
- an end of the head contact with the airbag (backward displacement of the head).

The films featuring the tests of the same car model, inter alia, from the T8 test. Figure 9a refers to the M50 at the car impact velocity upon hitting the barrier of 32 and 48 km/h. In both cases the dummy head hits into the inflated airbag although at the velocity of 48 km/h an inflation degree of the airbag upon its contact with the head is lower. A decompression of the airbag at the velocity of 32 km/h begins when the head moves backward towards the seat back. A decompression of the airbag at the velocity of 48 km/h begins already when the head moves forward what mitigates its hit into the airbag. Here it is important that at the maximum forward displacement of the head the airbag is still partially inflated. Figure 9b refers to the F5 dummy at the car impact velocity upon hitting the barrier of 32 and 56 km/h. In both cases the head of the dummy positioned closed to the steering wheel (forward position of the seat) hits in the developing airbag. At the velocity of 32 km/h the head is rejected by the airbag, which is a subject of the very small deformation. At the velocity of 56 km/h the head causes a significant collapse of the airbag, which decompression starts in the end phase of the forward movement of the head.

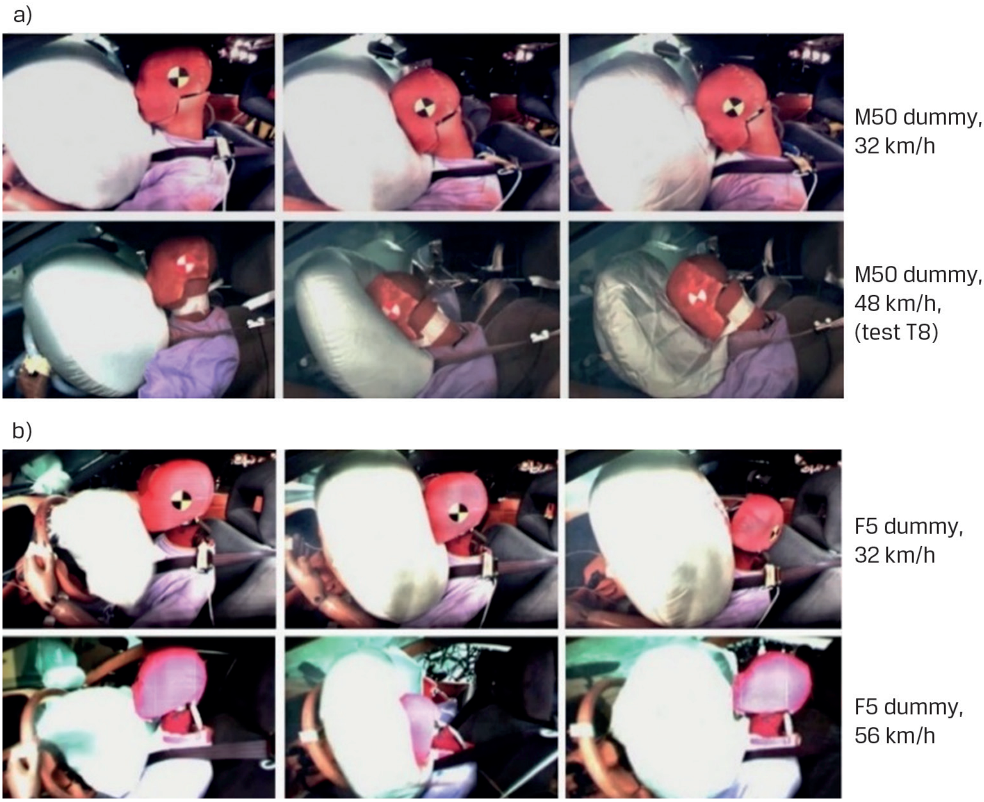

Fig. 9. The displacements of the dummy in respect of the airbag in the same car model (elaborated on the basis of [24]); a) M50 dummy, 32 and 48 km/h; b) F5 dummy, 32 and 56 km/h

The children usually ride in the back seats. The displacements of the dummies in the back seats are not limited by the airbag, and the seat belts feature no pretensioners. The effectiveness of the seat belt depends on the type of the protection device for a child [20]. In Fig. 10 are shown the displacements of the 6YO dummies.

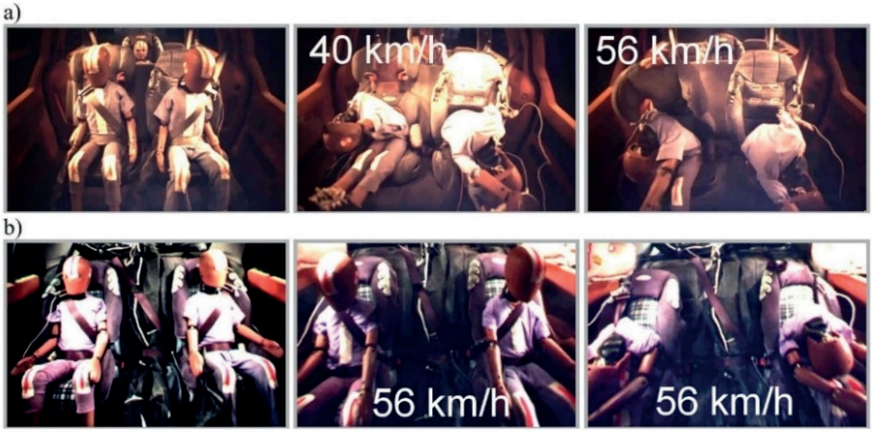

Fig. 10. The displacements of the 6YO dummies in the back seats (elaborated on the basis of [24]); a) cars in the T5 tests (40 and 56 km/h); b) car in the T2 test (56 km/h)

Figure 10a presents the dummies in the cars from the T5 tests just prior to hitting into the barrier and when the head is maximally moved down, at the car impact velocity upon hitting into the barrier of 40 and 56 km/h. Here the dummies are in the different child safety seats however in both cases the belt webbing slides off from the shoulder what allows for a significant displacement of the dummy. As a result, the head of the dummy sitting on the left side hits into the thigh, both during the test at the velocity of 40 km/h, and at 56 km/h. A deflection of the dummy chest is greater here (45÷65 mm) than the permitted deflection determined in Table 3.

In Figure 10b are the dummies in a car from the T2 test during a collision at the velocity of 56 km/h (in order from the left side: before a collision, a beginning of the movement of the dummies and a maximum displacement of the dummies). Both dummies in the same child safety seats. The belt webbing is in the rail provided in the back of the child safety seat and do not slide off from the shoulder onto the arm but slides off from the chest under the neck (middle photography in Fig. 10b). At the velocity of 40 km/h occurred the similar displacements of the dummy and the belt webbing. The deflection of the dummy chest during the T2 tests is significantly lower than during the T5 tests, where the belts slid off downwards the chest, while heavily pressing the ribbons.

7. Summary

The analysis of the results of 28 crush tests (14 car models) enabled to evaluate the influence of the impact velocity on the injury risk related to the occupants in the front and back seats. Three values of the car frontal impact velocities upon hitting the barrier were considered: 40, 48 and 56 km/h, what resulted from the availability of the results of the crush tests [24]. At the higher impact velocity upon hitting into the barrier the frontal crumple zone subjected the greater deformation however the car deceleration value increases.

The maximum value of the latter is significantly lower than a maximum deceleration value of the dummy because a movement of the dummy in respect of the seat result from an operation of the protective safety devices (seat belt and airbag). For instance, in the T6 tests (Fig. 4) a maximum value of the F5 dummy head deceleration in the back seat is circa two times higher than a maximum value of the car deceleration at the impact velocity of 40 km/h and more than 2.5 times higher at the velocity of 56 km/h.

The results of the measurements of the dummy loads were used to calculate the injury indicators, and then the risk of the serious injuries AIS3+. The loads of the torso, regardless of the car impact velocity upon hitting into the obstacle decide about the value of the injury risk P_{Joint}. While generalising the obtained results it was determined that the increase of the car impact velocity upon hitting the obstacle from 40 km/h to 56 km/h increases the risk of the serious injuries AIS3+ of:

- the 5-centile woman in the front seats from 25÷55% to 35÷85%;
- the 5- centile woman in the back seats from 45÷60% to 70÷90%;
- the 6-year-old child in the back seats from 30÷55% to 50÷80%.

The increase of the car impact velocity upon hitting the obstacle from 48 to 56 km/h increases the risk of the severe injuries of the 50-centile man in the front seats from 25÷40% to 30÷55%.

Regardless of the value of the car impact velocity upon hitting the barrier you may notice an improper functioning of the seat belt, that maintains a position of the 6YO dummy in the child safety seat in both models of the studied cars. The seat belts slide off from the shoulder onto the arm (in the T2 tests) or under the neck (in the T5 tests). It was also paid attention that the effectiveness of the airbag while protecting a 5-centile woman may depend on the car impact velocity upon hitting the obstacle. When the head hits into the airbag too early it may result in the significant load of the head and the neck.

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

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

References

[1] Anderson R, Doecke S, Mackenzie J, Ponte G. Potential Benefits of Autonomous Emergency Braking Based on In-Depth Crash Reconstruction and Simulation. The 23th International Technical Conference on the Enhanced Safety of Vehicles (ESV). Paper Number 13-0152. Seoul 2013.

[2] Augenstein J, Perdeck E, Stratton J, Lehman W, Digges K, Bahouth G. Characteristics of Crashes that Increase the Risk of Serious Injuries. 47th Annual Proceedings Association for the Advancement of Automotive Medicinel. Lisbon, 2003: pp. 561-576.

[3] Blincoe L, J. The economic cost of motor vehicle crashes 1994. NHTSA Technical Report DOT HS 808 425, USA 1996.

[4] Blincoe L, Seay A, Zaloshnja E, Miller T R, Romano E, Luchter S, Spicer R. The Economic Impact of Motor Vehicle Crashes 2000, NHTSA Technical Report DOT HS 809 446. Washington 2002.

[5] Cichos D, Otto M, Zölsch S, Clausnitzer S, Vetter D, Pfeiffer G, de Vogel D, Schaar O. Crash analysis criteria description. Arbeitskreis Messdatenverarbeitung Fahrzeugsicherheit. Germany 2011.

[6] Jaździk-Osmólska A et al. Metodologia i wycena kosztów wypadków drogowych na sieci dróg w Polsce na koniec roku 2011. Instytut Badawczy Dróg i Mostów. Warszawa 2012.

[7] New Car Assessment Program. National Highway Traffic Safety Administration (NHTSA), Federal Register Vol. 73, No. 134. USA 2008.

[8] Nusholtz G, Xu L, Berliner J. Evaluation of the Hybrid III 10-year-old Dummy Chest Response in the Sled Test Environment. SAE 2010-01-0137, 2010.

[9] Prochowski L, Żuchowski A. Analysis of the influence of passenger position in a car on a risk of injuries during a car accident. Eksploatacja i Niezawodnosc-Maintenance and Reliability 2014; 16(3): 360-366.

[10] Proposed Amendment to FMVSS No 213 Frontal Test Procedure, NHTSA, USA, 2002.

[11] SAE J1727, Calculation Guidelines for Impact Testing, 2010.

[12] Schmitt K U, Niederer P F, Muser M H, Walz F. Trauma biomechanics. Accidental injury in traffic and sports. Springer-Verlag Berlin Heidelberg 2010.

[13] Spicer R S, Miller T R. Uncertainty Analysis of Quality Adjusted Life Years Lost. Final Report to the National Highway Traffic Safety Administration. Pacific Institute for Research and Evaluation, 2010.

[14] Stitzel J D, Kilgo P, Schmotzer B, Gabler H C, Meredith J W, A Population-Based Comparison of Ciren and NASS Cases Using Similarity Scoring. 51st Annual Proceedings Association for the Advancement of Automotive Medicine. Melbourne, 2007.

[15] Symon E. Wypadki drogowe w Polsce (2001-2017); (http://statystyka.policja.pl).

[16] Tire Pressure Monitoring System FMVSS No. 138 – Final Regulatory Impact Analysis, U.S Department of Transportation. Washington, 2005.

[17] U.S. Department of Transportation NHTSA, Laboratory Test Procedure, TP208-14, 2008.

[18] Wicher J. Is it worth limiting the travel speed? The Archives of Automotive Engineering 2015; 69(4): 105-114.

[19] Żuchowski A. Analysis of the influence of the impact speed on the risk of injury of the driver and front passenger of a passenger car. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2016; 18 (3): 436–444, http://dx.doi.org/10.17531/ein.2016.3.16.

[20] Żuchowski A. Influence of the type of a child restraint system used on the kinematics and loads of a child in a motorcar during a frontal impact. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2013; 61(3): 65-79.

[21] Żuchowski A. Risk of injury for the front and rear seat passengers of the passenger cars in frontal impact. Journal of KONES Powertrain and Transport 2012; 19(3): 507-518.

[22] Żuchowski A. The use of energy methods at the calculation of vehicle impact velocity. The Archives of Automotive Engineering 2015; 68(2): 85-111.

[23] Żukowska J, Piskorz K, Radzikowski T. Stan bezpieczeństwa ruchu drogowego oraz działania realizowane w tym zakresie w 2014 r. Krajowa Rada BRD, Warszawa 2015.

[24] National Highway Traffic Safety Administration [cited 01 Mar 2018]. Available from www.nhtsa.gov.