THE ANALYSIS OF SAFETY OF REAR SEAT OCCUPANTS OF A PASSENGER CAR DURING THE ROAD ACCIDENT

ANDRZEJ ŻUCHOWSKI[1], LEON PROCHOWSKI

Summary

The test results indicate that in many structural solutions of the passenger cars, dynamic loads of the rear seat passengers can be significantly higher compared to the front seat passengers, so the risk of injuries is higher for them. The work specifies examples of courses of dynamic loads that occur during the frontal collision with an obstacle and that affect the front seat and the rear seat passengers. At the same time, the attention is paid to relations between a seat occupied in a car and the probability of injuries in various road accidents.

The analysis of dynamic loads that affect the rear seat passengers in many cars has been carried out. In order to do that, the laboratory test (crash test) results have been used. Dynamic loads affecting the passengers of various anthropometrical features have been considered. The results of those analyses have been referred to the loads affecting a driver and a front seat passenger, that is the persons who drive a car and are protected by typical passive safety systems on the front seats. The indexes of biomechanical human body resistance to impact load results have been used during the evaluation.

Keywords: transport, road safety, vehicle safety, crash tests, rear seat occupant

1. Introduction

In critical road situations, human life and injuries are determined by the equipment of the individual protection system installed in a car, as seat belts, airbags, head restraints, seats and child seats. Efficiency of operation of that equipment depends on many factors that are usually hard to consider at the design stage, e.g. passenger's weight and height, seat occupant's position, seat adjustment and steering wheel condition, direction of impact.

The safety of the car occupants on the second and the third row seats in the passenger cars has been treated as a secondary issue so far. The achieved stage of the structure of that equipment for the rear seat occupants makes an important confirmation of that state.

[1] Military University of Technology, Department of Mechanical Engineering, e-mail: azuchowski@wat.edu.pl, tel. 22 683 74 54

Usually there is no adjustment of the seat belt fixing point position, seat belt tensioners, seat adjustment. Safety approvals for motor vehicles within a scope of protection of the car occupants during front and side collisions (Directive 96/79/WE and 96/27/WE of the European Parliament and Council) refer only to the front seat occupants.

The purpose of this work is to compare dynamic loads affecting the occupants of the second and the third row seats with the loads affecting a driver and a front seat passenger during the road accident. Actuality of this work results from several important aspects:

- the increasing number of seats in the passenger cars, from 4-5 to 5-7 or even more;
- the third row of the seats has appeared, usually in the cargo area;
- the safety equipment for the second and the third seat row is usually worse than for the first row of the seats.

This paper has carried out the analysis of the results of measurements made during the crash tests [8]. Analyzed results refer to the frontal collision of a car with a rigid flat barrier, placed perpendicularly to the direction of the car motion.

The test results indicate that in many passenger cars dynamic loads of the rear seat occupants can be significantly higher than of the front seat occupants so the risk of injuries is much higher for them [3,6,7,9].

2. Static characteristics of the road accident victims in the passenger cars

The majority of the passenger cars is used only by the drivers. The data about the number of other occupants in the passenger cars is published rarely. In the studies carried out in Cracow in the 90's, it was found that a average occupation of cars in the city traffic when commuting to work amounts to 1.4 – 1.7 persons per car [2]. On the basis of detailed data on the road accidents in Japan during 1995-2000, this paper [7] presents the following structure of occupation in over 530 thousand cars:

- 84,6 % only a driver,
- 11,7% a driver +1 passenger,
- 2,5% a driver +2 passengers,
- 0,6% a driver +3 passengers,
- 0,1% a driver +4 passengers.

The data indicates that the rear seat occupants make only about 3% of a total number of people in the passenger cars. Similar results are presented on figure 1. The figure shows the results of the measurement of passenger presence in the rear seats compared to the front seat occupants [6]. A driver is excluded from the seat occupancy frequency calculations.

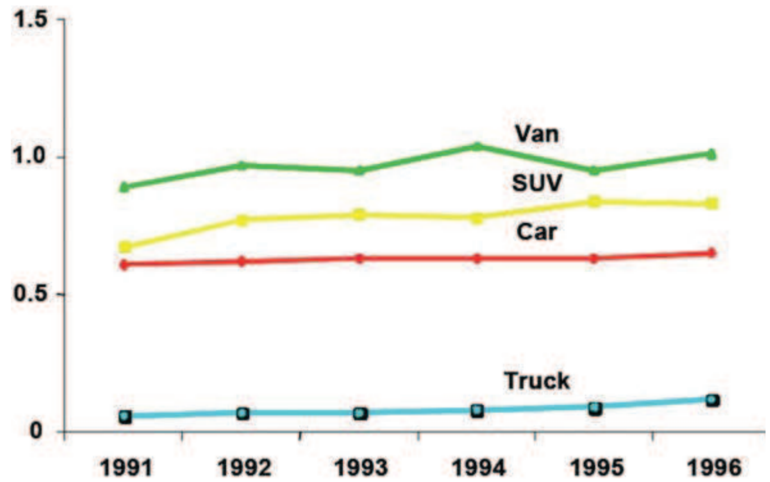


Fig.1. The rear seat occupant share compared to the front seat occupants (excluding a driver) in various types of cars [6].

The structure of the road accident victims involving the passenger cars in Poland is given in table 1. The data concerning the victims among the drivers, the front seat occupants and the rear seat occupants are given separately. Victims among the passengers include children, however the available statistical data do not include the information in what type of vehicle a child passenger was injured in the road accident.

Table 1. The structure of the road accident victims in Poland involving the passenger cars (p.v.) [4].

Year	Total		p.v. driver		p.v. passenger – front		p.v. passenger – rear		Passenger - child*	
	Killed	Injured	Killed	Injured	Killed	Injured	Killed	Injured	Killed	Injured
2007	5583	63224	1517	18355	882	15057	183	2 668	-	-
2008	5437	62097	1465	17469	904	15097	171	2 549	81	2591
2009	4572	56046	1334	16030	702	13554	143	2 291	60	2319
2010	3907	48952	1125	14033	595	11684	133	1 872	60	2115

*) children 0-14 years old are included as occupants of the passenger cars and other vehicles.

On the basis of the data from table 1, figure 2 shows the share of drivers and passengers of the passenger cars in a total number of the road accident victims during 2007-2010. Fatal victims made 46…48 % and injured victims made 56…57 %, including:

- drivers 27…29 % fatal and 28…29 % injured victims;
- front seat passenger 15…17 % fatal and 23…24 % injured victims;
- rear seat passengers 3 % fatal and 4 % injured victims.

The rear seat passengers made:

- 6,6...7,2% fatal victims and 6,8...7,4% injured victims among the passenger car victims (driver + passengers);
- 15,9..18,3% fatal and 13,8...15,1% injured victims among the passengers (excluding drivers).

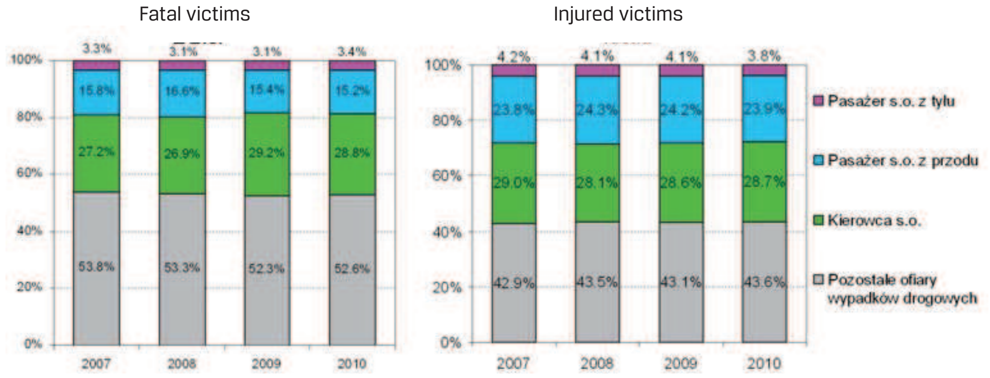


Fig.2. Passenger car occupant share in a total number of road accident victims during 2007-2010.

Figure 3a shows the statistical data on the road accident victims in the passenger cars (people of age over 13). It also presents the position of those victims in a car. Very interesting information results from a combination of seat occupancy frequency and the statistics of the victims in the passenger cars, as shown on figure 3b [6]. Columns on figure 3b show the quotient of victims with severe injuries (MAIS 3+) against a number of occupants on particular seats during an accident. It indicates an unfavourable situation of rear seat occupants in a passenger car.

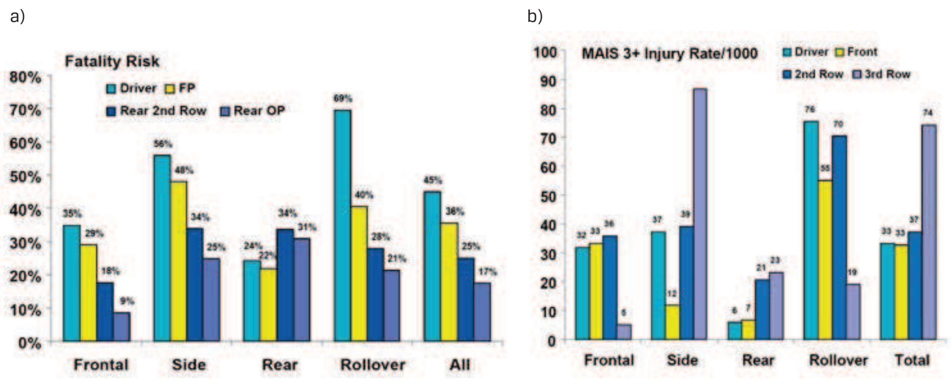


Fig.3. Statistical data on the road accident victims in the passenger cars (FARS 1991-1999) [6].

When completing this information, it is worth mentioning that a constant increase of the automotive industry development index (number of passenger cars per 1000 inhabitants) indicates decreasing number of people per one car (table 2). The number was reduced from 15 in 1980 to 2.25 in 2010.

Table 2. Automotive industry development index in Poland [4,5].

Year	1980	1990	2000	2005	2010
Number of inhabitants (thousand)	35 735	38 183	38 644	38 157	38 187
Number of passenger cars (thousand)	2 383	5 261	9 991	12 339	16 990
Automotive industry development index	67	138	259	323	445
Number of people per one passenger car	15,00	7,26	3,87	3,09	2,25

3. Arrangement of car occupants and the scope of analysis

Main factors affecting the injuries of occupants on the particular rows of the seats are as follows:

- availability of individual protection means on the first seat row and the next seat rows;
- position of car occupants and the available space on those seats.

The influence of those factors on the injuries of car occupants, regardless of the seat occupied by them in a particular row of seats, has been considered. Figure 4 shows the car seat designation that will be used in the following part of this paper.

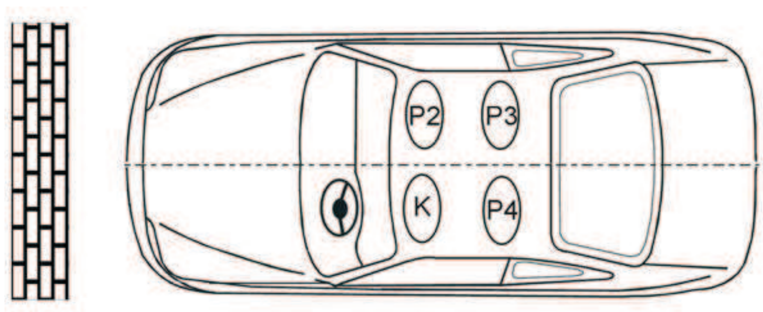


Fig.4. Car seat designation.

Considering the factors determining the injuries and the crash test results, the further analysis uses the results of measurement of dynamic loads applied on the head, torso and pelvis, courses of forces in the legs and the neck as well as the results of measurement of forces in the seat belts. The examples of the courses of those physical values are shown on figure 5. They were obtained during a frontal car collision with a rigid obstacle at the speed of 56 km/h. A dummy (F5 – 5-centile female) was placed on a driver's seat, on a passenger's seat next to a driver's seat (P2) and the right rear seat (P3). The following executions were specified in the following diagrams:

- head, torso and pelvis resultant delay;
- resultant force affecting the neck;
- chest (torso) deflection;
- forces affecting the thigh bones.

Resultant delay and force values were calculated on the basis of components measured in three mutually perpendicular directions (x,y,z):

$$a(t) = \sqrt{a_x^2(t) + a_y^2(t) + a_z^2(t)} \ , \qquad F(t) = \sqrt{F_x^2(t) + F_y^2(t) + F_z^2(t)} \ .$$

Direct comparison of executions indicates significantly higher loads affecting the P3 dummy compared to the similar loads observed on the K and P2 dummies. For example, on the basis of figure 5, the P3 passenger's head load criterion amounts to HIC=1140 (fatal injury), however that criterion for a driver and the P2 passenger amounts to HIC=280 and 331 respectively. The above values confirm that there are situations where the threat of life is much higher for the rear seat occupant than for the front seat occupants.

The values measured during the crash tests were used to define two types of numerical criteria:

$$W1 = \frac{P2\ passenger\ load}{driver\ load} \ ,$$

$$W1 = \frac{P3\ or\ P4\ passenger\ load}{P2\ passenger\ load}$$

Those criteria will be applied for the results of the experiments where two dummies, with comparable antropometrical features, were placed on particular seats. It is worth mentioning that the index product always gives supplementary information and at the same time in accordance with the purpose of the analysis.

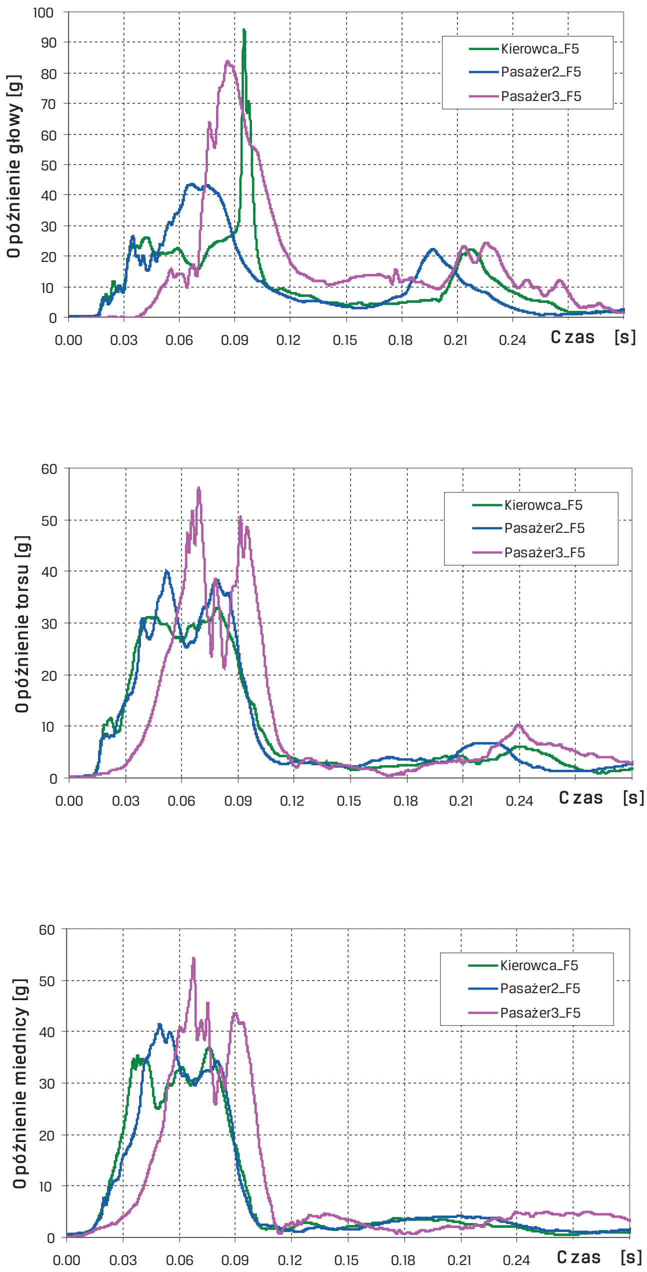
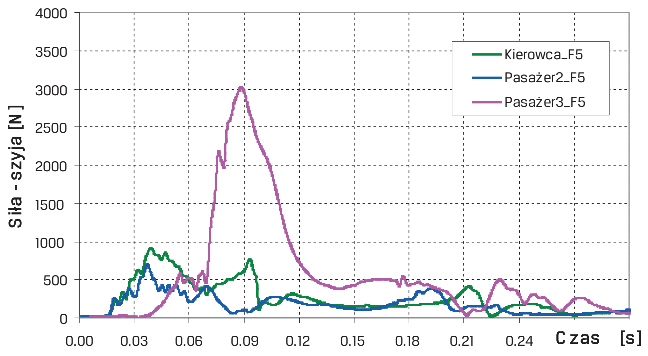
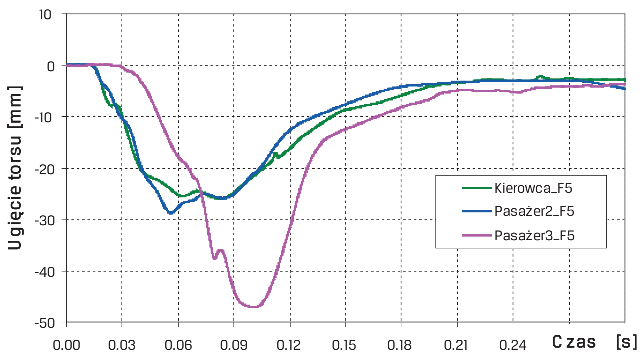


Fig.5. Courses of dynamic loads applied on the F5 dummy's head, neck, torso, pelvis and legs during frontal collision with a rigid obstacle (2004 four-door sedan, weight of 1654 kg).





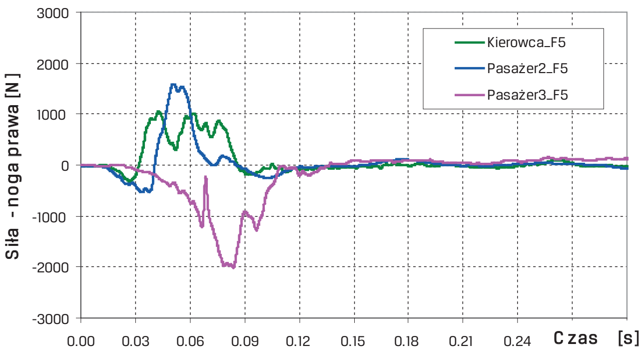


Fig.5. Courses of dynamic loads applied on the F5 dummy's head, neck, torso, pelvis and legs during frontal collision with a rigid obstacle (2004 four-door sedan, weight of 1654 kg). (cont.)

During a detailed evaluation of dynamic loads affecting the rear seat occupants, the criteria an values referring to the biomechanical resistance of a human body to the results of the impact loads, namely:

- HIC - Head Injury Criterion;
- Nij – Neck Injury Criterion;
- maximum neck stretching and pressing force;
- maximum torso delay;
- maximum chest (torso) deflection;
- VC – Viscous Criterion);
- maximum force affecting the tight bone;
- maximum seat belt stretching force.

4. The analysis of the state of passenger protection equipment on the further seat rows

A driver (K) and a passenger sitting next to a driver (P2) are protected (against the results of the frontal impact) by means of seat belts with tensioners and limiters and the airbags. These elements are permanently improved. The rear seat occupants (P3 and P4) are usually equipped only with the seat belts without tensioners and limiters. The airbag significantly reduces the occupant displacement against the seat and reduces the dynamic loads that result in injuries. However, the passenger displacement on the rear seats is high. The example of such displacement is shown on figure 6.

Fig.6. F5 dummy displacement on the P3 seat during frontal collision of a car with a rigid flat barrier at the speed of 56 km/h [8].

The lack of seat belt tensioners and limiters in the rear seats significantly reduces the possibility of protecting the rear seat occupants against injuries. This is reflected by the results of the work [9], where the Hybrid-III (50-centile male) dummy was tested on the rear car seat with application of various individual protection means (no airbag):
A – seat belt without a tensioner and limiter;
B – seat belt with a tensioner and limiter;
C – seat belt with a tensioner and limiter.

The measurement results presented in table 3 clearly confirm that there is a possibility of reducing the loads affecting the head, the torso and the neck by development of individual protection equipment.

Table 3. Extreme values of the loads affecting a passenger (description in the text) [9].

	Value	A	B	C	A/C [%]	B/C [%]
Head	HIC36	888	663	458	194	145
	Delay [g]	73,0	67,3	57,3	127	117
Neck	Force Fx [kN]	1,64	1,53	1,14	144	134
	Force Fz [kN]	2,75	2,49	2,24	123	111
	Moment span My [Nm]	218	181	174	125	104
Torso	Deflection [mm]	61	50	37	165	135
	Delay [g]	60,8	54,6	56,7	107	96
	VC [m/s]	0,95	0,55	0,28	339	196
Seat belt	Force – arm section [kN]	10,8	10,0	5,9	183	169
	Force – hip section [kN]	11,4	11,1	10,4	110	107

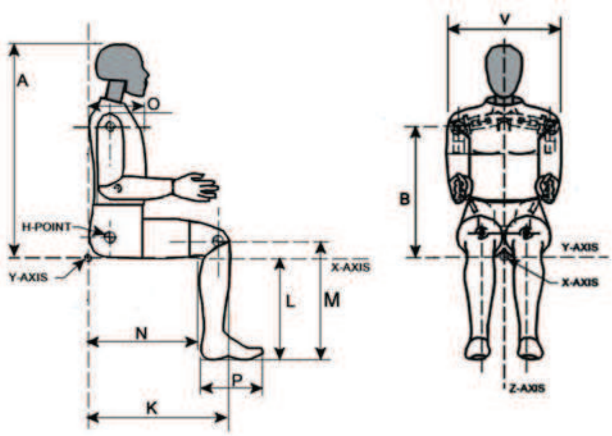
The seat belt tensioners and limiters successfully reduce the risk of passenger injuries during the road accident. Two last columns in table 3 clearly indicate a possibility of improvement of the safety conditions for the rear seat occupants. The work [10] states that the head and torso dynamic loads are clearly lower in the cars where the seat belts with tensioners and limiters are installed: the HIC index is reduced by 20–40%, the maximum torso acceleration is reduced by 10–20%.

5. Car interior dimensions and their influence on the passenger safety

The occupant body position on a seat and resulting distance between the head, the torso, the legs and the car components makes an important factor which affects the injuries during the road accident. These factors are conditioned by the anthropometrical human features and the car interior dimensions.

Several characteristic values, describing the anthropometrical features of a human being are shown on figure 7, where some dimensions of the Hybrid III dummies are given: M50 (50-centile male) an F5 (5-centile female).

The car interior dimensions and a possibility of the seat position adjustment (usually only the front ones) provide many various possibilities of positioning the body on the seat. For example, figure 8 shows the position of the M50 and F5 dummy's legs in a car. Calculations



Marking	M50	F5
A	884	787
B	513	445
K	592	533
L	442	366
M	493	470
N	465	427
O	221	183
P	259	226
V	429	358

Fig.7. Dimensions of the Hybrid III dummy [mm] [1].

were made for h=20, 25 and 30 cm (h – height of point H of the dummy above the floor) and the seat inclination angle χ =15, 25 and 30 degrees. Leg position angle and the place of the leg rest on the floor affect the kinematics of the human body motion during the road accident, and first of all on the displacement of the hips and the torso against the seat of the dummy fastened with the seat belts.

Figure 9 shows characteristic dimensions of the space available for the car passengers (the drier and the rear seat occupant). Driver's position in a car mostly results from the arrangement of the steering elements (fig. 9a). However the position of the rear seat

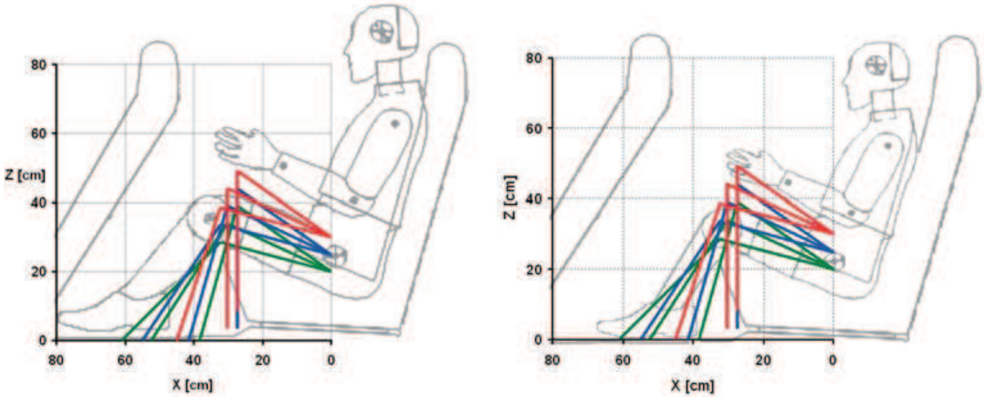


Fig.8. Position of the M50 (left) an the F5 (right) dummy's legs on the rear seat.

passengers is limited by the seat dimensions and its position against the floor (height and inclination angle), backrest inclination angle and the distance to the front seats. In some cars (e.g. SUV, pickup) the space for the rear seat occupants is significantly reduced and forces the passengers to take the upright position. As a result, the centre of the human body weight is located higher than in case of a typical position in a passenger car.

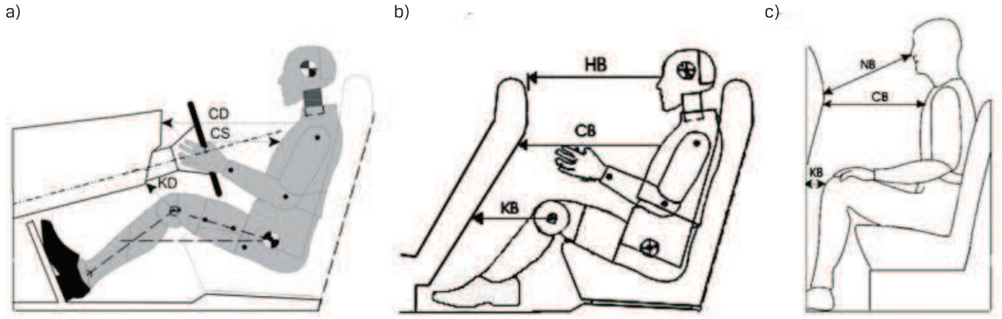


Fig.9. Dimensions of the space available for the seat occupants in a car
a – driver's position, b, c – the rear seat occupant's position.

Figure 10 shows the comparison of the distance CB of the passengers P3 (or P4) with the distance CD of the passenger P2. The specification includes the situation when the dummies of the same size (M50 or F5) were placed on the front and the rear seats of a car. Obviously the higher space for the rear seat passengers can be obtained where only two F5 dummies are placed in a car. Considering the dimensions of the dummies (fig.7) and dimensions of the space available for the rear seat passengers (fig. 9), we can come to a conclusion that there is a possibility that the head or the knees can hit the back part of the front seats. The tension of the seat belts, that should successfully keep the passenger on the seat, is of high significance in such case.

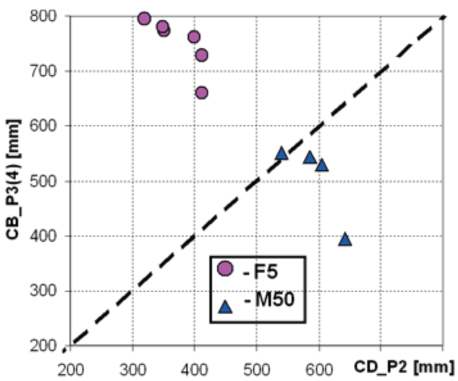


Fig.10. Association of the distance CB of the passengers P3 (or P4) with the distance CD of the passenger P2.

6. Examples of the comparative test results

The loads affecting the driver and the passengers P2, P3 and P4 were compared on the basis of the available car crash tests results (frontal collision). The tests were chosen where the passenger dummy placed on the "i" seat was the same as the driver's dummy and fastened with the seat belts. The airbags for the driver and the passenger P2 were installed in all cars. The tests for the cars, weight: 1500-2700 kg, manufactured during 2004-2006 were used.

The results of W1 and W2 index calculations are presented on figures 11...15. The W2 index calculations include the passengers P3 and P4. The continuous lines W1=1 and W2=1 divide the calculation results on those figures into four areas:

- G1: P2 passenger load 〈 than the driver's and P3(4) 〉 P2;
- G2: P2 passenger load 〉 than the driver's and P3(4) 〉 P2;
- G3: P2 passenger load 〈 than the driver's and P3(4) 〈 P2;
- G4: P2 passenger load 〉 than the driver's and P3 P3(4) 〈 P2.

In the majority of cars, the results from the areas G1 and G2 dominate, regardless of the value used for the calculation of W1 and W2 indexes. So the collected results lead to the following conclusions:

1. The head protection level is clearly the highest for the driver. The load affecting the head of the passenger P2 is often 1.5 times higher than for the driver and the loads of the heads P3 and P4 are 1.5-2.5 times higher than P2).

2. The loads affecting the chest are the lowest for the passenger P2. In case of passengers P3 and P4, the chest deflection is 1.5-2.5 times higher than for P2, so the VC index is higher.

3. The passengers P3 and P4 are particularly exposed to the neck injuries. The values of the Nij index and the neck stretching force are much higher than the load affecting the driver and the passenger P2. It results from the lack of the equipment that can reduce the head displacement (airbags) for the second and the third seat row occupants.

4. The loads affecting the legs on the rear seats are usually lower than on the front seats. The legs of the passengers P3 and P4, due to their positions (usually different than position of the driver's legs and the P2 passenger's legs), usually do not touch the backrest of the front seats and the axial squeezing forces in their thigh bones are not high. However, in such case the legs do not support the operation of the seat belts in order to keep a passenger in the seat.

5. The forces affecting the seat belts on the rear seats are 1.5-2.5 times higher than on the front seats. In case of the arm section, equipped with a tension force limiter on the front seats, we have W2×5. The forces affecting the seat belt of the passenger P2 are not higher than for a driver and they are comparable in the hip section.

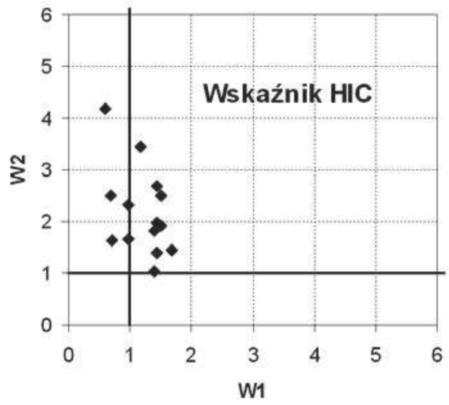


Fig.11. Association of W1 and W2 indexes – head load.

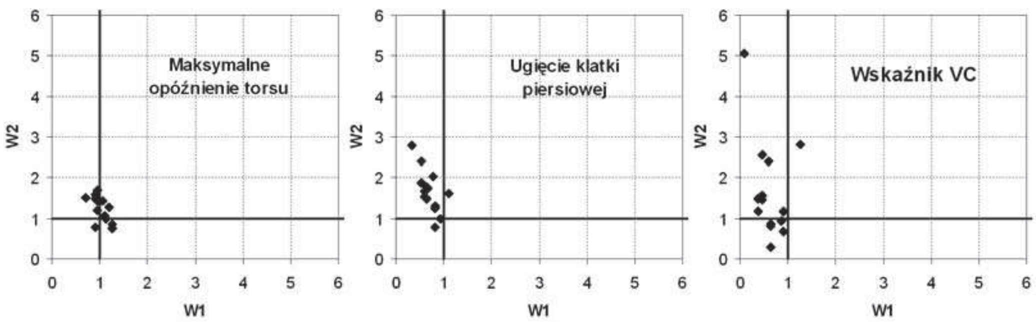


Fig.12. Association of W1 and W2 indexes – chest load.

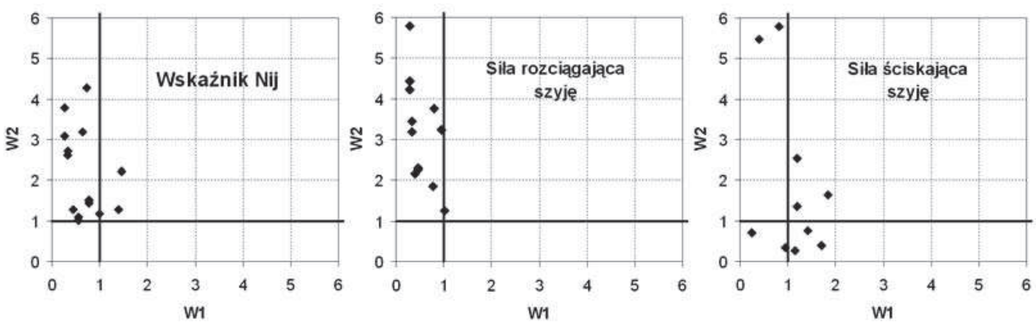


Fig.13. Association of W1 and W2 indexes – neck load.

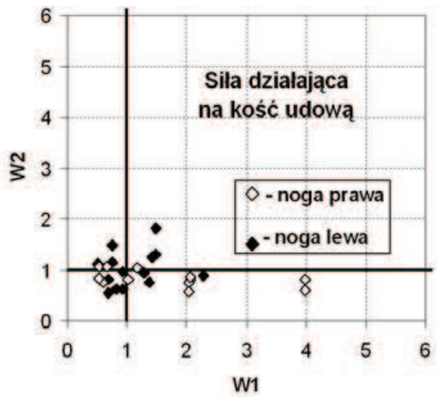


Fig.14. Association of W1 and W2 indexes – leg load.

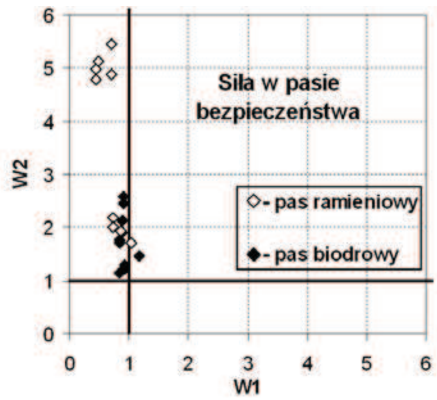


Fig.15. Association of W1 and W2 indexes – forces stretching the seat belt tape.

Conclusions

The analyses that have been carried out confirm the fact that injuries of the car occupants also depend on their seat location in a car. In order to facilitate such evaluation, the W1 and W2 indexes have been introduced. They facilitate the comparison of dynamic loads affecting the occupants in the second and the third seat rows. Their dimensionless nature provides many possibilities of using that index to define the car passenger safety level.

The values of the W2 index confirm that during a frontal collision with a rigid obstacle, the observed dynamic loads affecting the rear seat occupants are often many times higher than for the front seat occupants. They are particularly exposed to the risk of fatal head and neck injuries. The calculation results given in this paper are confirmed by the statistical data on the road accident victims.

Separate analyses indicate basic actions that lead to the improvement of situation of the rear seat occupants. The examples of results compared in the last two columns in table 3 clearly indicate the possibilities of improving the safety condition for the rear seat occupants by the development of the passive safety systems.

Reference

[1] *Final Report of New Car Assessment Program Testing*, Report Number: CAL-05-03, National Highway Traffic Safety Administration, USA, Washington, 2004 (www-nrd.nhtsa.dot.gov).

[2] GACA, S., SUCHORZEWSKI, W. and TRACZ M.: *Inżynieria ruchu drogowego. Teoria i praktyka*, WKŁ, 2008

[3] KUPPA, S., SAUNDERS, J. and FESSAHAIE, O.: *Rear Seat Occupant Protection in Frontal Crashes.* The 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Washington 2005.

[4] Materiały informacyjne Policji.

[5] Materiały informacyjne GUS.

[6] PARENTEAU, CH. AND VIANO, D.C.: *Field Data Analysis of Rear Occupant Injuries Part I: Adults and Teenagers,* SAE 2003-01-0153.

[7] SHIMAMURA, M., YAMAZAKI, M. AND FUJITA, G.: *Method to Evaluate the Effect of Safety Belt Use by Rear Seat Passengers on the Injury Severity of Front Seat Occupants*. Accident Analysis & Prevention 37/2005.

[8] www.nhtsa.dot.gov.

[9] ZELLMER, H., LÜHRS, S. and BRÜGGEMANN, K.: *Optimized Restraint Systems for Rear Seat Passengers.* The 16th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Kanada 1996.

[10] ŻUCHOWSKI, A. AND JACKOWSKI, J.: *Analysis of Properties Operation of the Supporting Equipment for The Seat Belts,* Journal of KONES Powertrain and Transport, Vol.18, No.1, Warszawa 2011.

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