

ANALYSIS OF PROPERTIES OF OPERATION OF THE SUPPORTING EQUIPMENT FOR THE SEAT BELTS

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Abstract

Applying the pretensioners and the belt force limiters in cars had a positive impact on the seat belts effectiveness in protecting the people driving against the effects of collisions. In this way, delayed action of the seat belts, resulting from the flexibility of the belt and the operating time of the retractor locking mechanism, was partially eliminated. The tasks and properties of the pretensioners and force limiters used in cars will be described in the paper. Implementations of the forces acting at the driver's lap belts and shoulder belts during a frontal collision into a rigid barrier, at the speed of 56km/h, will be presented. On this basis the properties of the pretensioners and belt force limiters will be determined. The characteristics of rigidity (force - displacement) of the shoulder belts of various designs will be presented, too. On the basis of the results of the crash tests (NHTSA, USA) for several cars the dynamic loads, which act on the driver during a frontal collision into a rigid barrier, will be analysed. The biomechanical indices of the human immune to the effects of shock loads will be taken into account. The analysis will include the passenger cars (sedan) from the years 1995 – 2004, which were fitted with the seat belts of various designs.

Keywords: *vehicle safety, crash tests, safety belt, pretensioner, force limiter*

1. Introduction

The loads acting on the driver and passengers result from the car decelerated movement and the human body movement against the seat limited by acting of the seat belts and the gas cushion. The seat belt is the most important element of the car safety passive system. It is estimated that the use of the seat belt reduces the risk of death or serious injury during a crash by more than 50%. The delayed action of the seat belts is a major limitation of their effectiveness. The reason for this is the belt flexibility and the delay of the retractor locking mechanism. The cloth, that increases the active length of the belt, is also the reason for this delay.

The design of the seat belts is being constantly improved. New equipment increasing their effectiveness is being applied. The pretensioners partially compensate excessive belt lengthening. Their goal is to tension the belt as soon as possible in order to press a person, fastened with the belt, to the backrest. This is to prevent the excessive forward movement of the body. In recent years, there has been a tendency to limit the force, generated by the seat belt, acting on the chest to reduce the risk of damage to internal organs. Reducing the force acting at the shoulder belts was possible after implementation of the car gas cushions, which take over part of the load during the deceleration of the human body.

The aim of this study is to analyse the impact of operation of the supporting equipment for the seat belts on the driver's load during the car frontal collision into a rigid barrier. The Authors focused on the pretensioners and the belt force limiters.

In the paper there were used the car crash test results published on the Internet by NHTSA (*National Highway Traffic Safety Administration*) [1].

2. Tasks of the seat belts

As defined in ECE R16he Regulations, the seat belt is a belt system with a safety lock, mounting and adjusting elements, capable of fitting inside the vehicle and intended to reduce the risk of injury by an accident or sudden deceleration of the vehicle, by limiting the movement of the user's body. The term also includes any device supporting the effectiveness of the belt, e.g.: the retractor, the tensioner and the belt force limiter.

The proper functioning of the safety belt is conditioned by the tight adherence of the belt to the user's body. Therefore, already in 1960 the belts with a retractor (called inertia reel seat belts) were applied. The belts provided matching the shoulder belt to the human body. The retractor is being locked during a collision (in accordance with ECE R16, during the car deceleration: 0.45g). The retractor causes the belt tension with the force of 0.2 – 0.7daN. Such small forces ensure the adequate belt user's comfort while driving, but they are insufficient to resist the motion of the human body during a collision.

In Figure 1 there is presented the location of the driver's body in the final stage of a collision (90...120ms) for unbelted (a), lap-and-shoulder belted (b), lap-and-shoulder belted with a pretensioner (c).

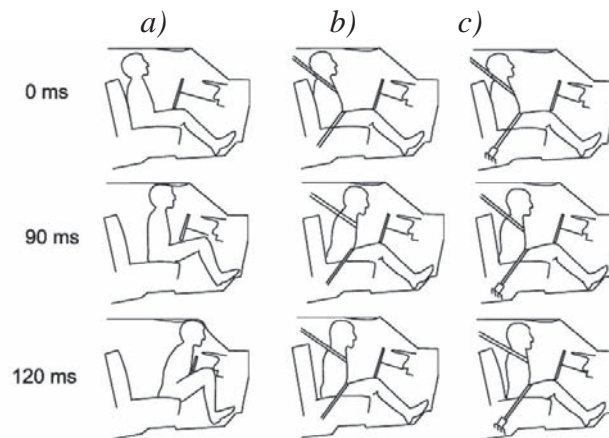


Fig. 1. Impact of the seat belts on the driver's body during the frontal collision (described in this paper) [4]

The driver not protected by a seat belt hits the whole body on the vehicle interior, typically sustaining a fatal injury (Fig. 1a). The driver fastened with a seat belt is being effectively held down in his seat, but his displacement against the seat is high (Fig. 1b). The correct use of the belt is conditioned by the tight adherence of the belt to the user's body. Meanwhile, because the belt does not lie directly on the human body, but on his clothing, the existing clearance (which can be up to several inches) results in additional displacement of the body. This negative effect is partially eliminated by the use of a pretensioner (Fig. 1c).

3. Belt pretensioners

The pretensioners were applied in the belt fastening elements construction in the eighties [3]. Their task is to reduce the active section of the belt by 150 ... 200 mm and to fasten the human body to the seat backrest, over the time of 15 – 20 ms. The belt tensile force increases to 100 – 300 daN and elimination of the belt clearance between the belt and the human body effectively reduces the value of the dynamic loads acting on the user fastened with the seat belt [2,7]. Thus, the belt protects the user from being hit by the car interior elements.

The pyrotechnic pretensioners are commonly used. The energy of a small explosion is being used for causing the seat belt tension in these pretensioners. The first pretensioners interoperated with the retractors only. This type of a pretensioner primarily caused the shoulder belt shortening. At present, two types of the pretensioners are being used at the front seats of the passenger cars.

The first one is the pretensioner placed near the belt retractor. The second one is located near the seat, next to the belt lock or the clamp fastening the seat belt to the seat frame (Fig. 2).

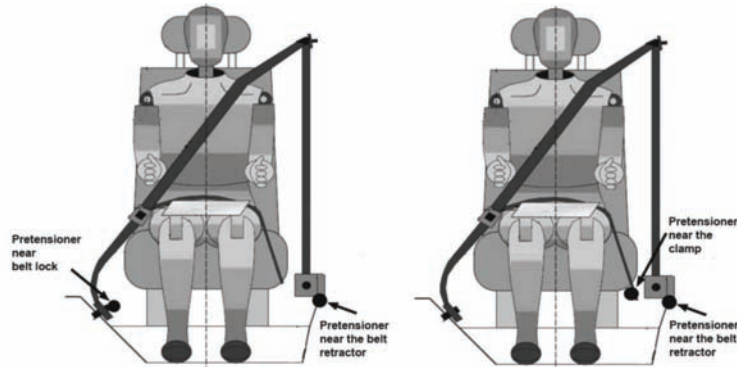


Fig. 2. Pretensioners' placement

The pretensioners placed near the lock are being used more often than the ones next to the fastening clamp. Thanks to this solution, both the lap and the shoulder belt are being tensioned. The pretensioner placed in this position causes shortening the belt by 16 cm when the three-point belt lock moves back by 8 cm. Currently, the two-stage pretensioners are being applied. In the first phase of a collision, the pretensioner connected to the belt lock presses the passenger's body against the seat. At the same time, within the first 10 milliseconds of the collision, the controller assesses the car deceleration. Depending on the result of this assessment, the second pretensioner is being activated to press the body stronger against the seat and keep it there [8].

The latest control systems activate the pretensioners just before hitting an obstacle. For example, PRE-SAFE safety system used by Mercedes can detect the risk of near-accidents and activate the pretensioners before the collision. The pretensioner is being activated electrically and therefore may operate reversibly. If it is succeeded to prevent an accident, preventive seat belt tension is being released automatically and the system is ready for use again [3].

In Figure 3 there are shown the timings of the force tensioning the belt when the seat belts without the pretensioner, with a standard pretensioner, and the Pre-Safe pretensioner are being used. Using the pretensioners shortens the seat belt operation delay by reducing the belt length and the clearance between the user's body and the belt. As a result, the dynamic loads acting on the human body are minor.

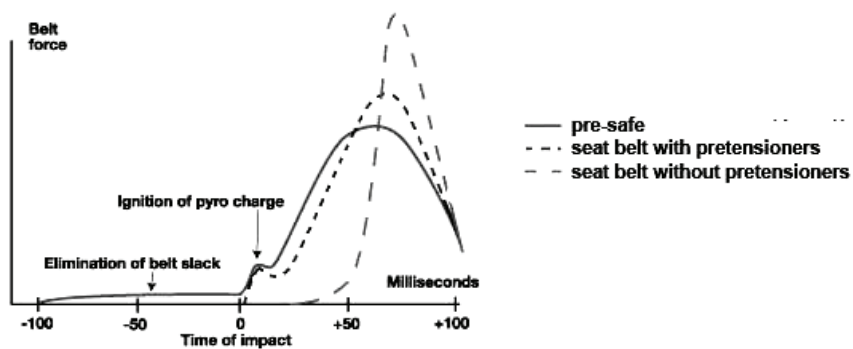


Fig.3. The belt force [7]

4. Belt force limiters

The force limiters are elements built into the seat belt mounting location in a vehicle, which, with the occurrence of an excessive chest loading, is being deformed in a controlled manner, causing the elongation of the shoulder belt.

During the collision, the pretensioners limit the human body movement against the seat, protecting it from damage resulting from the hitting on the vehicle interior hard elements.

However, the pressure exerted on the chest by the belt may cause excessive congestion, and thus, threatening injuries, especially in older people. To avoid the situation, in the last phase of the collision, i.e. after filling the gas cushion, the force limiter reduces the belt tension.

The chart of the load of the seat belt fitted with the force limiter is shown in Figure 4. The standard force limiter characteristics are shown in Figure 4a. The standard force limiter keeps nearly constant level of the chest loading. However, detailed crash test results proved that from the point of view of interoperation with the gas cushion, the gradation of the belt load limiting level (Fig. 4b, c) is more advantageous solution [6].

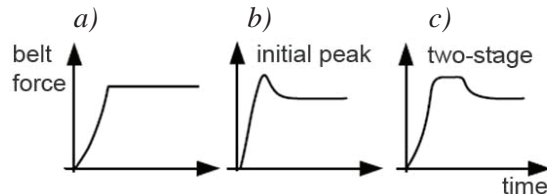


Fig. 4. The belt force limiter characteristics [6]

Exemplary characteristics of the rigidity of the shoulder belts, namely the relationship between the tensile force acting on the belt and the belt elongation (displacement) are shown in Figure 5. Both quantities (force, elongation) were being recorded during a frontal collision into a rigid barrier at the speed of 56 km/h. The same dummy (Hybrid III 50-centile male) was placed on the driver's seat in every vehicle. The analysis of the listed timings indicates the following:

- significant reduction of the belt load maximum value after applying the force limiter, thus lesser probability of injuries;
- larger hysteresis area of the characteristics of the rigidity of the belt with a force limiter, thus better usage of the seat belt energy-consuming properties.

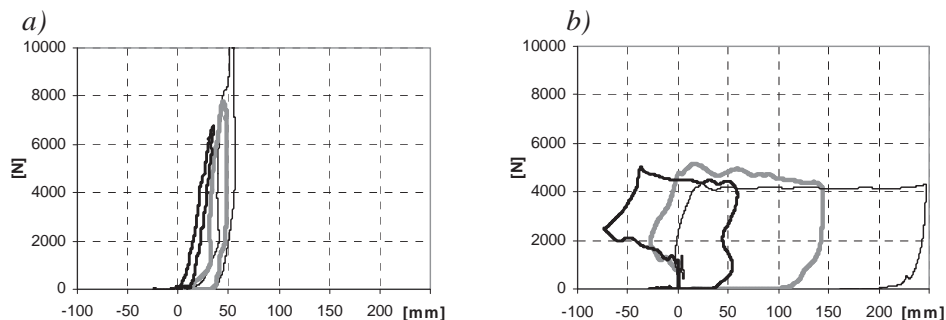


Fig. 5. Characteristics of the shoulder belt rigidity: a – the seat belts without a pretensioner and a force limiter; b – the seat belts with a pretensioner and a force limiter

During a frontal collision the upper parts of the human body are being at the greatest risk of overload. Large congestion of internal organs located in this part of the body (e.g. brain, heart, lungs) may cause death. It is particularly important to limit the load carried by the shoulder belt. The timings of the force acting on the shoulder belt (Fig. 6a) and the lap belt (Fig. 6b) are shown in Figure 6. Such compilation of implementations shows significant differences between the impacts of the seat belts on a man in a car. After implementing the pretensioners and force limiters some effects improving the effectiveness of the seat belts, and reducing possibility of human injury, were obtained:

- getting the belt tension effect in a very short time, after about 15 – 20 ms, with the force of 100 – 300 daN;
- a gentle increase of the belt force, which helps reduce the speed of chest sagging, significant for VC (Viscous Criterion) parameter;
- reduction of the shoulder belt forces down to 400 – 600 daN level, which helps reduce chest sagging and the risk of injury.

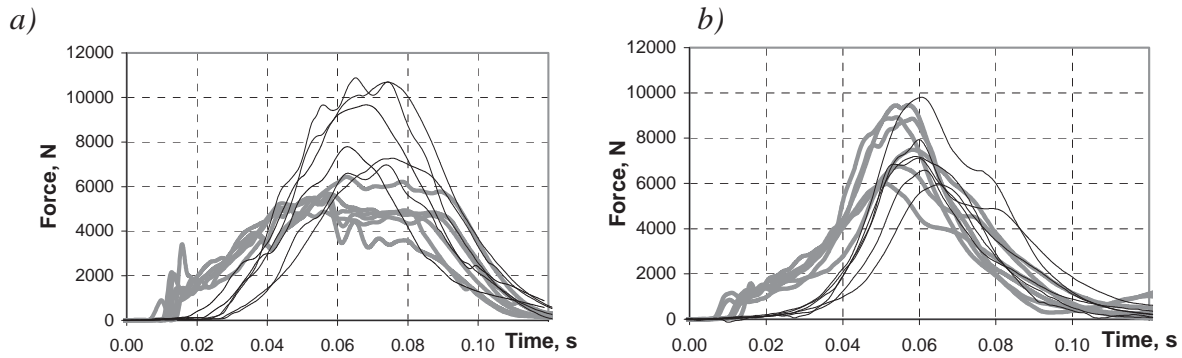


Fig. 6. Implementation of the tension force of the seat belts without a pretensioner and a force limiter (thin lines) and with a pretensioner and a force limiter; a – the shoulder belt, b – the lap belt

5. Analysis of the impact of the pretensioners and force limiters on the driver's load

Six pairs of cars, which crash test results are available on [1] website, were taken into account during the analysis of the impact of the pretensioners and force limiters on the driver's dynamic load. During the crash test, each of the cars was hitting head-on into a rigid barrier at the speed of about 56 km/h. All test cars were new. General information about the cars is shown in Table 1.

Tab. 1. Data on the cars, seat belts, and the dimensions [cm] describing the location of the driver dummy in the car, according to Figure 8

Car	Production year	Weight, kg	Pretensioner		CD	CS	KD
1. BMW 325i	1995	1717	Not		50.5	32.5	16.8
	2002	1731	Yes		54.8	32.4	20.0
2. Ford Crownvictoria	1998	2028	Not		48.8	22.6	13.2
	2001	2013	Yes		52.7	27.5	15.8
3. Honda Accord	2000	1584	Not		52.7	29.2	14.9
	2001	1589	Yes		53.5	31.5	16.5
4. Nissan Altima	1999	1566	Not		53.5	34.4	18.7
	2000	1576	Yes		53.0	31.1	17.6
5. Nissan Maxima	1998	1617	Not		56.0	30.0	12.0
	2000	1718	Yes		53.1	28.0	16.5
6. Mitsubishi Galant	1999	1740	Not	Yes	56.1	33.0	15.5
	2004	1727	Yes	Yes	54.5	30.0	15.0

In each pair there were cars of the same model that met the following criteria of similarity:

- production year;
- sedan body type;
- engine capacity and setting (longitudinal, transverse);
- drive type (front, rear);
- weight and dimensions.

Various equipment supporting the effectiveness of the seat belts was used in the individual pieces of the given car pair. The older production year cars did not have the pretensioners and force limiters in the seat belts (in the following part of this paper marked with “b/N” symbol), and the newer ones were fitted with these devices (labelled with “N”). All cars were fitted with a front gas cushion for the driver.

Since the difference between the production years of the given car models is significant in the two cases and amounts 7 and 5 years respectively for BMW 325i and Mitsubishi Galant, and the difference between the mass of Nissan Maxima cars “b/N” and “N” was 6 – 7%, it was additionally verified whether the properties of the energy-consuming leading zones of each pair were comparable. The implementations of the deceleration measured in the car cabs in the vicinity of B bars are shown in Figure 7. This compilation of the test results shows the similarity of the deceleration for the pieces of

the same car model. It entitles the Authors to conclude that the deceleration timings measured in the cabs of the analysed “b/N” and “N” pairs of cars are similar, and thus the characteristics of the rigidity of the front crumple zone may be considered comparable [5].

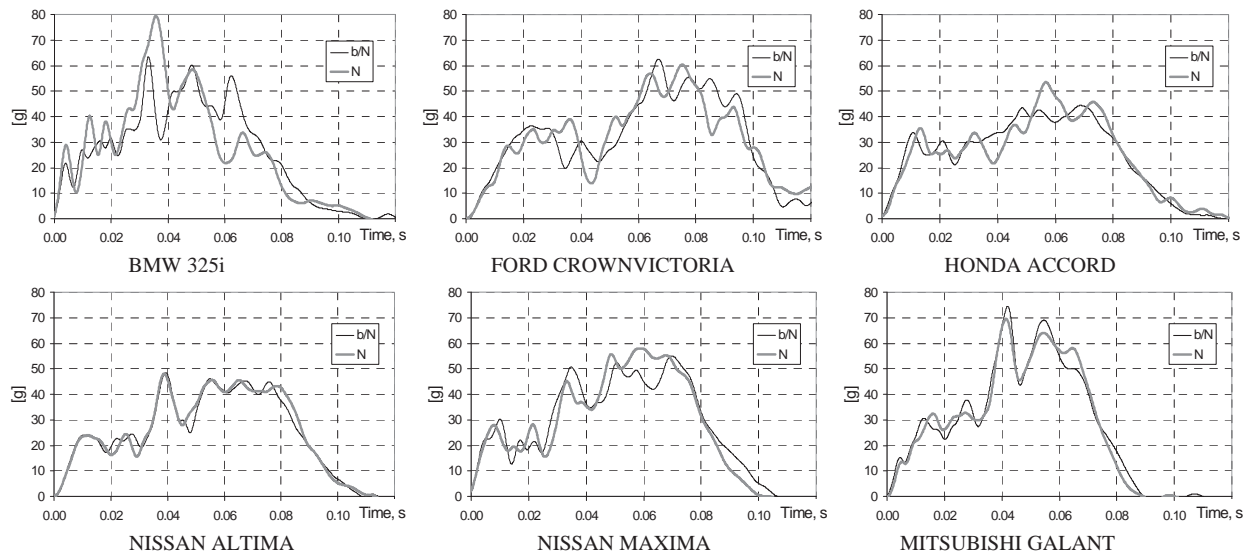


Fig. 7. Car cab deceleration implantation

The loads of the Hybrid III M50 dummy (50-centile male) placed on the driver's seat were discussed. During the collision the dummy comes in contact with the elements inside the car body. The forces resulting from the operation of the seat belts and the gas cushion, but also the forces transmitted from the legs, through the pelvis, to the torso, are particularly important for shaping the dummy loads. That is why the distances between the car body internal elements and the dummy are important. The distances are shown in Figure 8 and summarized in Table 1. The differences between distances CD, CS and KD for the pieces of the same car model are small, and usually do not exceed 3 cm.

On the basis of the information presented above it was found that the dummy on the driver's seat in the both pieces (“b/N” and “N”) of the given car model was:

- subjected to similar inputs (cab delay timing);
- placed on the seat in a similar manner (CD, CS and KD sizes);
- protected by the seat belts of different designs.

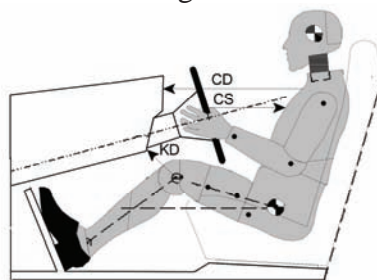


Fig. 8. Dummy positioning in vehicle [1]

The exemplar results of measurements of the loads acting on the dummy on the driver's seat in two pairs of cars are shown in Figure 9. The dummy in Nissan Altima car was fastened with the seat belt:

- without the pretensioners and force limiters (b/N),
- with the pretensioner in the shoulder belt and without a force limiter (N).

In Mitsubishi Galant cars the dummy was fastened with the seat belt:

- without the pretensioners, but with the shoulder belt force limiter (b/N),
- with a pretensioner and a force limiter in the shoulder belt (N).

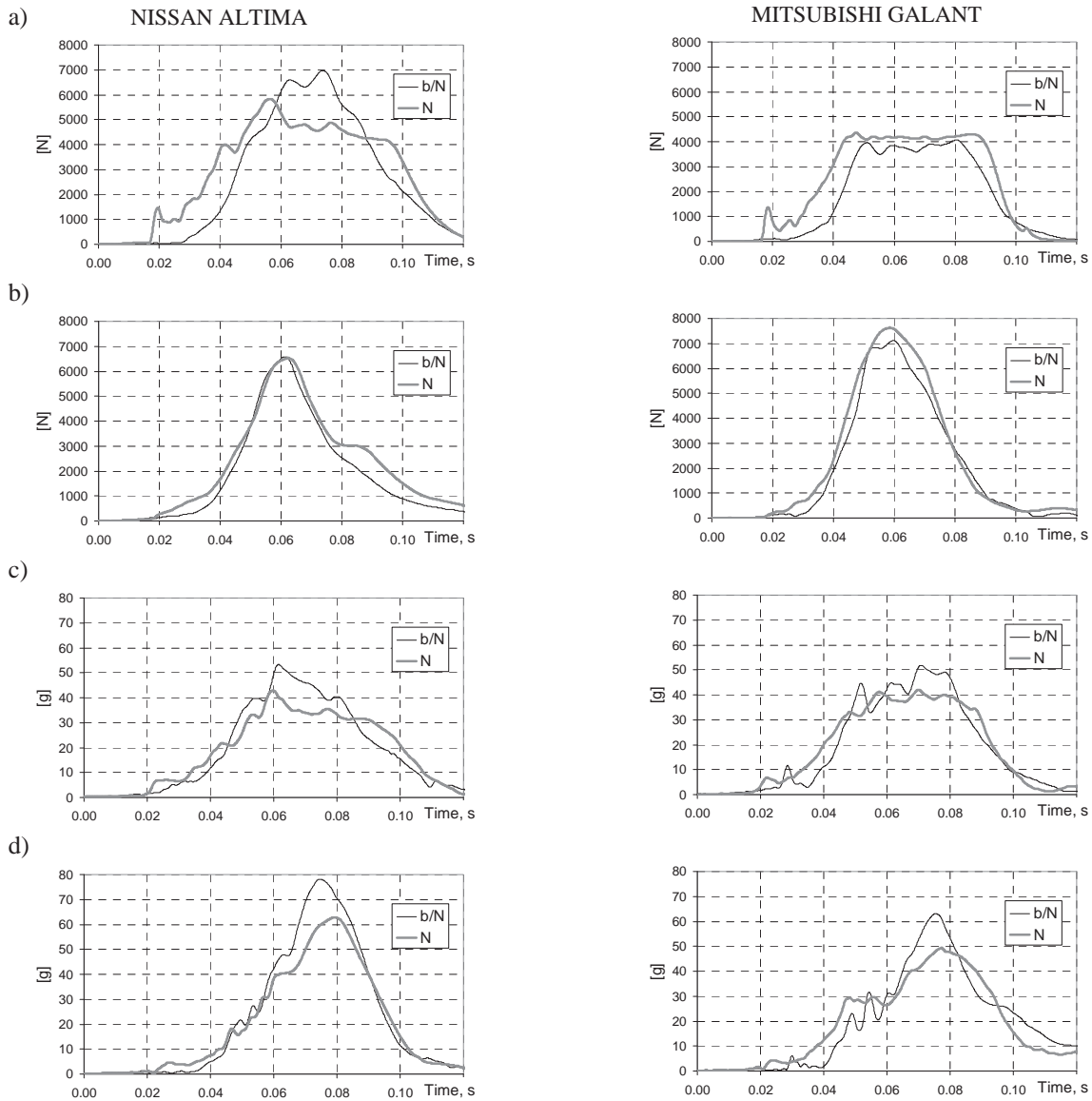


Fig. 9. Loads acting on the dummy on the driver's seat;
 a — force in the shoulder belt [N], b — force in the lap belt [N],
 c — the torso resultant deceleration [g]; d — the head resultant deceleration [g]

The pretensioners used in the two car models acted on the shoulder belt. Small differences between timings of the shoulder belt force in cars “b/N” and “N” indicate that the shoulder belt pretensioners only slightly tighten the lap belt. This is due to large frictional forces occurring during the movement of the belts. Sudden shoulder belt tension speeds up the effect of the seat belts on the dummy by about 15 ms, causing earlier limitation of its motion and, consequently, reduction of the speed at which the torso and head hit the gas cushion. The force limiter of the belt protects the ribs against excessive deflection and the risk of injuries that may occur when too high pressure of the chest against the belt occurs. It also affects the body deceleration time extension, and thus the reduction of the deceleration maximum values.

In Figure 10 there are shown the biomechanical indices of human resistance for the dummy on the driver's seat in the car are presented in Table 1. The indices were associated with the shoulder belt maximum force. In “N” cars the forces are lower by about 20 – 30% than in “b/N” cars (not applicable to Mitsubishi Galant, because the force limiters were mounted in the both car models).

The pretensioners and force limiters particularly positively affect the reduction of the head load. The HIC (Head Injury Criteria) ratio for “N” cars is lower by about 20 – 40% than for “b/N”

ones (for Honda Accord by almost 60%). The torso maximum acceleration is lower by 10 – 20% than for “b/N” cars.

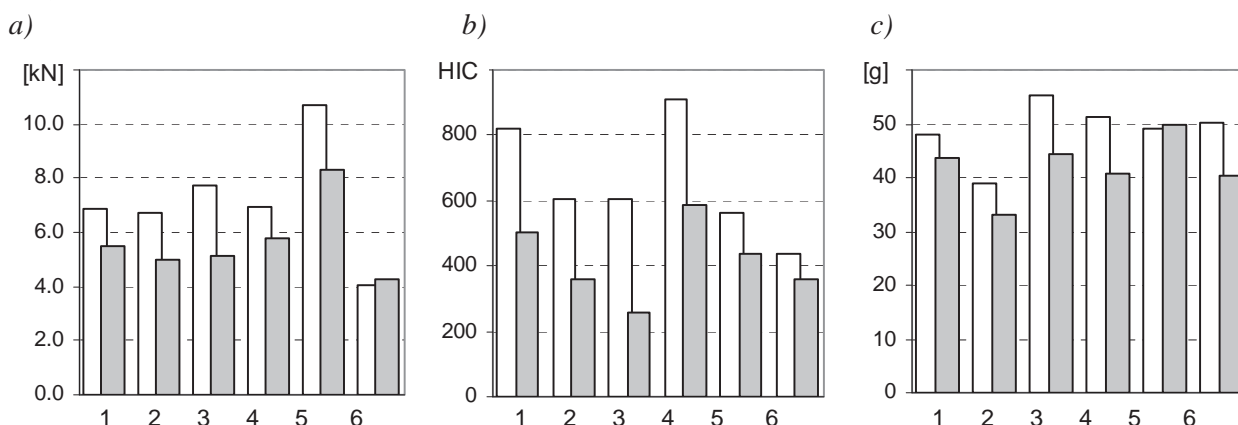


Fig.10. Maximum values of the shoulder belt forces (a) and the load indices for the dummy on the driver's seat: HIC (b), maximum chest accelerations (c); 1,2,3,... – number of car in Tab.1

6. Summary

On the basis of the analysis it was found that the pretensioners cause the belt tension at about 15-20 ms from the moment the car hit the barrier. The pretensioner tightens the belt with the force of 100 – 300 daN. When the speed during the impact amounts 56 km/h, the deceleration time of the dummy on the driver's seat is about 120 ms. The effective interaction of the seat belt with the pretensioner starts about 15 – 20 ms earlier than without the pretensioner. Earlier affecting of the seat belt on the dummy body effectively limits the forward movement of the dummy against the seat. As a result, the dummy hits the gas cushion with a lower speed. Application of the force limiters caused a reduction of the force acting at the shoulder belt down to 400 – 600 daN (It was 700 – 1100 daN without the force limiters). The observed dynamic load of the driver's head and torso were clearly smaller in the cars where the seat belts with the pretensioners and force limiters were applied: HIC ratio by 20 – 40%, and the torso maximum acceleration by 10 – 20%.

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