# INFLUENCE OF THE PRE-TIGHTENING OF SEAT BELTS ON THE LOADS ACTING ON REAR SEAT OCCUPANTS DURING A FRONTAL COLLISION

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## Summary

Results of investigations of the dynamic loads acting on the occupants of backseats in a passenger car during a frontal collision and an analysis of such loads have been presented. The analysis was based on results of experimental tests carried out on a crash-test stand at the Automotive Industry Institute (PIMOT). It was focused on the influence of the pre-tightening of seat belts on the state of loading of test dummies representing a 50 centile male (M50) and a child aged about 10 years. The child dummy was placed in a child safety seat (which included both a seat cushion and a backrest), designed for children with a mass of 15 to 36 kg. The dummies were restrained with the use of standard seat belts. The quantities taken into consideration included head and thorax accelerations measured for both dummies and, for the M50 dummy, forces and moments acting on the neck, thoracic deflection, and axial forces in the thighs. In the analysis, results of three crash tests with different seat belt pre-tightening force values were taken into account. To estimate the risk of injury, indicators of biomechanical immunity of the human body to the effects of impact loads were used. Conclusions drawn from a frame-by-frame analysis of films recorded by means of high-speed cameras were also taken into consideration at this work. The benefits of adequate pre-tightening of seat belts by the user, especially by seat belt pretensioners, were confirmed. In the case of seat belts with pretensioners, the risk of severe injury to an adult passenger (AIS4+) was estimated at 18%, i.e. about a half of that incurred when seat belts without pretensioners are used. For a child, the pretensioners were found to reduce this risk to 9%, i.e. to about one-third.

**Keywords:** vehicle safety, seat belts, rear seat passengers

## 1. Introduction

Probably nobody needs persuading of the advisability of using seat belts in passenger cars. It is generally known that the fastening of seat belts significantly reduces the probability

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of injuries to vehicle drivers and passengers involved in a road accident. The authors of publication [4] came to a conclusion that a 10% increase in the number of seat belt users results in a reduction of the number of casualties among vehicle occupants by 1.35%. Based on various statistics published for many years, a statement may be made that seat belts protected about 50% of vehicle users involved in road accidents from death. More details can be found in Table 1.

**Table 1. Influence of the use of seat belts on the probability of reduction of injuries in collisions of various types [12]**

| Severity of injuries | Percentage reduction of the number of injuries | |
|---|---|---|
| | Estimated | 95% confidence interval |
| **Drivers of passenger cars and delivery motor vehicles** | | |
| Fatal injuries | -50 | (-55...-45) |
| Severe injuries | -45 | (-50...-40) |
| Minor injuries | -25 | (-30...-20) |
| All injuries | -28 | (-33...-23) |
| **Passengers of front seats of passenger cars and delivery motor vehicles** | | |
| Fatal injuries | -45 | (-55...-25) |
| Severe injuries | -45 | (-60...-30) |
| Minor injuries | -20 | (-25...-15) |
| All injuries | -23 | (-29...-17) |
| **Passengers of backseats of passenger cars** | | |
| Fatal injuries | -25 | (-35...-15) |
| Severe injuries | -25 | (-40...-10) |
| Minor injuries | -20 | (-35...-5) |
| All injuries | -21 | (-36...-6) |

However, opinions can also be heard that not only the benefits to be gained but also the threats that may emerge in connection with the use of seat belts should be popularized. The first type of the danger, let us call it "mental," is related to the idea of risk compensation, introduced in 1970s by Sam Peltzman, a professor of Economics at the University of Chicago. According to his research, people in reaction to enhanced safety level (e.g. the fastening of seat belts) tend to behave more riskily than they would do in the absence of such protection measures. This was confirmed by research carried out in 1994 by W. Janssen [9], who ascertained that the drivers wearing seat belts drive in a more risky way, faster, and less carefully than those who drive without fastening their seat belts.

Another type of the danger that may emerge in connection with the use of seat belts, let us call it "technical," is related to the design and method of use of the belts. The important factors include pre-tightening of the strap (webbing), adjustability of location of the upper seat belt anchorage points, and proper or improper positioning of the seat belt strap in relation to the torso and hips. These factors are decisive for the possibility of generation of injuries in the form of bruises and epidermal abrasions on the neck as well as blood extravasations in the regions of clavicle, thorax, abdominal cavity, and hips. In severe cases, fractures of the transverse processes of the cervicothoracic spine, rib fractures, contusions to lungs, ruptures of the aorta, clavicle fractures, and oblique fractures of the sternum may occur. The lap portion of a seat belt may cause injury to the organs in the abdominal cavity [10]. The seat belt positioning is particularly important in the case of fixing a child in a safety seat and fastening the child safety seat to the car seat. Meanwhile, almost 80% of child safety seats are improperly installed [10]. The improper positioning of seat belts or safety seats is decisive for the degree of loading of the human body and, in consequence, the severity of injuries incurred during a road accident.

The correct functioning of seat belts often depends on vehicle user's care of the technical condition of the seat belt system. The seat belt webbing is made of polyester fibres, sometimes reinforced with transverse layers of stiffening fibres. During a collision, the seat belt is subjected to heavy loads. However, the belt must not break in any circumstances. Therefore, it is very important to keep the belt webbing in faultless condition, because its strength depends on the degree of its wear. Even minor damage to the webbing (Fig. 1) may significantly increase the probability of the webbing to break at the moment of a collision.

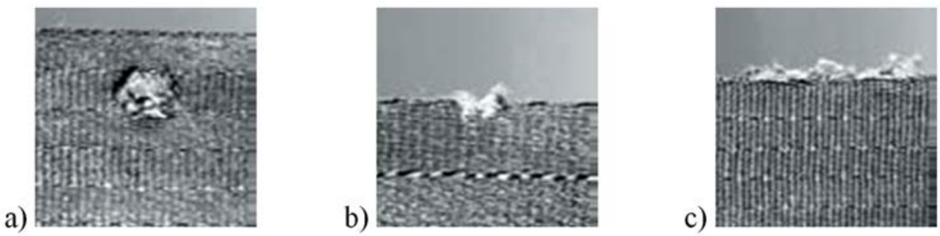



**Fig. 1. Examples of wear of the seat belt webbing [2]:**
**a) a small hole; b) belt webbing slightly torn; c) frayed edge of the webbing**

Any abrasion damage to belt seams, slight tears of the webbing, melting marks (caused by abrasion in fairleads), or narrowings in the webbing qualify the seat belt for replacement with a new one. A slight tear as shown in Fig. 1b may reduce the seat belt strength even by 40%. The webbing may also be weakened by the action of chemicals or solar radiation.

The seat belt webbing parts that are most susceptible to damage are those being in contact with fairleads at the seat belt tongue and retractor. Folds resulting from careless use of the belt (Fig. 2) may be a reason for the breaking of even a new strap; moreover, they may hinder free sliding of the webbing when the seat belt is fastened and thus make it difficult to position and pre-tighten the belt correctly.

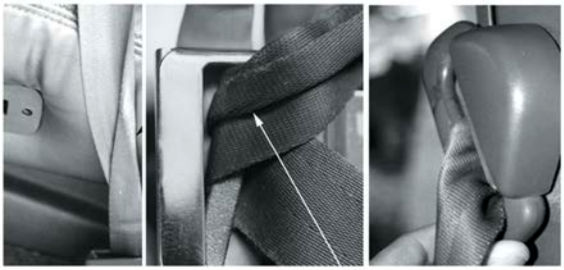


Fig. 2. Examples of folded seat belt webbing [2]

The paper presents some results of the investigations carried out within a research project No. N N509 559640. Previously, a comparative assessment of the loads acting on the occupants of front and rear seats in a car was presented in publications [17–19]. The dynamic loads acting on backseat passengers were found in many cases to be several times as high as those acting on the occupants of front seats. The work described herein was done to determine the influence of the pre-tightening of seat belts on the effectiveness of seat belt operation during a frontal collision. The analysis was carried out for the dynamic loads acting on the passengers occupying the rear car seats, where the passenger protection systems are significantly less developed than those provided for the occupants of front seats. At the tests, dummies were used that represented an adult and a child aged about 10 years; the latter was placed in a child safety seat designed for children with a mass of 15 to 36 kg.

## 2. Description of the test stand and the scope of testing

The measurements were carried out on a crash-test stand AB 554 at the Automotive Industry Institute (PIMOT) in Warsaw. A passenger car body was installed on a trolley (Fig. 3), which was brought up to a speed of about 48 km/h by means of rubber ropes. The effect of braking the car was produced by forcing steel balls present at the ends of mandrels 1 through polyurethane sleeves installed in pipes 2 (Fig. 3). The mandrels with the balls were fastened to the trolley and the sleeves were fixed to the ground.


Fig. 3. Trolley and braking system of the PIMOT measuring stand for crash tests

The passenger car body prepared for tests (Fig. 4) was provided with front and rear seats. A test dummy Hybrid III representing a 50 centile male and a dummy representing a child aged about 10 years, hereinafter denoted by M50 and P10, respectively, were placed on the rear seats, with the latter dummy being fixed in a *Graco Junior Plus Maxi* child safety seat, which included both a seat cushion and a backrest. Both dummies were fastened with the use of standard seat belts, which were replaced with new ones after every crash test.


**Fig. 4. Test dummies in the car body and a child safety seat for the P10 dummy**

Results of three crash tests, hereinafter denoted by N, S, and L, were considered, where the seat belts were pre-tightened with forces of different values.

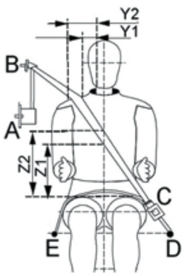
N – Strong pre-tightening: the seat belt retractor was replaced with a tightening mechanism, which was used to pre-tighten the shoulder portion of the belt with a force of 47 daN. Due to friction of the belt webbing against the dummy and in the fairlead of the seat belt tongue, the tension in the lap belt portion was significantly lower and equal to 12 daN and 11 daN for the M50 and P10 dummies, respectively. Thus, the pretensioner operation was simulated at this test.

S – Standard pre-tightening: the seat belt was tightened manually, with trying to shorten the lap and shoulder portions to a minimum. The tension in the shoulder belt portion was as caused by the retractor, i.e. equal to about 1 daN [16].

L – Loose pre-tightening: a sponge layer 3 cm thick was placed between the belt strap and clothing of the dummies and then the belt was tightened as in variant "S." This was done to simulate the impact of winter clothing or careless tightening of the seat belt.

At successive tests, the locations of front seats and upper seat belt anchorage points were kept unchanged and the dummies were placed in similar positions. At the N test, the tightening of the seat belt caused the P10 dummy to be pulled closer to the rear seat backrest, which resulted in an increase in the distance between the dummy's thorax and driver seat's backrest by 6 cm in relation to this distance at the S and L test variants (60 cm). The dimensions describing the initial position of the seat belt strap in relation to the dummies have been specified in Table 2.

Table 2. Dimensions describing the position of the seat belt strap in relation to the dummy (sketch based on [20])




| Dimension [cm] | | M50 dummy | | | P10 dummy | | |
|---|---|---|---|---|---|---|---|
| | | N | S | L | N | S | L |
| Distance to thighs | Z1 | 23 | 23 | 25 | 24 | 22 | 20 |
| | Z2 | 30 | 30 | 31 | 30 | 28 | 26 |
| Distance to neck | Y1 | 5 | 5 | 6 | 4 | 4 | 4 |
| | Y2 | 11 | 11 | 11 | 9 | 9 | 9 |
| Length of belt portion | BC | 78 | 82 | 87 | 79 | 85 | * |
| | CE | 60 | 66 | 72 | 71 | 76 | * |
| Total belt strap length | BCE | 138 | 148 | 159 | 150 | 161 | * |

*) Not measured

The car body deceleration vs. time curve was in conformity with the requirements laid down in UN ECE Regulation No. 44, which is applicable to the testing of child restraint systems. Fig. 5 shows car body deceleration realizations at successive crash tests. They confirm high repeatability of car body deceleration at successive measurements, which is of crucial importance for the subsequent analysis. The maximum deceleration of the car body was equal to about 22 g.

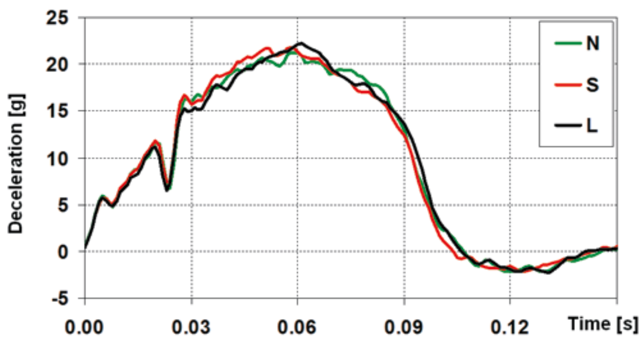



Fig. 5. Car body deceleration realizations at successive crash tests

## 3. Loads of the seat belts

The transducers to measure forces in the lap and shoulder belt portions were installed close to points E and B (see the sketch at Table 2). The realizations of forces in the lap and shoulder portions of the seat belts of dummies M50 and P10 have been presented in Fig. 6. Regardless of the size of a specific dummy:

- At all the measurements, the maximum values of the forces in the shoulder portion of the seat belt were similar to each other;
- The lowest maximum values of the forces in the lap belt portion were recorded at the

N test, which probably resulted from strong pre-tightening of the strap of the shoulder portion of the seat belt and, in consequence, limited possibility of movement of the dummy in relation to the seat cushion;

- At the S and L tests, the force growth rates were similar to each other and clearly higher than that recorded at the N test, especially in the lap portion of the seat belt.

At the L test, the M50 dummy's belt was strained clearly later than it was at the N and S tests (by about 30 ms and 24 ms, respectively), which had an unfavourable impact on the displacement of the dummy in relation to the seat cushion. In the case of the P10 dummy, the difference in the time of straining the lap belt portion at the S and L tests was much bigger than that recorded for the shoulder belt portion. For the M50 dummy subjected to the S and L tests, the maximum values of the force in the lap belt portion were higher by about 20% than those recorded in the shoulder belt portion. A different situation was observed for the P10 dummy, where the maximum values of the force in the lap belt portion were lower by 16% (the S test) and 32% (the L test) than those recorded in the shoulder belt portion. These differences indicate different mechanisms governing the action of the seat belts on the M50 and P10 dummies, which may result from different positioning of the seat belt webbing in relation to the dummies of different sizes.

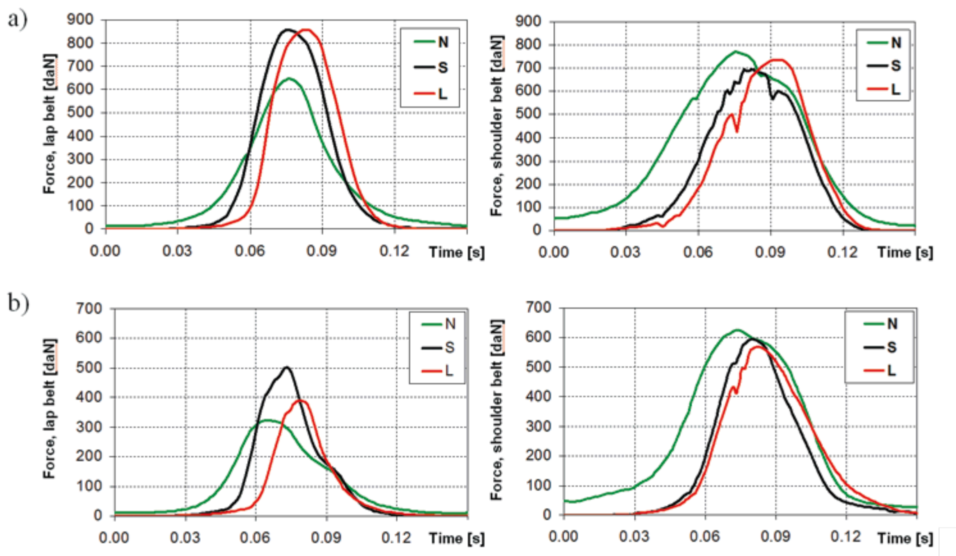



**Fig. 6. Force vs. time curves recorded for the lap and shoulder portions of seat belts: a) dummy M50; b) dummy P10**

According to the requirements laid down for the limit loads of seat belt webbing in Federal Motor Vehicle Safety Standard No. 209: Seat belt assemblies, the breaking strength of the webbing shall not be less than 2 224 daN (5 000 lbf) for the lap portion of the seat belt and 1 779 daN (4 000 lbf) for the shoulder belt portion. In European standards (UN ECE

Regulation No. 16), the minimum acceptable breaking load of the strap has been specified as 1 470 daN without differentiation between the lap and shoulder portion of the seat belt.

The maximum values of the forces occurring in the lap and shoulder portions of the seat belts used for both dummies were significantly lower than the said limits, regardless of the method of pre-tightening the seat belts. For the M50 dummy, the maximum loads of the lap and shoulder portions of the belt reached values of 650÷850 daN and 750 daN, respectively, i.e. 29÷38% and 42% of the applicable limits laid down in FMVSS 209, and, for both belt portions, from 44% to 58% of the limit specified in UN ECE R16. For the P10 dummy, the corresponding figures were as follows: lap belt 300÷500 daN and shoulder belt about 600 daN (13÷22% and 35% of the limits according to FMVSS 209 and, for the whole belt, from 22% to 42% of the limit according to UN ECE R16).

The effects of the loads acting on vehicle occupant's body depend not only on the value of the force applied but also on the time during which the force is applied. Therefore, the differences in the seat belt operation during individual test variants (at the N, S, and L tests) were evaluated in quantitative terms with additionally calculating the impulse of force:

$$I = \int_{t=0}^{t_K} (F - F_o)\,dt \tag{1}$$

where:

$F_o$ – seat belt pre-tightening force
$t_K$ – the time after which the seat belt strap was released

The calculation results have been summarized in Fig. 7, in association with the maximum values of the force developed in the seat belts. Thus, the relations between the maximum value of the force and the impulse of this force have been shown to differ from each other. This has confirmed the advisability of using the formula for an impulse of force as a supplement to the description of the state of loading of the belts during a collision. The values of the impulse of force were clearly higher for the shoulder belts, especially in the case of the P10 dummy.

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The state of loading of the belts at the N, S, and L tests was also assessed by displacement of the strap in relation to the belt fixing parts. The belt strap unreels from the retractor even after locking mechanism is actuated (the so-called "film reel effect"). The maximum acceptable elongation of the lap and shoulder portions of the seat belt webbing when loaded with a force of 1112 daN (2 500 lbf) is 30% and 40%, respectively, of the total length

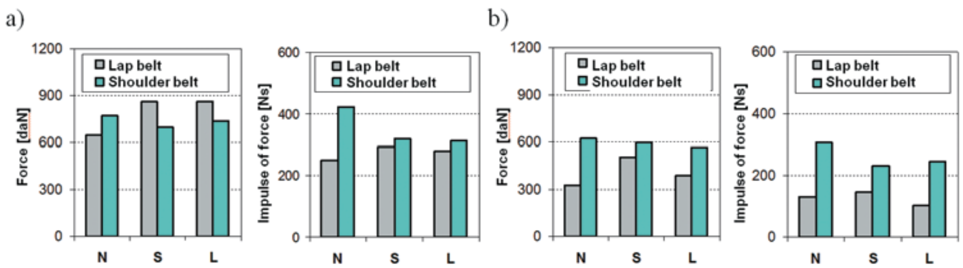


**Fig. 7. Maximum values of the force and the impulse of the force acting in the lap and shoulder portions of the seat belt strap: a) dummy M50; b) dummy P10**

of the belt strap (FMVSS 209). Moreover, a question was answered during the tests whether the belt pre-tightening force affects the range of movement of the belt strap in relation to the fairleads at the seat belt tongue and retractor. Results of the measurements, carried out before and after the crash test, have been given in Table 3. At the S and L tests, the values of webbing displacement in relation to the upper fairlead (point B) were similar to each other and amounted to 11÷12 cm for the M50 dummy and 10 cm for the P10 dummy (5÷7% of the original length of the belt strap, i.e. of section ABCE). The length of the unreeled part of the belt strap was small because the strap remaining on the retractor reel was about 80 cm long. At the N test, the belt strap did not move in relation to the upper fairlead (point B). The displacements of the strap in relation to the fairlead at the seat belt tongue (point C) were within a range of ±2 cm, where the negative values meant shortening of the CE section.

Table 3. Displacement of the seat belt strap (for the symbols used see the sketch at Table 2)

| Dimension [cm] | M50 | | | P10 | | |
|---|---|---|---|---|---|---|
| | N | S | L | N | S | L |
| Displacement at B | 0 | 12 | 11 | 0 | 10 | Not measured |
| Displacement at C | 1 | 2 | 1 | 2 | 2 | Not measured |

## 4. Analysis of loads of the dummies

The M50 and P10 dummies used at the tests were provided with a number of measuring transducers, which made it possible to record the head and torso accelerations of both dummies in three mutually perpendicular directions (x, y, and z as shown in Fig. 4); additionally, forces and moments acting on the neck, thoracic deflection, and axial forces in the thighs could be measured in the M50 dummy. The measurement results have been brought together in Figs. 8 and 9. The curves in the graphs represent the following quantities measured at the N, S, and L tests:

- Resultant decelerations of dummy's head and torso;
- Resultant force acting on dummy's neck;

- Moment bending the dummy's neck, acting around the 0y axis ($M_y$);
- Torso (thorax) deflection;
- Sum of the forces acting on the left and right thigh (the realizations of these forces for the left and right leg were comparable with each other).

The time histories of the resultant vectors were calculated from the vector components measured along three mutually perpendicular directions.

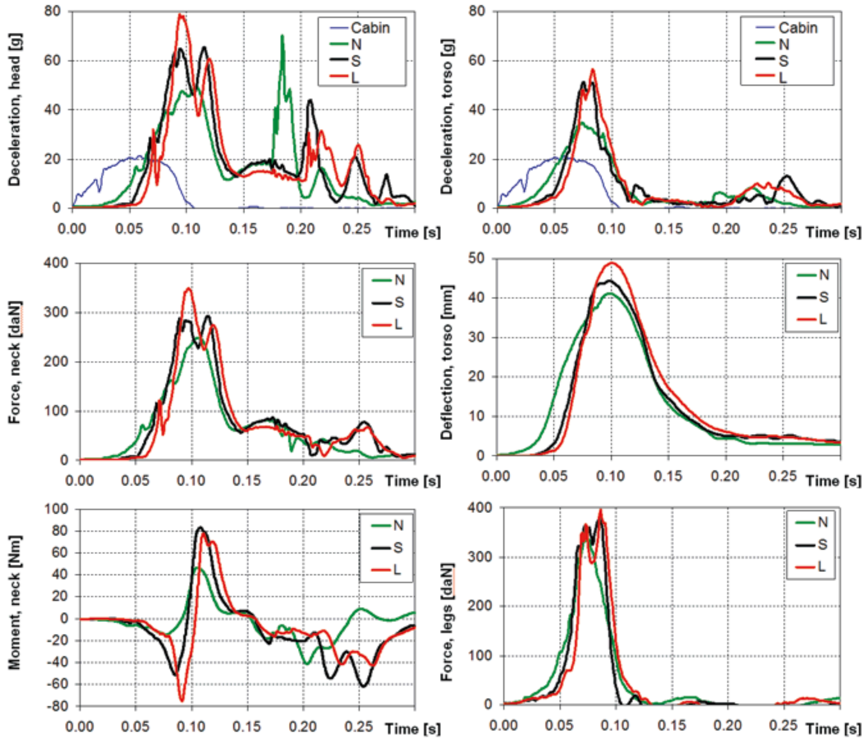


**Fig. 8. Realizations of dynamic loads of the M50 dummy**

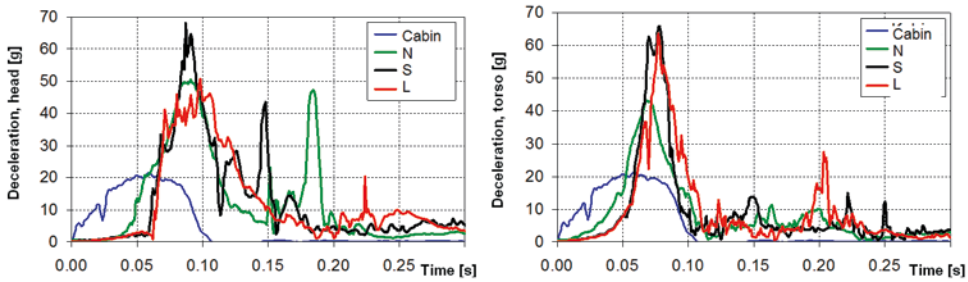


**Fig. 9. Realizations of dynamic loads of the P10 dummy**

In Fig. 10, noteworthy is the shorter time of dummies' movement at the N test (in every phase F1, F2, and F3), when the seat belts were more strongly pre-tightened than it was at the S and L tests. This may be explained by clearly shorter displacement of the dummies at the N test. The characteristic time instants during the collision process have been shown in Table 4.

The peaks that can be seen in the load vs. time curves (Figs. 8 and 9) after the 150 ms time instant reflect the impacts of the dummies against the seat (or safety seat) backrest. They are generally of secondary importance; in the case of the M50 dummy, however, the impact of dummy's head against the seat backrest is very strong. This unfavourable effect results from seat belt resilience and small dissipation of the kinetic energy of the dummy. In seat belts with pretensioners, it is usually eliminated by the operation of a force limiter [16].

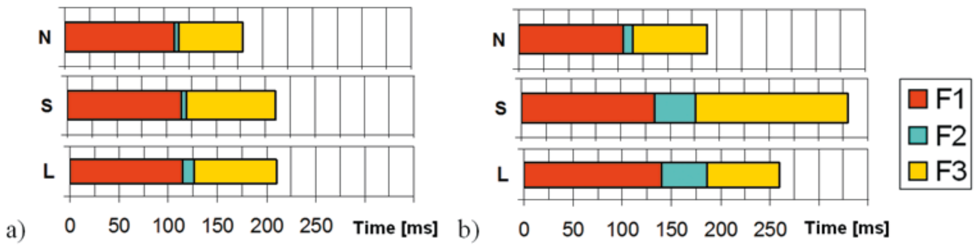


**Fig. 10. Illustration of dummies' movements in the car body (description in the text): a) dummy M50; b) dummy P10**

**Table 4. Characteristic time instants [ms] during the collision process**

| **Time until:** | M50 | | | P10 | | |
|---|---|---|---|---|---|---|
| | N | S | L | N | S | L |
| car body stopped | 84÷86 | | | | | |
| the force in the lap belt reached its maximum | 77 | 76 | 84 | 66 | 73 | 79 |
| the force in the shoulder belt reached its maximum | 76 | 82 | 92 | 74 | 80 | 85 |
| the torso reached its maximum displacement | 76 | 84 | 88 | 76 | 80 | 90 |
| the head reached its maximum bend | 110 | 115 | 115 | 105 | 135 | 140 |
| the head started moving backwards | 115 | 120 | 126 | 115 | 175 | 186 |
| the head reached its maximum backward displacement | 180 | 210 | 210 | 190 | 330 | 260 |

The time histories of dummy loads are qualitatively similar to those of the forces in the seat belts and they resulted from the joint action of inertia forces and reaction forces on the dummies, with the reactions forces chiefly coming from the seat belts and the friction between the dummy and the seat cushion. The maximum values of the torso deceleration and displacement and of the forces in the shoulder belt portion occur at similar time instants. The head can move in relation to the torso; therefore, the head deceleration and the force in the neck reach their maximum values later. The M50 dummy's head is strongly bent forwards, at a time of up to 140 ms (Fig. 11). With increasing head bend, the position of measuring transducers in the dummy's head in relation to the drive direction changes as well. For this reason, the head acceleration component measured in the $Ox$ axis direction has been recorded as declining in the time interval from 95 to 110 ms (see the graph in Fig. 11). At the S and L tests, the M50 dummy's head hit its lower jaw on the sternum, which can be seen in the time histories of head acceleration and force in the neck as a peak in the time interval from 110 to 130 ms (Fig. 8). In Fig. 11, this is represented by a negative peak in the "Head X" curve.

The moment $M_y$ bending the M50 dummy's neck changes its sign when the force in the shoulder belt portion reaches its maximum value and the dummy's torso stops. When the force in the shoulder belt increases, an inequality $M_y < 0$ holds; after the stoppage of the torso, the inequality is inverted to $M_y > 0$.

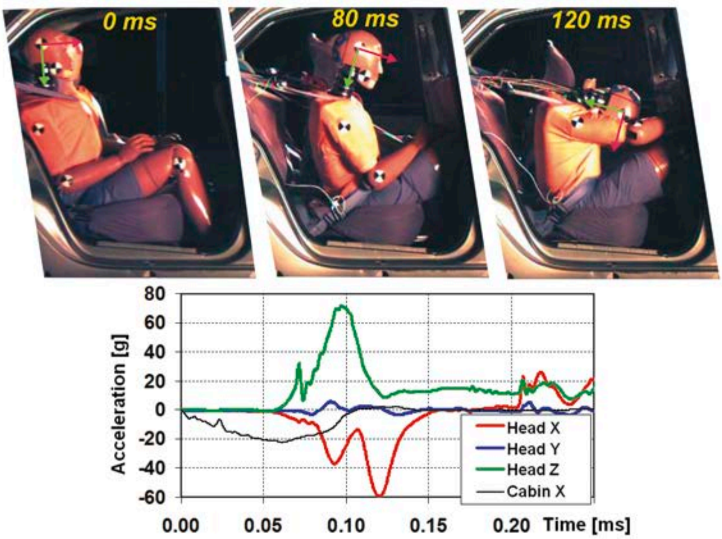


**Fig. 11. Displacements of the M50 dummy and head acceleration components (the L test)**

The M50 dummy used for the S and L tests hit its knees on the backrest of the front seat. This effect can be seen in the realizations of force in thighs, in the time interval from 70 to 90 ms. The thighs were stretched by an inertia force, the growth of which was clearly reduced after the dummy's knees hit the front seat backrest. This additional reaction acting on dummy's legs was relatively small (about 100 daN) and it did not significantly affect the loads of the seat belts and the dummy. Its influence can be seen in the form of a small peak in the time histories of the loads of the shoulder belt and the dummy's head and neck (force), at the time of about 75 ms, especially at the L test, when the knee impact was the strongest. The effect of hitting the knees on the front seat backrest can only be seen in the curves representing the vector components acting in the $Oz$ axis direction.

The movement of the P10 dummy was quite complex (Fig. 12). Since dummy's left shoulder was restrained by the belt strap, the torso and head of the dummy turned to the left. The head was displaced by a significant distance towards the thighs while the torso and hips already moved towards the backrest of the car backseat. At the S test, the dummy hit its head on its left thigh (a peak at the instant of about 150 ms in Fig. 9). At the L test, the dummy's head displacement was similar to that recorded at the S test, but the impact of the head against legs did not take place.

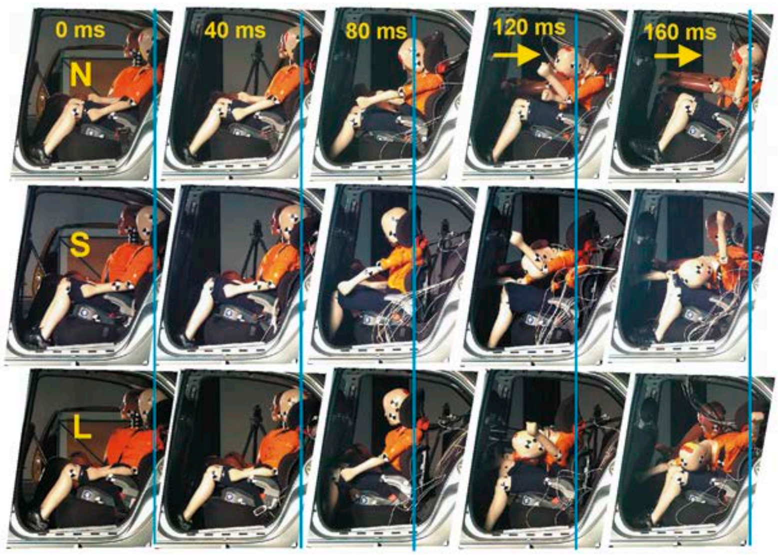


**Fig. 12. Displacements of the P10 dummy at the N, S, and L tests (the vertical lines were drawn through a mark on the dummy's head at the N test; arrows indicate the direction of dummy's movement at the N test)**

## 5. Analysis of biomechanical indicators and the risk of injury

The differences observed in dummies' displacements and in the time histories of dynamic loads of the dummies resulted from different pre-tightening of the seat belts. It is difficult to make quantitative assessment of the differences in the loading of the dummies at the N, S, and L tests based on the analysis presented in section 4. Therefore, the measurement results were used for determining biomechanical indicators for the head, neck, and thorax. The values of these indicators may be then used to assess the risk of injury to the human body or to its specific parts [11, 19].

To assess the risk of head injury, the Head Injury Criterion (HIC) was adopted, which was determined for a time interval of 36 ms ($HIC_{36}$). Based on the calculated $HIC_{36}$ values, the risk of injury may be estimated according to the Abbreviated Injury Scale (AIS), which offers

6 injury severity classes: minor injuries (AIS=1), moderate injuries (AIS=2), serious injuries (AIS=3), severe injuries (AIS=4), critical injuries (AIS=5), and unsurvivable injuries (also referred to as maximal, currently untreatable injuries; AIS=6). The HIC36 limit for the Hybrid III dummies representing a 50 centile male (M50) and a child aged about 10 years has been determined as 1 000, which has a meaning of a 50% risk of injury of at least AIS2 (AIS2+) severity score or a 24% risk of injury of AIS3+ score. The relation between the HIC and the risk of injury is not a linear one. An example of other relations between the $HIC_{36}$ values and the risk of injury defined according to the AIS system has been presented in Table 5.

**Table 5. The $HIC_{36}$ values representing a 25% and 50% risk of injury of the Hybrid III dummies representing a 50 centile male (M50) and a child aged about 10 years [6, 7]**

| | 25% risk of injury | | | 50% risk of injury | | |
|---|---|---|---|---|---|---|
| | AIS2+ | AIS3+ | AIS4+ | AIS2+ | AIS3+ | AIS4+ |
| $HIC_{36}$ | 600 | 950 | 1 400 | 1 050 | 1 680 | 2 113 |

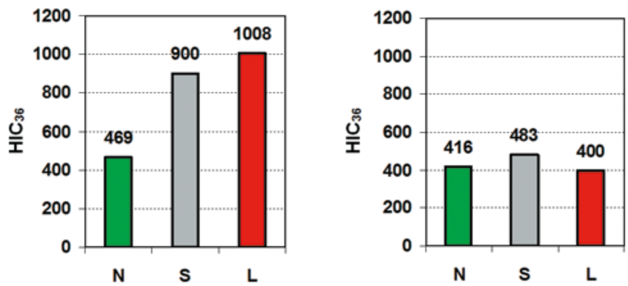


**Fig. 13. $HIC_{36}$ values for dummies M50 (left) and P10 (right)**

The $HIC_{36}$ values determined have been shown in Fig. 13. For the M50 dummy, the most dangerous case is the one denoted by L, corresponding to loose pre-tightening of the seat belt. In this case, the $HIC_{36}$ value exceeds the limit value, which means a 25% risk of injury of AIS3+ severity score. The safest case is the one where the operation of a seat belt pretensioner was simulated (the N test); here, the $HIC_{36}$ value is below a half of that determined for the L test and the risk of injury of AIS3+ score is as low as one-fifth of that at the L test.

The state of loading of the P10 dummy's head at the N and L tests is on a similar level (HIC36 is about 400 in both cases). The highest $HIC_{36}$ value occurred at the S test. It was determined within the 73÷109 ms time interval, i.e. the head impact against the thigh did not affect the HIC value. The differences between results of successive measurements are small and, therefore, difficult to be explained.

To assess the risk of injury to the neck, a Normalized Neck Injury Criterion denoted by $N_{ij}$ is used, where the "$i$" and "$j$" subscripts represent four neck load types, i.e. $N_{CF}$, $N_{CE}$, $N_{TF}$, and

$N_{TE}$. The former subscript (C or T) defines the axial load of cervical vertebrae (compression or tension) and the latter one (F or E) defines the bending of cervical vertebrae (flexion or extension, taking place when the neck is bent forwards or backwards, respectively). The acceptable value $N_{ij}$ = 1 does not depend on dummy size because it is calculated with taking into account different critical force and moment values for dummies of different sizes. The value $N_{ij}$ = 1 corresponds to a 30% risk of injury of AIS3+ severity score or an 18% risk of injury of AIS4+ severity score [1]. Results of calculation of the $N_{ij}$ indicator values have been given in Fig. 14. The predominating load type is the tension and flection of the neck ($N_{TF}$ and $N_{TE}$) during the forward motion of the dummy (phase F1). The lower the seat belt pre-tightening force is, the higher value is taken by the $N_{TE}$ indicator. At the L test, the value of this indicator was thrice as high as that at the L test. In general, the lowest neck load was observed at the N test. As it was in the case of the head load, this again has confirmed the benefits of adequate pre-tightening of the seat belts. The $N_{CE}$ loads constitute a matter of importance only at the stage of the dummy's head being bent backwards, during the return movement of the dummy; the $N_{CF}$ loads do not practically occur.

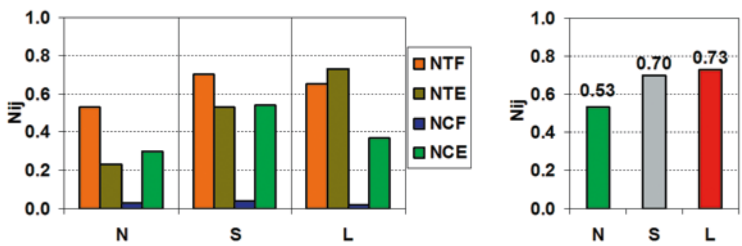


**Fig. 14. $N_{ij}$ indicator values for the M50 dummy**

The thorax load may be measured by the value of thoracic deflection, maximum acceleration CAcc (acting for at least 3 ms), or Viscous Criterion (VC) [3, 13, 14]. A basis for the VC calculation is provided by the maximum value of the product of thoracic deflection velocity and instantaneous thoracic deflection values. The value of CAcc = 60 g means a 20% risk of injury of AIS4+ severity score [8] and VC = 1 means a 25% risk of injury of AIS4+ severity score [13].

Results of calculation of the biomechanical indicators used for the assessment of risk of thoracic injuries have been summarized in Fig. 15. The maximum thoracic deflection values (C) determined for the M50 dummy fall within the range from 40 to 50 mm and make about 50% of the acceptable figures. In Fig. 15a, they have been associated with the CAcc indicator value. The line plotted in the graph shows limits for the acceptable values of these quantities. Only the N test results fall within the range of acceptable values. The most diversified results have been obtained for the Viscous Criterion (VC); the highest VC value has been recorded at the L test and this may be explained by a rapid growth of the force in the shoulder belt strap, which took place in the 76÷83 ms time interval (cf. Fig. 6a). This growth resulted in rising thoracic deflection velocity and, in consequence, an increase in the VC value. For the P10 dummy, the CAcc indicator values at the N test are lower by about 30% than those recorded at the S and L tests, which in turn are quite close to each other (63 g and 60 g, respectively).

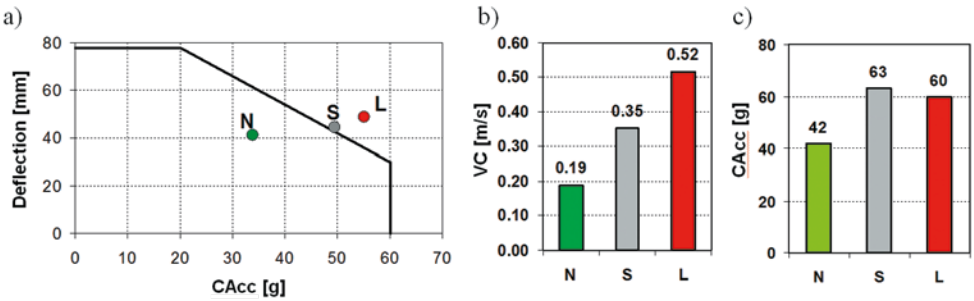

**Fig. 15. Thoracic load indicator values for the M50 dummy (a and b) and the P10 dummy (c)**

The risk of thoracic injury is sometimes assessed on the grounds of the maximum force developed in the shoulder belt during a collision. In consideration of the fact that these forces measured for the M50 dummy were on a level of 700÷800 daN, the risk of serious injury (AIS3+) for people aged 30 and 50 years is 10% and even as high as 95%, respectively, based on publication [5]. The force in the shoulder belt that restrains a P10 child dummy can rise to a level of 600 daN.

## 6. Recapitulation

The kinematics of test dummies, the forces developed in the seat belt webbing, and the dynamic loads acting on test dummies strongly depend on the value of the seat belt pre-tightening force at the instant immediately preceding the vehicle impact against an obstacle. The strongly pre-tightened seat belts act faster on the dummy and effectively restrain it on the seat, with reducing the displacements of dummy's hips and torso. This has a favourable impact on the reduction of loads acting on the dummies, head inclusive. Different values of the seat belt pre-tightening force have significant influence on the maximum value of the force developed in the lap belt, while the forces developed in the shoulder belt are close to each other at all the tests. At the N test, the maximum values of the forces in the lap belt ale lower by 30÷40% than those measured at the S and L measurements. The maximum forces in the lap and shoulder portions of the seat belt that restrains the M50 dummy are similar to each other, while in the case of the P10 dummy, the forces in the lap belt are considerably lower than those in the shoulder belt (Fig. 6).

The biomechanical indicator values obtained at different belt pre-tightening forces have been summarized in Table 6. The indicator values obtained from the N and L tests have also been presented in relation to the values of these indicators measured at the S test, i.e. with the standard pre-tightening of the seat belts (symbols "N/S" and "L/S").

Table 6.Summary of the biomechanical indicators obtained from the N, S, and L tests

| Belt pre-tightening/ Indicator | N | S | L | N/S [%] | L/S [%] | N | S | L | N/S [%] | L/S [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| | M50 dummy | | | | | P10 dummy | | | | |
| $HIC_{36}$ | 469 | 900 | 1008 | 52 | 112 | 416 | 483 | 400 | 86 | 83 |
| $N_{ij}$ | 0.53 | 0.70 | 0.73 | 76 | 104 | – | – | – | – | – |
| CAcc [g] | 34 | 50 | 55 | 68 | 110 | 42 | 63 | 60 | 67 | 95 |
| C [mm] | 41 | 45 | 49 | 91 | 109 | – | – | – | – | – |
| VC [m/s] | 0.19 | 0.35 | 0.52 | 54 | 149 | – | – | – | – | – |
| Risk of injury AIS4+ [%] | 18 | 34 | 41 | | | 9 | 26 | 22 | | |

For both dummies, the lowest values of the biomechanical indicators were obtained at the N test, i.e. when the seat belts were strongly pre-tightened. The benefits gained from the introduction of pretensioners to the seat belts for backseat occupants were confirmed [15, 16]. The $HIC_{36}$ values measured for the P10 dummy reached a level of about 50% of the acceptable limit values. The risk of serious injury (AIS3+) to the M50 dummy's head at the N test was about one-fifth of that at the L test. For the P10 dummy, the highest values of the $HIC_{36}$ and CAcc indicators were obtained at the S test. They were slightly higher than those at the L test. Results of calculations of the risk of injury, obtained with taking into account the state of loading of head, thorax, and neck, have been given in the bottom line of Table 6. The calculations were done according to the method described in publications [11, 19].

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