OPTIMISED PRETENSIONING OF THE BELT SYSTEM: A RATING CRITERION AND THE BENEFIT IN CONSUMER TESTS

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ABSTRACT

A common understanding is that in a frontal crash an early coupling of the occupant to the vehicle deceleration is required. This is provided by pretensioning of the belt system. The objective of our study was to set up a rating criterion for pretensioner performance, to benchmark current pretensioner systems, to define requirements for an optimal pretensioning, and to quantify the benefits in both US- and EuroNCAP testing.

A generic test environment was developed and sled tests with different pretensioners and combinations of pretensioners were conducted. As a result, systems with either both retractor and anchor plate pretensioning, or buckle and anchor plate pretensioning gave direct reduction of the dummy chest acceleration values. Additional to the reduction in dummy loading, a reduction in dummy forward displacement occurred. Using this additional space by reduction of the load limiter level of the seat belt resulted in a further reduction in occupant loading, especially in chest deflection. For the determination of the appropriate load limiter level, MADYMO simulation was used. In a further step, a rating criterion for pretensioners was defined. It rates the energy difference of the dummy compared to the vehicle during the crash as percentage of the vehicle energy, i.e. a low figure indicates a good coupling.

As a result, with double pretensioning and respectively tuned load limiter level, chest deflection and acceleration in both EuroNCAP and US-NCAP can be reduced by about 20% - 25% compared to single pretensioning. A low energy difference in the pretensioning rating criterion showed a good correlation to the dummy readings.

With the outcome of the study, requirements to an optimal pretensioning are discussed in respect to a good coupling and to possible injuries induced by aggressive pretensioning.

1. INTRODUCTION

Consumer tests world-wide are posing constantly increasing demands on the vehicle structure and the occupant protection system. As a consequence of the offset-crash, the rigid vehicle structure results in increased loads on the occupants, in particular in frontal crash tests with 100 % overlap. Thus an optimised restraint system consisting of a safety belt with pretensioner, load limitation and airbag has to reflect these demands. Here particular attention has to be paid to the belt system, since it is exclusively the belt system which is responsible for the restraint of the occupant during the first phase of the crash.

The effect of the belt system can be classified into two phases:

1) the belt pretensioning following the crash only by a few milliseconds and creating the optimum pre-requisites for the restraint of the occupant;
2) the load limitation which keeps the force at the shoulder belt to a pre-defined level during the forward displacement of the occupant thus leading to an optimum utilisation of the space available in the interior.

1.1 Belt pretensioning and load limitation

Too much slack in the belt system results in a deterioration of the occupant loading in frontal crashes and may favour submarining. For instance, 80% of car drivers have a slack varying between 40mm and 90mm in the summer and 40mm to 120mm in the winter /1/. The pretensioner is intended to minimise this slack even before an occupant forward displacement in a crash. So to say, the belt system is fine tuned for an optimum starting position in the first milliseconds following a crash.

The load limiter in the 3-point belt is intended to limit the forces exerted by the belt and thus the values for the thoracic load. Already in the early 1970ies load limiters were applied in serial production, at that time, of course, without airbag. Their benefit has been demonstrated by accident analyses /2/. Today load limiters are mostly applied in combination with an airbag to achieve an optimum alignment of the restraint system.

Even if the impact of the load limitation is of importance for the occupant load /3,4/, in the following we intend to focus on the influence of the pretensioner.

1.2 Pretensioning approaches for front seats

Figure 1 depicts various approaches for pretensioning of the belt system. It is differentiated between the following pretensioner systems each positioned at the respective fixation points:

- retractor pretensioning
- buckle pretensioning
- anchor plate pretensioning
- any combination of the above three methods.

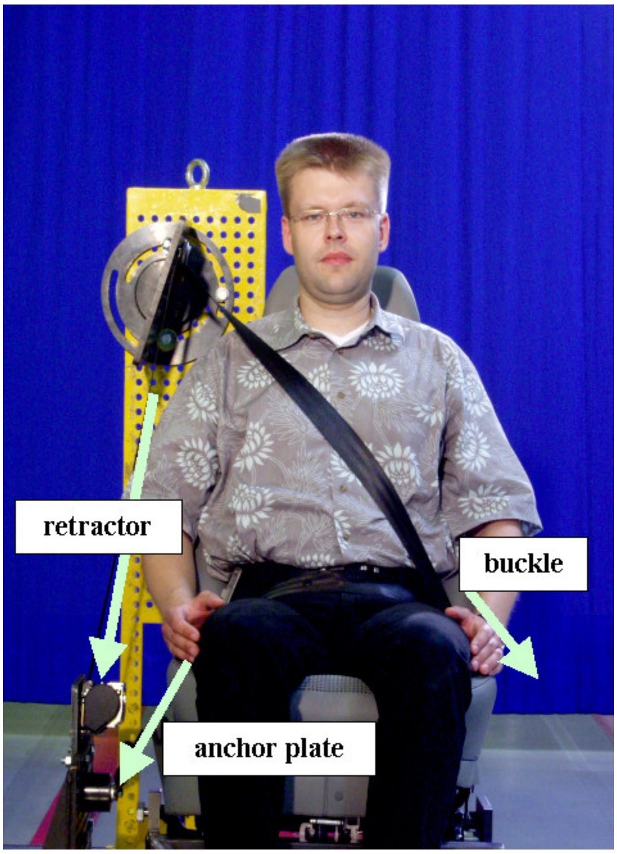

Figure 1. Pretensioning of the Belt System

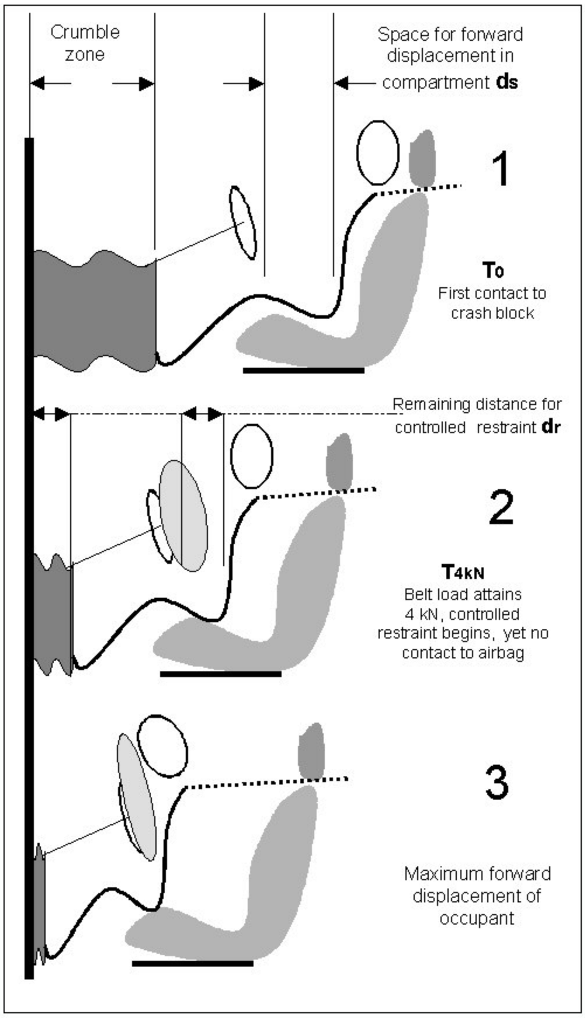

Figure 2. Car and occupant behaviour in frontal impact

1.3 Criterion for occupant coupling

In frontal impact events, one of the main functions of the belt system is an early coupling of the occupant to the vehicle deceleration. In order to evaluate this, a coupling criterion was defined /5/ on the basis of the "Ride Down Effect" (RDE) /6/. The RDE gives a percentage value of the remaining crumple zone, when the dummy retardation starts. The criterion we defined evaluates the path remaining for the passenger when a load of 4kN is reached on the shoulder belt. The point in time when this happens is defined as $\mathbf{T_{4kN}}$. In doing so, we assume that this is the moment when a controlled restraint starts. The forward displacement of the dummy in the area of the upper thoracic vertebra T1 at $\mathbf{T_{4kN}}$ is defined as $\mathbf{d_{4kN}}$ and the remaining distance for the retardation of the occupant $\mathbf{d_r}$ is computed as follows (please refer to figure 2):

$$\mathbf{d_r = d_c + d_S - d_{4kN}}$$

with:

d_c = remaining length of crumple zone at T_{4kN}
d_S = space for forward displacement at T_0

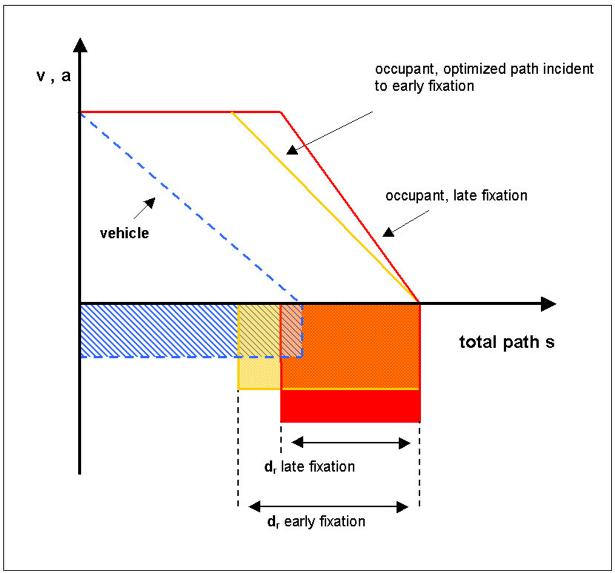

Figure 3. Speed v and deceleration a vs. distance at idealistic square shaped decelerations

Figure 3 shows that a high value for $\mathbf{d_r}$ results in a marked reduction of the occupant acceleration. This has been confirmed in tests and simulations /5/.

1.4 Limitations posed by single pretensioning

From the technical point of view, increasing the pretension load aiming at achieving 4kN on the shoulder belt already during the pretensioning phase would be feasible. This would result in an optimum occupant coupling. However, this achievement would fire back on the occupants. For biomechanical reasons, the force exerted on the shoulder should not exceed 1.5kN – 2.0kN, see fig. 4. This holds true in particular since a pretensioning does not only make sense for frontal impact situations. In this case, it would be reasonable to assume that shoulder forces of this type are reached during the crash incident anyhow. In the cases of rear impact or roll-over we do not assume a priori that forces of this magnitude are reached. These loadcases would then require an additional pretensioner with lower performance or a retractor pretensioner with variable tension performance.

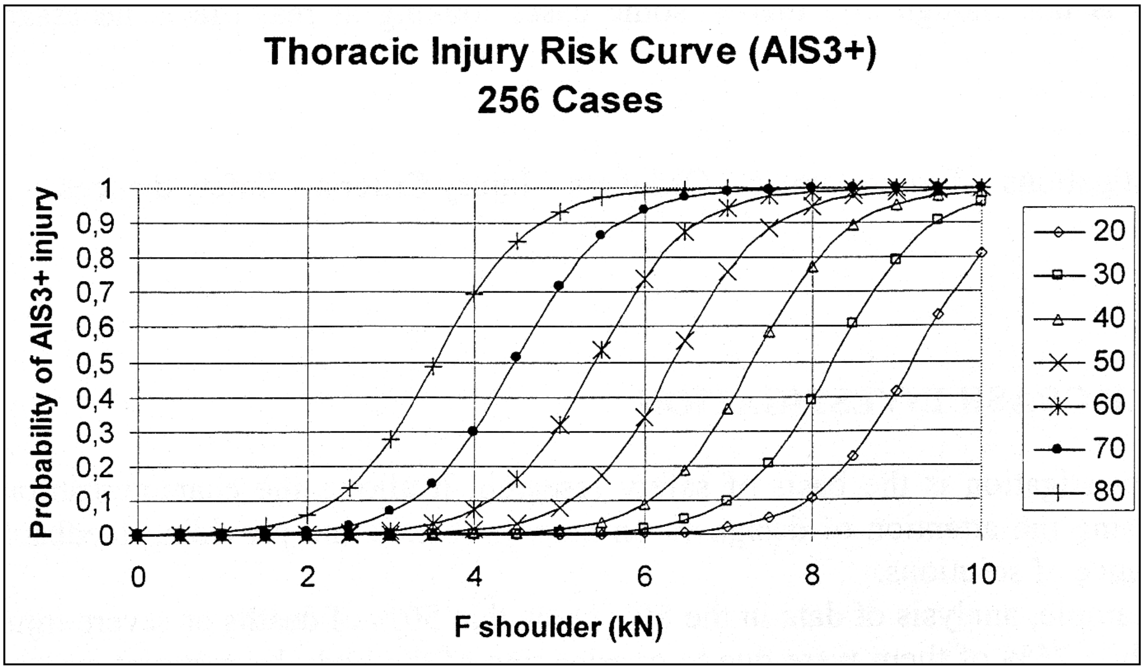

Figure 4. Probability of severe thoracic injuries (AIS3 or more severe) depending on the shoulder belt force and the occupant´s age /7/

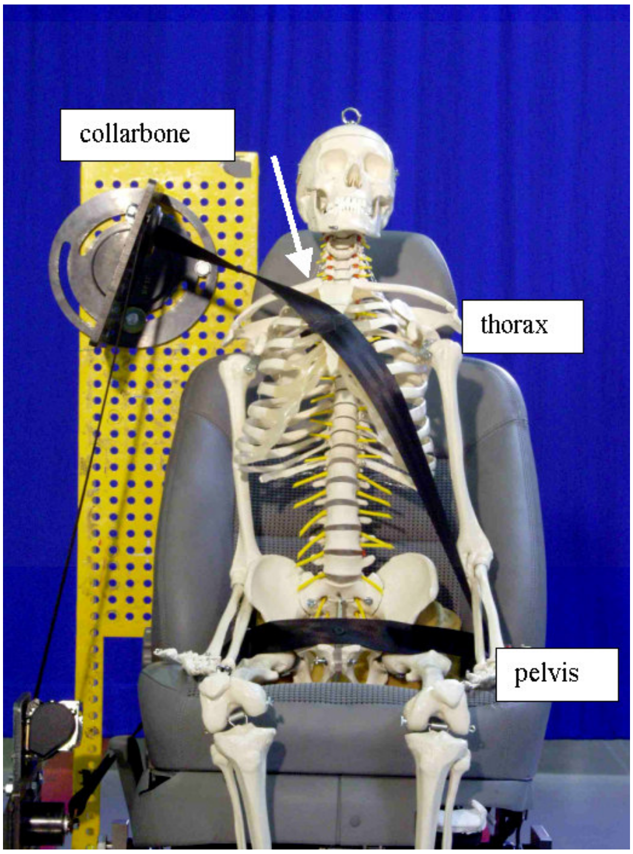

Figure 5. Loading to the body by the belt

1.5 Optimisation of the pretensioner system

Now, which combination of pretensioners is the most suitable choice to achieve an optimum occupant fixation? The following pre-requisites have to be met:

1. Strong fixation of the occupant as early as possible;
2. Limitation of the shoulder force to 1.5kN – 2.0kN;
3. Set-up of a suitable force on the retractor to minimise the film spool effect.

In order to meet these pre-requisites, it is necessary to guarantee that a high load is applied in the pelvis area by means of an anchor plate pretensioner. From the biomechanical point of view, this area can withstand higher loads than the shoulder area. In our opinion, even a value of 4kN would not pose any problem. As a consequence, we need a first pretensioning at the buckle or retractor to take out the belt slack observing conditions 2 and 3, and the second pretensioner to be fired at the anchor plate. Moreover, a high application of load in the pelvis area makes sure that an essential factor of the restraint effect is performed there, see figure 5.

1.6 Scope

The objective of our study is to quantify the benefits of the above outlined double pretensioning strategy. The rating criterion for occupant coupling described in section 1.3 is no longer valid for this kind of pretensioning as it only rates the force at the shoulder belt and not at the lap belt in which we want to impose the stronger part of pretensioning. Furthermore, there are other ways to couple the occupant to the car deceleration in the very first part of the frontal impact, such as the knee airbag or the pelvis restraint cushion, an inflatable seat ramp which is in production in some cars. A new rating criterion should take care about these as well. In order to develop such a criterion,

1. a generic test environment was developed,
2. sled tests with different pretensioners and combinations of pretensioners were conducted, simulating both US- and EuroNCAP crash pulses,
3. the load limiter level of the seat belt was tuned to use the gained space for forward displacement to its optimum,
4. the benefit in terms of occupant loading in the tuned configuration was determined,
5. a new coupling criterion was developed and compared with the outcome of the sled tests.

2. TESTS: SET-UP AND RESULTS

The generic test environment developed should represent a European mid-size car (cf. figure 6.) The seat has a stiff structure but a seat cushion with a deformable sheet metal below from a serial car in order to simulate the pelvis seat interaction. The steering wheel with airbag is fixed to a stiff bar. The dummy used was a Hybrid III 50th percentile. Two different pulses, one representing an US-NCAP, the other presenting an EuroNCAP pulse were selected (cf. figure 7.)

The following pretensioners were tested:

1. baseline: without pretensioner,
2. buckle pretensioner only,
3. retractor pretensioner only,
4. retractor and anchor plate pretensioner,
5. buckle and anchor plate pretensioner,
6. retractor and buckle pret. (EuroNCAP only.)

In the double pretensioner configurations the pretensioner named first was fired first, the second one with a time delay of 5ms to 11ms in order to avoid interactions between both.

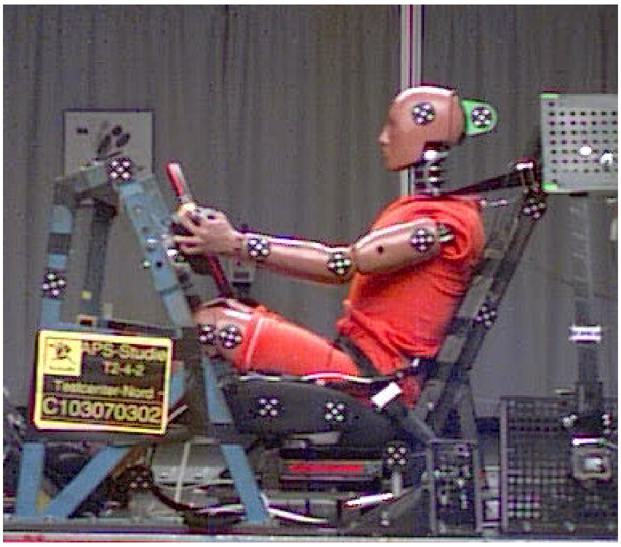

Figure 6. Generic test set-up

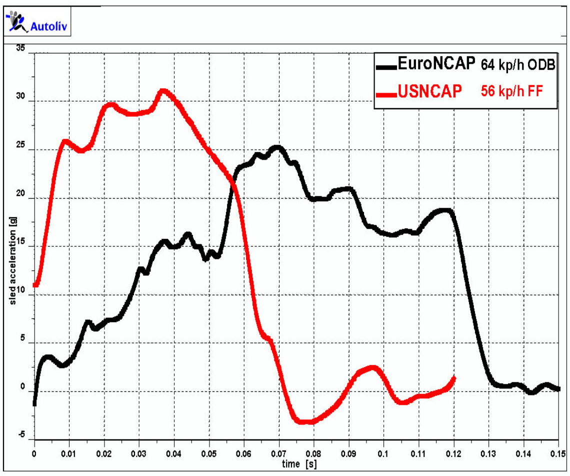

Figure 7. Crash pulses simulated in sled tests

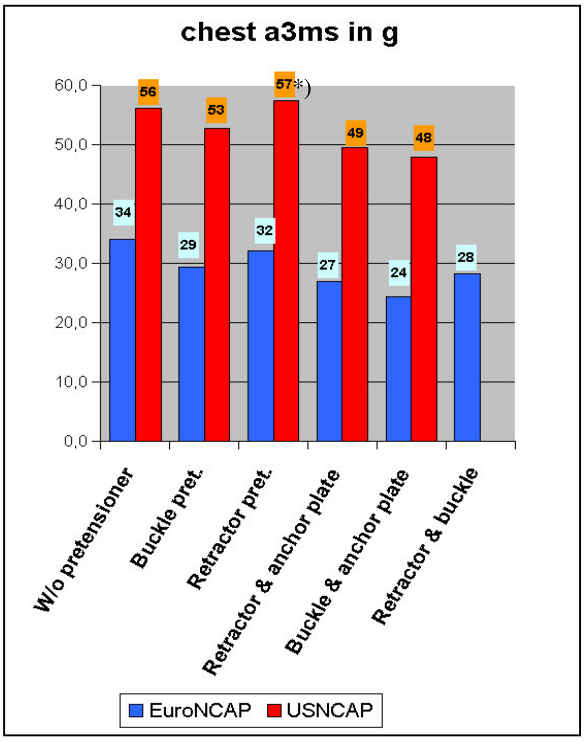

Figure 8. Chest acceleration a3ms

*) this value is higher than expected and caused by contact of the dummy pelvis to stiff substructures in the seat, see text

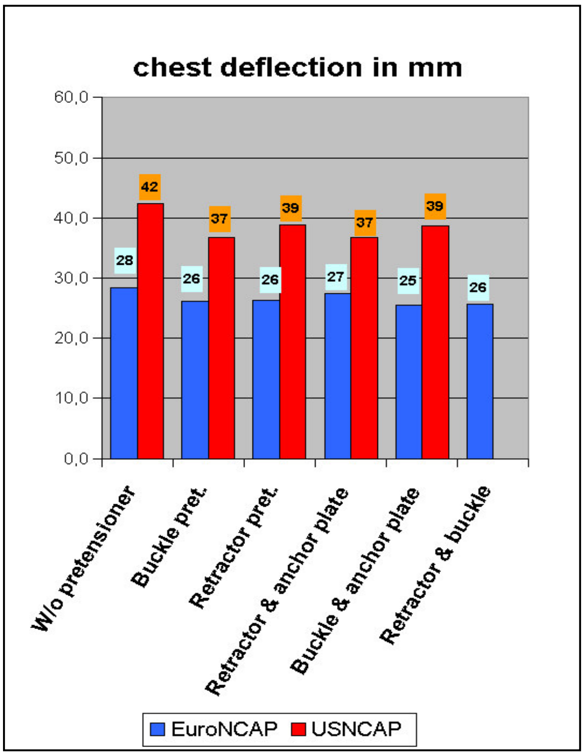

Figure 9. Chest deflection

In the further description of the test results we will focus on chest loading, i.e. chest acceleration a3ms and chest deflection, as these are the parameters that predominantly are influenced by the belt system. Figures 8 and 9 show the results. For each test configuration two tests were performed, the figures listed are the mean values. Figure 8 shows that pretensioning in general gives a benefit in chest acceleration with the one exception of the retractor pretensioning in the US-NCAP configuration. This one is to be considered being an artefact of the generic test set-up: the dummy pelvis had contact to the stiff seat substructure resulting in a pelvis z-acceleration which gave rise to a chest z-acceleration. Thus, the resultant chest acceleration given in the figure rose as well. In terms of chest acceleration, double pretensioning again reduced the figures.

Figure 9 shows the results for chest deflection. It can be seen that pretensioning in general reduces chest deflection, but at this stage no advantage of double pretensioning can be detected.

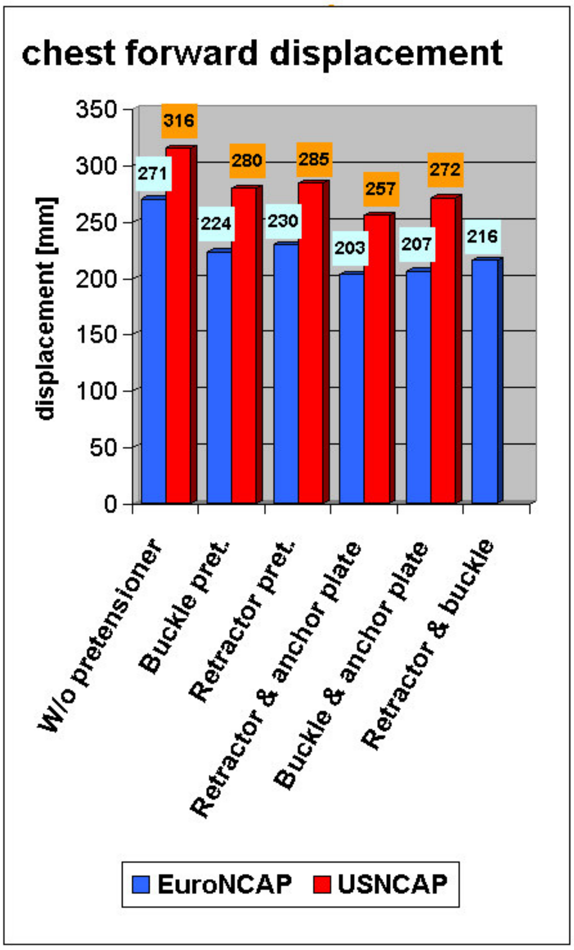

Figure 10. Maximum chest forward displacement at lower steering wheel level

Figure 11. Double pretensioning reduces chest forward displacement

Dummy chest forward displacement at the level of the lower steering wheel rim is reduced by single pretensioning by about 10% compared to the tests without pretensioner and again by around 10% when comparing double with single pretensioning (cf. figures 10 and 11.) It shows that the combinations retractor, resp. buckle and anchor plate pretensioner show significant bigger reductions than the combination of retractor and buckle pretensioner. Therefore, in the following discussion the latter combination is disregarded.

Taking the forward displacement of single pretensioning as baseline, the question is which benefit would provide double pretensioning when the load limiter force is reduced to a figure that forward displacement is equal to the one of single pretensioning. In order to answer this question, a MADYMO model was set up and validated. As a result, lowering the shoulder belt force, which was about 5000N in the baseline set-ups, by 500N to 1000N reduced the chest deflection by 2mm to 4mm in both US- and EuroNCAP configurations.

In order to validate the findings of the MADYMO investigation, a new test series (series 2) was set up. The configuration with buckle pretensioning was chosen as baseline because it gave the lowest chest forward displacement in the first test series. As it is well known that especially chest deflection is very dependant on the individual dummy, two repeat tests of this configuration were performed. The mean values of the two repeat tests now serve as baseline for the further comparison. The figures are listed in table 1 for the US-NCAP test condition and in table 2 for the EuroNCAP one. Compared to the tests of the first series, the chest deflection of the new baseline tests is 3mm to 5mm higher and the forward displacement in the EuroNCAP set-up 18mm lower. Additional to the above mentioned dummy problem, the latter one might be the result of slight deviation of the EuroNCAP test pulses between the two series.

Table 1.
Chest deflection and acceleration in relation to pretensioning and load limiter level, US-NCAP test condition, test series 2

	Shoulder belt force [N]	Chest forward displacement [mm]	Chest deflection [mm]	Chest acceleration a3ms [g]
Baseline buckle pretensioner only	5000	279	40	48
Buckle and anchor plate pretensioner	4500	276	34	44
Retractor and anchor plate pretensioner	4000	279	35	44

Table 2.
Chest deflection and acceleration in relation to pretensioning and load limiter level, EuroNCAP test condition, test series 2

	Shoulder belt force [N]	Chest forward displacement [mm]	Chest deflection [mm]	Chest acceleration a3ms [g]
Baseline buckle pretensioner only	5000	206	31	30
Buckle and anchor plate pretensioner	4500	204	25	27
Retractor and anchor plate pretensioner	4500	199	26	28
Retractor and anchor plate pretensioner	4000	218	23	29

The shoulder belt forces listed in tables 1 and 2 are to be regarded displaying the order of magnitude. The shoulder belt force in general is dependant on the diameter of the torsion bar in the spindle of the retractor, the number of turns of the torsion bar by pay out of webbing, the amount of webbing on the spool, and the friction in the pillar loop. With this, the load limiter level at the shoulder does not remain constant over the crash and can deviate from the given values by about 200N.

All load limiter levels are tuned to show the same forward displacement as the respective baseline test. The only exception is the case with retractor and anchor plate pretensioning in the EuroNCAP loadcase and 4000N shoulder belt force. This test had 12mm forward displacement more than the baseline. As this configuration showed in the US-NCAP loadcase the same forward displacement as the respective US-NCAP baseline, it can be assumed that this can be a valid configuration for both loadcases.

For each configuration two tests were performed. The mean deviation was ±0,61mm (1,89%) in chest deflection and ±0,19g (0,61%) in chest acceleration a3ms for an overall of 14 Euro- and US-NCAP sled tests. Thus, the figures can be regarded being quite reliable.

As a result, with double pretensioning, chest deflection was reduced by 16% to 26% in the EuroNCAP set-up and by 13% to 15% in the US-NCAP set-up.

3. COUPLING CRITERION

As outlined in the introduction, an early coupling of the occupant to the car deceleration is required. In section 1.3 a coupling criterion is described. This criterion is related to the force in the shoulder belt. As shown in the previous chapter, a strong coupling in the pelvis area is beneficial for the dummy loading, but this does not show in the shoulder belt force. Thus, there is a need for a new coupling criterion which reflects this. The goal is to define a calculation method to compare different pretensioning systems in the same test environment in respect to occupant coupling. The following conditions were defined:

- direct calculation of dummy data, no use of indirect forces (like belt forces);
- separate calculation for chest and pelvis, to pay respect to pretensioning at the pelvis.

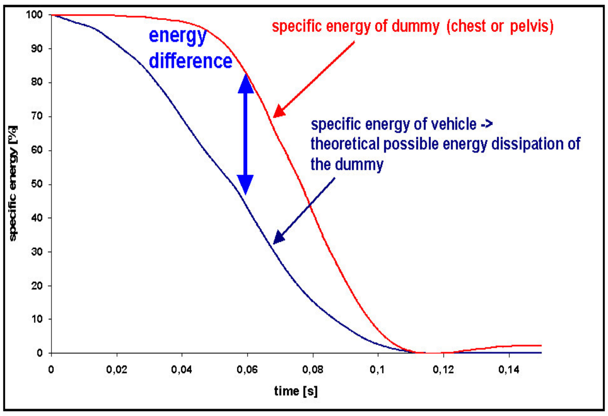

Figure 12. Energy loss of car (blue line) and occupant (red line) in a specific sled test

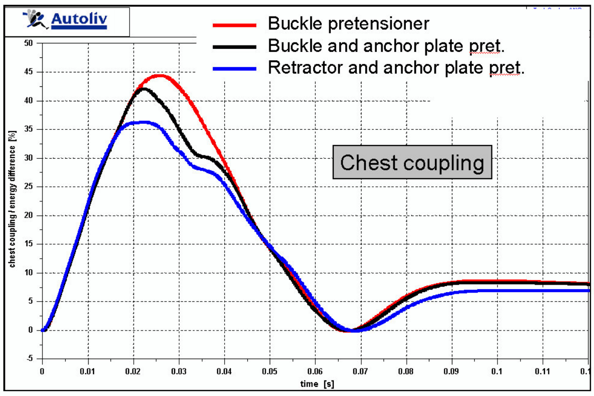

Figure 13. Relative energy loss detected from the thorax accelerometer of the dummy, US-NCAP test pulse

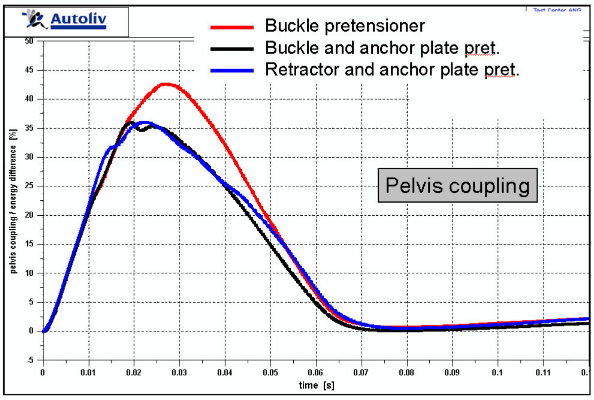

Figure 14. Relative energy loss detected from the pelvis accelerometer of the dummy, US-NCAP test pulse

The approach chosen is a comparison of theoretically possible and real energy reduction of the dummy during deceleration. Figure 12 depicts the relative energy reduction of the car, resp. sled and the dummy during a frontal crash. The energy at the beginning of the crash is taken as 100%.

The relative energy **e** is calculated from the car acceleration **a** by integration:

$$e = \frac{E}{m} = \frac{1}{2}\left(v_0 - \int a\,dt\right)^2,$$

with $\mathbf{v_0}$ being the velocity at the beginning of the crash.

The same energy calculation is done for the dummy, for practical reason independently for chest and pelvis. In the theoretical case that the dummy is optimally coupled to the car deceleration, its energy path will follow that of the car. Therefore, a deviation from this is a loss in coupling. Lower energy difference means better coupling.

Figures 13 and 14 depict the relative energy loss of chest and pelvis in the US-NCAP test condition. The lowest energy loss is detected for the double pretensioning set-ups. In the pelvis coupling both double pretensioner configurations show almost the same coupling. For the chest the combination of retractor and anchor plate pretensioner show the lowest energy loss.

It has to be mentioned that the maximum of energy difference is reached before airbag contact and before activation of the load limiter. Tests with a pelvis restraint cushion as supplementary restraint system to a retractor pretensioner were evaluated in the same manner. They showed that the coupling criterion here was as well a valid rating criterion.

Figure 15 depicts the coupling figures for the EuroNCAP and the US-NCAP loadcases from the first test series. It shows that the relative energy loss in general is bigger in the US-NCAP loadcase. In both loadcases it is reduced significantly by pretensioning and especially double pretensioning. Figure 16 shows as an example the relative energy difference of the dummy plotted vs. chest acceleration for the EuroNCAP loadcase. They show to be well correlated.

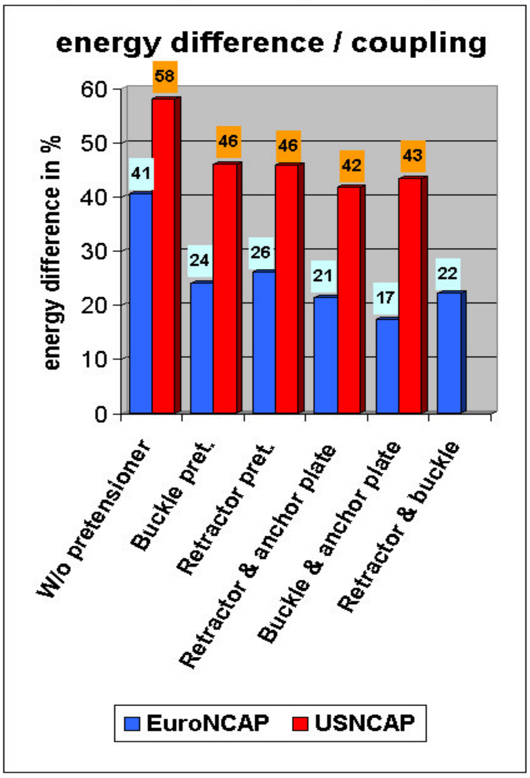

Figure 15. Maximum relative energy difference of the dummy compared to the sled from the first test series. The figures listed are the mean of chest and pelvis figures.

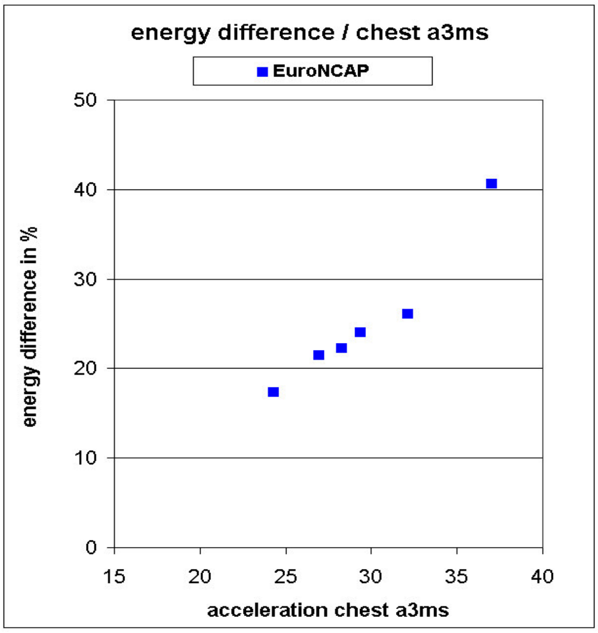

Figure 16. Maximum relative energy difference of the dummy plotted vs. chest acceleration, EuroNCAP loadcase, test series 1

4. DISCUSSION

In the following the benefit of double pretensioning in US-NCAP and EuroNCAP rating shall be discussed. For this we focus on test series 2, the results of which are listed in table 1 and 2. The outcome for the US-NCAP is shown in figure 17. For the generic test set-up it would mean an improvement from 3 to 4-star rating. As in our test series the airbag performance was left unchanged, improvements in terms of HIC might be achievable.

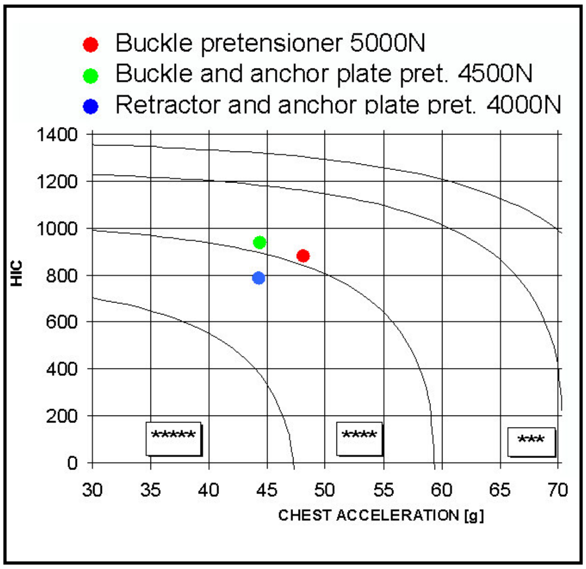

Figure 17. US-NCAP rating for test series 2

In the EuroNCAP loadcase, the chest deflection was reduced from 31mm to 23mm. This would mean in terms of points for the chest body region in the EuroNCAP rating an improvement from 2.77 to 3.80 points, i.e. one full point more in the total rating. Furthermore, the pelvis forward displacement is reduced by 44mm with double pretensioning. This can help in avoiding knee contact to the dash board and thus avoiding knee modifiers.

It has to be mentioned that by keeping the load limiter level at 5000N, pelvis forward displacement can be reduced by up to 75mm. Depending on whether the focus is on reduction of chest deflection or avoiding knee contact, the belt system can be adjusted accordingly.

The question arising is which additional benefit could be expected by further increasing pretensioner strength. This was investigated with the MADYMO model mentioned above. A double pretensioning set-up was chosen for the EuroNCAP loadcase. Both anchor plate and retractor pretensioners were fired without any time delay at T_0 (t = 0ms.) The anchor plate pretensioner was tuned to yield 4000N pre-load at the outer lap belt, the retractor pretensioner was tuned to yield 2000N pre-load at the shoulder. Both pretensioning forces being values considered to be close to biomechanical maximum values (cf. chapter 1.4). The load limiter in the shoulder belt was adjusted to 2000N, i.e. to the pretensioner level. As a result, chest deflection could be reduced by less than 10% compared to the benchmark of the best real system. This shows, that current double pretensioning systems are very close to the optimum. A further reduction in especially chest deflection can only be achieved by improved load limiter characteristics /4,5,8/.

The introduced coupling criterion (chapter 3) is a good tool to rate the coupling of the occupant to the car. As it only rates the beginning of the crash, it can be used in early stage of car development for improving coupling separately without being influenced by load limiter or airbag performance. As well it is a good tool in developing new pretensioner systems.

5. CONCLUSIONS

In US- and EuroNCAP test conditions, double pretensioning directly reduces chest acceleration by 10% - 20% compared to single pretensioning. Preliminary tests and simulations show that this is valid as well for the 5^{th} percentile female Hybrid III dummy. Double pretensioning and reduction of the load limiter level, in order to use the full space for dummy forward displacement gained by better occupant coupling, reduces chest deflection by about 15% - 25%.

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