THE MECHANISM OF BELT INDUCED CHEST DEFLECTION: ANALYSIS AND POSSIBILITIES FOR REDUCTION.

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Paper Number 07-0202

ABSTRACT

A precondition for a good rating in Euro-NCAP frontal impact is a low value for chest deflection. To achieve this, detailed knowledge of the mechanism of chest deflection is needed. Consequently, the objectives of this study were a detailed analysis of the belt induced chest deflection and a finding of solutions to reduce it.

Theoretical investigations as well as simulation (software Madymo 6.1) were used to study the mechanism of chest deflection. The simulation environment represented a typical middle class vehicle. A special simulation dummy which allowed a detailed analysis of the internal and external forces acting on the thorax was used. Finally, sled tests were carried out in order to confirm the theoretical and numerical results.

For the environment investigated, the belt force turned out to be the dominant factor for chest deflection. In fact, the value for chest deflection showed a good correlation to the arithmetic mean of the shoulder belt force (FB3) and the force of the inner diagonal belt (FB4). While FB3 is commonly limited by a load limiter in the retractor, FB4 is strongly influenced by the forces in the lap portion of the belt. These forces are usually 1kN to 2kN larger than the level of load limitation. Preventing the belt slippage through the buckle tongue proved to substantially reduce FB4. Along with this chest deflection in tests with Euro-NCAP deceleration pulse was reduced.

A prototype of a locking tongue was developed and sled tests were carried out in different vehicle environments. It was shown that depending on belt geometry a reduction in chest deflection of 10-25% could be achieved.

1. INTRODUCTION

During the past years load limiting of safety belts has become standard in vehicles on front seats. The reason of the implementation of load limiters was to reduce the force at the shoulder belt to a pre-defined level and achieve an optimal usage of the space available in the passenger compartment during retention /1/. The benefit of load limiting is evident and can be seen as well in real life, cp. fig.1.

Due to the importance of chest deflection in real life and testing (Euro-NCAP, e.g.), effects which influence chest deflection were analyzed. As a result of this, the correlation between shoulder belt load and chest deflection is commonly accepted /1/ /2/ /3/ /4/ /5/.

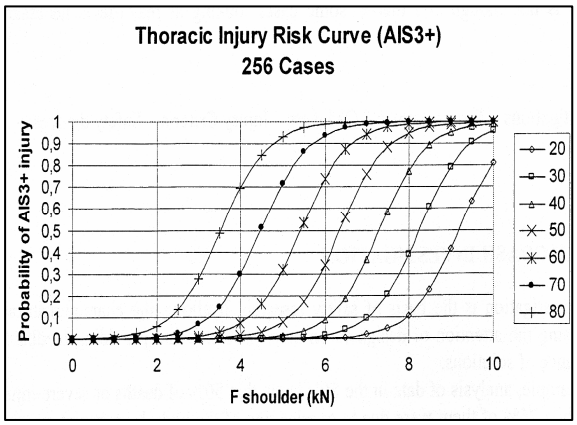

Figure 1. Probability of severe thoracic injuries (AIS3 or more severe) depending on the shoulder belt force and the occupant's age /2/.

In fact, previous studies discuss the interaction between shoulder belt load and chest deflection. Other belt parameters, which might influence chest deflection, are not matter of previous investigations.

As a result of these considerations, belt induced chest deflection has to be analysed in detail to find other belt parameters which effect on chest deflection.

2. BELT INDUCED CHEST DEFLECTION

Belt induced chest deflection is caused by the resultant force on the sternum. This force depends on

- the geometry of the belt system
- the magnitude of the forces FB3 (shoulder belt) and FB4 (diagonal inner belt), cp. figure 2.

Figure 2. Location of belt force sensors.

2.1 Belt Load

In a typical frontal crash with a standard belt system which includes a constant load limiter the belt load FB3 has an almost constant level. In contrast to this an increasing in belt load FB4 and FB6 (belt force at the anchor plate) is noticeable, cp. figure 3. The increase in belt force FB4 is caused by higher forces in the lap belt compared to the diagonal belt.
As the resultant force on the thorax depends on the magnitude of both forces FB3 and FB4, it is also increasing.

As a result of these considerations, the belt force FB4 should be also limited respectively reduced to decrease belt induced chest deflection.

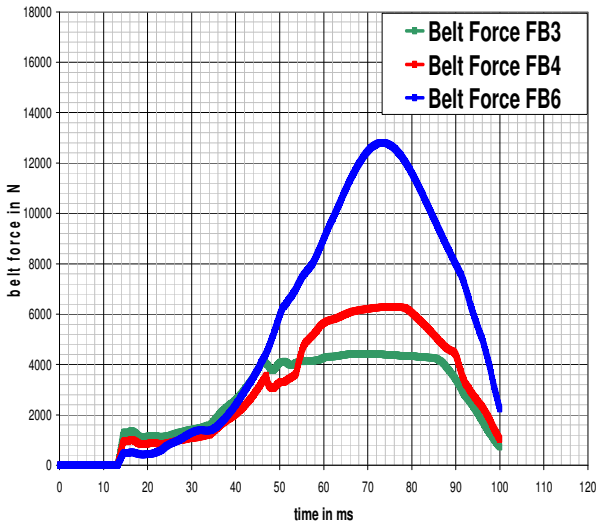

Figure 3. Exemplary curve progression of belt forces versus time with a constant load limiter. The belt force FB3 has a constant level, an increasing in belt forces FB4 and FB6 is noticeable.

2.2 Geometry effects

Assuming a constant load in the webbing, the resultant force of the belt on the thorax depends on the direction of the belt forces FB3 and FB4. During forward displacement, the load on the thorax increases due to the change of the direction of the belt forces, cp. figure 4.

Furthermore, during forward displacement of the dummy with rotation, the load on the clavicle increases and consequently the load on the sternum decreases.

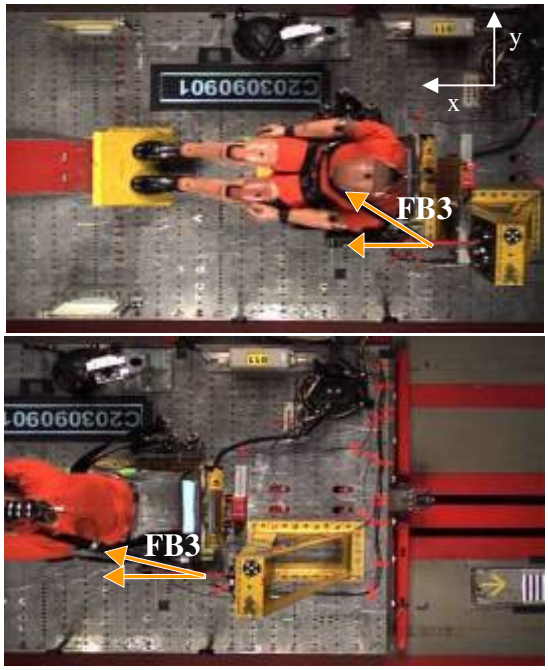

Figure 4. Belt force vector of the shoulder part increases in x-direction due to forward displacement which leads to an increase in the resultant force on thorax.

3. METHODS

3.1 Environment used for testing and simulation

In addition to theoretical considerations sled-tests and MADYMO simulations were done in an environment which represents a typical middle class vehicle on the driver side.

For the calculation a MADYMO 6.1 model was used. Following properties have to be mentioned:

- the original steering column was replaced by a fixed one
- a special software dummy called Force Balanced Dummy was used

Compared to the standard simulation dummy the Force Balanced Dummy can record and evaluate internal forces (like shear forces between parts of the body), airbag, seatbelt and seat forces on the dummy segments separately. It is comparable with the simulation dummy, which is known as E-Dummy /6/.

Concerning the set-up of the dynamic tests following conditions characterise the environment:

- serial seat
- serial driver airbag
- rigid steering column
- no IP (no knee contact)
- belt system with load limiter and retractor pretensioning
- Dummy Hybrid III 50th percentile
- US - / Euro-NCAP pulse

3.2 Reduction of the belt force FB4

As a result of the considerations in chapter 2.1, the reduction of belt load FB4 has to be realised in simulation and test environment.

One way to reduce the belt force FB4 is to prevent slippage from the diagonal belt into the lap belt. Slippage from lap into the diagonal belt is

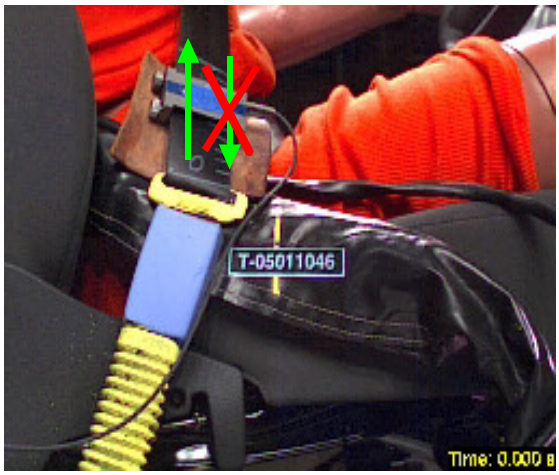

Figure 5. Principle of a tongue, which prevents slippage from diagonal in the lap portion.

possible (in order to enable webbing slippage through the tongue during retractor pretensioning). The opposite direction of webbing slippage, from the diagonal to the lap portion, is prevented, see figure 5. The expected effect is a reduction in belt force FB4 (diagonal inner) and an increase in the force on pelvis due to higher forces in the lap belt. Furthermore, the change of the load path should lead to higher shear forces between pelvis and thorax, cp. figure 6.

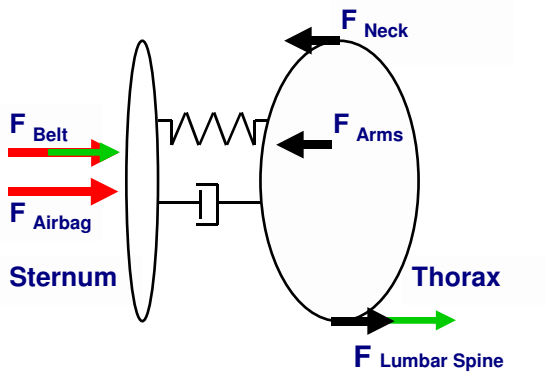

Figure 6. Change of the load path: Reduction of the resultant belt load on the thorax, increasing in shear force F Lumbar Spine.

4. SIMULATION AND TEST RESULTS

4.1 Simulation Results

In order to demonstrate the effect, simulations were done in the described environment. Figure 7 points out the forces on the thorax with a standard belt system, and a tongue, which prevents slippage in one direction (hereafter referred to as locking tongue).

As expected a reduction in the belt force on the thorax and an increase in the shear forces between thorax and pelvis can be observed in the simulation environment by using the locking tongue. The change of the load path is evident.

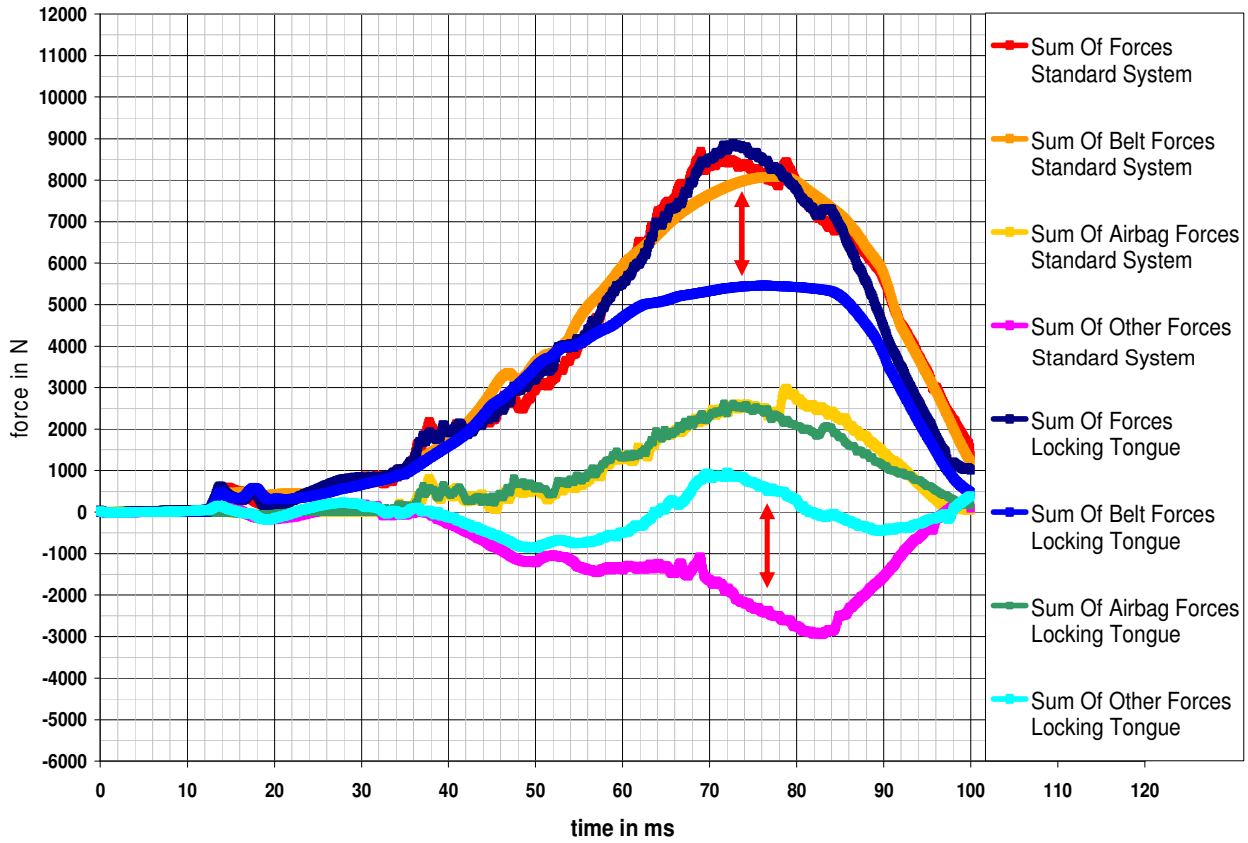

Figure 7. Forces on the thorax with a standard belt system and a tongue, which prevents slippage in one direction. A reduction of the resultant belt load on the thorax and a increasing in the shear forces can be noticed.

The effect on injury criteria and the dummy forward displacement is given in table 1.

	Chest deflection in mm	Chest acceleration 3ms in g	Pelvis forward displacement in mm
Standard Tongue	39	51,4	233
Locking Tongue	32	52,8	229

Table 1. Simulation results with HIII 50% and Euro-NCAP pulse. The reduction in chest deflection is evident.

As a result, a reduction in chest deflection of 7mm (18%) with a usage of the locking tongue is noticeable. Furthermore a not relevant increasing in chest acceleration can be established. Finally, the forward displacement of the dummy decreases marginally compared to the standard belt system.

In addition to this two relevant influences on the effect should be mentioned.
In table 2 the difference between HIII 50% and HIII 5% is demonstrated, calculated with an US-NCAP pulse (56km/h, 0°). As we can see, the effect depends on the occupant's mass. A higher mass leads to enlarge the effect.

	HIII 50%	HIII 5%
Percentile benefit concerning chest deflection by using a locking tongue	33%	13,5%

Table 2. Benefit concerning chest deflection with different dummies, calculated with US-NCAP pulse. A higher reduction in chest deflection with the 50% dummy compared to the 5% dummy can be noticed.

As a second influence the stiffness of the pulse has to be mentioned. Stiffer pulses lead to amplify the effect, cp. table 3.

	35 km/h crash velocity	45 km/h crash velocity	56km/h crash velocity
Percentile benefit concerning chest deflection by using a locking tongue	11%	28%	33%

Table 3. Benefit concerning chest deflection with different pulses. Stiffer pulses lead to amplify of the effect.

As described in chapter 2.2, geometry effects lead to different loading of the thorax. Under the condition of constant belt loads FB3 (shoulder) and FB4 (diagonal inner), realised with a locked tongue,

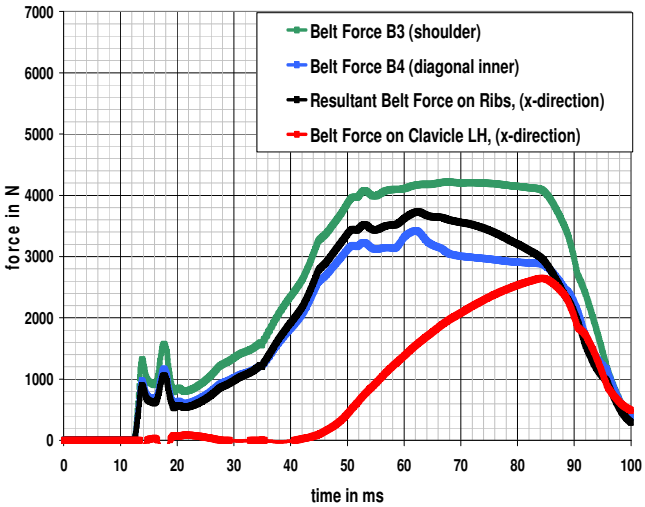

Figure 8. Almost constant belt loads FB3 and FB4. The result of the belt loading is an almost constant load on ribs and an increasing in load on clavicle.

chest deflection shows an almost constant behaviour in the environment investigated. Furthermore an increasing in load on the clavicle was noticeable, cp. figure 8.

Summarised: An increasing in the resultant force on the thorax is calculated, see figure 7. The resultant force itself is the sum of the load on the sternum (which has an almost constant curve progression) and the load on the clavicle (which increases), cp. fig. 8.

4.2 Test Results

To verify the simulation results and to measure the benefit concerning chest deflection, sled-tests were performed in the described environment, cp. chapter 3.1.

The following figures will describe the results of this comparison with a standard belt system (conventional tongue) and a system, which includes a locking tongue. The locking mechanism of the tested tongue is equivalent to the mentioned principle in chapter 3.2.

Due to the importance of chest deflection in Euro-NCAP tests, a Euro-NCAP pulse was used.

In figure 9 the belt force FB3 of both systems are shown. As expected, the curves are comparable.

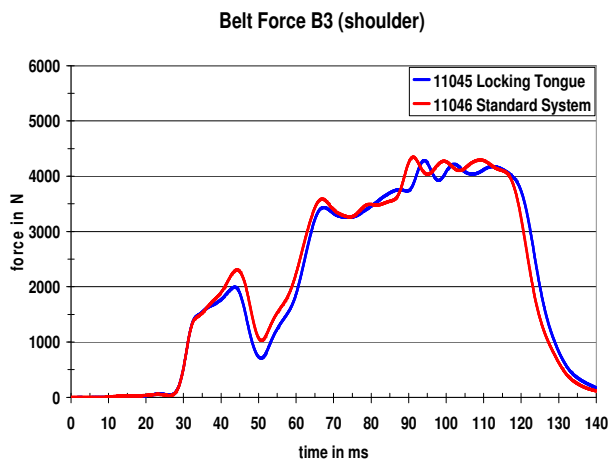

Figure 9. Shoulder belt force FB3 versus time.

In contrast to this, a difference in belt force FB4 (diagonal inner) is noticeable. After 78ms the belt force increase with the standard system and achieve a level of about 6 kN, the system with locked tongue has a maximum value of about 4 kN belt force. Consequently, the system with the locked tongue reduces the belt force of about 2 kN compared with the reference system, cp. figure 10.

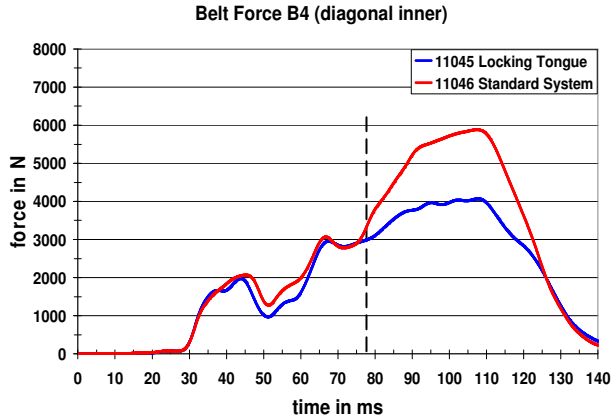

Figure 10. Belt force FB4 (diagonal inner) versus time. A reduction of belt load with the locked tongue of about 2 kN is noticeable.

As described in chapter 3.2, the change of the load path with a locked tongue leads to higher belt forces on the pelvis lap compared with a standard tongue. An increasing in belt force FB6 (anchor plate) of about 1.5 kN can be noticed (fig. 11).

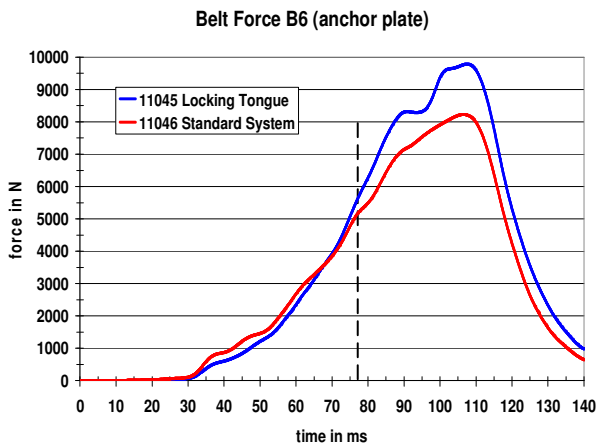

Figure 11. Belt force FB6 (anchor plate) versus time. An increasing belt force with the locking tongue can be observed.

After about 78 ms the differences in the chest deflection between the locked tongue and the reference tongue are noticeable, cp. figure 12.

In fact, the maximum value of chest deflection could be reduced at about 8mm and 25%, respectively.

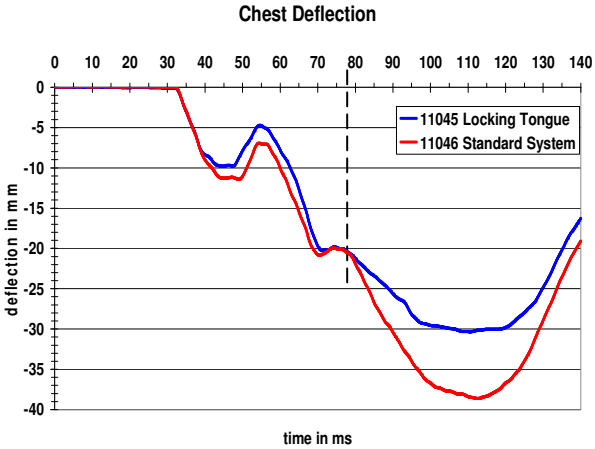

Figure 12. Reduction in the chest deflection with a locked tongue.

The following figures show the influence of the effect on chest and pelvis acceleration.
The resultant chest acceleration with both tongues is comparable, cp. figure 13.

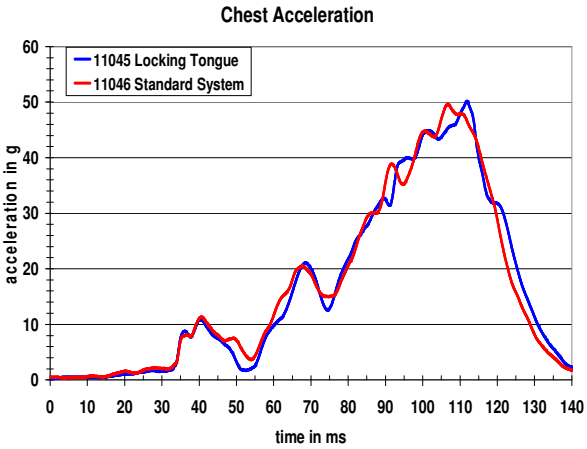

Figure 13. Resultant chest acceleration with comparable curve progressions.

Concerning pelvis acceleration the measured data show an increase in the maximum value of about 3.5g, see figure 14.

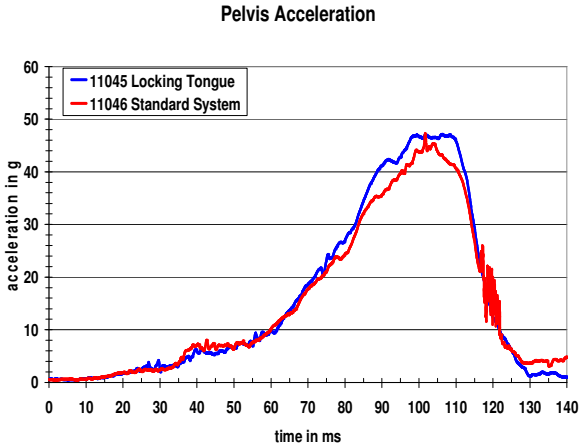

Figure 14. Resultant pelvis acceleration versus time. A small increasing in acceleration with the locked tongue can be noticed.

5. DISCUSSION

As shown in theoretical consideration, simulation and sled-test results, belt induced chest deflection depends on belt force shoulder FB3 and diagonal inner FB4 and the belt geometry.

Due to the usual limitation of the shoulder belt force FB3 by the retractor the belt load diagonal inner FB4 was the focus of the investigation.
Chest deflection is directly influenced by this belt force. A benefit of 18% concerning deflection in simulation with a reduced belt force diagonal inner was achieved, cp. table 1.
In sled tests comparable magnitude of reduction in chest deflection could be achieved, cp. figure 10 (belt forces) and fig. 12 (chest deflection).

The maximum value of the belt force FB4 depends on pelvis retention. Components (e.g. knee bag, pelvis restraint cushion, double pretensioning /1/), which lead to higher pelvis retention, will reduce the belt load in the lap portion of the belt. As a result of this the belt force diagonal inner FB4 also decreases. As an example, the benefit concerning chest deflection by using a knee – airbag is, among others, the result of this effect.

Concerning the injury values chest- and pelvis acceleration, simulation and testing lead to minor different results. Both show an increasing in pelvis acceleration. In contrast to this simulation results show a small increasing in chest acceleration, too, which wasn't measured in testing, cp. fig. 13.
In terms of the usage in Euro-NCAP with the focus on chest deflection, the calculated / measured

increasing in dummy acceleration values seems to be not relevant.

Concerning the geometry two important effects have to be mentioned: An increasing in the resultant force on the thorax and a reduction of load on the ribs by increasing in load on the clavicle. In the environment investigated, these effects are compensating each other, cp. fig. 8. The dimension of each effect depends on the vehicle environment, of course. On the one hand, they are affected by buckle and pillar loop geometry in respect of the dummy position. On the other hand, the reduction of belt load on the ribs by loading the clavicle depends on the dummy rotation during the load limiting phases. More rotation of the dummy or occupant leads to more load on the clavicle and less on the ribs.

In Euro-NCAP knee impact is also an important point of interest. A system with a locked buckle tongue, which prevents belt slippage from diagonal into the lap portion, will lead to less pelvis displacement. As a result of this, femur forces (induced by knee impact) can be potentially reduced. In the environment investigated, no knee contact was defined. So, the evidence about the dimension of this effect can't be given and should be investigated.
However, the positive effect on femur forces seems to be smaller compared with double pretensioning systems.

Closing, the utilization of a system with a locking tongue has to be discussed. To reduce chest deflection with a reduction of the belt force FB4 following boundary conditions have to be analysed:

- Belt slippages with a standard buckle tongue.
  The slippage shows the dimension of the pelvis retention. If no slippage is noticeable, an implementation of a locking tongue won't affect the chest deflection positively.

- Airbag influence
  Chest deflection is a function of loads from belt and airbag on the sternum. The magnitude of loading on the sternum by airbags varies. In some cases the airbag becomes possibly the dominant factor for chest deflection. As a result of this, the locking tongue would not reduce the maximum of chest deflection.

To analyse this, however, further investigations are needed.

6. CONCLUSIONS

Chest deflection is induced by airbag and belt loads on the thorax. Concerning the belt induced load on the thorax, both belt loads FB3 (shoulder) and FB4 (diagonal inner) influences chest deflection. The belt load FB3 is mainly influenced by the load limiter of the retractor, FB4 by the belt load in the lap portion.

In current belt systems the force in the lap portion of the belt is much higher compared with belt force of the shoulder. The result of this is an increase in belt forces of the lower diagonal portion. As a result of this, chest deflection also increases.

The dimension of the difference in belt loads between the lap portion of the belt and the diagonal portion depends on the pelvis retention. Furthermore, pelvis retention is responsible for the dummy kinematics – and, as well known, dummy rotation is beneficial for the deflection values.

One solution to reduce the belt force FB4 is preventing the slippage through the buckle during load limiting. In the environment investigated, tests with a modified tongue reduced the deflection of about 25%.

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