OPTIMIZED RESTRAINT SYSTEMS FOR REAR SEAT PASSENGERS

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Paper Number 98-S1-W-23

ABSTRACT

Restraint systems for front seats have experienced continual improvement in recent years, in particular through the introduction of airbags. The standard for rear seats, however, is still the conventional three-point belt on outer seats and the lap belt for the middle seat position. As using airbags in rear seats is very problematic, the feasibility and protective effect will be examined of a belt system equipped with a belt pretensioner and a load limiter. To do so, first the marginal conditions constituted by legislation, findings from accident investigations, and seat position and belt geometry in rear seats will all be discussed in detail. Results from sled testing and MADYMO simulations allow the following to be said: Optimized belt systems very much reduce thorax loading, the largest effect for chest deflection coming from the load limiter, but for V*C, on the other hand, from the pretensioner. It emerges that a vehicle crash pulse that is 30% harder with an optimized belt system produces lower thorax loading values for rear seat occupants than a corresponding "softer" pulse with a conventional three-point belt.

1. INTRODUCTION

The restraint systems on the front seats of automobiles have been continuously improved in recent years. Thus the best restraint systems today consist of a safety belt with a pretensioner and load limiter, and an airbag. In rear seats, however, the standard is an automatic three-point belt for the outer seats and a static lap belt for the middle seat. Only very few models have a three-point belt on the middle seat and/or a belt system with pretensioner.

Due to the forthcoming introduction of the 40%-ODB crash test as a prerequisite for type approval of automobiles in Europe, and an improvement in vehicle structure for this test, the crumple zones of cars - especially small cars - are becoming stiffer. This can be seen especially in crash tests according to the US-regulation FMVSS 208 against a rigid barrier with 100% overlap. With vehicle deceleration like this, the dummy loading on rear seats can exceeded the respective acceptance levels. It is therefore necessary for the restraint system to be adapted to such vehicle deceleration.

Introducing an airbag also for rear-seat passengers, however, appears problematic. For one thing, there are hardly any suitable mounting locations available, and for another, the out-of-position problems in rear seats would be much greater than in the front passenger seat, also and especially because children are usually transported in the rear seat.

This examination is to show what additional protective effect an improved belt system alone can have. This improvement can be broken down into two stages:

1) Belt-pretensioning, which starts within the first milliseconds of an impact, thus creating the optimal preconditions for the restraint system to have its effect,

2) Load-limiting, which, while the occupant is being shifted forward, limits the belt forces affecting the occupant and makes the best possible use of the available interior space to decelerate the occupant.

In the following, a survey will first be given of the marginal conditions in which the optimization can take place. To do so, the legislative situation will be described first and the occurrence of accidents with rear-seat occupants explained. A discussion then follows of the special circumstances for rear-seat passengers with regard to seat position and belt geometry. Marginal conditions for optimizing belt systems in rear seats can be derived from these explanations. The improvement possible in the occupant loading values is estimated using sled tests. A MADYMO model was prepared to determine the parameters influencing the dummy loading.

2. LEGISLATION

The ECE-R 16, or the corresponding EC Directive 77/541 form the legal basis for type approval of safety belts in Europe. In the ECE-R 16, the tests are listed that a safety belt has to pass through to be approved, or which must be carried out along with production to maintain licensing. Two kinds of testing can be distinguished:

1. Laboratory testing
2. Dynamic sled testing

1. The laboratory tests include testing of sensor systems for locking behavior, measuring of the belt's retracting force, opening force of the buckle, environment-simulation and durability testing, as well as quasi-static breaking load testing of buckles, belts and retractors.

2. A dynamic sled test is to simulate the strength of the belt system in a head-on collision. This is done using a test sled with a steel seat, on which a 75-kg standardized manikin sits, which in its dimensions is supposed to represent a 50-percentile man. The standardized manikin is buckled up with the belt system to be tested with reference to its H-point in the vehicle geometry. The belt system is tested in new condition and after environment-simulation and durability testing. The test sled is accelerated to 50 km/h and exposed to a nearly rectangular deceleration pulse of 26 - 32 g. When this is done, the test manikin may shift forward in the pelvic area between 80 and 200 mm, and in the chest area between 100 and 300 mm; for pretensioner systems, the lower limits are reduced by one half. The belt system must not suffer any damage during the testing.

The ECE-R 16 therefore describes a method for testing belt systems that originates from a time when passive vehicle safety in Europe was still in its infancy. The lower limit of the forward displacement is supposed to assure that the belt system assumes the manikin's energy, without allowing great belt forces to occur; limiting the value upwardly is supposed to prevent the chest and head from coming into contact with any parts of the vehicle in a real accident at a high impact speed. Biomechanical response values, however, were not determined; the manikin is not designed for this purpose.

When optimizing safety belts, the forward displacement of the chest being limited to 300 mm can be a great restriction in the selection of the load-limiter level most favorable for the occupant. The ECE-R 16 does in fact, under certain marginal conditions, allow for the 300 mm to be exceeded, but these exemptions can only be used for front seats. The relevant regulation for the USA, however, the FMVSS 209, generally allows greater forward displacement of chest.

3. ACCIDENT INVESTIGATIONS

There are numerous accident studies that supply evidence for the effectiveness of safety belts in rear seats /1/, but only few that describe the types of injuries to occupants protected by safety belts. The following account is based on an investigation carried out in Great Britain /2/. The study covers accidents that were recorded between 1992 and 1995.

Table 1 shows an overview about injuries and severity of injuries to individual parts of the body. The study included occupants of head-on collisions, roll-over accidents, and in side impacts on the side away from impact. In comparison with the front seat, the severity of injury in the rear seat is much less. Thus in the collective accidents, injuries were suffered by 41.5% of the occupants in the front seats, but only by 23.8% of the occupants in the rear seats.

There is a greater probability of abdominal injuries in the rear seats that is very obvious. The belt can be established as the cause of these injuries for 85% of the MAIS 1 injuries and 60% of the MAIS 2+ injuries, allowing one to infer submarining. In addition to arm injuries, which are only classified as MAIS 1, thorax injuries occur most frequently. In these cases, too, the safety belt is considered to be responsible. Among the collective of occupants who had not been wearing a safety belt, the frequency and severity of injuries was higher, as expected. The study estimates that safety belts reduce the risky of injury in rear seats by 40%.

	Rear seat (N = 126)		Front seat (N = 755)	
	%MAIS 1+	%MAIS 2+	%MAIS 1+	%MAIS 2+
Head	3,2	0,8	7,2	2,5
Face	-	-	0,8	-
Neck	0,8	-	2,4	0,9
Arms	6,3	-	8,3	1,7
Thorax	6,3	1,6	10,9	3,8
Abdomen	**3,2**	1,6	2,1	1,2
Spine	0,8	-	2,8	0,5
Legs	3,2	2,4	7,0	2,8
Sum	**23,8**	**6,4**	**41,5**	**13,4**

Table 1: Injury severity degrees MAIS 1 or MAIS 2 or more severe for individual parts of the body of automobile occupants protected by safety belts /2/.

4. SEAT POSITION AND BELT GEOMETRY IN REAR SEATS

The belt geometry in rear seats is many times less favorable than in front seats; cf. Figures 1 and 2. This is due on the one hand to vehicle geometry, which does not permit optimal belt-anchoring points - the rear wheel house, for example, restricts the possibilities of fastening the anchor fitting. On the other hand, the rear seat running all the way through results in restrictions in fastening buckles. The seat position of the occupant in the rear seat is also different from in the front seat. Due to the restricted foot space extending to the front seat, the knees bend further causing the pelvis to tilt further backwards. The geometry of belts and the seat position result in the angle between the lap belt and the pelvis normal becoming comparatively small. As a consequence, the risk in a head-on collision of the lap belt slipping over the wings of ilium is evident, i.e., submarining can occur /3/. The upper fastening point of the shoulder belt, which has frequently been positioned far to the rear (cf. Fig 2), also promotes submarining.

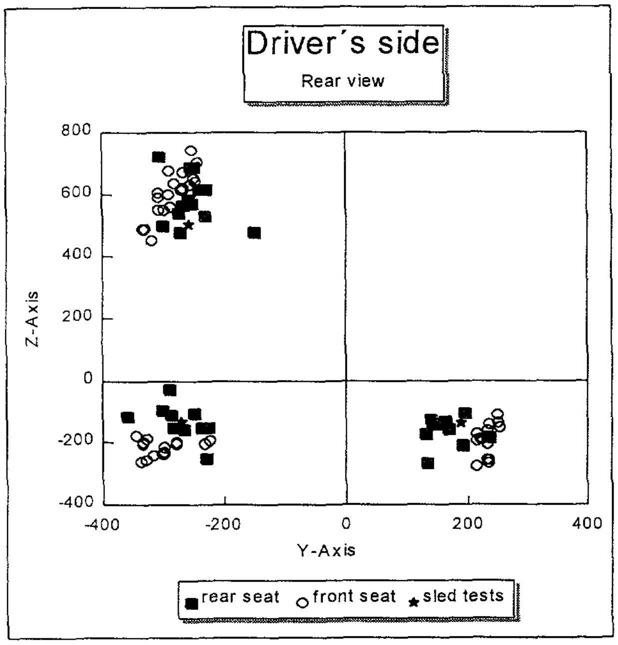


Figure 1: Position of the belt-anchoring points of various cars, measuring from the H-point of the dummy, in the direction of traffic. Also shown are the anchoring points as they are used in the testing in Section 7.

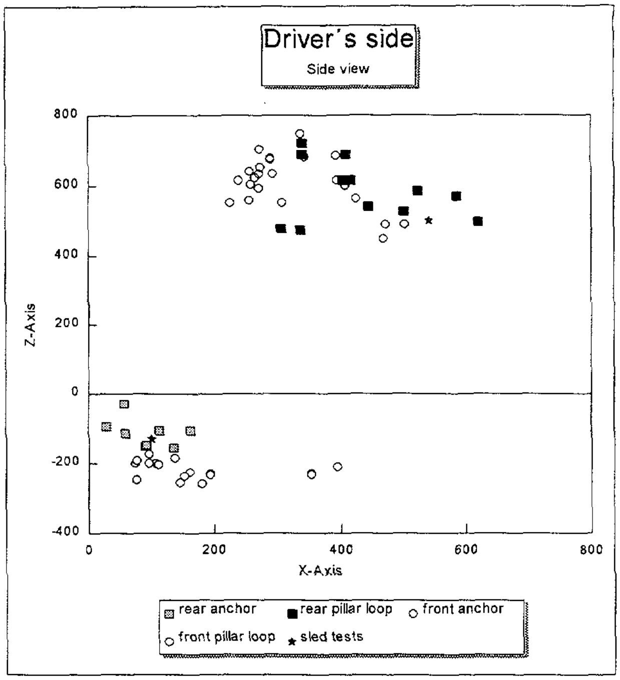


Figure 2: Position of the belt-anchoring points of various cars, measuring from the H-point of the dummy, in the direction of traffic. Also shown are the anchoring points as they are used in the testing in Section 7.

Another point requiring special attention is the back-rest of the front seat. It restricts the room for movement available in frontal collision. The back-rest itself, however, also moves forward during an impact, increasing the room for movement for a certain time window.

5. BELT PRETENSIONING AND LOAD LIMITING

A large amount of slack in the belt system results in a worsening of the occupant loading values during a head-on collision and can promote submarining. Thus 80% of car drivers' belt slack is between 40 and 90 mm in summer and between 40 and 120 mm in winter /4/. Similar belt slackness rates can be expected in rear seats. The pretensioning system is meant to pull the slack out before the shift forward caused by impact has even begun. The belt system is as it were put in the best possible starting condition during the first milliseconds of an accident. In principle the belt system can be tightened at all of its fastening points on the vehicle. The common methods used today are the buckle pretensioner and the retractor pretensioner. With the former the buckle is pulled down approx. 60 to 80 mm, with the latter the belt roller is wound. Whereas mechanical pretensioner systems were frequently used in the beginning, new vehicles today are usually equipped with pyrotechnically operated systems.

The force limitation in a three-point belt is supposed to limit the belt forces and thus in particular keep the thorax loading values down. Load limiters were used in mass production as early as the beginning of the 70's - back then of course without airbags. Accident analyses substantiate their use /5/. Today load limiters are mostly used in combination with an airbag for optimal performance of the total restraint system.

6. MARGINAL CONDITIONS IN OPTIMIZING THE RESTRAINT SYSTEM FOR REAR SEATS

The following marginal conditions in optimizing the rear-seat belt system can be derived from the preceding explanations:

1) Owing to belt geometry and seat position, a tendency to submarining occurs, which must not be reinforced through pretensioning and load limiting but rather ideally should even be reduced.

2) The load limiting has to be designed such that the free space available to the occupant, which increases dynamically through the back-rest moving forward, is optimally exploited without injury-relevant contact to the head coming about.

3) The belt system must qualify for type approval in accordance with ECE-R 16. This means that in the relevant sled testing in accordance with ECE-R 16, the standardized manikin must not move forward at chest height any further than 300 mm.

4) The restraint system must be optimized with regard to a chest loading criterion, ideally the viscous criterion V*C, because it is evident from the accident analyses that thorax injuries are the ones that play the decisive roll.

7. SLED TESTS AND RESULTS

A series of sled tests were carried out to estimate the expected reduction in dummy loading values through an optimized belt system. To do so, a belt geometry and seat position were selected that in our experience are typical (cf. Figs. 1,2 & 6). A Hybrid-III-50-percentile man was used as the dummy. A relatively stiff crash pulse was deliberately selected (peak deceleration of 33g, cf. Fig. 3), to allow for the fact that modern vehicles are becoming more stiff. The following tests were carried out:

1. Conventional belt system without pretensioner and load limiter,
2. Belt system only with retractor pretensioner, without load limiter,
3. Belt system with retractor pretensioner and load limiter.

A load limiter level of 5.5 kN was selected first because with such a system the ECE-R 16 requirement for maximum chest forward displacement of 300 mm can be met. In all the tests, after approx. 60 ms, the seat upholstery bottomed out, which resulted in strong vertical deceleration and influenced the dummy data measured. Such behavior can also be observed in real crash tests in which the dummy pelvis pushes through against the underseat panel.

Table 2 gives an overview about the test results. The data measured, which is against a gray background, have their maximum during the time interval of the pushing through and cannot be compared directly like this. A clear reduction can be seen in chest loading with a pretensioner and especially with a pretensioner and a load limiter. This appears especially in the values measured for V*C and chest deflection, which are not influenced by the seat upholstery being pushed through (Fig. 4). V*C in test 3 is around 70% lower in comparison with reference test 1, and the chest deflection by 40%. A possible reduction in the resulting chest deceleration by 20% can be estimated from the chest deceleration in direction x. A clear drop in head and neck loading can also be seen. As no contact to the head took place, in this case the HIC can only be considered as a reference value.

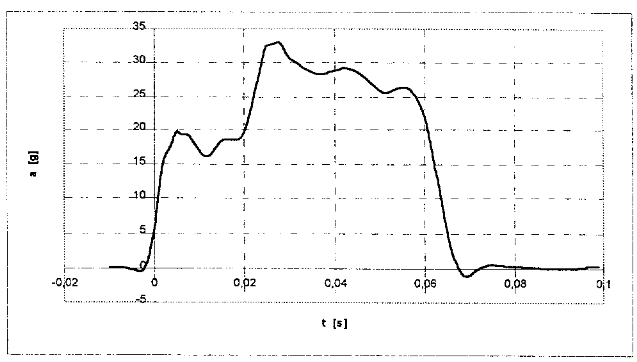


Figure 3: „Stiff" crash pulse for sled tests and MADYMO simulation

		Test		
		1	**2**	**3**
Head	HIC36	888	663	458
	a 3ms [g]	73.0	67.3	57.3
Neck	Fx [kN]	1.64	1.53	1.14
	Fz [kN]	2.75	2.49	2.24
	Extension [Nm]	66	18	73
	Flexion [Nm]	152	163	101
Thorax	Defl. [mm]	61.0	49.8	36.9
	a 3ms [g]	60.8	54.6	56.7
	a max x-Dir. [g]	60.5	54.8	47.6
	V*C [m/s] *)	0.95	0.55	0.28
Pelvis	a 3ms [g]	71.7	77.3	91.8
	a max x-Dir. [g]	54.2	52.2	44.9
Belt Force	Shoulder [kN]	10.8	10.0	5.9
	Anchor Fitting [kN]	11.4	11.1	10.4

*) calculated in accordance with SAE J 1727

Table 2: Test results of the sled tests.

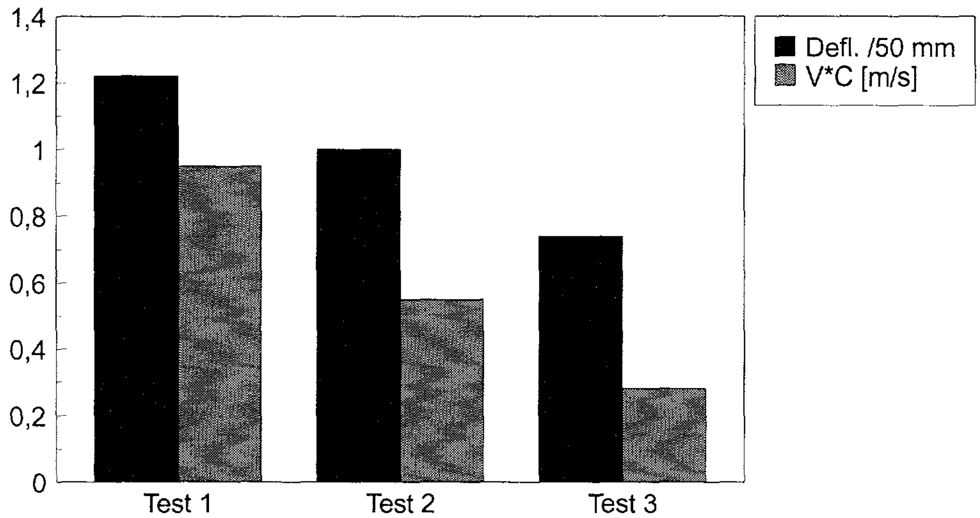


Figure 4: Sled tests 1-3, V*C and chest deflection as a function of the belt system

8. THE DEVELOPMENT OF A MADYMO MODEL

Analogously to the sled tests, a MADYMO model was set up and validated. The geometry of the simulation model matched the structure of the sled tests. The model was correlated using test no. 2 (with pretensioner, without load limiter) and checked on tests 1 and 3.

Good agreement appears both in the kinematics and in the time history of acceleration, especially in the chest and pelvic areas (Figure 5). As a result, the simulation model describes reality very well and serves as a basis for the following parameter study.

It was not, however, possible to reproduce in the MADYMO model so markedly the strong snapping over of the neck (approx. 90° relative to the upper part of the body). One possible cause for this might be the nape modeling of the TNO HIII dummy model possibly being too course for such extreme head/neck movements. Since the study concentrates primarily on the chest area, this was accepted in this case.

A further point is the difference in the V*C values between simulation and testing. The V*C value is calculated from the product of chest deflection and the deflection speed in relation to a reference value. In the test, the deflection speed is derived from the filtered signal from the chest potentiometer. This signal is by its nature not a curve with a smooth shape, and so an oscillating signal results for the speed derived from this. This oscillation also turns up again in the time history of the V*C. Furthermore, the signal is very dependent upon the filtering method selected - e.g. SAE J1727 and EC Directive 96/79/EC prescribes different methods. The testing therefore yields a maximum V*C because of a vibration peak and not from the global shape of the curve. This behavior is not to be seen in the simulation because there the signals are not provided with metrological static. The course of the V*C is "smoother" on the whole with a lower maximum value resulting from this. This is to be taken into account when one makes a comparative examination.

Furthermore, an attempt was made to obtain an indicator for submarining with the simulation model. In the parameter study carried out this was done by looking at the time history of the belt/pelvis angle, although the relatively simple belt modeling in the simulation model used only allows a relative belt/pelvis motion in the direction of the belt and not perpendicularly; i.e., true slippage of the belt over the pelvic pan is not possible in this case. Nevertheless, using a definition of relevant limiting angles (cf. /3/), it should, with comparatively little modeling expenditures, still be possible to make a statement about possible submarining. In no cases must submarining be allowed such that a yes/no statement is sufficient in this case.

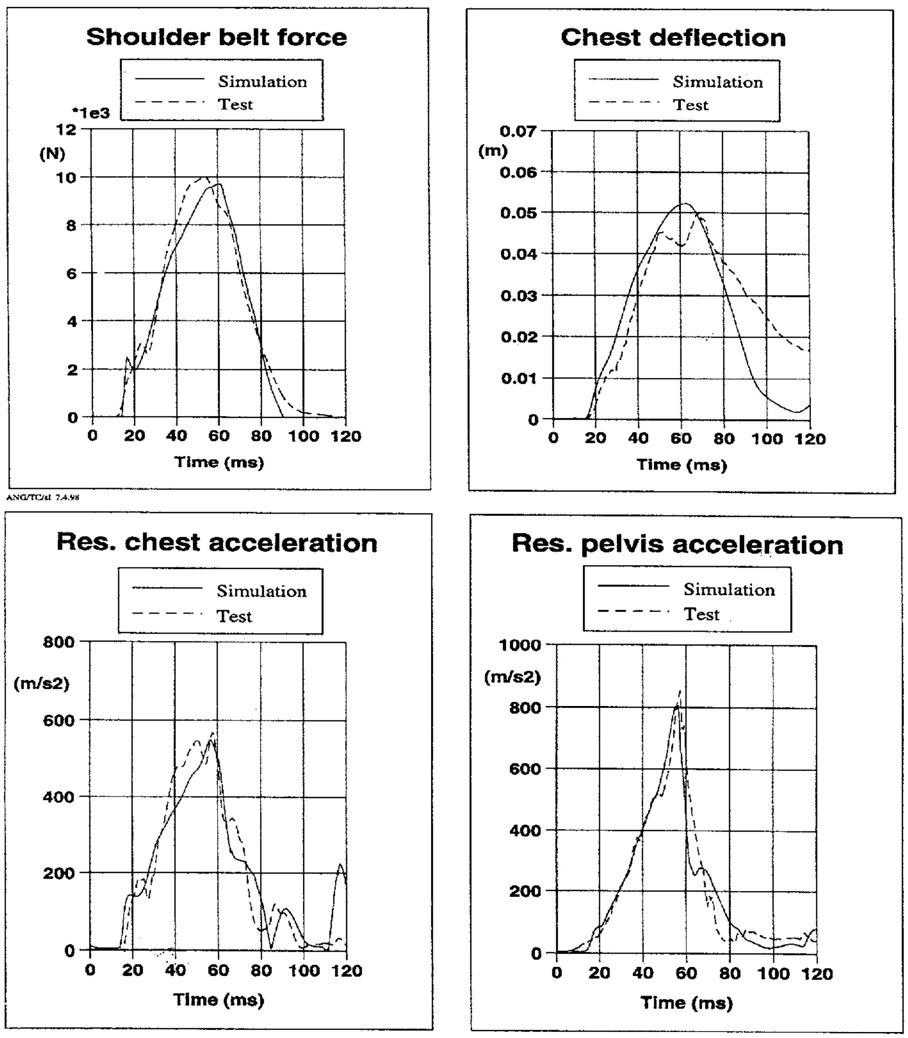
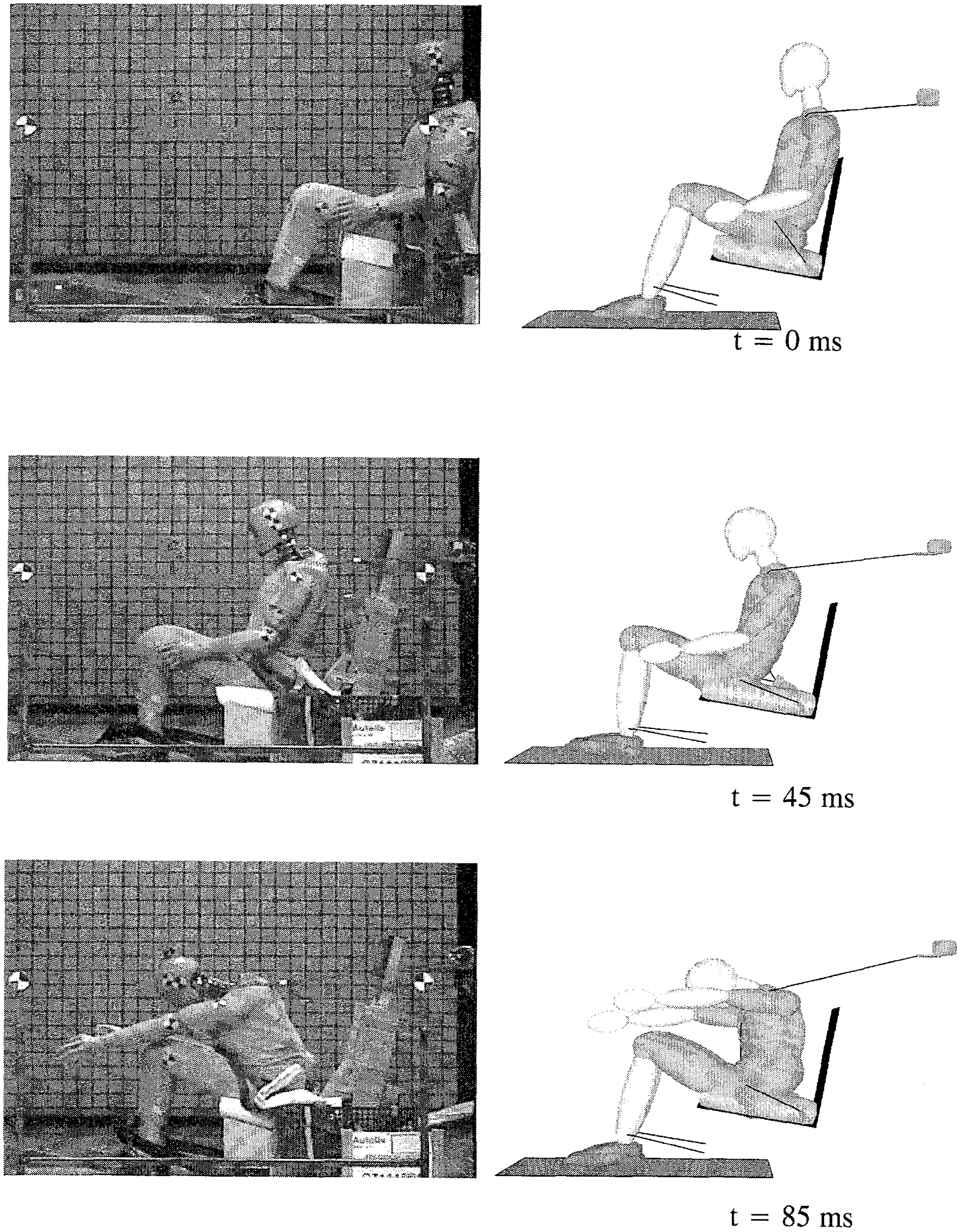


Figure 5: Results of the MADYMO simulation in comparison with the sled test.



Picture 6: Sled test No. 2 in comparison with MADYMO-Simulation

9. DETERMINING THE INFLUENCING PARAMETERS ON THE DUMMY LOADING

To determine the influence of individual parameters on dummy loading, three series of MADYMO simulations were carried out and evaluated for the effects of the individual parameters. In doing so, special attention is given to chest deflection and V*C. The testing was carried out separately for the three possible pretensioner systems - retractor, buckle and anchor-fitting pretensioners. To keep the simulation expenditures as low as possible, the influences were examined in a test matrix following the partially factored plan L16 2^{8-4}. This makes it possible to separate the individual influences from one another; only 16 simulations per type of pretensioner were necessary. Table 3 gives an overview about the individual parameter settings. The most favorable setting in each case is against a gray background. The corresponding settings for the sled tests are given as a comparison.

The variation of the belt anchoring points (parameters A and B) is supposed to cover the area possible in the vehicle (cf. Figures 1 and 2). The belt slackness approximately represents an average value of real belt slackness in summer and winter, cf. Section 5. The two stages of the foot position are supposed to represent the positions possible for the lower extremities with the front seat pushed forward or to the rear respectively. The range of variation of the angle of the seat ramp is supposed to cover a wide range of possible settings. The load limiter level was first selected according to the marginal conditions given (cf. Section 7). The variation of the vehicle pulse is supposed to make it possible to determine the influence of "stiff" and "soft" vehicles.

Table 4 and Fig. 7 give an overview about the effects of the individual parameters on chest deflection and viscous criterion. Interactions between two parameters only occur starting with the sixth position for chest deflection and starting from the fourth position for V*C and are not considered in the following.

The following picture results as far as chest deflection goes: A substantial reduction of 10 mm is caused by the force limitation, followed in second place by the vehicle pulse at 6 mm. The pretensioning contributes with approx. 5 mm and is in third place with retractors and anchor-fitting pretensioners.

For V*C, tightening for retractor and anchor-fitting pretensioners has the greatest influence; for buckle pretensioners, the belt slack that follows in second place for the other pretensioners. For buckle pretensioners it has to be mentioned that their tightening distance was limited to 60 mm in this study. If correspondingly longer distances were provided, it would definitely be possible to reduce the influence of belt slack in such cases. Vehicle pulse follows in third place for all types of pretensioners. Load limitation only follows starting from the fifth position. This can be explained in that V*C already assumes its maximum value before the force limitation comes into effect.

The simulations clearly shows that the influence of the characteristics of a modern belt system, i.e., pretensioning and force limiting, is greater on the chest loading values than the influence of a 30% stiffer crash pulse.

A goal was set in the beginning to obtain a reliable quantitative statement about submarining also with a simple MADYMO belt model by looking at the belt/pelvis angle, but during the course of the study, it turned out that this could not be achieved. This applies in particular to the parameters of tightening and belt slack, which change the belt geometry in the pelvis area from the very beginning. The following qualitative statements about these influences, however, can be made:

- *Rear, upper fastening point of shoulder belt:*
  This anchoring point should be as far forward as possible toward occupant shoulder. An anchoring point far in the rear promotes submarining.
- *Anchor fitting, buckle attachement*:
  Fastening points should be placed as far down as possible to avoid submarining.
- *Angle of seat ramp:*
  A steeper seat ramp has an effect against submarining.
- *Load limiting:*
  Force limitation in the retractor reduces the danger of submarining. The dummy's bending in the pelvic area enables the chest to move forward further and this a more favorable course of the belt in the pelvic area.

Caution must be exercised in interpreting the influences of the belt geometry (parameters A and B) on V*C and chest deflection. Low chest loads are obtained especially with the belt geometries that produce the greatest danger of submarining. A pelvis that is shifting forward sharply and turning in relieves the load on the chest area. But since submarining must definitively not be allowed, these parameter settings must be classified as less favorable on the whole (c.f. Table 3).

	Parameter	Stage 1	Stage 2	Sled tests
A	Anchor fitting, buckle (from H-point) x,z [mm]	100/-180 low	100/-80 *) high	100/-130 medium
B	Upper fastening point of shoulder belt (from H-point) x,z [mm]	350/700 to front, high	540/500 *) rearward, low	540/500 rearward, low
C	Belt slack (each 50 mm pelvis and thorax)	without	yes	without
D	Foot position (from H-point) x [mm]	-470 to front	-300 rearward	-470 to front
E	Seat ramp	5° small	15° big	10° medium
F	Load limiter	5.5 kN	without	5.5 kN, without
G	Crash pulse[g]	33 „stiff“	25 „soft“	33 „stiff“
H	Pretensioner	yes	no	yes/no

Table 3: Selection of the parameters for MADYMO simulation; against gray background the most favorable parameter settings for thorax loading.
*) This setting is in fact the best one for thorax loading, but extremely unfavorable for submarining, cf. text.

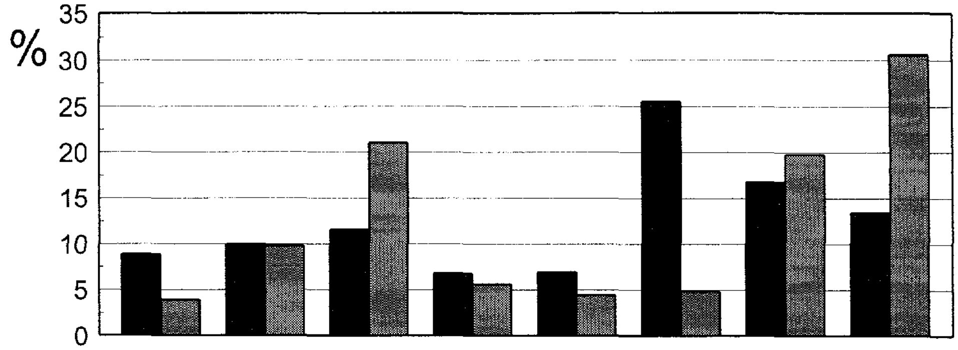
	Pretensioner	Retractor		Buckle		Anchor Fitting	
	Parameter	Defl. [mm]	V*C [m/s]	Defl. [mm]	V*C [m/s]	Defl. [mm]	V*C [m/s]
A	Anchor fitting, buckle	3.47	0.020	3.18	0.020	3.36	0.027
B	Fastening shoulder belt	3.89	0.051	4.32	0.060	4.05	0.051
C	Belt slack	4.52	0.109	5.13	0.141	4.53	0.109
D	Foot position	2.67	0.029	2.48	0.022	2.49	0.023
E	Seat ramp	2.70	0.023	3.13	0.020	2.82	0.019
F	Load limiter	9.96	0.025	10.16	0.027	10.41	0.027
G	Crash pulse	6.57	0.103	6.46	0.099	6.47	0.095
H	Pretensioner	5.24	0.159	4.13	0.126	5.08	0.143

Table 4: The parameters' influence on chest deflection and viscous criterion, each showing the effect of the optimal setting in accordance with Table 4; the three main influencing quantities against a gray background.

10. THE LOAD LIMITER LEVEL AND THE DUMMY'S FORWARD SHIFT

As shown in the previous section, the force limiter provides the greatest contribution to reducing chest deflection. In another simulation series, the influence of the force limiter level on chest loading was therefore systematically investigated, the geometry having been selected corresponding to the sled tests with stiff crash pulse (Fig. 3), but with a seat ramp angle at 15° to avoid submarining. The results are listed in Figure 8 as a function of the maximum shift forward determined in the head's center of gravity. One first sees a clear reduction in chest deflection with a reduction of the force limiter level from 10 kN to 7 kN without forward shift increasing a great deal. With a further reduction of the force level, a clear increase in the head's forward shift results, which, however, at 5 kN is still less than 550 mm. With regard to the reduction mentioned in the previous section of the tendency toward submarining through a low load limiter level, the space available in a vehicle should definitely be taken advantage of and a force level selected below 6 kN if possible.

In the course of the V*C it can be seen that no clear reduction occurs until between 4 kN and 5 kN. Since the clearance to the limit value is large in this case, however, a drop to under 5 kN does not appear necessary. But especially because of the problems dealt with in Section 8 concerning the comparability of the V*C of real testing and simulation, when optimizing the belt system for a certain model of vehicle, this should be examined in body-in-white and full-size crash tests.



	Anchor, Buckle	Shoulder Belt	Belt slack	Foot position	Seat ramp	Load limiter	Crash pulse	Pretensioner
Defl. % of total	8,9	10,0	11,6	6,8	6,9	25,5	16,8	13,4
V*C % of total	3,9	9,8	21,0	5,6	4,4	4,8	19,8	30,6

Figure 7: The influence of the parameters on chest deflection and V*C for retractor pretensioning.

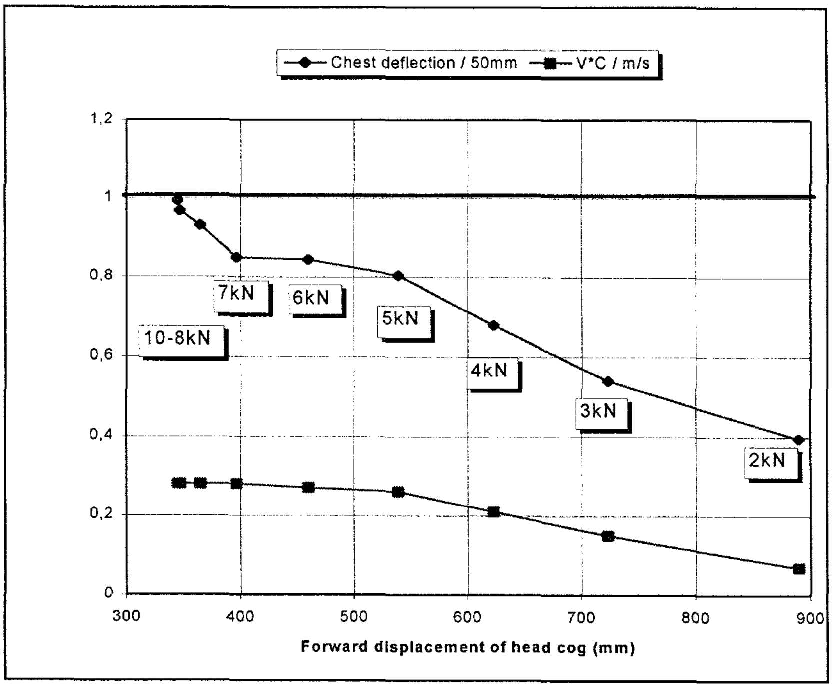


Figure 8: Chest deflection and V*C as a function of the forward displacement of the head measured in the center of gravity.

11. CONCLUSIONS

Accident investigations show that thorax injuries are the predominant type of injury to rear seat occupants. Using sled tests, it has been proven that chest loads in particular can be very much reduced through belt systems with pretensioners and load limiters. There is a validated MADYMO model available with which the quantities influencing the chest loading values have been investigated. It turns out that a 30% stiffer crash pulse with an optimized belt system produces lower thorax load values than a corresponding "softer" pulse with a conventional three-point belt.

The selection of an optimal force limiter level, however, depends in particular on the room to move available for the rear seat passenger in the individual car. The aim of further studies must be to examine the optimal setting also for other types of dummies (i.e., 5% female, 95% male). One must assume and first simulations show that for 95% male at a constant load limiter force level, greater and possibly inadmissible head shifts forward will result. A solution could be to use adaptive force limiters that automatically adjust itselves to the respective occupant /6/.

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