The Potential Injury-Reducing Benefits of a Well Designed Car Seat.

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ABSTRACT

In this study the potential injury-reducing benefits in frontal impacts of a well designed seat have been evaluated through mathematical simulations. In these simulations various seat properties have been studied.

In order to help set up the mathematical model and to verify the results from the simulations, a test-rig has been developed and constructed. The rig enables measurements of the forces at the points where the seat is anchored to the vehicle.

The results show that considerably improved protection can be achieved through proper seat design. They also show that the time at which the lower torso come into contact with the load-carrying structures in the seat is essential for the risk of injury. In particular the risk of submarining and the risk of the head striking the vehicle interior are affected by variations in the design of the seat.

INTRODUCTION

The protective capacity of the three-point seat-belt (lap/shoulder-belt) has been demonstrated in many investigations (Evans, 1991). However, for any seat-belt system to function well, the car occupant has to be adequately supported by the seat. Thus some work on improved car occupant protection has also dealt with the properties of the seat.

Severy*et al.* (1976) showed that significantly improved occupant protection could be achieved in frontal as well as side and rear impacts by modifying a standard production seat and seat-back. However, these modifications were elaborate, for instance the seat-back was joined to the car roof.

Adomeit and Appel (1979) showed that the design of the seat significantly influences various injury criteria. They also pointed out that a carefully designed energy absorbing structure in the frontal part of the seat improves the protective capacity of the seat.

A similar idea was presented by Svensson (1978). Through a number of sled-tests he demonstrated that a good match between the restraint system and the seat, which incorporated an energy absorbing structure, led to a large reduction of the load to the occupant.

Furthermore Adomeit (1979), Leung *et al.* (1982) and Otte (1990) have shown that a poor seat design can have considerable adverse effects in terms of injury, particularly to the abdomen and neck areas.

Despite this, few details about the behaviour of the car seat in accidents are known. Most studies of how seat properties can influence frontal crash safety have dealt with specific problems, such as submarining (Adomeit, 1979, Lundell *et al.*,1981). Some work has also addressed the static force-deflection characteristics of various seats (Crane, 1988).

In general the focus of the work with seat design has been to optimise between long-term comfort and convenience on the one hand and fatigue on the other (Viano and Andrzejak, 1992). Thus a number of methods to analyse sitting comfort have been published, e. g. Matsuoka and Hanai (1988), Schneider *et al.* (1991), Yamazaki (1992), as well as recommended values for various seat design parameters, both for driver seats and passenger seats (Diebschlag *et al.*, 1988).

The aim of this work was to establish the potential injury-reducing benefits obtainable through seat design. Another aim was to gain better understanding of the interaction between the occupant and the seat, in order to enable implementation of those design concepts that were found to be beneficial.

MATERIALS AND METHODS

Methodology

The mathematical model MADYMO3D, version 5.0, has been used to evaluate numerous seat designs in terms of occupant protection. In order to evaluate the current state-of-the-art as well as to achieve a basic understanding of the interaction between the occupant and the seat, mechanical testing of various seats was also carried out.

Mechanical testing

Test samples

Four car seats, hereafter referred to as seat A, B, C and D, have been tested under identical conditions. Seat A, B and C were of similar design, each comprising a cushion, which was attached to a frame by means of springs, and a submarine-beam, which was located under the frontal part of the cushion. However, the size and strength of the beams differed from seat to seat. Seat D was of a design concept quite different to that of seat A, B and C. Seat D simply consisted of a cushion on top of a deformable metal ramp, and the frontal part of the seat was connected to the floor in its central part only.

Test set-up

The tests were carried out at Electrolux Autoliv's crash-test facility in Vårgårda, Sweden. The seats were mounted on a crash-sled. A 50-percentile Hybrid-III dummy substituted for the occupant. The dummy was instrumented with accelerometers in the head, the chest, the pelvis, and the thigh, with force and moment transducers in the neck as well as in the spine area, and with force transducers in the upper legs. The dummy also had markers in the head, the chest, the pelvis, and the knee area so that the motion of these parts could be determined through high-speed photography. The tests were filmed with three high-speed cameras (1000 frames per second) and with one high-speed video camera (1000 frames per second). One of the film-cameras and the video covered the overall motion of the dummy, and the two other cameras were attached to the sled and focused on the motion of the pelvis and the angle of the lapbelt-straps.

The seat-back was removed and replaced by a support which was fixed to the sled but not connected to the seat. The back of the dummy leaned 29° rearward when resting against the support. The feet of the dummy were placed on a rigid plate which was angled 45 ° with respect to the floor. The upward motion of the feet was prevented by a band that wound around the ankles of the dummy and was attached to the sled. The force in the band was measured.

The dummy was restrained with a three-point seat-belt. The belt elongation at 10 kN static load was 10 %. The belt geometry was identical for each test and can be seen in Fig. 1 and Table 1.

Table 1. Geometrical data of the belt system.

Position (fig. 1)	x (mm)	y (mm)	z (mm)
A	-148	-375	-241
B	-242	-293	630
C	-48	221	2
D	-158	238	-143
E	-158	-238	-143

A=Position of belt outlet from retractor
B=Position of belt passage through D-ring
C=Position of belt passage through buckle
D=Position of buckle attachment.
E=Position of belt attachment.

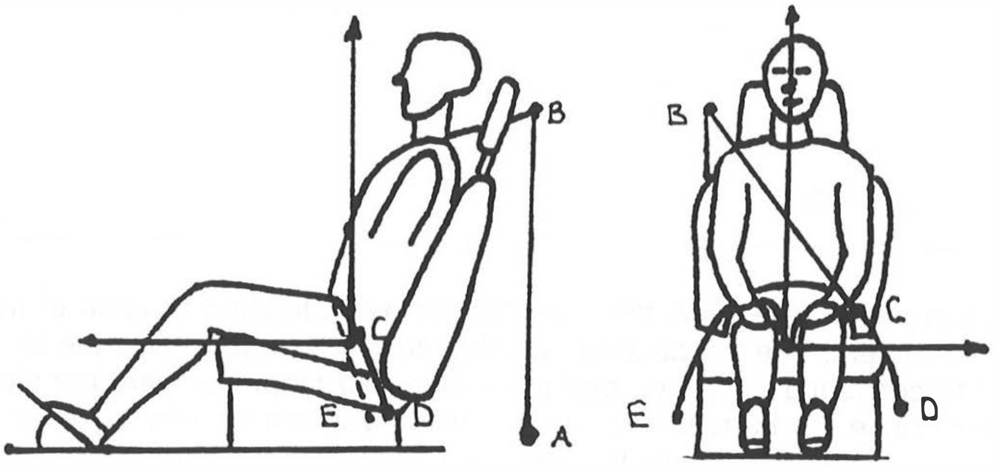

Figure 1. Belt geometry. The origin of the coordinate system is in the point where the line through the centres of the joints between the pelvis and the upper legs intersects with the mid-sagittal plane. The geometrical data can be found in Table 1.

Measurements of the response of the seat to the load generated by the dummy was facilitated by a specially designed test-rig (Lövsund *et al.*, 1993). In the rig, the points of the seat-frame that are normally attached to the car floor were attached via undeformable beams to three-axial force transducers. The beams were attached to the transducers by means of spherical joints which did not transfer any moments. The submarine-beam was cut out from the seat frame of seat C and connected to two additional force transducers which, in addition to the three forces, also measured the moment around the beam centreline. To maintain the stability of the seat-frame a bar was introduced, which replaced the beam as connection between the lateral sides of the frame. The bar did not interfere with any other seat or dummy structure during the tests. Fig. 2 shows the principal layout of the test-rig.Tests were run at two velocities, 40 km/h (25 mph) and 56 km/h (35 mph). After being accelerated to the chosen velocity, the sled was made to stop with an approximately square deceleration pulse of a magnitude of approximately 200 m/s^2 (20 g) (Fig. 3).

For more details about the mechanical tests, see Lövsund *et al.*, 1993.

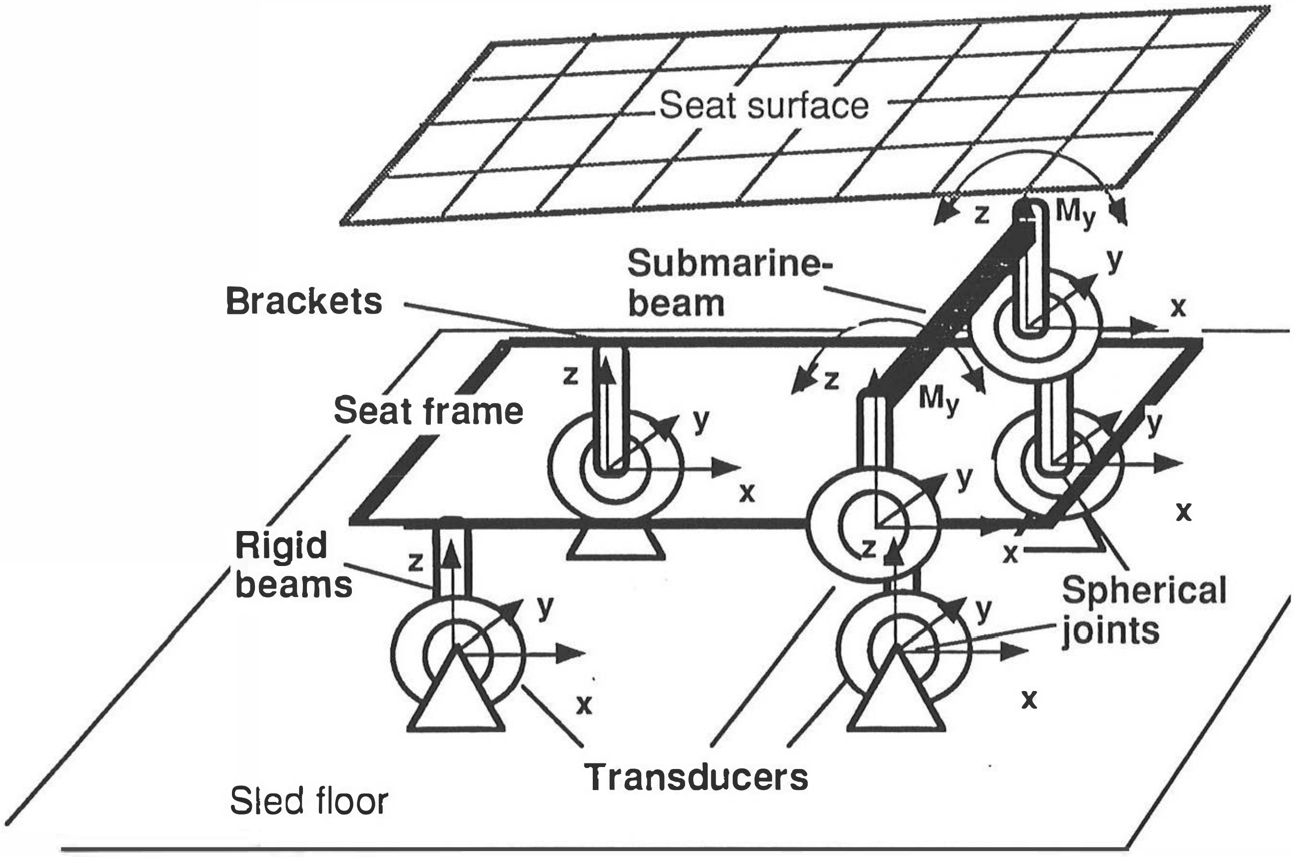

Figure 2. Sketch of the test-rig. A force transducer was attached to each of the floor attachments of the seat. The transducers, which were rigidly attached to the sled floor, measured the forces along the x-, y-, and the z-axes. No moments were transferred to the transducers, since the transducers were connected to the seat by spherical joints. For one of the seats in the test series two extra transducers were introduced which measured the three-axial forces in the submarine-beam. These transducers also measured the moment around the beam centreline.

Mathematical simulations

Transference of experiments

The experiments were transferred into the mathematical model MADYMO3D (version 5.0). All those parameters that were measured in the experiments, including the signals from the force-transducers in the rig, were used in the simulations. In addition, those forces in the points where the seat and the occupant came into contact were measured. Thereby the correspondence between the forces of interest, namely the internal forces in the seat, and the transducer readings could be determined.

Establishing the significance of seat design

In order to establish the potential improvements achievable through seat design, a series of runs was undertaken in which relevant seat properties were widely varied. In Table 2 these variations are summarised. The rest of the test set-up was kept constant from test to test. Fig. 4 shows a sketch of the seat.

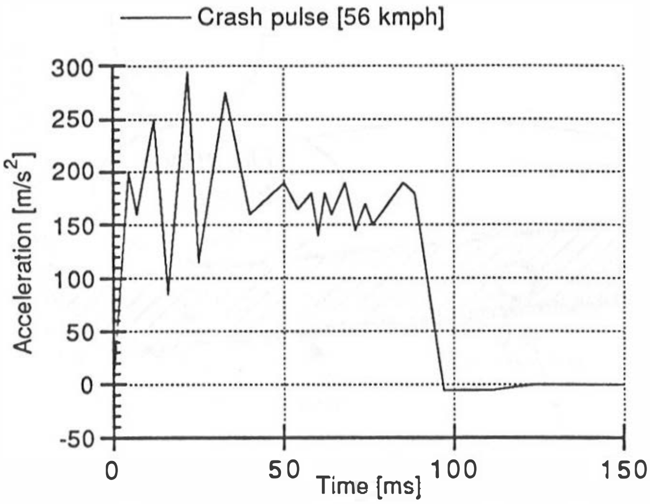

Figure 3. Sled deceleration pulse. Note: This curve is obtained through linear interpolation of digitally sampled values from the unfiltered accelerometer signal. The 40 km/h-pulse was of the same height but had a shorter duration.

Table 2. Variations in seat properties in the mathematical simulations.

Part of the seat	Variations
Submarine-beam	positioning (up-, down-, rear-, and forward) energy absorption (damping, plastic/elastic-ratio)
Seat frame	force-deflection (numerous types) angle (from horizontal to 45° upwards)
Cushion	coefficient of friction energy absorption

Criteria

Table 3 summarises the criteria used to evaluate the protection offered by the various seat designs tested.

RESULTS

Mechanical testings

In the mechanical tests, the results that relate to the risk of injury to the occupants were similar for all the seats. Seat D showed slightly better results in terms of chest and, to some extent, head loads than the others did (table 4), but on the other hand, in the tests with seat D the dummy was on the verge of submarining in all tests, and it probably did so in at least one of the tests.

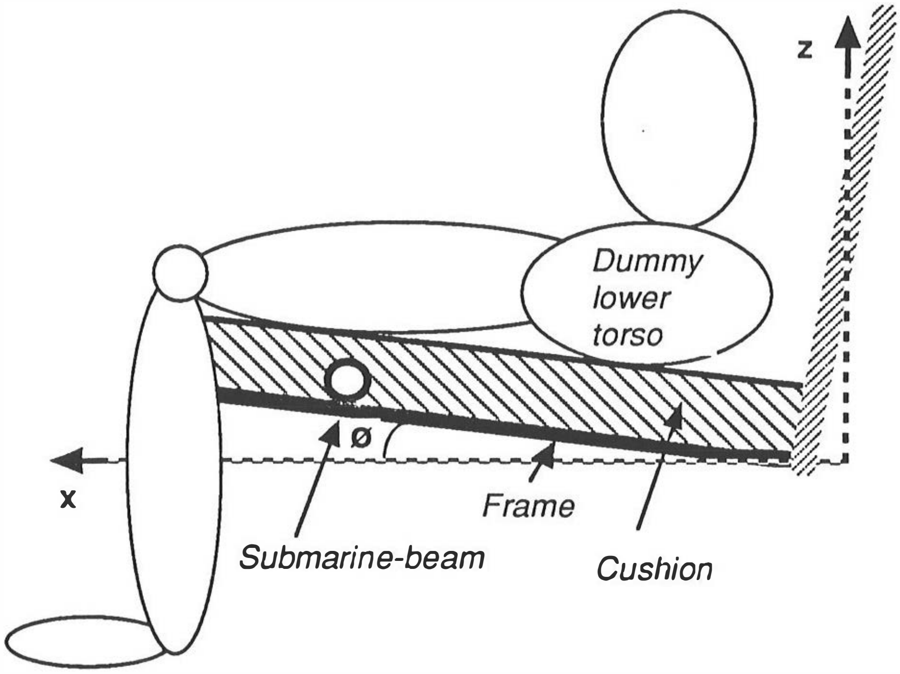

Figure 4. Schematic picture of the test-seat. The picture shows the seat-frame, the cushion, and the submarine-beam. The angle of the seat-frame is denoted ø. A stylistic picture of the dummy is included for reference, as well as the coordinate axes x (horizontal), and z (vertical).

Mathematical simulations

Duplicated experiments

The mathematical duplications of the sled-tests showed that in the seat with the most pronounced submarine-beam (seat C), the beam was virtually the only part of the seat that carried any load. In the seats (A and B) which had weaker beams with a smaller diameter other parts of the seat also carried significant loads during impact. The beams of these seats were residually deformed by the load from the dummy in the tests.

In Fig.5 dummy accelerations signals from the one of the tests are compared to their counterparts from the mathematical simulation of that test.

Design variations

Results from the simulations with various seat designs can be seen in Table 5. In the table are presented the results of those changes in the seat design that had the most significant effect on the injury criteria. Thus the results of the changes in positioning of the submarine-beam are presented, as well as the results of the changes in positioning and angulation of the seat frame. In the table can be seen that there is a difference in head trahjectory between the seats with a submarine-beam as load-carrying structure and those that have a flat ramp (seat frame).

Table 3. Injury criteria measured in the simulations.

Criterion	**Injury**
HIC	Internal head injury
Max. head displacement	Head injury due to contact with the car interior
Max. shear force in the neck	?
Chest compression	Rib fractures
Shoulderbelt-force	- " -
Chest 3ms	?
Max. tangent of pelvis to lap-belt angle for lapbelt-force ≥ 3 kN	Abdominal injury (submarining)
Femur force	Femur fracture

Table 4. Chest 3ms-values (upper) [g] and HIC36-values obtained in the tests. For multiplied tests, the mean value and the standard deviation are given.

Seat	A	B	C	D
40 kmph	50.0	50.2	48.0 (4.2)	46.4
56 kmph	50.6	50.6	50.4 (0.2)	42.3 (2.8)

Seat	A	B	C	D
40 kmph	700	684	1050 (119)	679
56 kmph	1404	1317	1584 (170)	1309 (136)

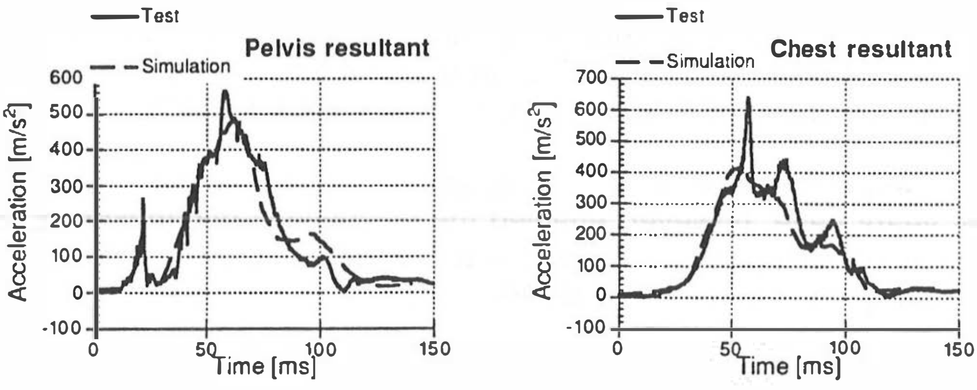

Figure 5. Comparison of pelvis (left) and chest resultant accelerations from the tests and the simulations with seat C at 56 kmph.

Table 5. Results of some of the simulations with a changed position of the submarine-beam (upper) (the beam has been moved 25 mm in the direction stated in the head of the table) and of some of the simulations in which a seat-frame was used as load-carrying structure (lower). In the lower table, the angle of the frame is given, as well as position in height of the mid-point of the frame. The note- 20 mm means that the frame was moved 20 mm downward.

	Reference	Rearward	Up	Down	Forward
Head x-disp. [mm]	476	482	460	472	468
Head z-disp. [mm]	-268	-255	-274	-282	-286
Chest compr. [mm]	41.3	40.5	38.0	43.9	42.4
Shoulder-belt force [kN]	8.7	8.5	7.7	9.2	8.9
Femur force [kN]	2.3	2.3	1.4	2.2	2.1
Chest 3ms [m/s^2]	428	414	451	432	424
HIC	499	490	618	533	533
Submarining param.	0.305	0.198	0.205	0.393	0.416

	7.5°, 0	15°, 0	15°, - 20 mm	30°, 0	30°, -20 mm
Head x-disp. [mm]	458	461	455	479	472
Head z-disp. [mm]	-283	-284	-294	-267	-273
Chest comp. [mm]	42.8	41.8	43.0	39.2	40.8
Shoulder-belt force [kN]	8.7	8.6	8.8	8.2	8.5
Femur force [kN]	1.5	1.5	1.5	1.6	1.7
Chest 3ms [m/s^2]	395	391	391	408	416
HIC	612	634	664	538	543
Submarin.	0.327	0.296	0.370	0.127	0.343

DISCUSSION

There is no doubt that the car seat plays an important role in the protection of restrained occupants in various types of accidents. However, the seat also has to meet requirements of, for instance, sitting comfort and ergonomical adequacy for the driver, and these requirements are often more important to car buyers, and thus to car makers, than those of crash safety. Furthermore, crash safety standards, such as the Federal Motor Vehicle Safety Standards in the USA, make no stipulations as far as the protective capacity of the seat is concerned. Therefore occupant protection has often been relegated to second place by seat designers. This has in turn meant that most studies of how the car seat influences car crash safety have analysed minor modifications to existing production seats.

The rapid improvements in computer technology and mathematical modelling techniques in recent years have, however, enabled the evaluations undertaken in this paper, in which numerous seat properties have been changed during simulations, in order to find general principles regarding the design of the seat with respect to occupant crash protection.

The results show clearly that in order to be adequatly protected by the seat, the occupant has to be supported by some firm, load-carrying structure, such as a ramp or a submarine-beam, early on in the crash process. This structure does, however, not have to be very stiff. The magnitude of the contact force between the occupant and the firm structure seems less important for occupant protection than do the time and location of contact.

Seats comprising a rigid structure close to the occupant may seem unrealistic when seating comfort is also an important criterion. However, most modern cars have triggers for car crash safety devices such as belt-pretensioners and airbags. These could also be used to trigger various safety devices in the car seat. Thus the seat-frame or the submarine-beam could be rapidly brought closer to the occupant in the event of a crash, thus solving the conflict of sitting comfort for normal riding conditions. According to the results of this study it is sufficient if the first contact between the occupant's pelvis and the rigid seat structure occurs at about 40 ms, whereas the critical time to trigger an aibag or a belt-pretensioner is often 20 ms or less, which means that no modifications to the triggers should be necessary. In addition, the results show that although the distance between the lower part of the occupant's pelvis and the rigid seat structure should be small, it would still be room for sitting comfort measures even if the position of the rigid structure were fixed to the seat.

The most pronounced effect of having a firm structure near the occupant is that the risk of submarining decreases significantly. The risk of submarining was measured with the method suggested by Håland and Nilson (1991). As a measure of the risk of submarining this method uses the peak value of the tangent of the angle between the lap-belt and the A.S.I.S. during the time when the lap-belt force is above 3 kN. The values obtained in this study were slightly higher than those obtained in the study by Håland and Nilson (1991), typically 0.25 instead of 0.15. There may be several reasons for this difference, for instance that the projection in the yz-plane of the belt angle was different, which could have changed the time-histories of the belt-forces. Another possible explanation is that the belt system was differently modelled in that study.

The risk of submarining is particularly critical since many measures that reduce other injury criteria can increase the risk of submarining. This was observed, for instance, in the sled-tests, where seat D had the lowest HIC- and Chest 3ms-values, but on closer analysis showed that the dummy did submarine.

Also the most valid criterion for chest injury in frontal impact testing, chest compression (Horsch *et al.*, 1991), was reduced in those tests where the occupant's lower torso was supported by a firm seat structure early on in the crash event.

Seemingly, another crucial parameter that proved to be sensitive to the seat design was the trajectory of the head. This could be explained by the fact that when the lower torso reaches its maximum forward displacement, the upper part of the body pivots around the point of contact between the pelvis and the vehicle. Thus the mode of loading to the lower torso in this phase of the crash to some extent determines the head trajectory, which in turn is a very significant factor for the risk of head injury. This factor, of course, will be studied more in-depth.

The fact that the simulations are based on measurements of the forces in the seat in sled-tests enhances the reliability of the results. However, a Multi Body System such as MADYMO can neither fully describe each and every material property, nor find the correct location and direction of force for each and every point of contact between the occupant and the seat. The latter is a problem especially when both of the contacting surfaces have a curved shape, such as when the lower part of the pelvis comes into contact with the submarine-beam. This means that a complete correspondence between calculated and measured data could not be accomplished here. This was particularly disadvantageous in the simulations of the tests with seat C, in which the contact between the dummy pelvis and the submarine-beam caused the pelvis and chest acceleration to peak. This contact was found hard to exactly duplicate in MADYMO. Nevertheless, since the measurements that were not directly influenced the contact show good correspondence there is reason to believe that the predictions of the model are realistic.

CONCLUSIONS

The design of the car seat is important for the protection of the occupant in frontal impacts.

In order to be adequatly protected by the seat, the occupant has to be supported by some firm, load-carrying structure, such as a metal ramp or a submarine-beam, early on in the crash process. The time and location of contact seem to be more important than the stiffness of the structure.

The risk of submarining and the risk of the head striking the vehicle interior are the two injury-related factors that are most affected by variations in the design of the seat. Also the chest compression, which is a measure of the risk of chest injury, can be significantly changed by changes in seat design.

REFERENCES

Adomeit, D.: "Seat Design - A Significant Factor for Safety Belt Effectiveness", SAE Technical Paper No. 791004, in proceedings of the 23rd Stapp Car Crash Conference (1979)

Adomeit, D., and Appel, H.: "Influence of Seat Design on the Kinematics and Loadings of the Belted Dummy", in proceedings of the IVth International IRCOBI Conference on The Biomechanics of Trauma (1979)

Crane, D. J.: "Seat Characteristics Determined by Physical Testing", Volume I and II, MGA Report No. G87ROO, U.S. Department of Transportation (1988)

Diebschlag, W., Heidinger, F., Kurz, B., Heiberger, R.: "Recommendation for Ergonomic and Climatic Physiological Vehicle Seat Design", SAE Technical Paper No. 880055 (1988)

Evans, L.: "Traffic Safety and the Driver", Van Nordstrand Reinhold, ISBN 0-442-00163-0 (1991)

Horsch, J D., Melvin, J W., Viano, D C., and Mertz, H J.: "Thoracic Injury Assessment of Belt Restraint Systems Based on Hybrid III Chest Compression", SAE Technical Paper No. in proceedings of the Thirty-fifth Stapp Car Crash Conference (1991)

Håland, Y., and Nilson, G.: "Seat-belt Pretensioners to Avoid the Risk of Submarining", in proceedings of the XIII:th Conference on Experimental Safety Vehicle (1991)

Leung, Y. C., Tarriere, C., Lestrelin, D., Got, C., Guillon, F., Patel, A., Hureau, J.: "Submarining Injuries of 3Pt Belted Occupants in Frontal Collisions - Description, Mechanisms and Protection". SAE Technical Paper No. 821158, in proceedings of the 26th Stapp Car Crash Conference (1982)

Lundell, B., Mellander, H., and Carlsson, I.: "System with Optimized Seat Cushion Design", SAE Technical Paper No. 810796, in proceedings of Passenger Car Meeting, Dearborn, Michigan (1981)

Lövsund, P., Nilson, G., Thorngren, L., Håland, Y., and Svensson, S.E.: "A Test-Rig for Parametric Studies on the Car Seat to Minimize the Risk for Injuries", SAE Technical Paper No.

MADYMO "Users' Manual 3D, Version 5.0", TNO Road-Vehicles Research Institute, The Netherlands (1992)

Matsuoka, Y., and Hanai, T.: "Study of Comfortable Sitting Posture", SAE Technical Paper No. 880054 (1988)

Otte, D.: "Comparison and Realism of Crash Simulation Tests and Real Accident Situation for the Biomechanical Movement in Car Collisions", SAE Technical Paper No. 902329, in proceedings of the 34th

Stapp Car Crash Conference (1990)

Schneider, L. W., Reed, M. P., and Manary, M. A.: "Accommodating the Driving Population", UMTRI Research Review, Jan-Feb 21 (4), pp 1-14 (1991)

Severy, D. M., Blaisdell, D. M., Kerkhoff, J. F.: "Automotive Seat Design and Collision Performance" SAE Technical Paper No. 760810, in proceedings of Twentieth Stapp Car Crash Conference (1976)

Svensson, L. G.:"Means for Effective Improvement of the Three-Point Seat Belt in Frontal Crashes", SAE Technical Paper No. 780898, in proceedings of Twenty-Second Stapp Car Crash Conference (1978)

Viano, D. C., and Andrzejak, V.: "Research Issues on the Biomechanics of Seating Discomfort: An Overview with Focus on Issues of the Elderly and Low-Back Pain", in "Analytical Modeling and Occupant Protection Technologies", pp 69-82, SP-906, Society of Automotive Engineers (1992)

Yamazaki, N.: "Analysis of Sitting Comfortability of Drivers' Seat by Contact Shape", J of Ergonomics 35 (5/6), pp 677-692 (1992)