A Force-Limiting Device to Reduce the Seat-Belt Loading to the Chest and the Abdomen in Frontal Impacts

Gert Nilson, Department of Injury Prevention, Chalmers University of Technology, Göteborg, Sweden, and Yngve Håland, Electrolux Autoliv AB

ABSTRACT

In car accidents the load of the seat-belt is often the cause of minor and moderate, in some cases even serious or severe injuries to the chest and abdominal areas. Several attempts to reduce this load have been made, but with little success.

In this study, mathematical modelling was used to find methods of reducing the forces in the seat-belt system in a frontal impact, without jeopardising the protective capacity of the system. One such method was to limit the x-component of the force at the point where the buckle stalk is anchored to the vehicle. In order to further evaluate the method, a physical device which accomplished the desired force-limiting effect was designed and evaluated in sled-tests.

In both the simulations and the tests, the forces in the different straps of the seat-belt, as well as the injury criteria Chest3ms and HIC, were significantly reduced without any observed adverse effects such as increased risk of impact of head to steering-wheel.

The limiting of the force in this method is progressive, thereby covering a wide velocity range, and it adapts somewhat to impact severity and occupant size. In the range of 30 to 55 kmph impact speed, the force-limiter allowed for an increase of up to 25 % (on average 13 %) of the barrier impact speed before the load to the chest and the abdomen surpassed those obtained with the standard seat-belt system.

A brief analysis of real-world crashes indicates that the benefit in terms of societal and medical savings of such a reduction of the load to the torso would be substantially greater than the cost for introducing the force-limiting device in the fleet of cars.

INTRODUCTION

There is little dispute that the three-point seat-belt, also known as the lap/shoulder-belt, greatly reduces the risk of injury in various types of car accidents. Most investigators have estimated the overall effectiveness of the seat-belt to be over 40 % in preventing fatalities [Evans, 1991], and even higher in preventing serious injury [Bohlin, 1967, Finch and Giffen, 1973].

However, seat-belts have also been found to be the cause of many injuries. Although the majority of these injuries are minor or moderate, some serious and even fatal injuries caused solely by loading from the seat-belt have been reported [Hill *et al.*, 1992, Huelke *et al.*, 1993a and b]. In addition, despite the generally low AIS-rating of injuries caused by the seat-belt, these injuries account for a considerable part of the human and societal costs associated with car accidents, because they are much more common than serious and fatal injuries. The results of a comprehensive Australian study showed that almost 11 % of the "harm" to restrained front-seat occupants in frontal collisions is caused by contact with the seat-belt [Monash University, 1992].

Most of the injuries caused by seat-belts are located in the thoracic and abdominal regions of the body [Monash University, 1992, Hill *et al.*, 1992]. Indeed the very idea behind the seat-belt is to apply the impact forces to the sternum and, especially, the pelvis, since these structures are comparatively strong [Aldman, 1962]. However, what level of force a specific structure tolerates before it sustains injury varies greatly within the population of car occupants. For instance, while the average adult that has not reached the age of 35 can withstand 9 kN of shoulder-belt force without sustaining rib fractures, the corresponding value has dropped to 2.5 kN by the age of 65 [Thomas *et al,* 1980]. Furthermore, variations in body weight widens the range of body tolerances. Thus a shoulder-belt force of 8 kN to a person that weighs 60 kg is equivalent to a shoulder-belt force of 9 kN to a person weighing 75 kg [Eppinger, 1976].

Another problem is the differing degrees of severity among crashes in road-traffic, which adds to the problem of optimising a seat-belt system. A velocity change (ΔV) of 50 kmph is typical for a severe but still survivable frontal impact. This ΔV is, consequently, common also in crash safety standards. However, in road traffic, frontal impacts with ΔVs of about 30 kmph are five times as common as those with ΔVs of about 50 kmph [Harms *et al.*, 1987].

There are numerous reports on attempts to limit the forces between the restraint system and the occupant, some of which have also been utilised in various production cars. Sarraihle (1976) mounted the seat in such a way that it started to move forwards when the force in the anchorages exceeded specified values. The principle was considered an effective means of reducing the load in the restraint system, but the body excursion increased considerably. Svensson (1978) has proposed an energy-absorbing structure to be incorporated in the frontal part of the seat. Together with a slot in which the buckle anchorage can slide forward he demonstrated that this device accomplishes a significant reduction in dummy-measured injury criteria without increasing the head-forward displacement. Several authors [Walsh and Kelleher (1980) among others] have demonstrated that many injury criteria can be significantly reduced by increased belt tensility. The effect of the "tearing" belt webbing that was introduced in the shoulder-strap in various French cars in the 1970s has been evaluated by, for instance, Foret-Bruno *et al.* (1978), Thomas *et al.* (1980), and Mertz *et al*. (1991). Volkswagen has evaluated the effects of limiting the force at the outer lap-belt anchorage point [Ensslen *et al*., 1985]. Due to adverse effects such as prolonged excursion of the occupant, which increases the risk of contact with the vehicle interior, force-limiting devices are, however, rare in today's cars.

The aim of this work was to find a method of reducing the restraint load to car occupants in crashes of medium and high severity, without jeopardising the protective capacity of the seat-belt system.

METHODS

Selection of method of limiting the restraining forces

General considerations

In a crash, a car occupant restrained with a three-point seat-belt is connected to the vehicle via three belt straps and the seat. Thus, theoretically there are four areas where a force-limiting device can act. However, in contrast to the seat-belt, the seat is not just a part of a protective system, but also has other functions, which means that modifications to the seat cannot be based solely on safety considerations. For this reason elaborations with the seat was ruled out in this study. That left us with three areas where force-limiting devices could be introduced. The suitability of limiting the force in any of these areas was tested by means of the mathematical model MADYMO3D, versions 4.3 [TNO, 1990], and 5.0 [TNO, 1992].

Test set-up for the initial study

In the MADYMO model, 32 kmph (20 mph) and 48 kmph (30 mph) sled tests were simulated. In each test, a restrained Hybrid-III dummy was seated on a simplified seat comprising a homogeneous cushion on top of a rigid steel-plate. The plate was angled 7° upward with respect to the x-axis, except for the frontal part, which was horizontal. The seat-belt geometry was taken from a production car and was considered well-performing in terms of occupant protection. The belt webbing was elongated eight percent at 10 kN static load. For a more detailed description of the set-up, see Håland and Nilson (1991). The 48 kmph and 32 kmph impacts were simulated by exposing the system to an acceleration of 250 m/s^2 during 54 ms and 36 ms, respectively.

First a standard restraint system was tested at both velocities. These runs were made for reference as well as to obtain the forces in the different belt straps and anchorage structures, in order to find reasonable levels at which to limit the forces.

Force-limiting methods

Four different methods of limiting the force were tested. The methods utilised force-limiting devices at the retractor anchorage, the stalk, the stalk anchorage and the outer lap-strap, respectively.

- The retractor anchorage yielded when a specific force-level was reached. Thus the force in the shoulder-strap was limited. To better control the force-limiting effect a webbing-locker was introduced, which prevented the retractor from spooling out belt material after locking.
- The force-limiting stalk yielded when the force exceeded the threshold value, which meant that the buckle could move in the direction of the force.
- The force-limiter located at the stalk anchorage guided the anchorage in the forward, horizontal direction when the horizontal component of the force in the stalk reached the specified value.
- At the outer lap-strap of the belt "tear" was introduced.

Design considerations stipulated a maximum deformation to each of the methods. This maximum was 50 mm for the yielding retractor attachment, and 60 mm for the others. If the force-limiter "bottomed out", the restraint system retained its normal properties (except for the change in geometry caused by the deformation). The levels of force at which the limiting occurred are listed in table 1.

Measured variables

In each test the injury criteria HIC_{36} and Chest 3ms were measured, as well as the forces in the belt-straps. The maximum displacements in the x- and z-directions of the centre of gravity of the head were registered, together with the velocity of the forehead at the instant when the c.g. reached its maximum forward displacement (fig. 2). Since the maximum displacement of the head is a measure of the risk of the head striking the vehicle interior, in particular for the driver's head hitting the steering-wheel, the velocity of the forehead was considered as giving an estimate of the severity of such an impact. The risk of submarining was measured using the method suggested by Håland and Nilson (1991). This method uses the tangent of the angle between the lap-belt and the upper, frontal surface of the pelvis (the Anterior Superior Iliac Spine), at the instant when the force in the lap-belt has peaked and dropped to 3 kN as a continuous and monotone measure of the risk of submarining. If the value stays below 0.14, the risk of submarining is low. If the value exceeds 0.18, submarining is very likely to occur. Since the risk of submarining is negligible at low velocities, it was calculated for the 48 kmph simulations only.

Table 1. Different methods of limiting the force in the seat-belt system .

Part of belt system	Method	Level
Shoulder strap	Retractor yields at specified level	4 kN 5 kN
Buckle	Stalk yields at specified level	14 kN
Buckle	Stalk moves in x-direction at spec. force	5-10 kN (linearly increasing)
Outer lap-strap	Belt material yields at specified level	9 kN

Results

The results of the study of the different methods to limit the force in the seat-belt system are summarised in table 2 a and 2 b.

The method of limiting the strength of the stalk anchorage in the forward direction was chosen for further analysis. As can be seen in Table 2, all four principles reduced various criteria, but the method chosen was the only one that performed well at both velocities. This method was also the only one with negligible adverse effects, such as increased head-forward motion and increased risk of submarining. In fact, the method was considered to have no adverse effects, since the few mms increase in forward displacement of the head was more than well compensated for by the reduction in the downward motion of the head and the reduction in forehead velocity.

Development of a prototype

In order to further analyse the method of limiting the force in the horizontal, forward direction at the stalk anchorage, a mechanical prototype which had the same properties as its mathematical counterpart was designed and constructed. This device comprised a force-limiting element and a metal plate with a slot which guided the lower attachment of the buckle stalk horizontally in the forward direction. The force-limiting element was a piece of metal, bent to the shape of an eight. Each part of the element is straightened out at a given load which can vary along the curvature. Thus the force-deflection characteristics of the device can be more or less tailor-made [Viano, 1987].

Mechanical testing

The force-displacement characteristics of the stalk attachment were measured quasistatically. A force pulled in the direction of the stalk and the magnitude of the force and the motion of the lower attachment of the stalk were registered. The force in the x-direction was obtained by multiplying the registered force by the cosine of the angle between the stalk and the x-axis (approximately 60 degrees). The result is shown in Fig. 1.

In order to verify the results of the simulations, the prototype was introduced in the set-up of the initial sled-test and tested under the conditions of the simulations (at 48 kmph). A new test with the baseline restraint system was made for comparison. In the tests, the head forward displacement, the HIC_{36}, the Chest 3ms and the shoulder-belt

Table 2 a. Results from the study. Tests at 48 kmph.

Criterion	Method					
	Reference	Retractor/4	Retractor/5	Stalk	Stalk anch.	Outer str.
Head disp. x [mm] z [mm]	421 -280	450 -287	437 -276	433 -268	433 -255	419 -270
Forehead velocity [m/s]	11.5	11.5	10.9	11.8	10.4	11.8
HIC_{36}	788	843	774	684	651	730
Chest 3ms [m/s^2]	504	486	442	467	433	475
Shoulderbelt force [kN]	9.3	8.2	7.7	8.9	8.6	9.2
Lapbelt force [kN]	13.9	13.9	13.7	13.1	12.2	13.2
Submarining	0.135	0.114	0.123	0.137	0.111	0.134

Table 2 b. Results from the study. Tests at 32 kmph. The risk of submarining was not considered.

Criterion	Method					
	Reference	Retractor/4	Retractor/5	Stalk	Stalk anch.	Outer str.
Head disp. x [mm] z [mm]	330 -198	347 -192	326 -198	337 -189	336 -188	330 -189
Forehead velocity [m/s]	8.1	7.4	8.0	7.7	7.5	8.0
HIC_{36}	223	221	222	201	192	218
Chest 3ms [m/s^2]	395	342	391	373	369	395
Shoulderbelt force [kN]	7.8	6.1	7.6	7.6	7.1	7.8
Lapbelt force [kN]	9.3	9.3	9.3	9.1	8.1	9.0

force were measured. The result showed that the mathematical model had predicted the difference between the baseline and the force-limiting system very accurately, although the absolute values obtained in the tests differed slightly from those predicted by the model.

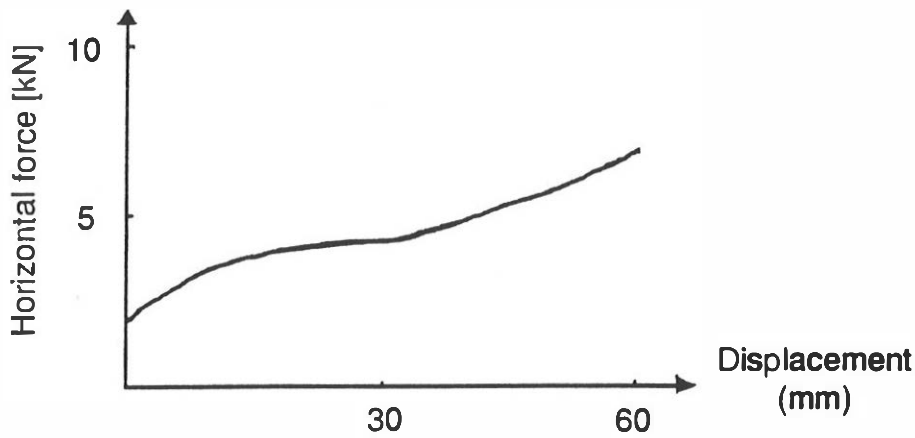

Figure 1. Force-displacement characteristics of the force-limiting device.

Final test programme

In order to quantify the improved performance of the seat-belt system with the force-limiting device at the lower attachment of the buckle stalk compared with a baseline system, the systems were compared at numerous impact velocities. Thus both systems were run at each three kmph (two mph) impact speed in the range from 30 to 60 kmph. The variation in impact speed was accomplished by altering the duration of the pulse.

Supplementary tests

Sled-tests of different impact severities

Because of the promising results from the initial tests, more trials with the prototype were carried out. In these trials two velocities were tested, 30 kmph and 50 kmph, with a more moderate crash-pulse than in the previous tests (level about 200 m/s^2), and a slightly changed geometry of the seat-belt (the lap-belt angle was reduced by approximately five degrees). A mechanical force-limiter was also tested at 56 kmph in a seat-belt system designed for a small four-door car with the crash-pulse of that car. This pulse was comparatively severe, reaching a level of about 300 m/s^2.

Simulations of different sizes of occupants

Since the motion of the lower attachment of the stalk is limited to the x-direction, part of the resitance to this motion is due to friction between the attachment and the upper edge of the slot in which it slides. This friction is in turn a fraction of the z-component of the force in the stalk, and thus the level of the limiting of the force to some extent depends on the force in the stalk. The original mathematical model did not take this effect into account. In the mechanical prototype, the coefficient of friction was approximately 0.1 (steel on steel) which meant that the influence of the friction was still small. However, if the coefficient of friction were greater, the level of the limiting of the force would become a function of the force in the stalk, which increases with increasing occupant mass and/or impact severity. Thus the force-limiting device would adapt to occupant mass and impact severity. In order to evaluate what effect this has on occupant protection, a series of runs was carried out in which the coefficient of friction as well as the size of the occupant were varied.

A 48 kmph impact with a 50 percentile male dummy was chosen as reference. Thus, for each tested coefficient of friction, the force-deflection curve of the force-limiting element in the force-limiter was adjusted so that the total effect of the force-limiter in this impact situation was kept constant from test to test (Fig. 2). Then a fifth percentile female dummy and a 95 percentile male dummy were tested under the same conditions. The crash-pulse had the same, constant 25 g level as in the original test series. In order to adapt to an easy switch of dummies, the test set-up was, however, slightly modified which meant that direct comparisons with results from the previous study were not possible. The coefficients of friction tested were 0.0, 0.1, 0.3, 0.5, and 0.7.

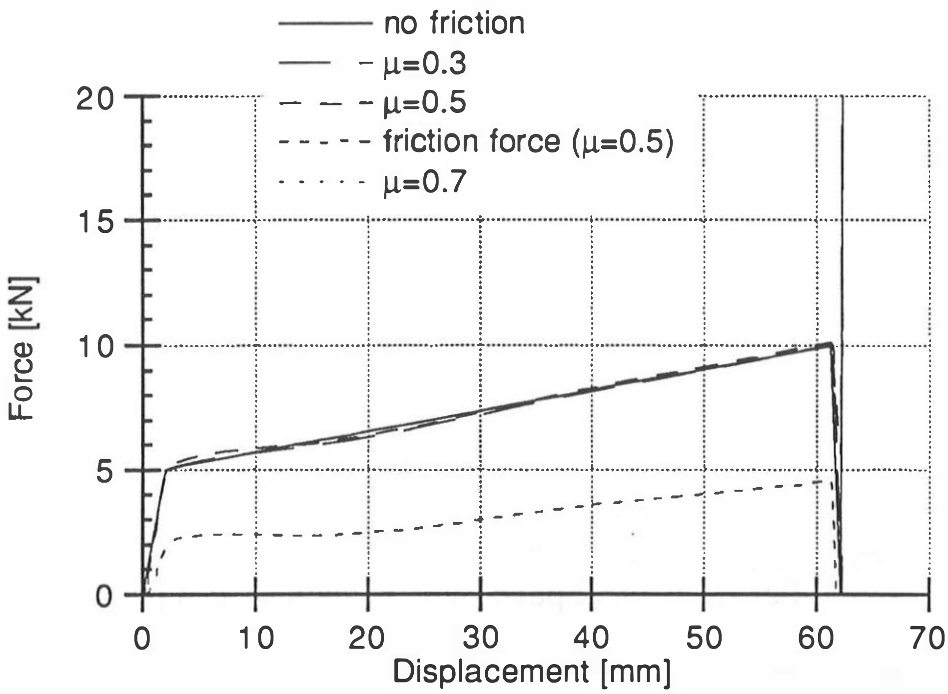

Figure 2. Force-displacement curves for the force-limiter in the simulations with a 50 percentile dummy and 48 kmph barrier impact speed when various coefficients of friction (μ) are used. The fraction of the force that originates from friction when μ=0.5 is also shown.

Simulation of different impact velocities

The effect of friction between the attachment of the stalk and the upper edge of the slot was also tested at different velocities, in a similar fashion to that described under "Final test programme" above. Thus simulations of a 50 percentile dummy were run at each three kmph (two mph) impact speed in the range from 30 to 60 kmph, with a constant 25 g crash-pulse. The coefficient of friction was 0.5 and the force-limiting element in the force-limiter was adjusted so that the total effect of the force-limiter at 48 kmph impact speed was identical to that of the original, friction-less force-limiter. Since the test set-up had been modified, new reference runs of a belt system without force-limiting were carried out.

RESULTS

Test programme

In a comparison of the tests of a baseline seat-belt system and a system with force-limiting in the x-direction at the lower attachment of the buckle stalk it was shown that it is possible to experience a crash with a 25 % increase in barrier impact speed (BIS) without increasing the load to the chest and the abdomen (50 kmph instead of 40 kmph). In the range from 30 to 55 kmph, the average increase in BIS was 13 percent (Fig. 3). The results upon which Fig. 3 is based can be seen in Table 3.

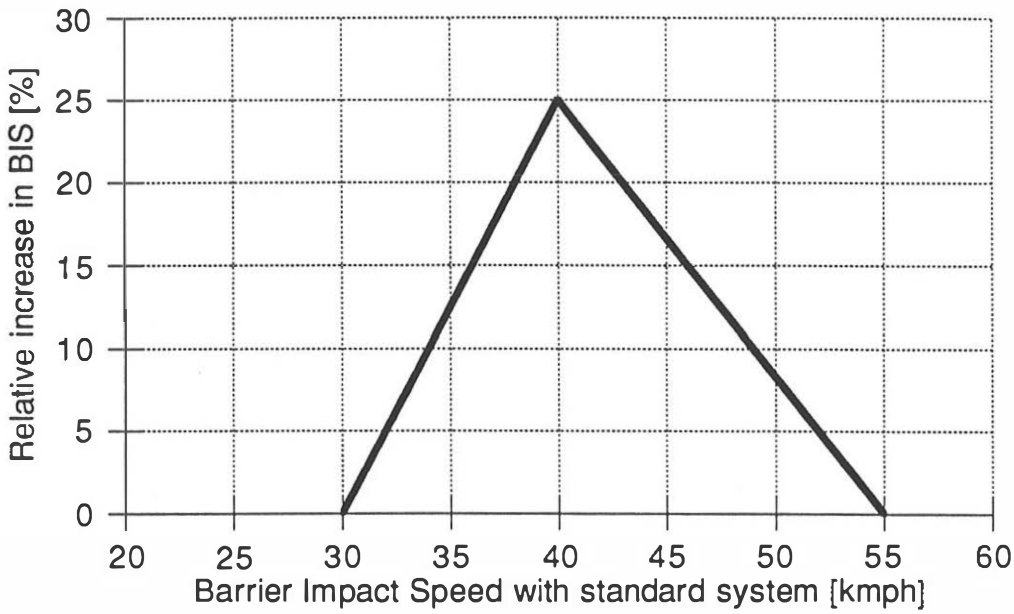

Figure 3. Increased barrier impact speed allowed without increased injury criteria for the chest and abdomen if a force-limiter is applied to the lower attachment of the buckle stalk.

Complementary tests

Sled-tests of different impact severities

The results from the mechanical tests of a moderate and a severe impact are summarised in table 5.

Simulations of different occupant sizes

The results from the simulations of different occupant sizes and coefficients of friction between the stalk anchorage and the slot can be seen in Table 6. The resulting level of the limiting of the force in the different cases can be seen in Fig. 5

Table 4. Injury criteria obtained from the simulations of various velocities with the baseline (upper) and force-limiting seat-belt system.

Vel.	30	33	36	39	42	45	48	51	54	57	60
Head x-displ. [mm]	151	172	191	210	227	242	256	269	280	292	302
Head z-displ. [mm]	-182	-203	-223	-241	-257	-270	-279	-286	-290	-291	-292
Chest 3ms [m/s^2]	367	402	431	460	482	496	503	505	505	505	505
HIC	161	240	321	414	517	623	752	904	1052	1164	1250
Sh.belt force [kN]	7.4	7.9	8.3	8.7	8.9	9.1	9.2	9.3	9.4	9.5	9.7
Lower Sh. b.f [kN]	6.4	6.9	7.3	7.5	7.7	7.9	8.0	8.0	8.1	8.2	8.3
Lap-belt force [kN]	8.5	9.6	10.6	11.7	12.6	13.4	13.8	14.1	14.2	14.2	14.2

Vel.	30	33	36	39	42	45	48	51	54	57	60
Head x-displ. [mm]	155	178	199	219	238	254	258	282	295	308	319
Head z-displ. [mm]	-174	-191	-205	-219	-230	-240	-253	-264	-268	-272	-274
Chest 3ms [m/s^2]	348	374	395	412	425	430	433	434	441	447	448
HIC	152	205	267	336	416	508	622	739	846	942	1016
Sh.belt force [kN]	7.2	7.6	7.9	8.2	8.4	8.5	8.6	8.8	9.3	9.6	9.9
Lower Sh. b.f [kN]	6.3	6.6	6.9	7.1	7.3	7.4	7.5	7.7	8.0	8.4	8.6
Lap-belt force [kN]	8.3	9.1	10.0	10.7	11.3	11.8	12.1	12.3	12.5	12.5	12.5

Table 5. Results from mechanical tests and mathematical simulations of the baseline seat-belt system and the force-limited system when a moderate (constant 20 g level, ΔV 50 kmph) and a severe (plateau at 30 g, ΔV 55.7 kmph) crash-pulse are used.

	Moderate pulse		**Severe pulse**	
	Baseline	With force-limiter	Baseline	With force-limiter
Head forward disp. [mm]	551	551	n.a	n.a
HIC36	815	554	1318	1109
Chest 3ms [g]	46	41	57.3	53.3
Shoulder-belt force [kN]	9	7	10.0	10.5
Outer lap-belt force [kN]	11	9	14.3	13.6

Table 6. Results from the simulations of the occupant sizes 95 %ile male (upper) and fifth %ile female when different coefficients of friction between the stalk anchorage and the slot were used. A run with no force-limiting effect present is included for reference.

	Reference	No friction	μ=0.1	μ=0.3	μ=0.5	μ=0.7
Head x-disp. [mm]	355	377	377	377	377	377
Head z-disp. [mm]	-442	-413	-413	-412	-411	-409
Sh.blt force [kN]	11.7	11.8	11.8	11.8	11.7	11.7
Lap.blt force [kN]	18.8	16.5	16.5	16.4	16.4	16.6
Chest 3ms [m/s^2]	612	575	574	569	560	550
HIC36	908	805	799	797	784	782

	Reference	No friction	μ=0.1	μ=0.3	μ=0.5	μ=0.7
Head x-disp. [mm]	277	295	295	295	294	294
Head z-disp. [mm]	-337	-326	-326	-325	-327	-329
Sh.blt force [kN]	7.8	7.5	7.5	7.5	7.5	7.5
Lap.blt force [kN]	11.2	10.2	10.2	10.2	10.3	10.3
Chest 3ms [m/s^2]	612	531	532	534	540	547
HIC36	844	786	783	791	791	792

Simulations of different impact velocities

The results from the simulations of the different impact velocities when the effect of friction was included can be seen in Fig. 5. The total benefit of the friction-controlled force-limiter was of similar magnitude to that of the original, although the former performed comparatively better at lower velocities.

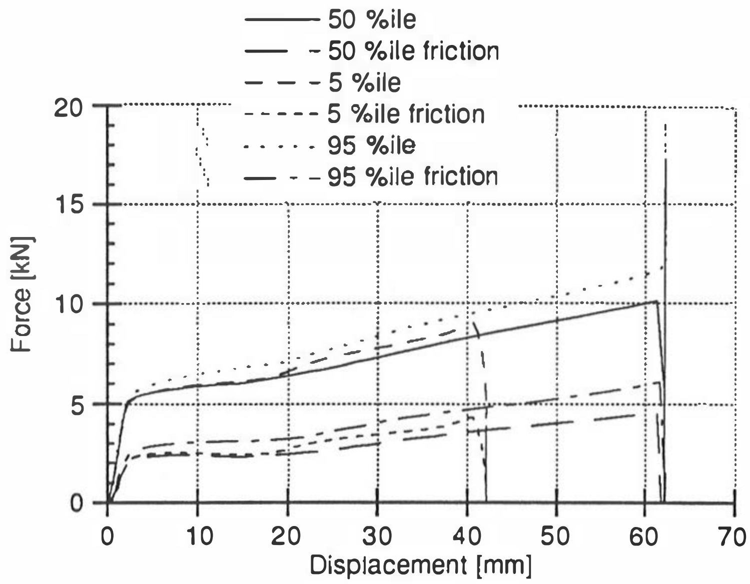

Figure 4. Force-displacement curves for the force-limiter in the simulations of 48 kmph barrier impacts with various dummy sizes and with a coefficient of friction of 0.5 between the sliding anchorage and the slot in which it slides.

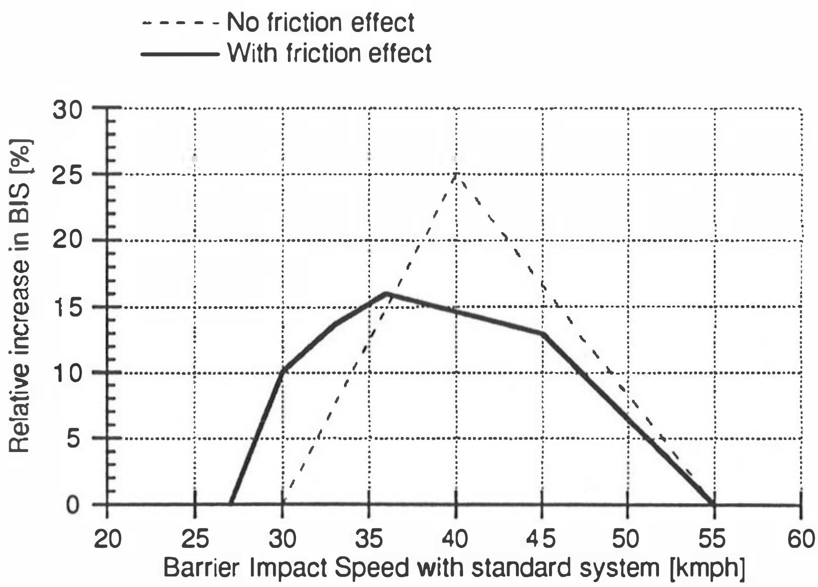

Figure 5. Increased barrier impact speed allowed without increased injury criteria for the chest and abdomen if the level of force-limiting is influenced by friction (μ=0.5). The corresponding curve obtained when no friction was present is included for reference.

Benefit-Cost Analysis

In order to translate the findings from the simulations into values for the reduction of injury in the real world, the results were dealt with according to the method suggested by Tingvall (1993). This method utilises the law of impulse to translate changes in barrier impact speed into changes in relative weight between colliding vehicles. In this case the increased BIS allowed with the force-limited seat-belt system corresponds to a reduction in the weight of the target vehicle by half of the increase in BIS. For example, to reach the same level of injury criteria for the chest and the abdomen as in a reference test with an BIS of 43 kmph, the BIS can be increased by 20 % if the occupant uses the force-limited system. Thus, for each bullet vehicle in the Folksam accident data file that had an BIS of 43 kmph, the number of injuries sustained by the occupants in that vehicle was compared with the corresponding number in an identical crash with a similar bullet vehicle but this time with a target vehicle of a ten percent lower mass. When all collisions in which the force-limiter would have made a difference were dealt with accordingly, it was found that the force-limiting device presented in this study could be expected to reduce the number of injuries to the chest and the abdomen by approximately 12 %. According to a comprehensive Australian study [Monash University, 1992], this reduction corresponds to a reduction in "harm" of about $ 25 per produced vehicle.

The cost for two force-limiters of the design described previously plus the cost for assembling the devices into a car is estimated to be approximately $ 10. Using the "equilibrium method" [Kahane, 1981; NHTSA, 1983], the Benefit-Cost Ratio (BCR) is estimated to be 25/10 = 2.5 for introducing the device in the car fleet.

DISCUSSION

Injuries caused by the loading of the seat-belt are common, and the human and societal cost associated with these injuries is high. Yet most investigators have found this an acceptable trade-off when considering the protection afforded by the seat-belt and the problems associated with ensuring this same protective capacity with lower levels of belt-force.

This studyshows that there is a method of lowering the load from the seat-belt system on the occupant and still maintain the restraining capacity of the system.

There may be several reasons why the principle of limiting the force at the lower buckle attachment has proven so successful. First of all, since the buckle anchors both the shoulder-strap and one of the lap-straps to the vehicle, the buckle and the stalk are exposed to very high forces in a crash. This means that even a small plastic deformation of the anchorage-point will absorb much energy. A person weighing 75 kg has a kinetic energy of 6,7 kJ when travelling at 48 kmph. When bottoming out, the force-limiter presented in this study has absorbed seven percent, or 480 J, of this energy. Ström and Lundqvist (1989) estimated that a standard seat-belt webbing (8 % elongation at 10 kN static load) worn in a standard configuration absorbs about eight percent of the occupant's kinetic energy in a 48 kmph crash. This means that the force-limiter more or less doubles the energy absorption of the seat-belt system.

It is also assumed that the more horizontal the movement of the pelvis in a crash, the better [Adomeit, 1979]. However, to maintain such a horizontal pelvic motion is difficult. The reason is that the centre of gravity of the lower torso is located lower than the lowest possible level for applying the restraining force, which means that if the force is applied in the horizontal direction only, the pelvis rotates its upper part rearward and the belt slips onto the abdomen, which cannot withstand the force without being seriously injured. The latter phenomenon is known as submarining.

To check whether the risk of submarining increased or decreased when the seat-belt system was modified was therefore a central part of this work. Håland and Nilson

(1991) had previously found a continuous variable that correlated well with the risk of submarining, and this variable was thus measured. The results showed that the horizontally sliding stalk attachment significantly reduced the risk of submarining compared to the standard system.

The benefits of increasing the forward motion of the pelvis by means of a sliding stalk attachment-point had already been observed by Svensson (1978), who could show that such an arrangement lowered the loads on the body without increasing the head-forward displacement. However, in Svensson's work the energy absorption took place in the frontal part of the seat, and the idea behind the sliding buckle was mainly to make sure that the lower torso would hit this energy-absorbing structure.

Another effect of limiting the horizontal component of the force in the buckle stalk is that the force-limiting device can be made sensitive to impact severity and occupant size. This presumes that a significant part of the resistive force in the horizontal direction is due to friction between the stalk anchorage and the upper edge of the slot that guides the anchorage. Then the force that resists motion in the horizontal direction will depend upon the force in the buckle stalk, which in turn is higher the heavier the occupant and/or the more severe the crash-pulse. The results in this study show that in a 48 kmph crash with a force-limiter designed for maximum protection of the 50 percentile male, the 95 percentile male is better off the higher the coefficient of friction. In the case of the fifth percentile female, the injury criteria show the opposite trend, although in her case the difference in criteria for different coefficients of friction is small. The reason for this small difference could be that the energy absorbed by the force-limiter is mildly influenced by the coeffiecient of friction, since the small female does not make the force-limiter "bottom out". This may also explain why the injury criteria increase for the small female when the coefficient of friciton increase: In contrast to the two cases with the heavier, "male", dummies, the force-limiter is still "active" when the belt forces of the female dummy peak. Therefore an increased coefficient of friction leads to a stiffer force-limiter in the most critical part of the crash process.

However, the injury criteria of the female dummy differed so little with different coefficients of friction that a coefficient of friction of 0.5, which proved very beneficial for the 95% male, was considered an appropriate value. This would widen the range of crash severities in which the force-limiter would have a positive effect. The results from the simulations of the various impact velocities indicate that such a wideening does occur. The effect of the force-limiter that used the friction as part of the resistive force was more or less constant over an interval of velocities, whereas the original force-limiter had a much more pronounced "peak performance" at an impact speed of 50 kmph. In this context it must, however, be pointed out that the layout of the simulations was simplified and thus less validated in the tests with friction than in the original test series. One reason for the modification was that the implementation of the force-limiter had to be changed in order to include the friction. Another reason was that it was difficult to position the fifth and 95th percentile dummies in the exact same way as the original 50th percentile dummy had been positioned. In order to obtain an identical position for each dummy, the 50 percentile dummy had to be repositioned.

The advantages accorded the force-limiting system tested in this work is to some extent based on the capacity of the system to reduce the Chest 3ms-criterion. This criterion is a poor predictor of chest injury, since it does not discriminate between the various ways in which the chest can be loaded in a car crash [Horsch *et al.*, 1991]. However, this work only comprised tests with a belt-restrained dummy, and, furthermore, the belt geometry and the sitting posture of the dummy were kept constant in each group of tests where comparisons were made. Thus, it is reasonable to say that the mode of chest loading was identical in all the tests, and, consequently, the acceleration of the chest (or rather of the thoracic spine) should be a valid criterion for comparison of chest loadings.This assumption is supported by the fact that the chest compression, which is regarded as the best predictor of chest injury for belted occupants in frontal impacts [Horsch *et al.*, 1991], showed the same pattern as the Chest 3ms-criterion. The chest compression was, however, only measured in the sled-tests, since it could not be satisfactorily calculated in the mathematical model.

Despite the fact that the Chest 3ms-criterion seems reasonable to use for comparing the improved restraint with the baseline seat-belt system, other measurements have been made as well, such as the forces in the belt-straps. When the improved protective capacity of the force-limiting belt was established in this study, the least improved of these measurements was used as "limiting factor". This meant in turn that the reduction of the Chest 3ms often corresponded to a much greater difference in BIS than is indicated in Fig. 4. This was especially true for the tests at the higher velocities. Measurements of the head displacement in the x- and z-directions were also made, as well as of the HIC_{36} and the forehead velocity, to ascertain that the reduced loading of the torso was not accompanied by an increased risk of head injury.

Even if valid injury criteria are at hand, it is still difficult to transfer results obtained in a laboratory or in a computer to the real world. In the real world, the configurations and severities of crashes vary a great deal, as well as the sizes and the tolerances of car occupants. To deal with this, several steps have to be taken, each one adding an element of uncertainty to the result. However, in the real world there is one parameter which can be obtained with a high degree of certainty, namely the mass ratio of two vehicles involved in a collision. It is reasonable to assume that the pre-impact conditions of the bullet vehicle is independent of the weight of the target vehicle. The real-world consequence of introducing a feature that allows an increased test impact speed without increasing any injury criteria can thus be estimated simply by translating the improved crash performance into a mass-reduction of the target vehicles. Such a method is suggested by Tingvall (1993). The method was thus used on the results from this study to 1) find what decrease in target-vehicle-mass the improved crash performance corresponds to, and 2) to calculate the difference in injury incidence if, for each vehicle, the distribution of target vehicle masses was changed in accordance with the result of step 1). In this process only half of the difference in protective capacity between light and heavy vehicles were considered to be a mass effect. The other half was considered to be due to additional safety features, such as more energy absorbing structures, in the heavier vehicles.

The reduced cost which would follow a reduced incidence of thoracic and abdominal injuries was obtained from the study undertaken by Monash University (1992), by subtracting the total cost due to chest and abdominal injuries by the number derived with the Tingvall method. The cost per vehicle was obtained by dividing the total cost reduction by the number of cars in the aforementioned study. This "equilibrium method" is supposed to give a proper estimate of the possible societal profit associated with the introduction of an injury countermeasure.

CONCLUSIONS

Limiting the strength of the anchorage of the buckle stalk in the horizontal direction has proven an effective means of reducing the load from the three-point seat-belt to occupant torso in frontal impacts, as well as to reduce the risk of submarining. These reductions have been accomplished without adverse effects, such as increased risk of impact of head to the car interior. The force-limiter is beneficial at above medium impact severity. In addition, it adapts to occupant size so that it benefits most adult occupants in a similar way.

Mathematical simulations of impacts indicate that the force limiter allows for an average increase in barrier impact speed of 13 % in the range from 30 to 55 kmph, with a "peak performance" of 25 % at 40 kmph. Translated into the Swedish road traffic situation, this equals the elimination of about 12 % of all thoracic and abdominal injuries to front seat occupants.

This corresponds to a reduction in cost of $ 25 per produced vehicle, which should be compared with the cost for introducing the force-limiter, estimated to be $ 10 per vehicle. This simplified analysis indicates that the introduction of the force-limiting device described in this study would be more than well paid for merely by the expected reduction in societal cost for car accident victims.

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