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BI-522

HIGH-RETENTION SEATBACK FOR SAFETY IN SEVERE REAR-END CRASHES

David C. Viano

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August 6, 1991

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BACKGROUND AND PURPOSE

While NHTSA was recently petitioned to increase the stiffness of seatbacks in rearward loading, laboratory and field research has shown that the current deflection performance is not only energy absorbing but also protective of occupant injury. However, in the more severe crashes, an unbelted occupant can rotate the seatback sufficiently to ride up and off the seat with potentially injurious impacts in the rear compartment of the vehicle. While safety belt use significantly enhances retention, excursions in rear crashes related to seatback rotation may be a factor associated with injury in some cases.

Current seat designs are effective in providing energy absorbing deflection and ride-down benefits for occupant protection. Yet, the designs rely on friction between an unbelted occupant and the seatback to prevent ramping and loss of retention in a rear crash. The greater the severity of impact, the more the seatback rotates rearward and the lower the frictional force holding the occupant. With current seat designs the greater the load, the greater the seatback deflection, and the greater the potential for occupant ramping up and off the seat. Thus, the recent controversy over seatback stiffness may be focusing on the wrong issue for further improvement in crash protection. An alternative mechanism for seatback deflection may be worth considering.

This study describes a new concept to improve retention of belted and unbelted occupants in severe rear crashes. It provides an alternative mechanism for seatback deflection which is stable in that the greater the occupant loading, the greater the resistance to seatback rotation and rearward displacement of the occupant. This maintains the occupant in equilibrium under the dynamics of a rear crash.

SUMMARY

A new concept for seatback deflection in rear crashes has been developed and validated in Hyge sled tests. It is called a High-Retention Seat (HRSEAT: ROI #R-5970/G-7993) and it incorporates two features which modify the seatback deflection. The first feature is a rearward moving pivot point during crash loading. This allows the seatback to displace 4"-6" (10-15 cm) under controlled EA loads. The second feature is a wire connecting the seat frame and back. This limits rearward rotation of the seatback. The new features do not affect normal use of the seat or recline functions as the support wires are slack and lay along the seat frame and back.

In a rear crash, the occupant loads the seatback and displaces the EA pivot. This has a geometric effect on the distance between the wire attachment points which causes the wire to become taut forming a triangular support which limits rearward rotation of the seatback. The greater the occupant loading the greater the resisting force in the support wires, and the greater the displacement of the EA pivot point. This action has the secondary benefit of not only reducing the rearward rotation of the seatback but also making it more upright. By making the seat more upright in the more severe crashes, even unbelted occupants are retained on the seat and ramping is reduced. The HRSEAT motion also reduces the risk of entrapping a rear seated occupant by the seatback folding down with conventional designs. The High-Retention Seat concept actually reduces the infringement on rear survival space.

A prototype High Retention Seat was developed by modifying a conventional bucket seat with a single-side recliner mechanism. It was subjected to a 9.5 m/s (21 mph) sled velocity with an unbelted Hybrid III dummy. At this severity level, a conventional seatback rotates rearward sufficiently that the occupant ramps up and off the seat. With the High-Retention Seat, the occupant displaced the EA pivot and engaged the support wires. In four tests, the occupant was fully restrained in the seat.

Fifteen out of sixteen biomechanical responses were similar in comparable tests with the standard and High-Retention Seats. This demonstrated that head and neck injury risks were not modified during seatback loading, whereas the potential adverse effects of subsequent impacts by loss of occupant retention were prevented with the new seat concept. There was an increase in chest acceleration which reflected the greater restraint of the occupant, and the response levels were well below tolerance levels. Load limiting by the EA pivot displacement reduced pelvic acceleration and improved whole body responses by keeping the occupant more upright during the impact.

During the development of prototype High-Retention Seats another modification in current bucket seats was made to improve occupant loading into the seatback. Seat frames have a perimeter sheetmetal construction. In normal use, the occupant is seated with the pelvis slightly below the frame. In a rear crash, displacement of the occupant requires an up-and-over motion. This lifts the occupant and increases the bending moment on the seatback. The rear lip of the seat frame was cut down to allow a horizontal displacement of the occupant into the seatback. This provided better loading into the EA pivot and improved subsequent motions. The modification was called a Low Profile Seatframe (ROI #R-6083/G-8260) and improves occupant safety irrespective of seat type by reducing the upward loads on the occupant which tend to lift the pelvis.

INTRODUCTION

Even though rear-end crashes have the lowest incidence of serious injury or fatality of all crash types, they represent an area for possible incremental improvements in safety. Table 1 summarizes recent work by Data Link (1990) on car crashes and occupant casualties in relation to involved occu

Table 1

Car Crash Casualties by Crash Type Based on Various Exposure Approaches (Average Annual Incidence based on the Six Years 1981-1986) Sources: The NASS, the FARS, and the R.L. Polk Data (Derived from Data Link 1990).

Car Exposure and Causalities	All Impacts	Rear Impacts	Percent Rear
Exposure: Car-Yrs in Service	110,042,000	Same	-
Casualties:			
All Car Crashes	7,670,000	850,000	11.1
Fatal Car Crashes	34,860	1,700	4.9
All Crash Involved Occupants	11,742,000	1,433,000	12.2
All Injured Occupants AIS≥1 pg 10	2,633,000	613,000	23.3
Seriously Injured Occupants - ≥2 ?	105,830	8,030	7.6
Occupant Fatalities	23,914	843	3.5
Based on Crash Involved Occupants			Ratio
Injured Car Occupants per Thousand	224.0	428.0	1.91
Seriously Injured Car Occupants per Thousand	9.0	5.6	0.62
Car Occupant Fatalities per Thousand	2.0	0.6	0.30
Fatal Car Crashes per Thousand Car Crashes in General	4.6	2.0	0.43
Based on Car Years in Service			
All Crash Involved Cars per Thousand	70.0	7.7	0.11
Fatal Crash Involved Cars per Million	317.0	15.5	0.05
Crash Involved Car Occupants per Thousand	107.0	13.0	0.12
Injured Car Occupants per Thousand	24.0	5.6	0.23
Seriously Injured Car Occupants per Million	962.0	73.0	0.08
Car Occupant Fatalities per Million	217.0	7.7	0.04

look at AIS≥1, AIS≥2, Pollack's scale ??

pants and vehicles in service. Nearly 5% of all fatal crashes involve rear impact. The fraction of all crash involved vehicles is 11% for rear-end impacts. In terms of injury, 3.5% of fatalities occur in rear-end crashes. The fraction rises to 7.6% for serious injury – defined as KA or B in police reports or approximately AIS 3+ injury – and increases to 23% for all injury. Surprisingly, nearly a quarter of occupant injury occurs in rear-end crashes. While a majority of the injuries are minor in severity, rear crashes represent an event with relatively high injury rate in comparison to other crash types.

A number of different injury risks are shown in Table 1. Injuries per thousand crash exposed occupants is nearly twice the rate for the average crash. The incidence of serious and fatal injury is, however, substantially lower in rear-end crashes as compared to all accident types. The rates of serious injury and fatality in rear crashes are 62% and 30% respectively of the average crash. Fatal injuries in rear crashes occur in 0.6/1000 occupants. This is 30% of the overall fatality rate of 2.0/1000 occupants in all crash types.

Injuries and fatalities in rear crashes also occur at substantially lower rates than all crash types when exposure is based on vehicles in service. While 317 fatal crashes occur per million vehicles for all accident types, the rate is only 15.5/million for fatal rear crashes. This is 5% of the rate in all crashes. The rates rise for injuries of lower severity but never exceed a quarter of the relative rate in all crashes.

Table 2 shows that over half of the rear crash exposed occupants are involved in so called "simple" car-to-car rear crashes. These accidents involve one vehicle striking the rear of another. Safety belt use significantly reduces the risk of injury. Rear chain collisions involve about 10% of exposed occupants. These crashes involve multiple impacts with the primary

Table 2

Safety Belt Effectiveness in Rear Impacts for Front Seating Positions
(Reprinted Table 11 from Data Link 1990)

TYPE OF ACCIDENT	UNRESTRAINED			RESTRAINED			SEAT BELT
	% Occup	% Harm	Harm/Occup	% Occup	% Harm	Harm/Occup	Effectiveness
Simple Car-to-Car	39.0	33.6	.27	14.0	6.5	.14	48%
Chain Collision	6.0	4.9	.26	2.5	0.8	.10	62%
All Others	29.5	44.0	.47	9.0	10.2	.37	23%
All	74.4	82.5	.35	25.6	17.8	.22	37%

damage in the rear, but subsequent frontal damage. The typical accident involves a string of impacts initiated by a rear impact of a vehicle which is pushed forward into another vehicle. Safety belts are most effective in reducing injury risks in rear chain collisions. The remainder of rear crashes are largely higher-speed single vehicle accidents, which are frequently preceded by loss-of-control and eventual impact of the rear. They constitute about 40% of all rear crashes.

Vehicle weight is a significant factor in the risk of fatal and serious injury rear crashes. Figure 1 shows that rear crashes pose a higher relative risk of fatal and serious injury than the average crash for occupants of vehicles weighing less than 2,500 lbs (1,140 kg). The data are normalized to the average risk for all crashes so the serious injury rate of 2.2 in the lightest vehicles is over twice the average rate and 59% greater than the relative risk in all crash types for light vehicles. Fatalities also occur at a higher relative rate (1.67 v. 1.32, or 27%) in rear crashes of light vehicles.

The greater injury risks in lightweight vehicles implies a relatively greater importance of the velocity change of vehicles involved in rear crashes. This point-of-view is consistent with greater fatality rates in multi-vehicle rear crashes. Figure 2 shows fatality rates by the type of rear crash. Multi-vehicle crashes constitute the majority of accidents, irrespective of vehicle weight. However, the risk of fatality increases steadily with lighter vehicles involved in multi-vehicle crashes. This is also true of multi-vehicle crashes that eventually involve a rollover in the accident sequence.

Table 3 shows that low-speed crashes are most frequent. Ninety-five percent (95%) of rear crashes involving large cars occur with less than a 9.0 m/s (20 mph) change in velocity. The velocity change of small cars is substantially greater in rear crashes than for other accident types. The relative

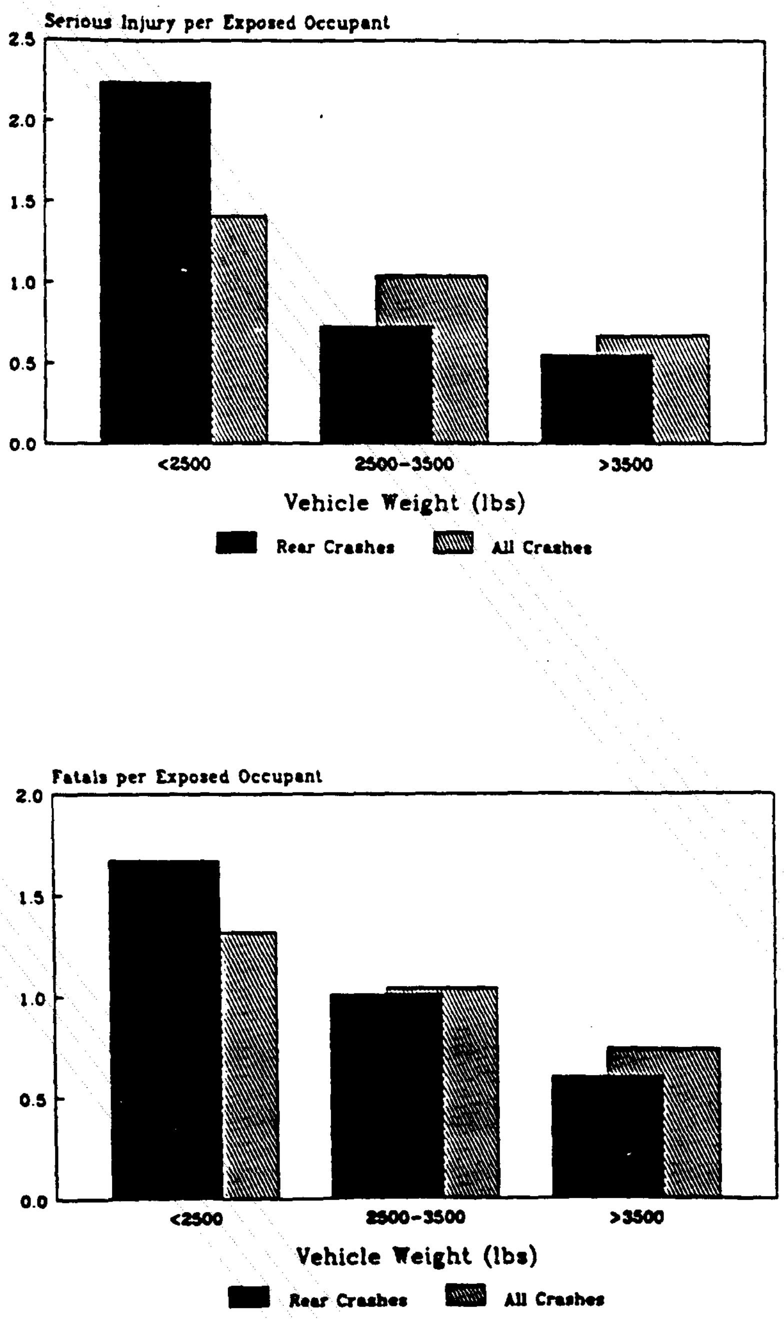

Figure 1: **Rates of serious and fatal injury per thousand crash exposed occupants by vehicle weight (developed from information in Data Link 1990).**

Table 3

Distribution of Car Occupants in Police Reported Accidents by Crash Severity in the Accident, Type of Impact, and Car Size
Source: The NASS 1981-1986
Smaller Cars: Under 2,500 Lbs; Larger Cars: Over 2,500 Lbs
(Reprinted Table A-19 from Data Link 1990)

Crash Severity	Rear Smaller	Rear Larger	All Other Smaller	All Other Larger	Impacts Cars
< 10 mph	20,215 (9.3)	227,458 (33.76)	472,542 (31.2)	1,781,334 (45.8)	2,501,549
10-20	151,458 (69.6)	413,055 (61.3)	849,107 (56.1)	1,776,991 (45.7)	3,190,611
20-30	40,745 (18.7)	29,643 (4.4)	154,816 (10.2)	272,164 (7.0)	497,367
> 30 mph	5,266 (2.4)	3,579 (0.5)	37,906 (2.5)	61,520 (1.6)	108,272
Total	217,685	673,734	1,514,371	3,892,008	6,297,798

Detail on Crash Severity Distribution

<u>Crash Severity by Car Size</u>

Crash Severity	Under 2,500 Lbs	2,500 to 3,500 Lbs	3,500 to 5,000 Lbs
Mean	17 mph	14 mph	12 mph
10 Percentile	27	20	17
5 Percentile	30	23	20
1 Percentile	42	31	30

incidence of crashes involving more than 9.0 m/s (20 mph) is 21% in small cars as compared with 5% for large cars. The comparable rate in rear crashes is therefore 4.2 (21%/5%); the rate in all crashes is 1.5 (12.7%/8.6%). Thus, there is a greater relative importance of rear crash protection in small, lightweight vehicles. This aspect of small car safety may have relevance to vehicle changes required to meet proposed increases in average fuel economy or CAFE.

The more frequent low severity rear-end crashes can result in whiplash-type injury. As shown in Table 1, the relative incidence of moderate or greater injury (AIS 2+) is greater in rear crashes than other crash types. Many of these crashes involve minimal damage to the vehicle structure and interior, and the biomechanics of injury is largely unknown (Viano et al. 1989). While severe rear-end crashes are less frequent at a rate of 1 per 75 police reported rear crashes (428 v. 5.6/1000 crash involved occupants), significant vehicle damage can occur and injuries may not only be life-threatening, but also permanently disabling if they involve the brain or spinal cord. In these crashes structural and interior deformations afford occupant protection by load limiting and energy absorption. This includes seatback deflection. However, too much seatback deflection can lead to a loss of occupant retention with risks of secondary impact with the rear interior of the vehicle, the zone of crash deformation, or rear seated passengers.

A comprehensive review of rear-end crashes, seat performance, and occupant protection was conducted by Strother and James (1987). This work was seminal to a clearer understanding of the role of seatback deflection in managing occupant energies and reducing injury risks in a rear crash. It surveys over thirty years of work on seat performance in rear crashes. Available published information was also summarized on the stiffness of production seatbacks and historic concepts were reviewed for rigidized and advanced safety seats.

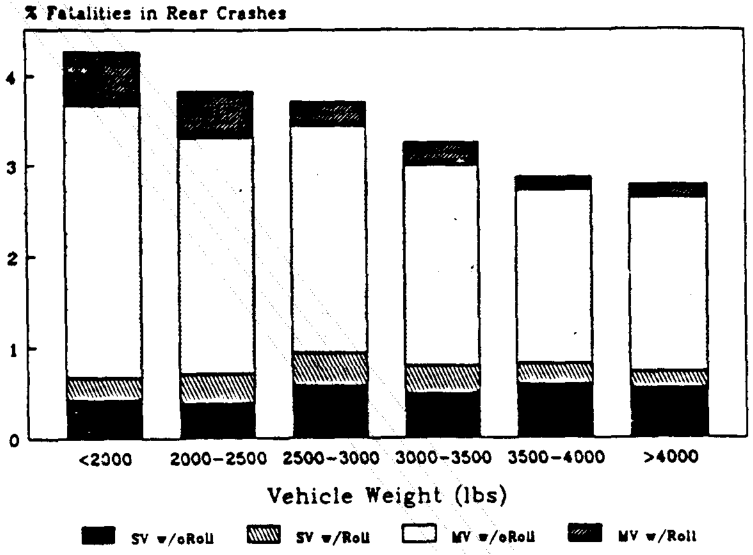

Figure 2: Fraction of fatalities in rear crashes in relation to vehicle weight for single and multi-vehicle crashes with and without rollover (developed from information in Data Link 1990).

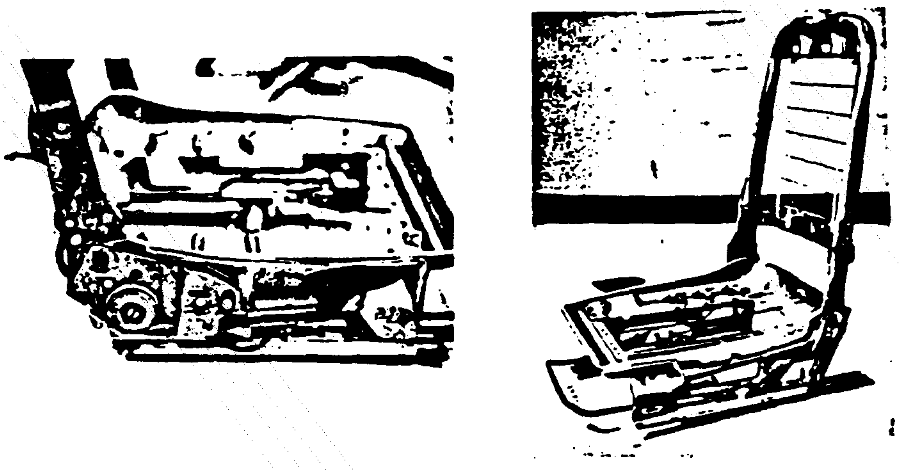

Figure 3: Example of one type of conventional bucket seat with single side recliner and sheet metal frame for the seatback and bottom.

Strother and James (1987) argued persuasively against the idea of rigidizing the seatback as an approach to further improving occupant safety, since such concepts may aggravate whiplash injury and may not prevent the occupant from ramping up the seatback. They also emphasized the benefits of safety belt use to enhance occupant retention.

More recent studies have been completed by NHTSA (1989) and Data Link (1990). Analysis of crash injury data indicates reasonable safety is provided by current seat designs in rear crashes. These analyses were used to deny recent petitions to modify stiffness requirements for seatback deflection during rear loading. While new rulemaking has not been initiated, investigation of potential safety improvements in rear crashes may provide incremental benefits. Obviously, current crash injury data indicate that significant reductions in injury risk can be realized immediately if the available safety belts are used. In addition, Warner et al. (1991) have indicated that occupants may not be in the design seating position at impact and rear crashes may involve vehicle pitching due to downward loads on the rear.

Based on the analysis of NHTSA, the performance of seats was judged acceptable when overall occupant safety is considered in rear crashes. However, a recent analysis of fatal crashes involving belted occupants by Viano (1991a) found that greater control of occupant kinematics in severe rear crashes may enhance occupant safety. Greater kinematic control, even of belted occupants, may be possible by controlling rearward deflection of the seatback. This may help limit movement of the occupant in rear and oblique-rear crashes.

CURRENT SEAT DESIGN AND RESPONSES

The current design of seats involves a separate seat cushion and a seatback. The seatback has a frame which attaches to the seat-bottom frame through pivots on the side (Figure 3). The attachment can be by a bolt or through a recliner mechanism. The latter permits rotation of the seatback forward for rear seat entry in two-door vehicles and rotation rearward for recline comfort. The pivot point is usually below a rearward support point, which stabilizes the seatback position in normal use and resists rearward deflection by normal occupant loading.

In severe rear-end crashes, the occupant can experience accelerations of 20g's or more (Strother and James 1987, Hilyard et al. 1973). This loads the seatback and rotates it backwards by hinging or pivoting action at the seat pivot and support and bending of the seatback. As more load is applied by the occupant, the seatback rotates more. When the rotation is sufficient, an unbelted occupant can ramp or slide up the seatback eventually displacing rearward and off of the seat.

In early laboratory tests, Viano (1982) found that loss-of-retention of unbelted Part 572 dummies occurred when the rearward angle of the seatback exceeded 60° from vertical--the normal seatback angle is 25°. In lower severity crashes, the occupant loads the seatback and rotates it rearward. However, the interaction retains the occupant so long as the seatback angle change is small enough that the occupant loading into the seatback is greater than the forces overcoming friction which hold the occupant from riding-up or ramping-up the seatback. This is the case for tests resulting in less than 60° overall rotation of the seatback.

In a follow-on series of rear-end crash tests conducted in 1981, Viano (1991b) recently reported that retention of an unbelted occupant can occur for rearward deflections of the seatback for angles above 60°. The critical factor related to unbelted occupant retention was the severity of sled velocity. Tests with greater than 8.3 m/s (18.4 mph) resulted in the occupant riding up and off the seatback. While safety belt use resulted in retention for all tests conducted, irrespective of crash severity, rotation of the seatback allowed substantial rearward excursion of the occupant.

Another observation from the previous research was that the mean acceleration of the sled did not seem to be a factor influencing occupant retention, whereas it did influence seatback rotation. This implies that the stiffness of rear-end vehicle crush may not be a significant factor in retention of front-seat occupants. However, this may not be the case for rear-seated occupants since survival space is critical in severe rear-end crashes and crush stiffness influences the extent of vehicle deformation.

The current pattern of seatback deflection is not self-limiting, since increases in occupant load increase rotation until retention is lost. This represents an "unstable" mechanism in severe rear crashes. Retention of the occupant occurs solely by the component of occupant loading into the seatback times the frictional effect being greater than the tangential component which promotes ramping or sliding. As seatback deflection increases, the greater rotation increases the relative magnitude of the tangential loading. This increases the possibility of losing occupant retention.

The loss of retention or large excursions of the occupant with seatback rotation in severe rear-end crashes can lead to secondary impacts with rear structures in the vehicle or with an impacting vehicle in the crash deformation zone. This may be a mechanism of injury in some crashes. While injuries may occur irrespective of improved retention because of human tolerance limits, enhancing occupant retention, controlling occupant kinematics, and improving energy management may be an area of potential incremental improvement in seat design.

HIGH-RETENTION SEATBACK CONCEPT

A new seat design approach was developed which modifies seatback deflection in severe crashes and improves occupant retention, energy management and kinematic control. The idea maintains current seat functions of pivot and recline in normal use. The approach incorporates a controlled rearward displacement of the seatback pivot and recline mechanism, and simultaneous tension in a reaction wire or structure on the seatback attached at a point above the height of occupant loading. This approach keeps the occupant in stable equilibrium as seatback deflection occurs.

Figure 4 shows the motion of a seatback with a High-Retention Seat (HRSEAT: ROI#R-5970/G-7993) mechanism. Severe occupant loading causes the seatback to displace rearward while rotating. This controlled deflection engages a wire or structure that is brought into tension by the geometric effects of seatback displacement. The point of attachment of the wire or structure on the seatback is placed above the center of occupant loading so the greater the loading by the occupant, the greater the force in the wire or structure and the greater the control and retention of the occupant. This is a self-limiting and stable engagement as the greater the EA pivot movement, the more upright the seatback angle becomes.

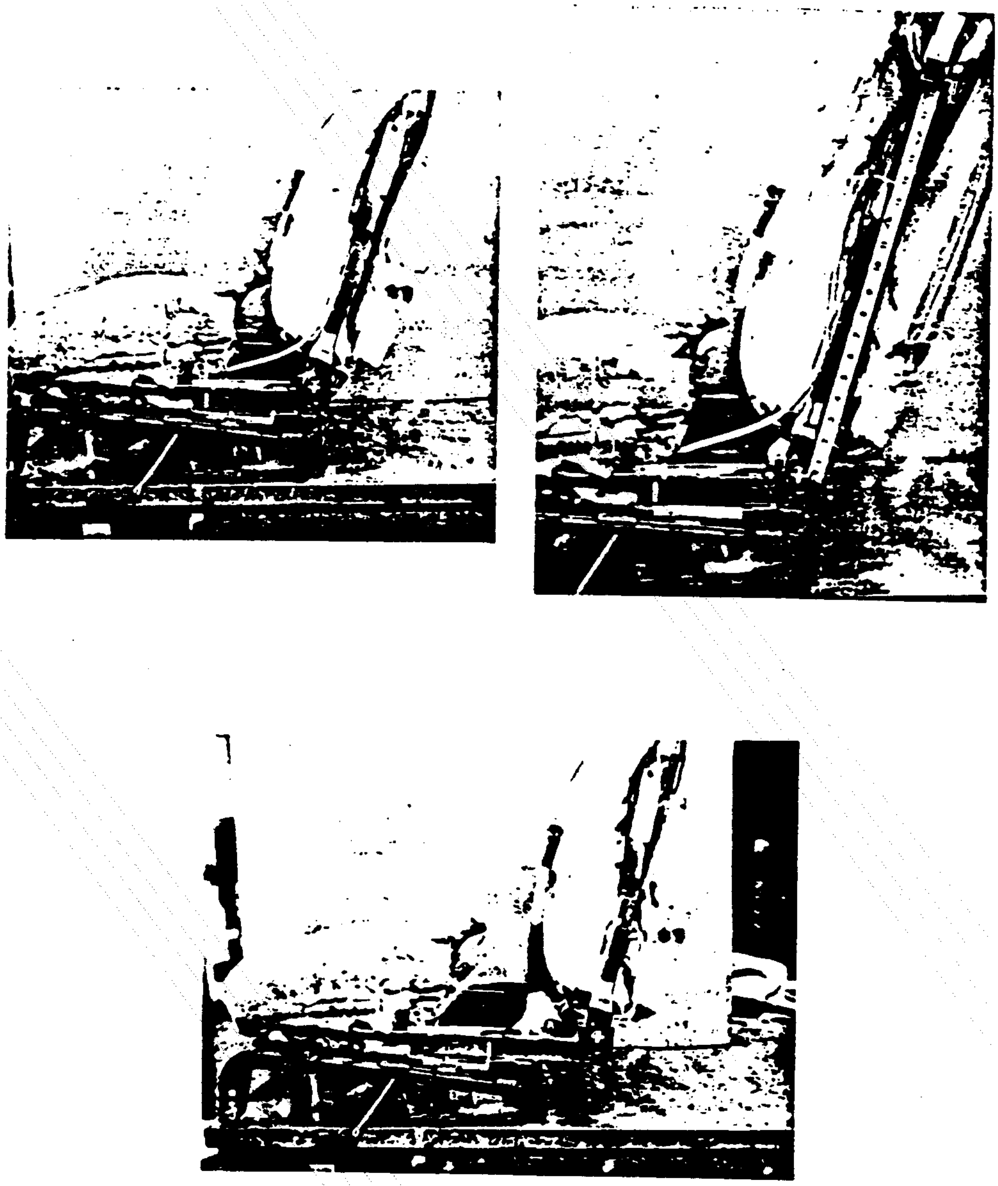

Figure 4: Prototype High-Retention Seat developed by modifying a conventional bucket seat to include a moving EA Pivot and Retention Wire on both sides.

Analysis of the geometric effects of this type of seatback motion is shown in Figure 5 and demonstrates the theoretical validity of the concept. For example, if the initial length of the wire or structure is 20" (51 cm) and involves an attachment to the seat cushion frame 6" (15 cm) forward of the pivot and 14" (36 cm) above the pivot on the seatback frame, the following calculations can be made.

Allowing a 1.5" (3.8 cm) controlled rearward displacement of the pivot and allowing an increase in the seatback angle from 25° to 45°, causes the distance between the wire or structure attachment points (P_1 and P_2) to slightly over 20" (51 cm). Since this distance is greater than the initial length of the wire or structure, it will be engaged in tension as that geometric position is reached. In addition, the greater the occupant loading into the seatback, the greater the movement of the EA pivot and reaction force developed by the wire to resist further rotation. This mechanism enhances occupant retention by increasing the seatback angle to a more upright position. At 4" (10 cm) EA pivot displacement, the seatback angle is 21.7° from vertical.

The controlled rearward displacement of the seat pivot or recline point is achieved by a load limiting mechanism that has a rigid-plastic response to force. Figure 6 shows a calculation of the approximate force-deflection response for each side of the seatback. The breakaway force of about 100 lbs (0.45 kN) per side is used to limit the engagement of the mechanism to severe rearend crashes and not to be engaged in normal seat use or recline performance. The reaction force in the plastic region increases to 300 lbs (1.34 kN) and increases further at maximum displacement. This maximizes benefits over the distribution in crashes by allowing some displacement in the more frequent low-severity crashes but also increasing energy absorption for the higher severity impacts.

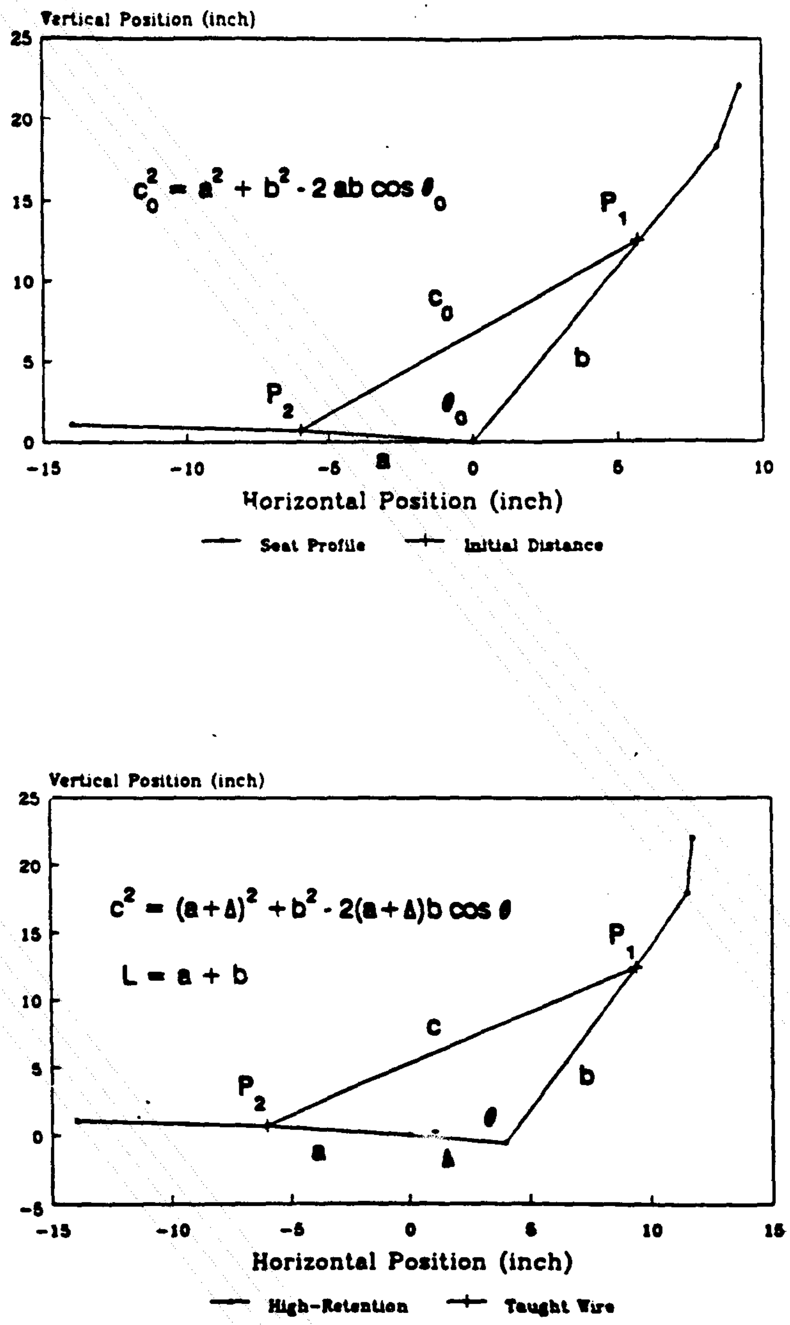

Figure 5a: Top shows the geometrics of a conventional bucket seat with the distance between point P_1 and P_2 given by c_0 based on distances a and b, which represent the initial length of wire; Bottom shows the geometric effects by moving the pivot point rearward by Δ. This yields a new relation for the distance between P_1 and P_2.

During the initial engagement of the EA pivot, the only reaction force and moment from the seat are provided by the typical seatback frame structure, recliner mechanism, and support mechanism. The response does not engage the reaction wire or structure initially. Thus the pivot mechanism resists rearward occupant force and moment until the breakaway of the EA pivot causes engagement of the reaction wire by geometric effects. This occurs at about 1.5" (3.8 cm) of EA pivot displacement based on the example calculations. Once the wire or structure is engaged, it provides significant resistance to occupant loading.

The ultimate design loads on the HRSEAT and vehicle attachments should be high enough to avoid catastrophic failure of the EA pivot and the reaction wire or structure. The analysis shown in Figures 5 and 6 are based on a 200 lb occupant. The High-Retention Seat engages the EA pivot with occupant accelerations above 1 g and provides maximum engagement of the reaction wire or structure in severe crashes approaching 20 g's occupant loading. A design limit provides stability for ultimate loading in a 30+ g environment.

The breakaway load for the EA pivot should be high enough not to engage it under normal driving conditions and use, but as low as possible to provide EA in low severity rearend crashes. The approximate breakaway level needs to be above the expected loading and abuses in normal driving situations, and high enough to include the effects of seatback inertial loading. Further clarification of this is required. During breakaway, the pivot provides all of the reaction force and moment resisting occupant loads. With EA displacement of the pivot, the reaction wire or structure is engaged thus providing an important additional force resisting occupant loading and seatback deflection.

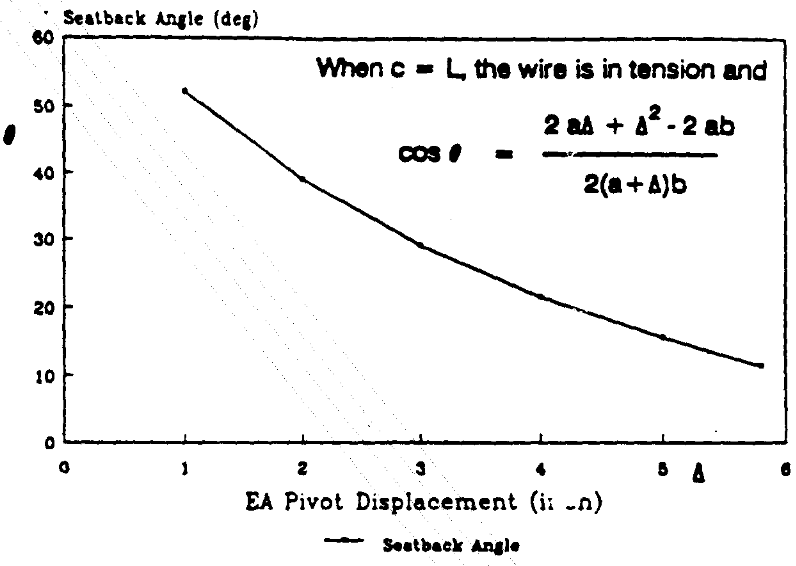

Figure 5b: There is a unique seatback angle at which the wire is in tension as the EA Pivot displaces. The relationship is given and plotted for the dimensions used in the example calculation.

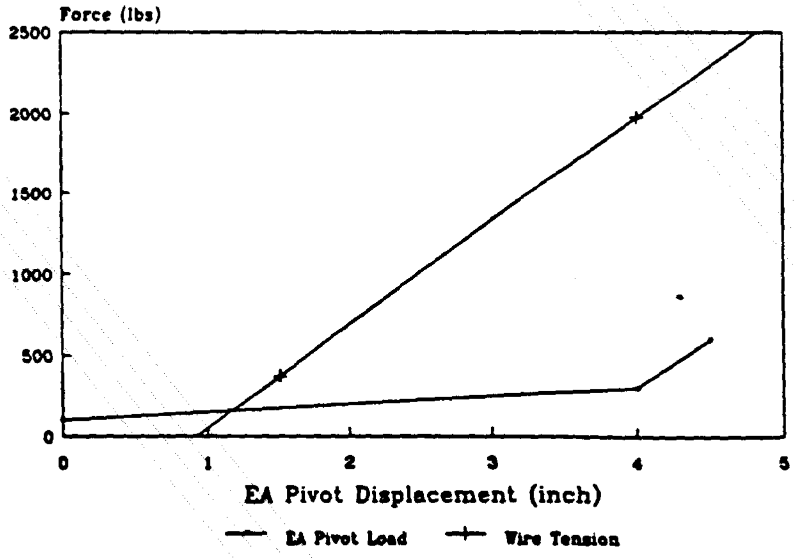

Figure 6: Equilibrium of occupant loads can be achieved by tension in the wire and resisting loads in the EA Pivot. This calculation provides the approximate levels of load based on the geometrics of the High-Retention Seat in the example.

Analysis of the force and moment equilibrium for the condition of a 20 g occupant load, a 4" EA pivot displacement, and 21.7° rotation of the seatback (a 3° decrease in seatback angle), indicates that equilibrium can be achieved by an EA pivot force of 500 lb (2.2 kN) and a wire or structure tension of 1970 lb (8.8 kN) per seatback side. This calculation assumes full extension of the EA pivot and a force above the pull strength to reflect greater resistance after maximum extension and the geometric effects of the example case excluding inertial effects from the seatback.

The example calculation also indicates that the reaction wire or structure carries the majority of the load resisting the occupant, once it is engaged by geometric effects of seatback displacement and rotation. The reaction wire or structure can be an EA element also so that occupant energy is absorbed during engagement. The design of the EA pivot and reaction wire should maximize energy absorption and minimize elastic deformation during a crash, since this approach reduces the potential for rebound of the occupant due to energy stored in the seat system by deformation. Clearly the additional loads born by the HRSEAT seat need to be considered in the design of the frame, seat-track, and attachments to the vehicle.

DEVELOPING A PROTOTYPE HIGH-RETENTION SEAT

A simple HRSEAT prototype is presented in Figure 7 to achieve the principles of a High-Retention Seat. In this experimental demonstration, a metal wire is fixed to the seatback and seat frame. The wire is routed along the frame and next to the pivot point so that it does not restrict normal rotation of the seatback forward or in the recline mode. The total length of the wire between the attachments is 20" (51 cm) as in the example case. This allows full recline of the seat under normal conditions. However, the wire engage

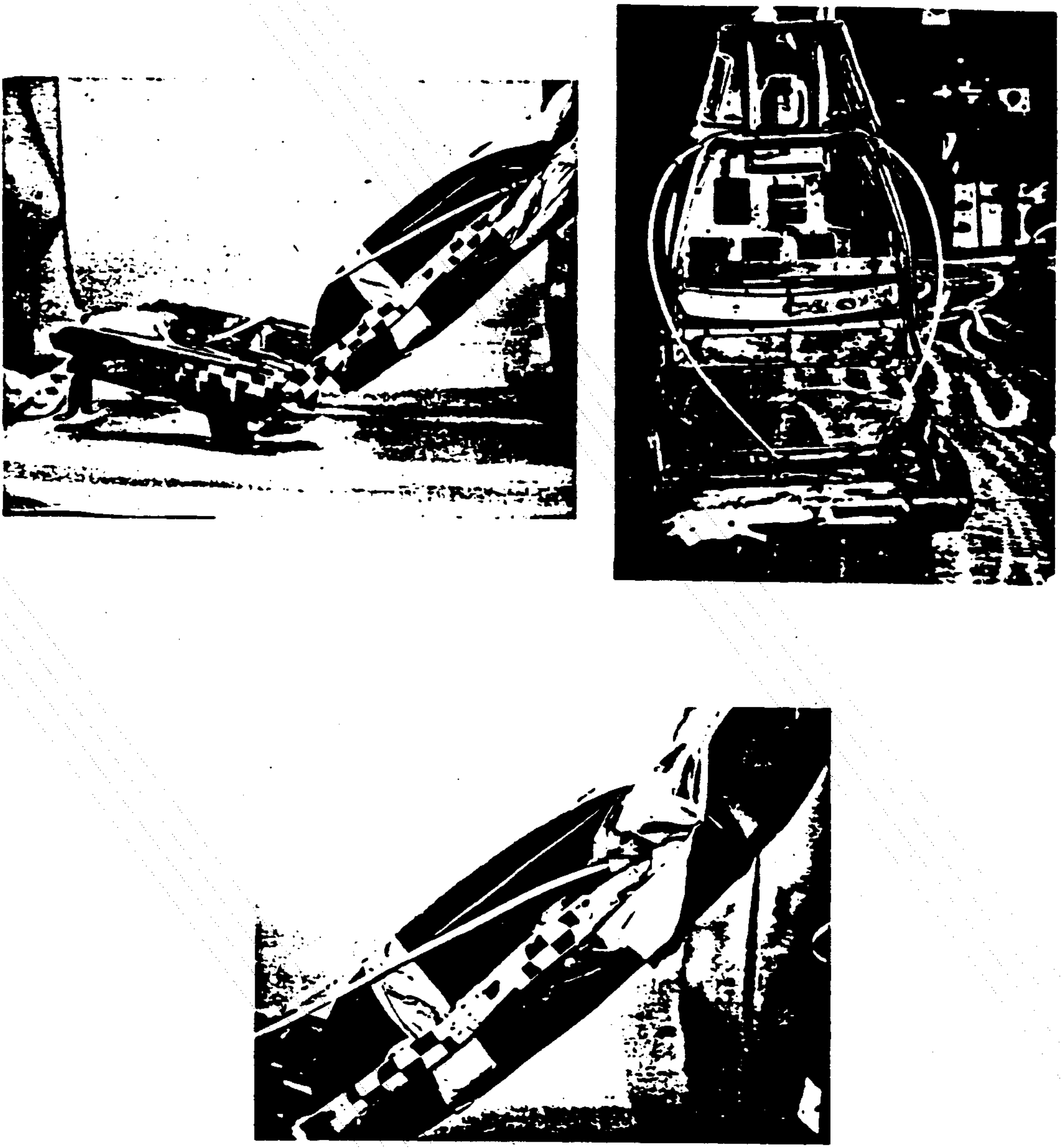

Figure 7: Photographs of the prototype High-Retention Seat involving an integrated headrest and wire insertion 20° above the pivot point.

ment in a crash requires the seatback to be in near normal orientation for the movement of the pivot to cause tension in the wire. This should not be a problem for the driver, but could be a factor in some situations with the passenger.

A prototype High-Retention Seat was developed by modifying a conventional bucket seat with recline mechanism. Two drawer slides were used to enable movement of the pivot point (Figure 8). The sliders were fitted into the sheetmetal sides of the seat frame after a slot was cut into the metal. The forward edge of the inner part of the slide was attached to a tapered strip of metal which was passed through two offset rollers to provide an energy absorbing element and controlled pull force. The taper ranged initially from 0.188" (4.8 mm) to 0.313" (8.0 mm) over the 4" pull length and the strip was 0.076" (1.9 mm) thick. This approach provided EA motion of the seatback pivot. A 0.188" (4.8 mm) nylon-coated braided metal wire was installed through the seat frame at a point 6" forward of the seatback pivot point.

The wire passed through a metal tube and the entire assembly was welded to the seatback frame at an angle simulating the line of tension with the High-Retention Seat under occupant loading (Figure 7). The other ends of the wire were routed through a hole drilled through the seatback frame at the angle of wire tension and welded in place. Static MTS pull tests confirmed that the wire and attachment had a yield strength of 3650 lbs (16.2 kN), which was sufficient strength for subsequent testing.

The initial HRSEAT prototype involved a seatback with a separate head restraint. This limited the upper insertion of the reaction wire to a height of 14" (36 cm). In subsequent tests, a seatback with integrated headrest was used. This allowed the wire insertion to be moved up to 20" (51 cm) from the pivot point for tests 2176 and 2179. The HRSEAT test data were similar for

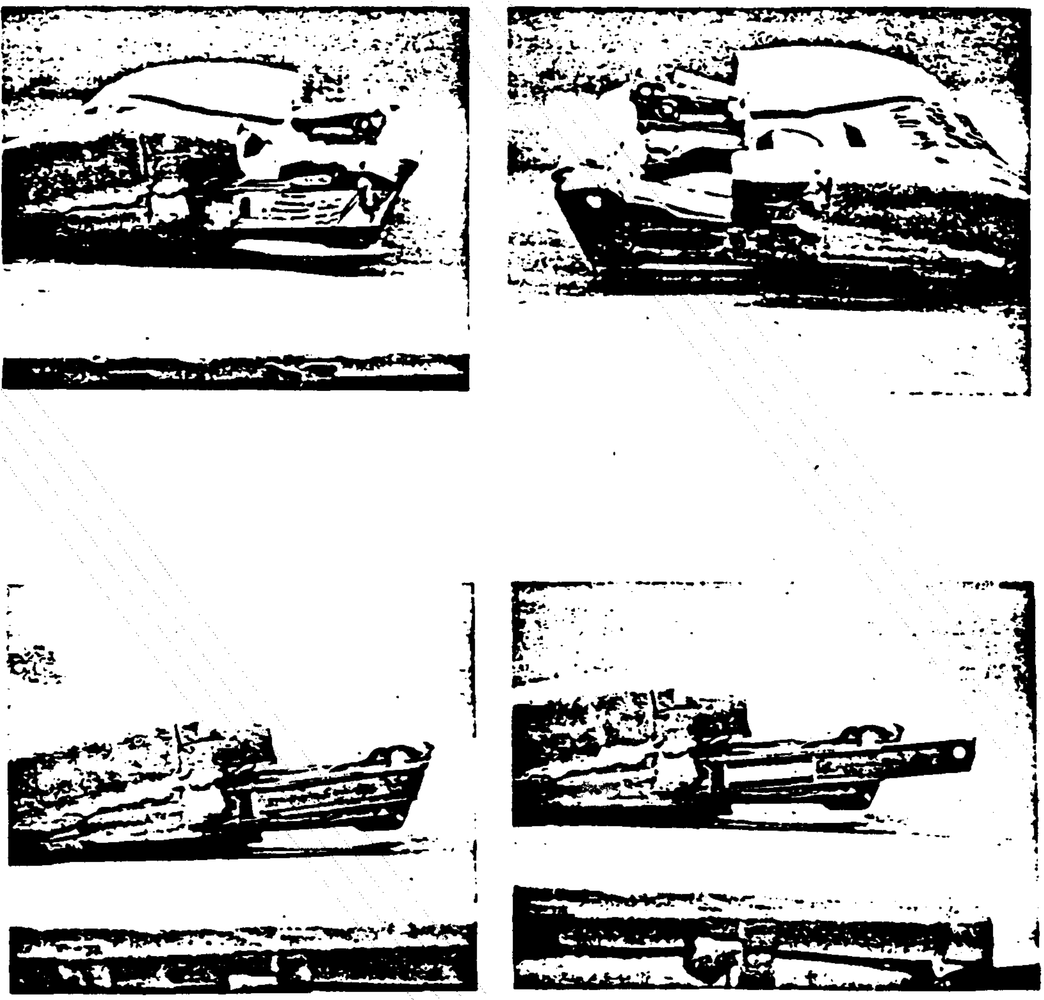

Figure 8a: Photographs of the EA Pivot displacement mechanism using a sliding channel and its insertion in the seat frame bottom.

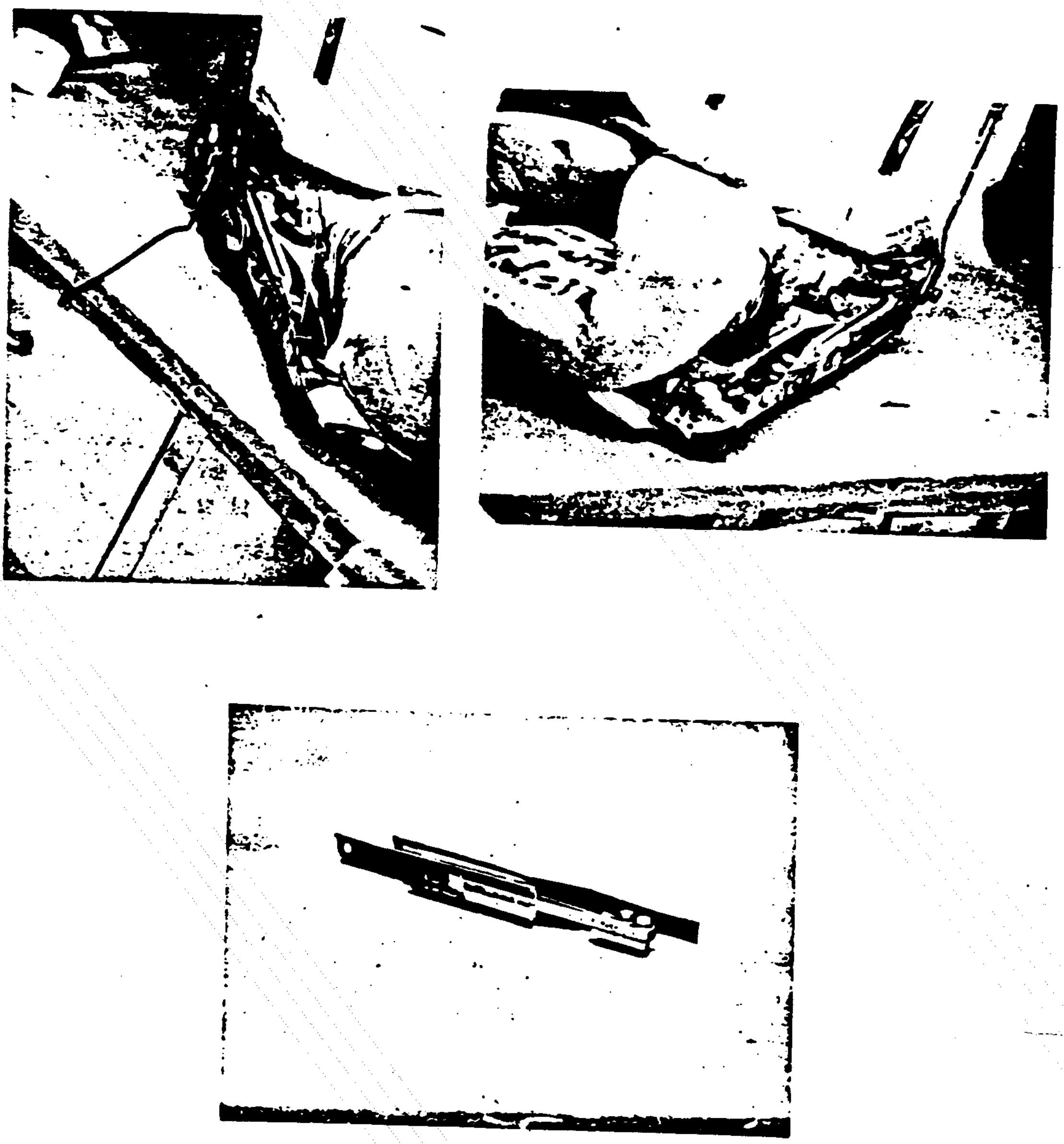

Figure 8b: Photographs of the EA Pivot load limiting mechanism using bending of a metal strip around two offset bolts.

both situations so the responses were merged for analysis and comparison with standard seats. The prototype seat was not optimized for minimal weight. Rather, the modification was made sturdy to validate the concept. A total of 15 lbs (6.8 kg) was added to the seat and included about 6 lbs (2.7 kg) per side for the slider mechanisms, side attachment plates and EA strip-pull mechanism, 1.5 lbs (0.7 kg) for the bottom cross bracing of the seat frame, and 1.5 lbs. (0.7 kg) for the low-back support on the seatback. With greater care, these modifications could have been made with an added weight of about 6 ibs (2.7 kg).

After preliminary tests with the High-Retention Seat, an additional modification was made in lowering the back edge of the sheet-metal seat frame. The preliminary tests showed that the occupant was forced up by the back edge of the sheet-metal frame of the seat bottom during rear impact loading (Figure 9). This action not only increased the height of the dummy, but also caused a greater moment on the seatback. This interfered with rearward movement of the EA pivot and caused significant seatback deflection before the pivot motion could properly activate the retention wire.

The up-and-over movement of the dummy also aggravated hyper-extension of the neck as the dummies head rose above the seatback. The rear lip of the seat frame was cut down to allow simple rearward translation of the H-point during rearward movement (Figure 10). A support bracket was welded across the bottom the seat frame to add rigidity for testing. A metal strip was also welded across the bottom edge of the seatback to provide support during pelvic loading into the seatback. These additional modifications were part of a Low Profile Seat Cushion Frame concept (ROI #R-6083/G-8260) successfully used in subsequent tests involving the High-Retention Seat.

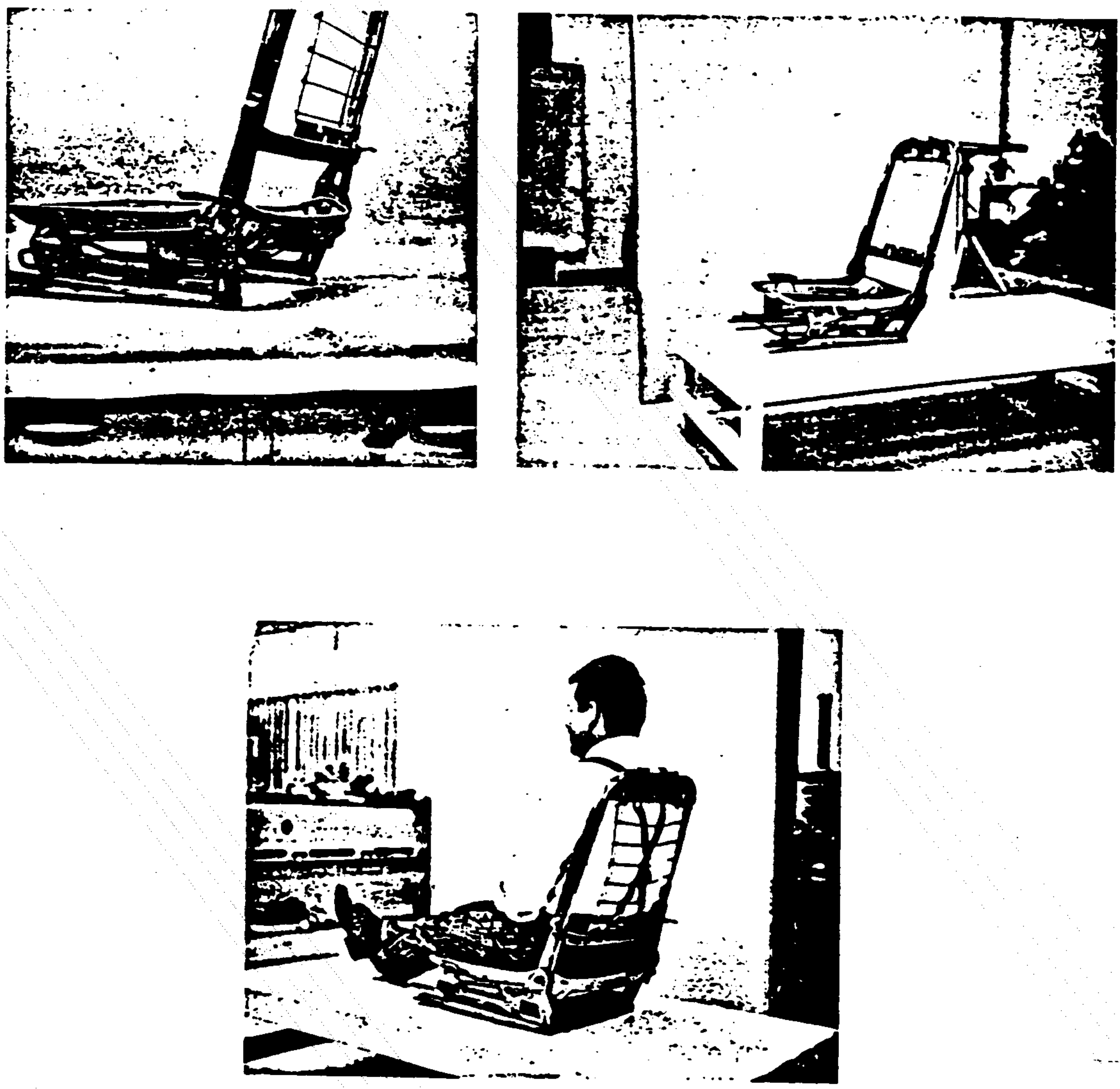

Figure 9: **Conventional bucket seat frame with sheetmetal around the perimeter of the seated occupant (the foam has been removed to demonstrate the position of the buttocks below the edge of the seat bottom frame).**

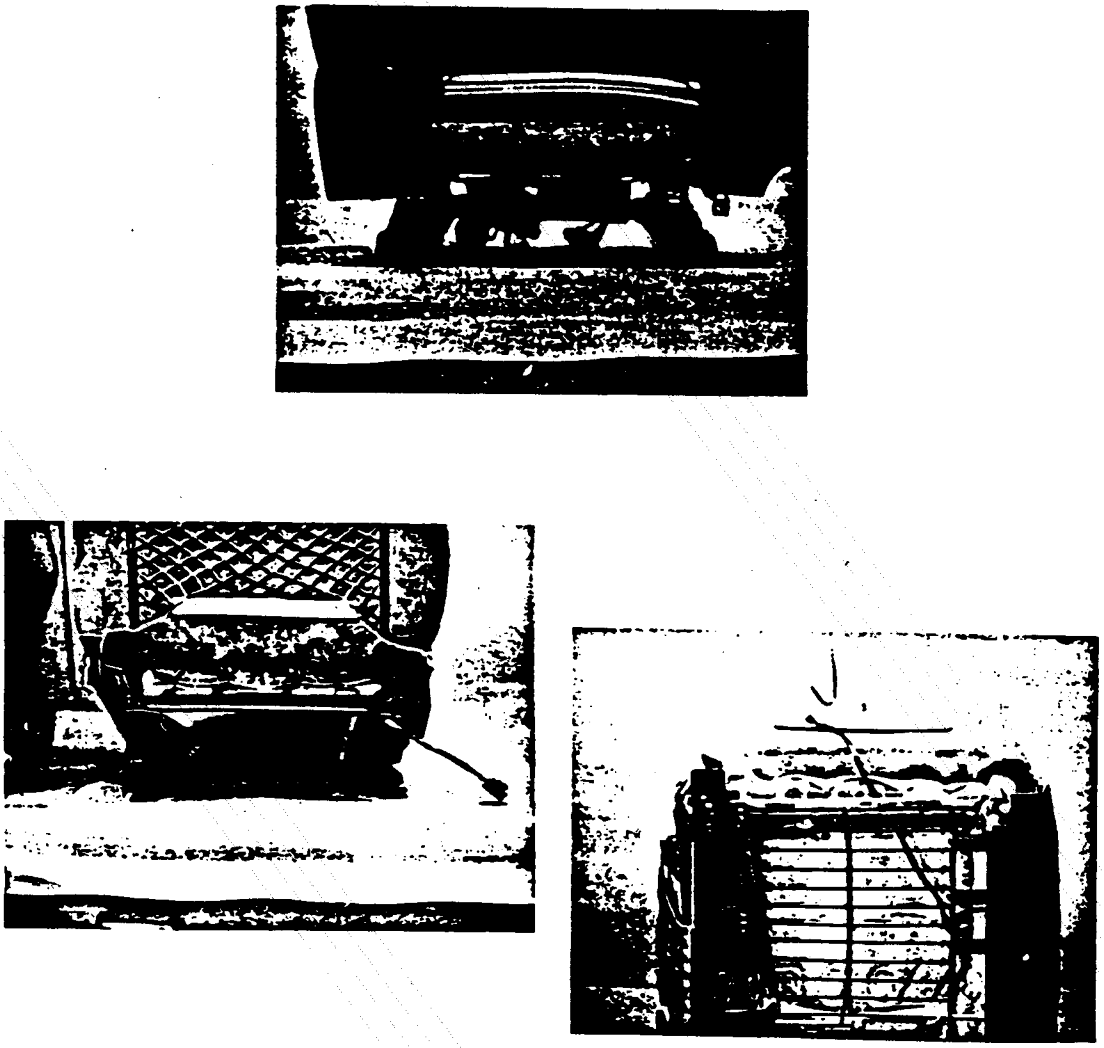

Figure 10: Top photograph shows the perimeter frame of a conventional bucket seat; and the Bottom photographs show the Low Profile Seat Frame approach involving cutting down the back edge of the sheetmetal frame and reinforcing the seat from the bottom. The modification also includes the insertion of a cross-member on the seatback frame at about the height of the removed sheetmetal. This engages the buttocks in rear impact and transfers loads to the EA Pivot.

RATIONALE FOR HIGH-RETENTION SEATS

The reaction wire alone is not sufficient to stabilize the rearward rotation of the seatback. Analysis of geometric effects indicates that the distance between the attachment points is smaller than the length of the wire for all angles of seatback rotation. The distance equals the length when the seatback angle is 90° or when the seatback is horizontal.

Thus, displacement of the pivot point of the seatback is needed to increase the geometric distance to a magnitude that is greater than the initial wire length. Figure 11 shows data for two angles of the seatback. One is 30° from vertical and the other 45° from vertical. These angles are not only within the expected rotations under impact conditions but also within the rotation levels in which friction effects retain the occupant.

For the smallest rotation, an EA pivot displacement of 3" (7.6 cm) is needed so that geometric effects involve the retention wire. Involvement occurs with slightly over 1.5" (3.8 cm) displacement with a rotation angle change of 20° (an overall angle of 45° from vertical). The normalized length change or apparent elongation of the wire for this condition is below 20% which seems reasonable considering deformations at the attachment of the wire to the seat.

The force and geometric analysis of the High-Retention Seat indicates that the concept is practical and should be able to perform as conceived. The displacements and rotations associated with the HRSEAT increase the rearward motion of the seatback at the pivot point by 4" (10 cm) but reduce the rearward displacement of the top of the seatback. This actually provides more leg room in severe rear crashes for egress of rear seated occupants. For example, a change in seatback angle from 25°-70° in a conventional seatback design

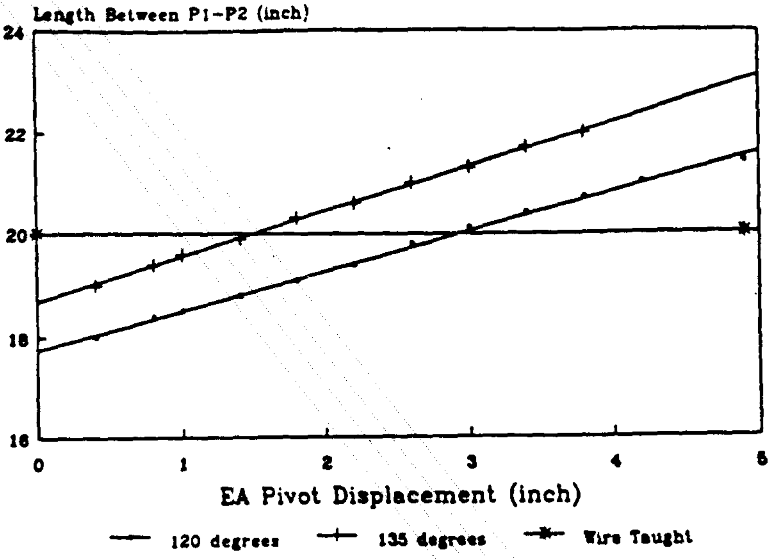

Figure 11: The distance between point P_1 and P_2 is plotted for two seatback angles. The relationship is given in Figure 5a and initial length of wire is 20" in this example.

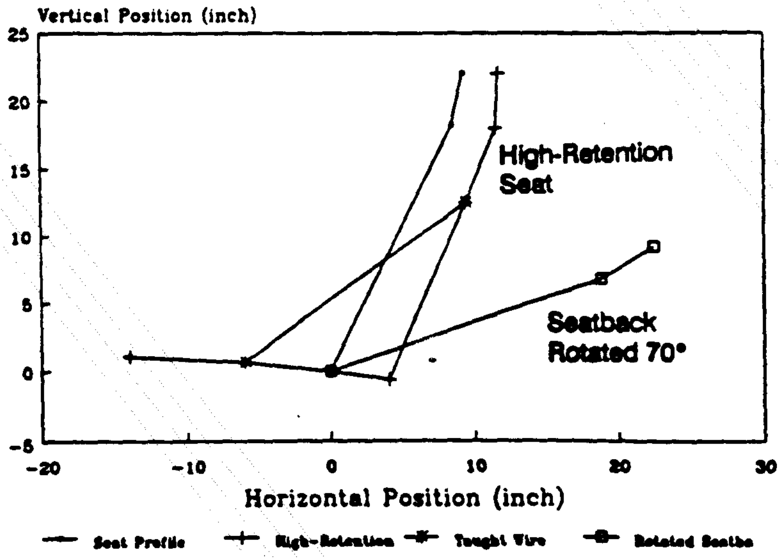

Figure 12: The initial configuration of the seat is shown with the position of the High-Retention Seat at 4" EA Pivot displacement and a conventional seat at 70° rearward rotation.

involves a 14° increase in rearward position of the top of the seatback (Figure 12). In contrast, a decrease in seatback angle from 25°-22° plus a 4° displacement of the pivot point with a HRSEAT, involves under a 4° total displacement change of the seatback. This is 10° less than current designs and indicates that entrapment of rear occupants should not be increased by HRSEAT. Rather, a reduction in total seatback rotation and improved occupant retention should reduce injury risks for rear occupants potentially due to loading by front-seat occupants.

There may be additional benefits with a High-Retention Seat. Some rear-end crashes involve an oblique impact angle from the rear. This type of loading not only causes rearward rotation of the seatback but also twists the seatback from the corner on which the loading occurs. This induces torsional loads on the seatback which can also reduce occupant retention.

The reaction wire or structure may improve retention under rear oblique crash conditions as well. The displacement and rotation of the seatback stretch the wire pulling it away from the seat frame and making a pocket around the buttocks of the occupant. This provides a lateral reaction surface to hold and further engage the occupant in the seat. It can also reduce the lateral excursion that may otherwise occur without its presence. In a practical application of this design, the wire or structure would be imbedded into the seat under the fabric covering to minimize the potential for injuring the occupant should loading of the wire occur. However, loading on the wire would probably push it down because of the flexibility of the system.

In addition, the reaction wire or structure can provide resistance to oblique rear loads that tend to twist the seatback. The wire can be engaged on one side and would resist this mode of loading. An analysis of fatal belted occupants indicted that oblique rear impacts with associated torsion and deflection of the seatback could result in excursion of the occupant toward the point of the crash (Viano 1991a). This increases the possibility of head contact with the impacting vehicle or crash zone.

While severe oblique rear crashes are rare events and typical of only the most serious collisions involving heavy tractor-trailer and truck impacts, a reduction in occupant excursions and enhanced retention may be beneficial for the safety of both belted and unbelted passengers. In this situation, asymmetric or one-sided deflection causing torsion of the seatback can engage the retention wire or structure, and the HRSEAT may absorb energy and limit displacements of the occupant toward the impact site.

The EA pivot can also be modelled conceptually by designing the EA mechanism into the sheetmetal frame of the seat. This might be done by cutting out the seat frame around the pivot and recline bolt insertions and re-attaching this piece in place on an EA attachment mechanism. In practice a pattern may be cut out in such a way that it provides the rigid resistance until the breakaway force is achieved in a crash. After breakaway, the metal deforms in such a way as to limit and gradually increase force as the pivot point displaces rearward.

Other mechanisms have been conceived to achieve the effects of HRSEAT, including bolts or tubes in slotted EA channels, recliner mechanisms attached to slots in the seat, deformable EA metal structures and other EA pivot mechanisms and metal structures which incorporate the tether into the seatback and cushion frame. For example, the seatback could be constructed with an inner and outer frame. Rear facing infant car seat designs have considered similar approaches since they have a similar situation. Under impact, the inner frame pivots rearward from the top causing the bottom portion to displace rearward. This motion results in a pocket to hold the occupant and engages the reaction structure which is the outer seatback frame. The connection between frames would provide the EA and the outer frame would be much stiffer than current systems; but, these changes would be consistent with and could be part of a fully integrated belt-to-seat system.

The design of the EA pivot needs to maintain or enhance the bending resistance of the seatback. This is important since significant seatback rotation prior to EA pivot displacement can prevent the engagement of the reaction wire or structure.

METHODOLOGY

Comparable sled tests were conducted with a conventional bucket seat and one modified to the concept of High Retention. A sled speed of 9.5 m/s (21 mph) was selected to challenge occupant retention on the conventional seat. This speed was slightly above the conditions used in previous tests which had a regular incidence of seatback deflection and loss of occupant retention. The sled velocity approximates the 95th percentile crash severity for large cars in rear crashes, but only the 80th percentile when small cars are considered. While it represents a severe pulse, it is significantly more severe than the 30 mph (13.5 m/s) 4000 lb. rear-moving barrier test required by FMVSS 301 to evaluate fuel system integrity. The velocity change of the NHTSA test is 15 mph (6.8 m/s) assuming a vehicle of equal weight as the barrier, and 17.6 mph (7.9 m/s) for the average 2800 lb vehicle. The velocity change in these sled tests is 20%-40% greater (9.5 m/s v. 6.8 m/s or 7.9 m/s) and the energy is one and a half to two times that of the federal test. The sled tests represent a 42 mph (19.0 m/s) rear impact of a stationary vehicle.

wrong
22 mph

Figure 13: Hyge sled test setup and position of the dummy after a test with the prototype High-Retention Seat.

For these tests, an instrumented Hybrid III dummy was seated on an open fixture with a loose lap belt draped over the legs and feet tethered to prevent the dummy from displacing off of the seat and sled in the simulated rear-end crash. The setup is shown in Figure 13. A full array of responses were measured including head acceleration and 2D In-line responses to calculate rotational acceleration of the head. Neck reaction forces and moments were measured at the occipital condyles and at the neck attachment to the chest. Acceleration of the chest and pelvis were measured. An In-line package was attached to the pelvis to compute rotation of the hip. The transducer signals were A/D converted, filtered to the appropriate SAE channel class, and stored for subsequent analysis with photographic information.

An on-board and off-board high-speed camera covered the lateral kinematics of the dummy interacting with the seat in the rear crash. An accelerometer was mounted on the top, middle and bottom surface of the seatback. The active axis of the transducer was pointed rearward to record the effects of occupant interactions. Photographic targets were place on the dummy, seat frame and seatback to determine rotation of body segments and the seatback. The filming speeds were 500 fps.

RESULTS

Table 4 summarizes the results of the Hyge sled tests. Three tests were conducted with a standard bucket seat and four with seats modified to the High-Retention Seat concept. For the severity of sled velocity, all tests with a conventional seat resulted in the occupant riding up the seatback and eventual loss of retention. Secondary tethers were used to restrain the dummy from displacing off the conventional bucket seat. For each of the tests with the High-Retention concept, the dummy was retained in the seat without safety belts or other restraints. The EA pivot motion and wire engaged to limit rearward rotation of the seatback, thus ensuring restraint of the dummy.

Table 4: Seat-Back Interaction by Occupant Loading

Test #	Sled Accel g	Sled Vel m/s	Head Accel x-g	z-g	Res.-g	Head Ang acc r/s2	r/s2	In-Line Ang vel r/s	Ang deg	Seat-Back Retention
Standard Seat										
2142	14.00	9.59	7.8	31.6	31.6	1,059	-1,030	36.0	142	No
2175	13.85	9.37	7.0	26.0	26.5	1,250	-870	42.0	180	No
2178	13.99	9.58	8.0	23.5	24.0	900	-1,040	36.0	178	No
Avg.	13.95	9.51	7.6	27.0	27.4	1,070	-980	38.0	167	
std.	0.07	0.10	0.4	3.4	3.2	143	78	2.8	17	
High Retention Seat										
2144	14.49	9.39	5.0	26.0	26.0	1,600	-800	36.0	172	Yes
2145	14.18	9.51	13.0	25.0	25.0	1,000	-1,200	44.0	~96	Yes
2176	13.87	9.37	6.0	28.0	29.0	1,200		44.0	160	Yes
2179	13.87	9.42	4.8	16.5	17.0	800	-450	28.0	142	Yes
Avg.	14.10	9.42	7.2	23.9	24.3	1,150	-817	38.0	170	
std.	0.26	0.05	3.4	4.4	4.4	296	306	6.6	23	

Test #	Neck Fx N	Fz N	My Nm	Nm	Thorax x-g	z-g	res-g	Pelvis x-g	z-g	res-g
Standard Seat										
2142	200.0	1,416.0	23.2	-38.0	8.4	8.2	9.0	17.8	8.0	18.3
2175	170.0	1,140.0	16.0	-36.0	8.0	8.0	10.0	16.0	6.0	17.0
2178	110.0	500.0	16.0	-35.0	6.0	7.5	8.7	14.5	5.0	15.0
Avg.	160.0	1,018.7	18.4	-36.3	7.3	7.9	9.2	16.1	6.3	16.8
std.	37.4	383.7	3.4	1.2	1.0	0.3	0.6	1.3	1.2	1.4
High Retention Seat										
2144	180.0	1,200.0	34.0	-30.0	23.0	5.0	24.0	16.5	7.0	17.0
2145		1,050.0	12.0	-32.0	16.0	8.0	17.5	18.5	8.0	20.5
2176	175.0	1,280.0	18.0	-44.0	18.0	8.0	20.0	11.0	9.4	14.5
2179	125.0	700.0	13.0	-22.0	15.0	7.2	16.5	16.0	6.2	17.0
Avg.	160.0	1,057.5	19.3	-32.0	18.0	7.1	19.5	15.5	7.7	17.3
std.	24.8	222.3	8.8	7.9	3.1	1.2	2.9	2.8	1.2	2.1

Table 4: Seat-Back Interaction by Occupant Loading

Test #	Seat-Back Angle	EA Pivot in	Wire Taught ms	Belt Tight ms	Head x in	Head y in	Head Angle deg
Standard Seat							
2142	47.0	--	--	80.0	20.4	5.3	36.5
2175		--	--				
2178	38.5	--	--	86.5	13.3	2.3	5.0
Avg.	42.8			83.3	16.9	3.8	20.8
std.	4.3			3.3	3.6	1.5	15.8
High Retention Seat							
2144	34.5	1.0	89.4				
2145	38.0	3.5	73.1		16.2	4.3	21.8
2176	30.0	2.8	75.0		16.1	2.1	18.5
2179	33.0	2.9	81.2		15.3	0.4	11.0
Avg.	33.9	2.6	79.7		15.9	2.3	17.1
std.	2.9	0.9	6.4		0.6	1.6	4.5

Test #	Chest x in	Chest y in	Chest Angle deg	Hip x in	Hip y in	Hip Angle deg
Standard Seat						
2142	16.5	1.9	56.5	7.3	3.2	23.0
2175						
2178	14.6	1.2	24.0	11.5	0.8	16.6
Avg.	15.6	1.6	40.3	9.4	2.0	19.8
std.	1.0	0.4	16.3	2.1	1.2	3.2
High Retention Seat						
2144	20.4	3.8		12.6	6.8	19.0
2145	12.0	0.2	12.3	9.4	0.8	15.5
2176	12.5	1.8	20.0	8.6	1.8	25.0
2179	12.9	1.6	21.3	10.8	1.6	9.0
Avg.	14.5	1.9	17.9	10.4	2.8	17.1
std.	3.5	1.3	4.0	1.5	2.4	5.8

Figure 14 shows kinematics of the dummy on a conventional bucket seat. Rearward movement of the dummy loads the seatback and causes rotation. With an increasing angle of seatback rotation, restraint of the dummy from frictional effects is reduced. The dummy eventually displaces up the seatback and off the seat. In contrast, Figure 15 shows the sequence with the High-Retention Seat. Rearward movement of the dummy displaces the EA pivot and develops tension in the wire support between the seat frame and seatback. This movement of the seatback and limiting of seatback rotation, improved occupant interaction with the seatback and resulted in restraint of the dummy. Figure 16 provides a close-up of the sequence of EA pivot movement and wire engagement.

Biomechanical responses reflect the interaction with the seatback. With loss of occupant retention from the standard seat, responses were not recorded during secondary restraint by the tethering belts. However, in a real crash, there would be impacts with interior structures in the rear seating compartment of the vehicle by an unbelted occupant. These impacts may cause injury.

During seatback loading, the average biomechanical responses are quite similar for the two seats. In fact, fifteen out of sixteen responses were statistically the same. Chest acceleration was statistically different between the two seats. Higher acceleration levels occurred with the HRSEAT and reflect greater occupant restraint by the seatback. This is consistent with the beneficial effects of occupant retention. The levels of acceleration are well below current tolerance limits. Figure 17 provides evidence of the restraining action of the HRSEAT. The dotted line reflects accelerations with the HRSEAT. The higher levels of the x- component of acceleration--the AP direction in the dummy--are indicative of the restraining action of the seatback.

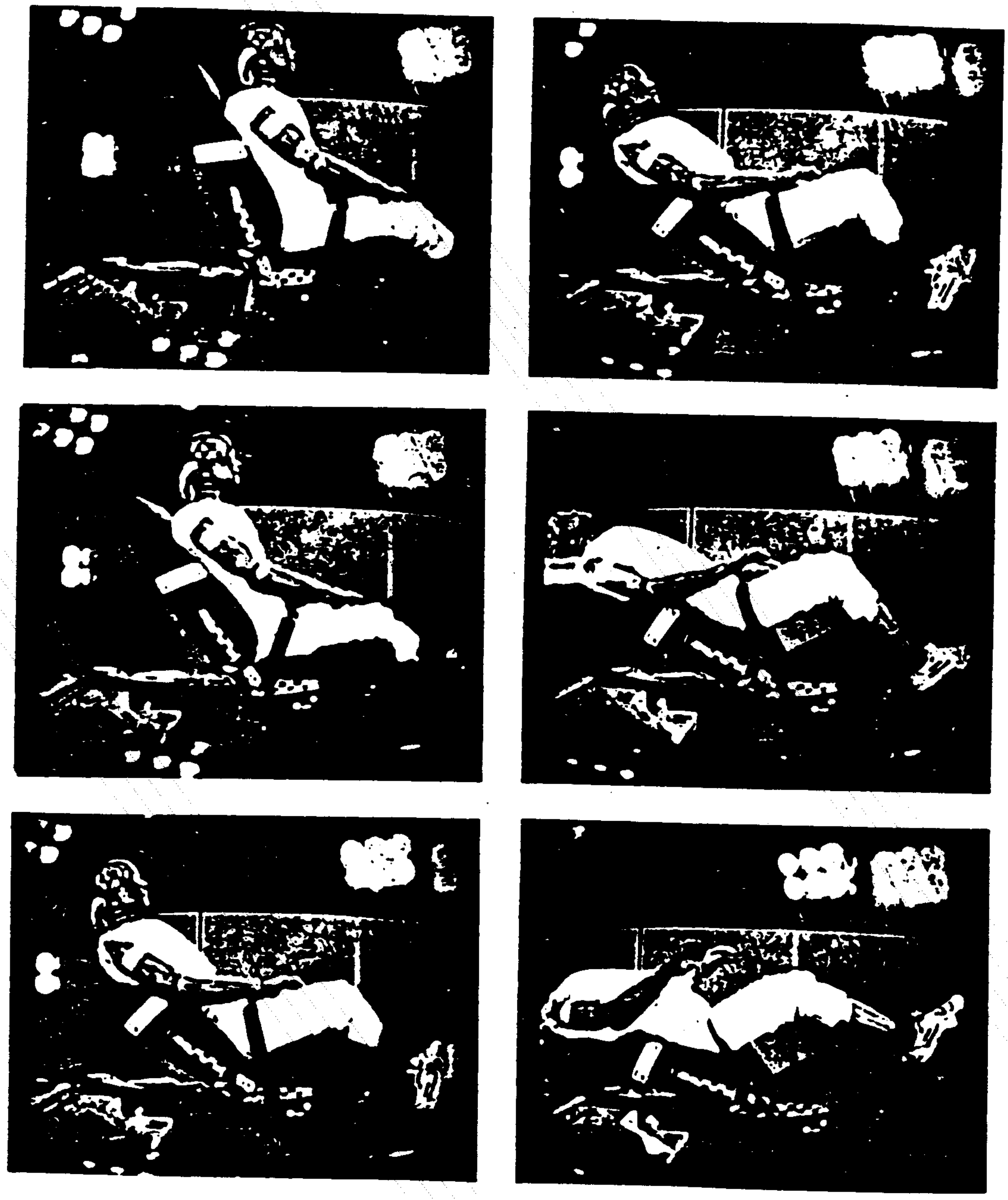

Figure 14: Sequence photographs from high-speed movies of a rear crash involving a conventional bucket seat. A loose lap belt was used to retain the dummy on the sled fixture.

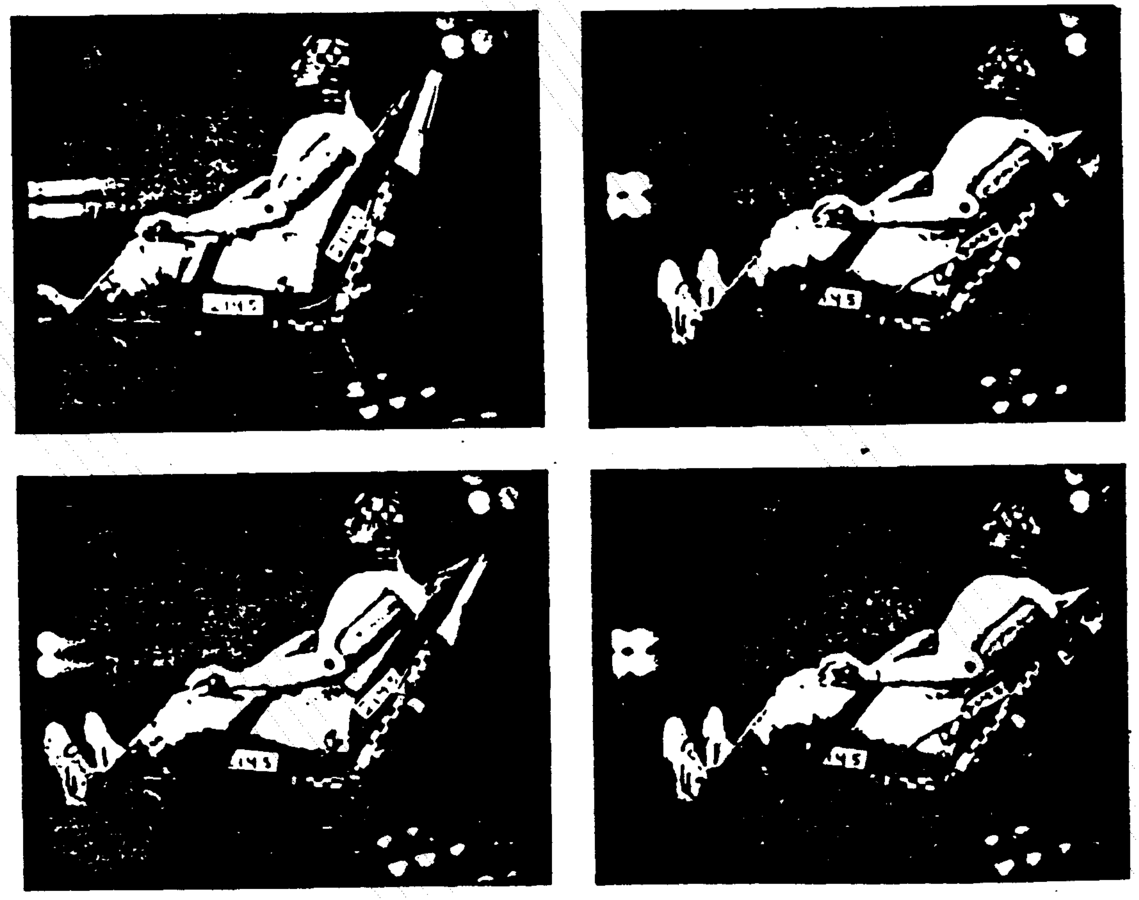

Figure 15: Sequence photographs from high-speed movies of a rear crash involving the prototype High-Retention Seat demonstrating displacement of the EA Pivot and tension in the retention wire.

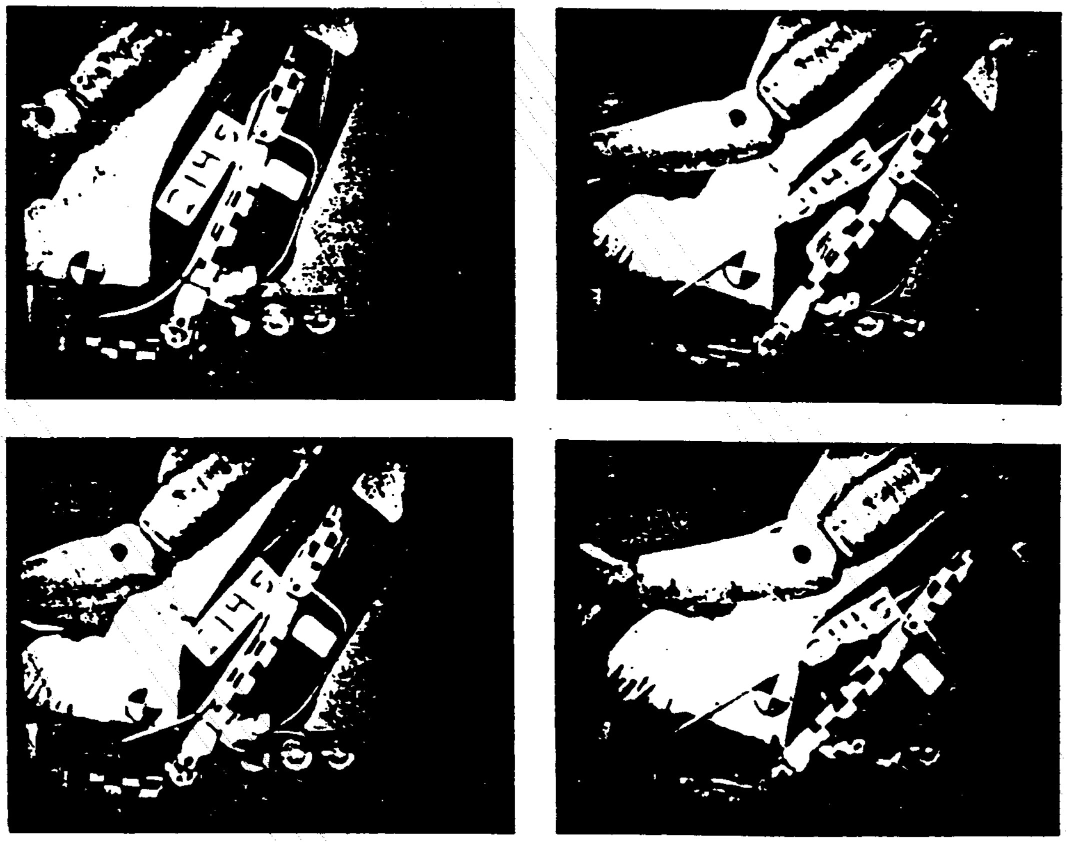

Figure 16: Close-up photographs of the displacement of the EA Pivot and tension in the retention wire.

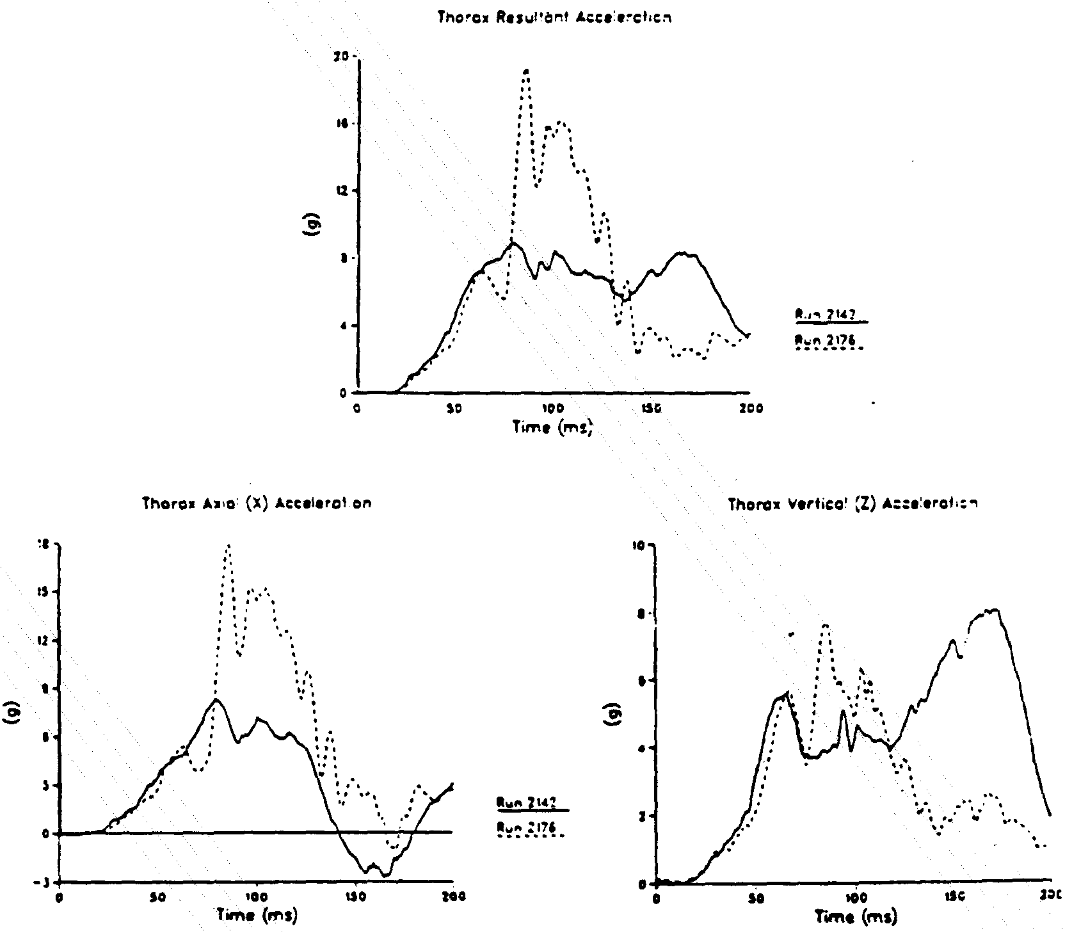

Figure 17: Comparison of thoracic acceleration from tests with the prototype High-Retention Seat (2176) and a conventional bucket seat (2142).

Figure 18 shows the pelvic response. In this case, the the x-component is lower with the HRSEAT reflecting the load limiting action of the EA pivot displacement. There is a higher z-component, again indicating restraining action by the wire supported seatback. The cumulative effect involves reductions in the resultant acceleration of the pelvis during EA pivot action and subsequently higher responses during restraining action by the seatback. The HRSEAT provides similar accelerations of the chest and pelvis reflecting a more uniform response of the dummy and better kinematic control. The larger differential accelerations with the standard seat indicate greater rotation of the chest and displacement of the body.

Figure 19 demonstrates very similar responses of the head and neck for the two types of seat. The neck moment, shear and tension are indicative of whiplash-type injury risk and are statistically similar, as are all of the head acceleration responses. The HRSEAT concept appears to provide a significantly improved retention of the dummy without increasing injury risks during seatback loading. The HRSEAT eliminates potentially subsequent impacts of rear areas in the vehicle with sufficient energy to involve serious injury.

Figure 20 shows the change in seatback angle for the conventional and high-retention seat in rearend impact. There is a continual increase in seatback angle with the conventional bucket seat which approaches 50° (76° overall rearward angle from vertical) at 150 ms. The angle changes with the HRSEAT is limited by the retention wire to 30° and becomes more upright after maximum rotation. Motion of the EA Pivot point is also shown to increase to about 2.7" (6.9 cm) and return to just over 1". The reduction is the result of upward movement of the dummy and loading on the upper edge of the seatback which forced the EA Pivot forward. Maximum benefit would be realized by a HRSEAT prototype that achieved a 4"-6" displacement of the EA Pivot.

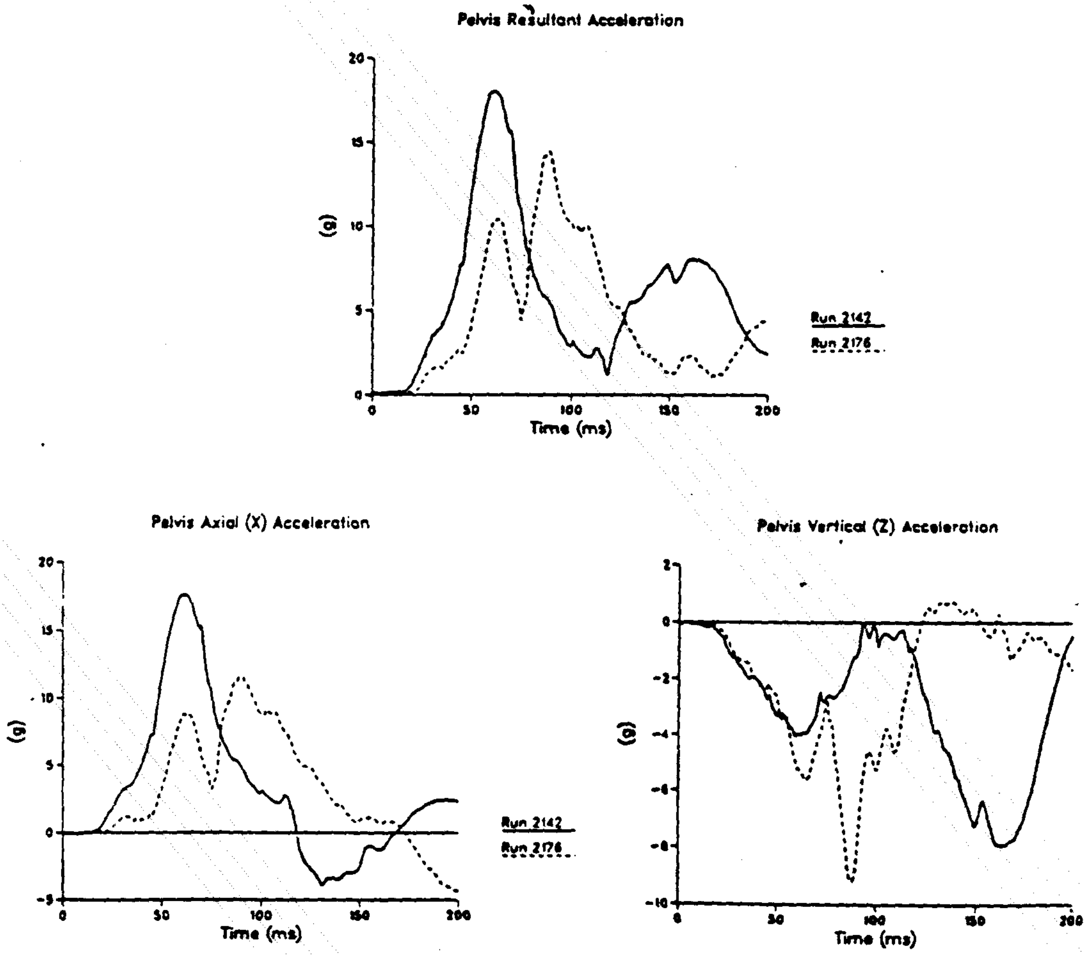

Figure 18: Comparison of pelvic acceleration with the prototype HRSEAT and conventional seat.

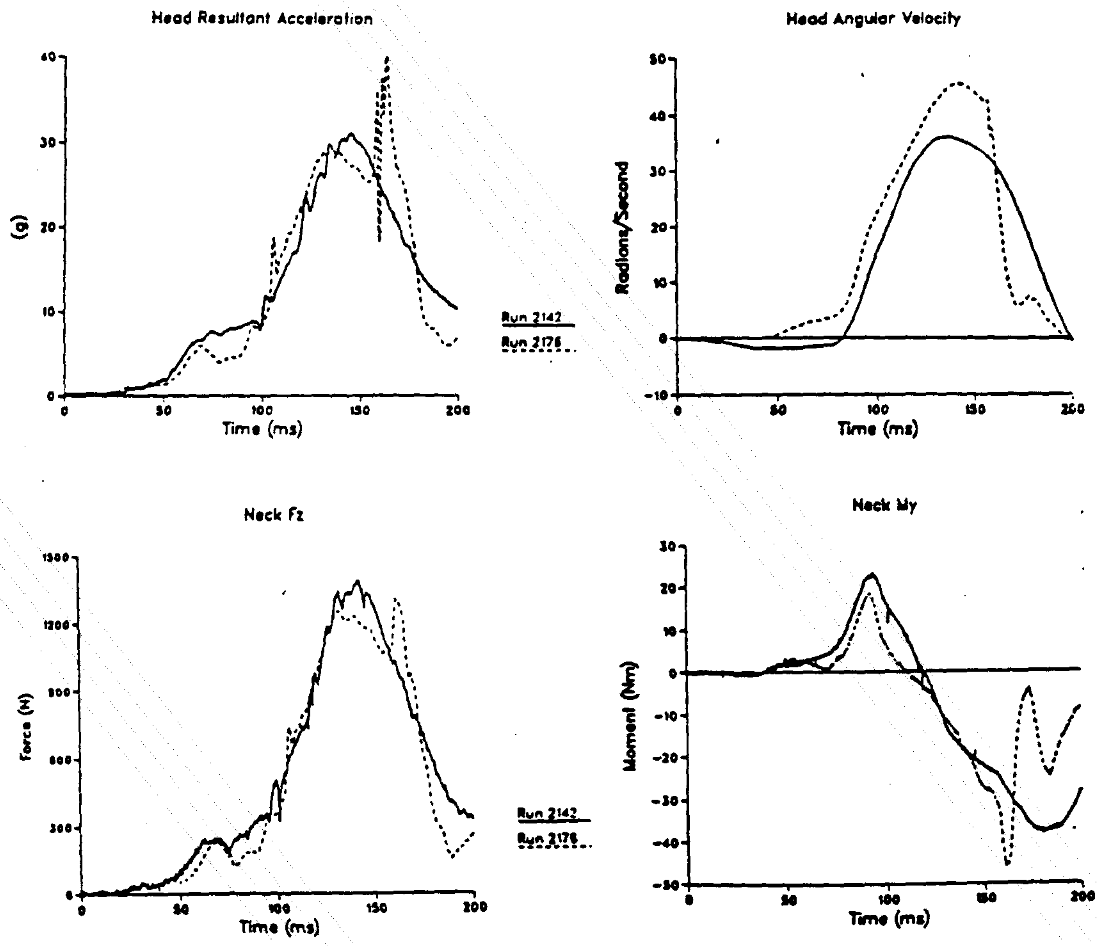

Figure 19: Comparison of head and neck responses with the HRSEAT and conventional seat.

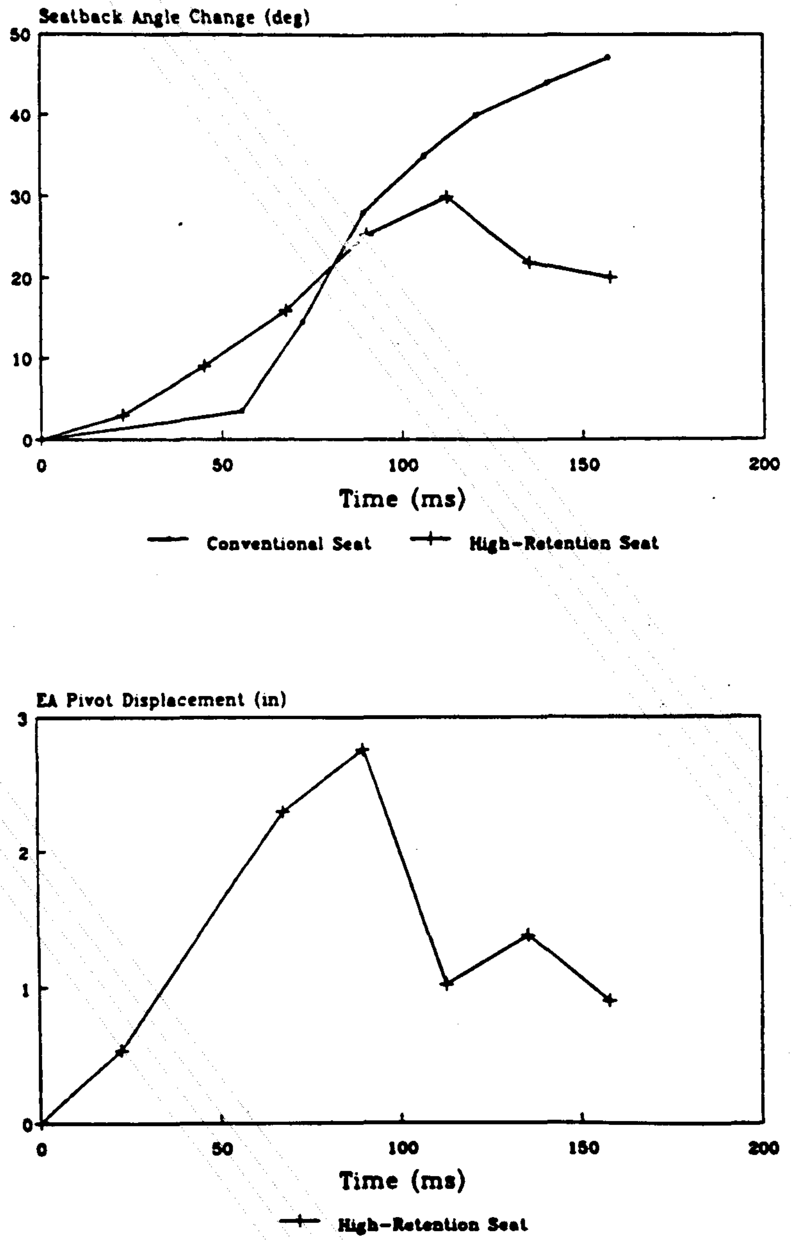

Figure 20: Top: Comparison of seatback angle changes for the prototype High-Retention Seat (2176) and conventional bucket seat (2142), and Bottom:: displacement of the EA Pivot point.

Figure 21 shows the displacement and trajectory of the hip. With the HRSEAT, the hip moves horizontally over 8" (20 cm) before it displaces up. In contrast, the conventional seat involves upward movement of the pelvis after only 4" (10 cm) rearward displacement. The overall rearward displacement of the pelvis is lower with the HRSEAT. However, the ultimate benefit of the High-Retention Seat is not demonstrated in these tests because of the secondary tethers which restrained the dummy in the conventional bucket seat tests. These restraints influence dummy motion beyond about 100 ms.

Figure 22 shows the displacement and angle change of the chest. This involves greater displacement in the HRSEAT earlier than with the conventional design reflecting movement of the EA Pivot. The ultimate rearward displacement is lower with the HRSEAT and would be greater if secondary restraints weren't used to limit motion in the conventional seat tests. The angle change of the chest is slightly lower during the time of maximum restraint by the HRSEAT, but similar in magnitude near 150 ms.

The kinematic and biomechanical data on the High-Retention Seat demonstrate that the concept is viable and provides occupant retention in severe rear crashes that would result in an unbelted occupant sliding up and off of a conventional seat or a belted occupant displacing into the rear compartment. The concept appears to be validated under the circumstances of the experimental evaluation conducted.

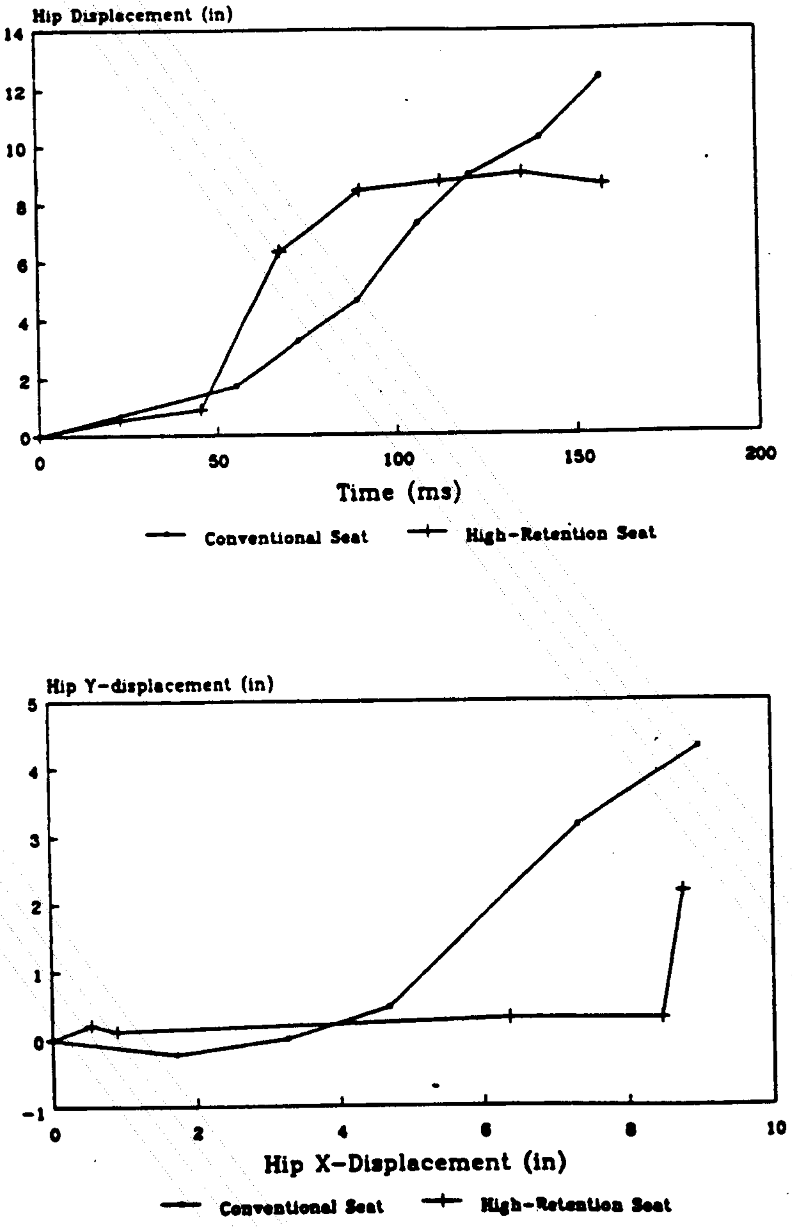

Figure 21: Displacement and trajectory of the hip with the High-Retention Seat (2176) and conventional bucket seat (2142).

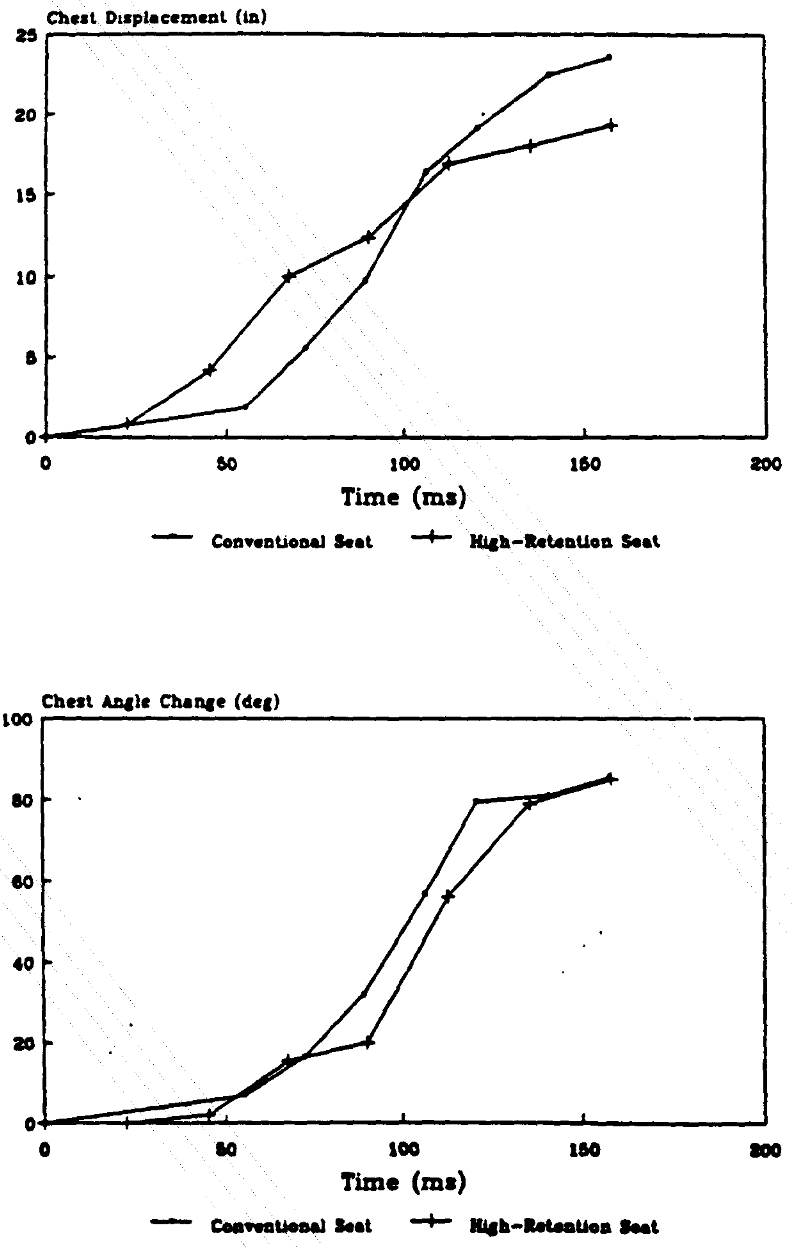

Figure 22: Displacement and angle change of the chest for the High-Retention Seat (2176) and conventional bucket seat (2142).

ACKNOWLEDGMENTS

The prototype High-Retention Seat was developed by Gerald Horn whose initiative and creativity are greatly appreciated in realizing the concept identified in the record of invention R-5970/G-7993 by D. Viano on March 15, 1991. While the preliminary tests were very encouraging, the up-and-over movement of the dummy was observed as a critical obstacle in maintaining a horizontal loading of the occupant into the seatback. Occupant interaction with the rear lip of the seat frame resulted in upward forces which lifted the occupant. This observation led to a record of invention R- 6083/G-8260 by D. Viano and G. Horn on April 19, 1991 for a Low Profile Seat-Cushion Frame. The assistance of Todd Townsend and others in the Biomedical Science Department is appreciated in conducting the sled tests and analyzing the film and response data. The comments of John Horsch, John Melvin, Roy Nagel, and Richard Neely on early drafts of this study are also appreciated.

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