EVALUATION OF EXPERIMENTAL RESTRAINTS IN ROLLOVER CONDITIONS

Mark W. Arndt, Gregory A. Mowry,
Charles P. Dickerson, and Stephen M. Arndt
Arndt & Associates, Ltd.

ABSTRACT

A controlled experimental program was conducted to determine the response of humans and a human surrogate with experimental lap belt restraints in -Gz acceleration environments. In the program, lap belt anchorage position (belt angle) and belt tension/slack were varied. Human volunteers were subjected to a static -1.0 Gz acceleration for each restraint configuration. A 95th percentile male Hybrid III dummy was subjected to a nominal 4.25 m/s (9.5 mph), -5 Gz impact while restrained by ch restraint configuration. For the -Gz acceleration, gnificant changes in occupant head excursion were observed with varied lap belt configurations. In general, less pre-crash belt slack and higher lap belt angles produced significant reductions in occupant vertical excursions. This research provides data for use in evaluating or developing occupant survivability systems for rollover crash environments.

INTRODUCTION

Statistics reveal that occupants involved in rollovers have a greater probability of suffering serious injury than occupants in other crash types. (1) Crash data shows that for 335,000 occupants involved in rollovers, 224,000 are injured or killed (9,800 fatalities; 1,141 serious, severely, or critically injured; and 200,400 moderately or lightly injured survivors). (2) While seat belts have been effective in reducing complete occupant ejection and associated out-of-vehicle injuries, they have exhibited lower effectiveness in preventing injuries due to partial or non ejection of occupants during vehicle rollover crashes. The most frequent harmful contacts of non-ejected occupants occur from contacting the roof, pillars, rails, and headers (28.1% combined). (2)

Rollover-caused injuries can be distinguished tween those that occur outside the vehicle after a complete or partial occupant ejection and those that occur inside the vehicle before or without ejection. Injury associated with partial ejection probably has some relationship to injury mechanisms associated with both outside- and inside-caused injuries. There is little disagreement as to the effectiveness of seat belts in reducing complete occupant ejection and the corresponding high probability of outside of vehicle injuries. (3, 4, 5) Even passive two-point shoulder belts are thought to have some effectiveness in reducing complete occupant ejection.(6)

A principal focus in the literature regarding in-vehicle rollover-caused injury has been the effects of roof crush. (7, 8, 9) Studies describe and explain the relationship (or non-relationship) between motor vehicle roof crush and injury rates. (10, 11) Numerous other studies discuss the overall physics of rollover events and attempt simplified models or descriptions of the rollover environment and its associated engineering crashworthiness problems, injury biomechanics, and possible protection systems. (12, 13, 14) Finally, at least two studies have been conducted defining a small portion of the rollover environment on a dolly rollover, and have provide insight into rollover, and non-ejection injury mechanism. (7, 8)

One understandable, pervasive, and well-documented description of the biomechanics of a non-ejection rollover injury is the head to roof contact-induced neck injury. The biomechanics of this injury are neck displacement (axial compression) and/or rotations (lateral or longitudinal flexion/extensions) caused by the occupant's head being held and/or forcibly moved while the occupant's body mass below the neck induces inertial-caused forces on the neck. This injury mechanism is sometimes called the "diving theory." This injury mechanism is demonstrated in comparison rollover tests of unrestrained dummy occupants in rigid versus non-rigid roof vehicles. (7) It is further demonstrated in follow-up, inverted drop tests in which it is noted that crash dummies suffer significant compressive axial neck loads due to roof contact even when there is negligible roof deflection (roll-caged vehicles). (8) Finally, it was observed in dolly rollovers with restrained occupant dummies that the buttocks of the dummy left the seat early in the roll maneuver and never returned until the vehicle came to rest. (8) The implications of observations of restrained

LAP BELT CONFIGURATIONS

Config. No.	Slack/Tension (mm) or (N)	Nominal Belt Angle (deg)	Static/Dynamic
1	62N	45	Both
2	222N	45	Dynamic
3	25mm	45	Both
4	50mm	45	Both
5	62N	90	Both
6	222N	90	Both
7	444N	90	Dynamic
8	50mm	90	Both

Table 1: Lap belt configurations

dummy buttocks leaving the seat during dolly rollover is that occupant flail in rollover crashes is a factor in neck compressive loading during head to roof contact.

Given the understanding of the biomechanics of neck injury in rollover crashes and the description of occupant exposure (crash environment) in rollover crashes, it has been possible to pursue the mitigation of non-ejection rollover injuries from a systems approach. The biomechanics of neck injuries in rollover crashes suggests that control of the pelvis to roof relative displacement/velocity may be the most important consideration/s. This test program does not replicate rollover conditions, but rather tests a single direction of acceleration (-Gz) under a relatively severe condition.

METHOD

Static measurements of human volunteers and a 95th percentile male Hybrid III dummy and dynamic testing of the 95th percentile Hybrid III male dummy were conducted at the Arndt & Associates, Ltd. test facilities.

All volunteers and the dummy were positioned upside down in an unpadded rigid steel seat mounted in a drop cage. Each volunteer and surrogate was restrained by lap belts of varying configurations. A schematic drawing of the seat and lap belt mounting positions is shown in Figure 1. The seat is 508 mm (20 in.) wide and lap belt anchorages are 559 mm (22 in.) apart. A list of the varied lap belt configurations is shown in Table 1. Lap belt tension/slack is induced from a baseline condition in which 62N (141bf) of adjustment force is applied to the seat belt adjustment strap. 62N of adjustment force is assumed for this program as zero tension/slack in the lap belt. Belt tension was produced by applying a controlled force to the seat belt adjustment strap. This variable is called the belt adjustment force.

Static measurements were recorded on an available population of human volunteers. Dimensions of individuals from this population are shown in Table 2. This population of volunteers is not meant to represent the overall population of seated motor vehicle occupants. Rather, the volunteers provide a basis for comparison to the static measurements to dynamic response of the 95th percentile male Hybrid III dummy for the various seat belt configurations in a -Gz acceleration environment.

Two lap belt parameters were changed for each of the eight tests. Lap belt configurations are shown in Table 1. Four tests were conducted with the lap belt at a nominal angle of 45 degrees while varying belt adjustment force or belt slack. Four tests were conducted with the lap belt angle at a nominal 90 degrees while varying belt adjustment force and belt slack. A nominal 45-degree lap belt angle refers to a belt anchorage point at an actual angle between the X-Y plane and a line drawn through the belt anchorage point and point made by the intersection of the seat back and seat bottom (SBRP). The nominal 90-degree lap belt anchorage position is for-

---

[1]**Tragion:** A point on the surface of the skin obtained by palpating the most anterior margin of the cartilaginous notch just superior to the targus of the ear (located at the upper edge of the external auditory meatus). (15)

DESCRIPTION OF VOLUNTEER

Volunteer	Stature (cm)	Sex	Weight (kg)	Age	Tragion Height[1] (cm)	Seated Height (cm)
No. 1	188	M	95	39	85.4	94.6
No. 2	183	M	84	30	82.2	89.1
No. 3	185	M	82	32	79.9	88.3
No. 4	188	M	104	33	76.2	94.0
No. 5	173	M	61	29	75.3	83.7
No. 6	173	M	77	36	72.4	86.5
No. 7	170	F	65	45	75.3	76.0
Hybrid III dummy	188	M	102	N/A	85.4	94.0

Table 2: Description of volunteer

Figure 1: Schematic drawing of the seat and lap belt mounting positions

the test seat in the drop cage. In all cases, a 95th percentile male Hybrid III dummy was utilized. Sheet aluminum inserts were added to the dummy to bridge the gap between flesh pieces which make up the thigh and seated pelvis. These inserts were taped to the pelvis. The purpose of these inserts was to assure that the lap belt position of the dummy was not influenced by the gap between the two segments of flesh, particularly at high seat belt angles. The dummy's arms were crossed and restrained across the chest, while the legs were allowed to flail freely during the test.

Prior to rotating the test seat for dynamic testing, a secondary strap which releases at the start of the free fall was attached around the upper thighs to maintain an initial position of the dummy pelvis approximately similar to the seated upright pelvis position. This means of pre-impact positioning of the dummy was repeated for all lap configurations. For each test, the drop cage, in which the test seat was mounted, was accelerated to approximately -5 Gz by energy absorbing paper honeycomb after a .914 m (3 ft.) free fall which produced impact velocities of approximately 4.25 m/s (9.5 mph). One test for each lap belt configuration listed in Table 1 was conducted utilizing the 95th percentile male Hybrid III dummy.

During the dynamic test utilizing the dummy, biaxial (X, Z) neck forces at the occiput were recorded. A high speed camera provided overall photographic coverage of the dummy kinematics. The camera had a framing rate of 500 frames per second and was mounted off board of the drop cage. Film analysis conducted from the high speed camera documented overall motion of the dummy head during and following the acceleration of the drop cage.
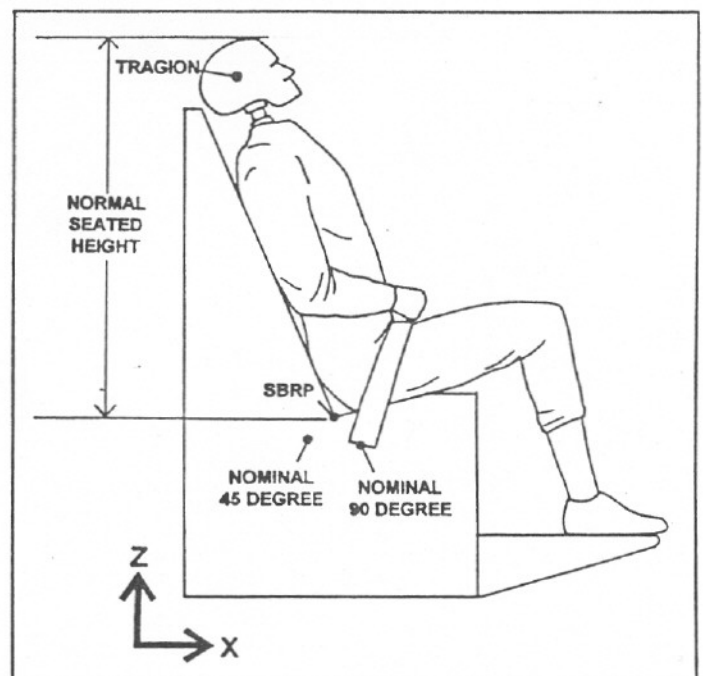
ward as shown on Figure 2. The actual lap belt angles measured for the 95th percentile Hybrid III are 39 degrees and 70 degrees, corresponding to the 45-degree and 90-degree nominal angle.

The procedure for conducting the static measurements of volunteers was first to obtain stature and weight. Subsequently, the volunteers were seated normally in the test seat in an upright position; thighs were positioned parallel to the seat bottom (10 degrees) by moving the feet in and out. Records of each normally seated volunteer while in the upright test seat include measurement of the normal seat height and tragion[1] position relative to SBRP (see figure 2). The tragion reference point was chosen so X-Z position of the head could be determined in static and dynamic conditions. Seating height only provides assessment of vertical displacement. Finally, the seat belt webbing and buckle were adjusted to specific conditions while measuring force and displacement.

Once initial conditions were produced in the upright seated position, the seat was rotated 180 degrees about the X axis. Seat rotation resulted in human volunteers being upside down in the rigid steel test seat restrained by a lap belt and subjected to a -1.0 Gz acceleration (gravity). In the upside down position, the position of the volunteer tragion was measured at the left and right sides. The distance from SBRP to top of head was also measured. Between each static measurement of a specific lap belt configuration, the seat and volunteer were returned to an upright position and properly positioned in the seat with a new lap belt configuration.

The setup of the dynamic test procedure is similar to that used in measuring volunteers. Figure 3 illustrates

Figure 2: Nominal 90-degree lap belt anchorage

DYNAMIC TEST SET-UP

Figure 3: Test seat in drop cage

SUMMARY OF PEAK DYNAMIC RESPONSE

Test No.	Nominal Belt Angle (deg)	Belt Tension /Slack (N) or (mm)	Peak Resultant Neck Load (N)	Peak Belt Load Load (N)	Peak Z Displacement (mm)
B	45	62N	867	8941	25.29
C	45	222N	890	10449	22.51
D	45	25mm	850	9924	26.44
E	45	50mm	841	10631	29.05
F	90	222N	721	6748	19.45
G	90	62N	716	6468	19.77
H	90	444N	672	6036	15.60
I	90	50mm	738	7117	23.13

Table 3: Summary of peak dynamic response

RESULTS

For varying restraint system configurations under the static conditions, the vertical tragion displacement from a normal seating position versus normal seating height above the SBRP of the volunteer's head for various restraint configurations is shown in Figures 4, 5. In general, static tragion displacements associated with the nominal belt angles of 45 degrees are greater than those at the nominal 90 degrees. The smallest static displacements were observed with a belt at the nominal 90 degrees with 222N (50 lbs.) of adjustment force, con-

trasted with the largest displacement which occurred at the nominal 45 degrees with 50 mm (2 in.) of belt slack.

The test conditions of the nominal 45-degree belt angle with 222N (50 lbs.) of adjustment force and nominal 90-degree belt angle with 444N (100 lbs.) of adjustment force were not conducted on volunteers because of the volunteers' expressed discomfort. When the test seat was rotated upside down with the seat belt condition at the nominal 45-degree and 222N (50 lbs.) of adjustment tension, pain was experienced through the lower back/coccyx contact with the seat back. Several, but not all volunteers expressed discomfort with being upside down. Temporary bruising and skin discoloration associated with lap belt contact was reported by all volunteers.

Static head displacement of the average volunteer and the 95th percentile male dummy and maximum dynamic head displacements of the 95th percentile male dummy are compared in Figure 6. Figures 7 and 8 show examples of the recorded instrument response of the nominal 45 degrees with 50 mm (2 in.) slack and nominal 90 degrees with 444N (100 lbs.) of adjustment force. In general, for all of the test, the peak resultant neck tension force of the 95th percentile Hybrid III was in the range of 302N (151 lbs.) to 405N (200 lbs.). Seat belt loads varied from 6,036N (1,357 lbs.) to 10,631N (2,390 lbs.). The nominal 45-degree seat belt angle produced significantly higher belt loads when compared with the nominal 90-degree belt angle. In general, the more slack in the belt, the higher the belt load. A summary of these peak responses is shown in Table 3.

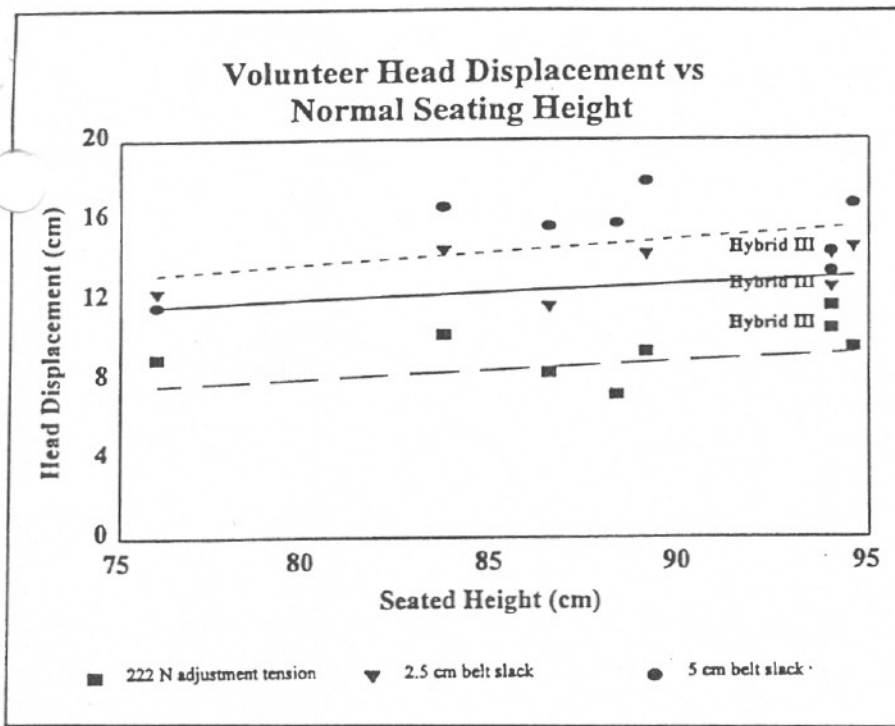Figures 9 and 10 show the head trajectories in the X-Z plane as recorded by the high speed camera for the

Volunteer Head Displacement vs Normal Seating Height

Figure 4: Static test condition; a nominal 45 deg.

Legend: ■ 222 N adjustment tension ▼ 2.5 cm belt slack ● 5 cm belt slack

Volunteer Head Displacement vs Normal Seated Height
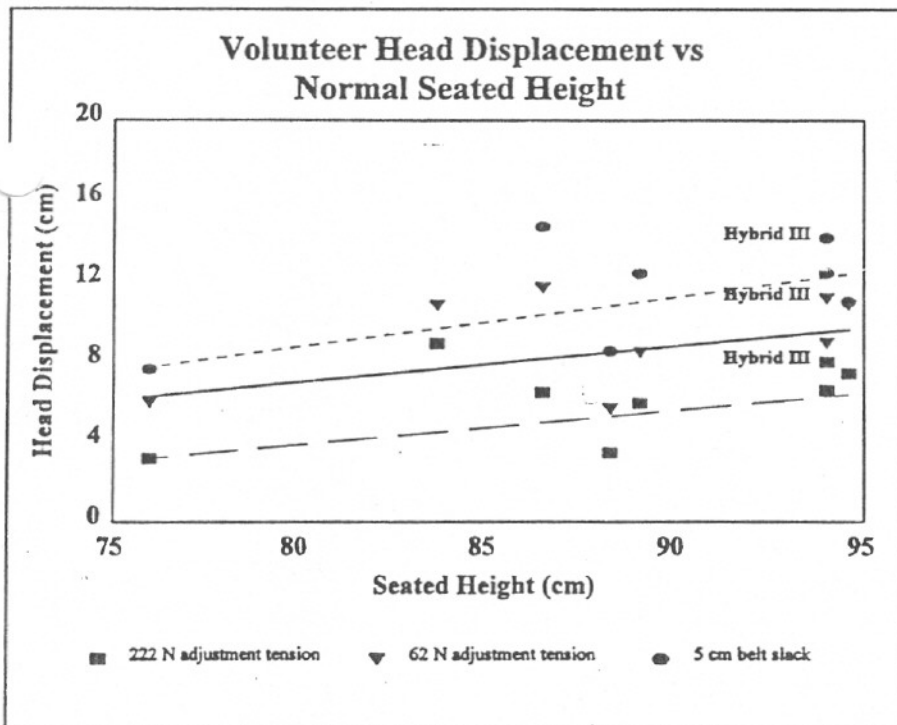
Figure 5: Static test condition; a nominal 90 deg.

Legend: ■ 222 N adjustment tension ▼ 62 N adjustment tension ● 5 cm belt slack

belt configuration at the nominal angles of 45 degrees and 90 degrees respectively. A summary of the maximum vertical head displacements from a normally seated dummy is listed in Table 3.

Finally, Figure 11 shows side-by-side kinematic response of the Hybrid III dummy at peak displacement as documented by the high speed camera. Specific frames from the camera coverage are shown document-

ing the differences in kinematic response at maximum head displacement between a lap belt at the the nominal 45 degrees with 50 mm (2 in.) of slack and a lap belt at the nominal 90 degrees with 444N (100 lbs.) of adjustment tension.

DISCUSSION OF TEST

The dynamic test pulse of -5 Gz for a 4.25 m/s (9.5 mph) change of velocity was used because it represents a high percentile of the probable CG acceleration to which passenger cars would be exposed in rollover conditions. Obviously, rollover crashes will produce translational and rotational acceleration which when combined produced a complex distribution of resultant velocity changes that are different for every point on the vehicle. This test program does not replicate rollover conditions, but rather tests a single direction of acceleration (-Gz) under a relatively severe condition.

The relationship demonstrated in Figures 4 and 5 shows vertical tragion deflections generally increasing for larger occupants, greater effective lap belt slack, and smaller seat belt angle. These results are predictable based upon geometrical analysis of the restraint system and simple kinematic analysis of a body's response to various restraint systems in a -Gz acceleration.

While a general linear relationship seems to exist between vertical tragion displacement and normal seating height above the SBRP for any specific restraint system, the scatter which is noted is probably a result of at least three factors, including body fat across the pelvis, variation in normal seating posture, and variations in body position during the upside down portion of the test. Except for the simple measurements of tragion position and normal seated height, no attempt was made to quantify volunteers' pelvis or thigh area body fat or details about normal seating posture. While upside down, changes in volunteer lower extremity position produced changes in the upper body CG position and body angle. This can be explained by considering the effect on the position of a volunteer's longitudinal CG due to flexing and extending the lower extremities about the hip joint while pivoting on the seat belt. If volunteers allowed their legs to flail freely, producing greater leg flexion, the whole body tended to move rearward. Likewise, if the volunteer, in reaction to discomfort, held the legs more extended with the feet closer to the footrest, the upper body tended to move forward. This change in the whole body CG position and angle effectively resulted in changes of head position.
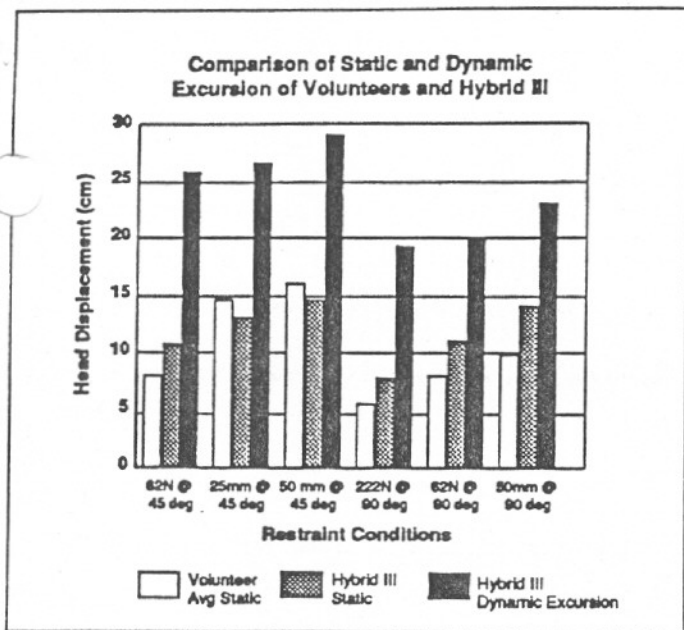
Figure 6: Comparison of static and dynamic excursion of volunteers and hybrid III

While the vertical displacement (Z) was relatively unaffected, the longitudinal (X) position of upside-down volunteers' heads in general produced wide scatter due to upside down body position differences.

The 95th percentile Hybrid III dummy, as shown in Figures 4 and 5, had the greatest normal seating height relative to the SBRP compared with all volunteers and appeared to be least sensitive in static vertical displacement to changes in the lap belt configuration. Incremental increase in displacement of the Hybrid III for corresponding changes in the lap belt restraints are smaller than those observed for volunteers. This phenomenon is probably attributed to the relative stiffness of the Hybrid III dummy. In addition, the response of the volunteers to being upside down and their discomfort probably affected the static measurements.

The dynamic test produced dummy head vertical displacements relative to the normal seating position greater than but consistent in rank to the static test. Again, parameters of the tested lap belt configuration played a major role in this result. Overall, head trajectories in the X-Z plane were significantly different for belt angles of the nominal 45 degrees compared with belt angles of the nominal 90 degrees. There was significant
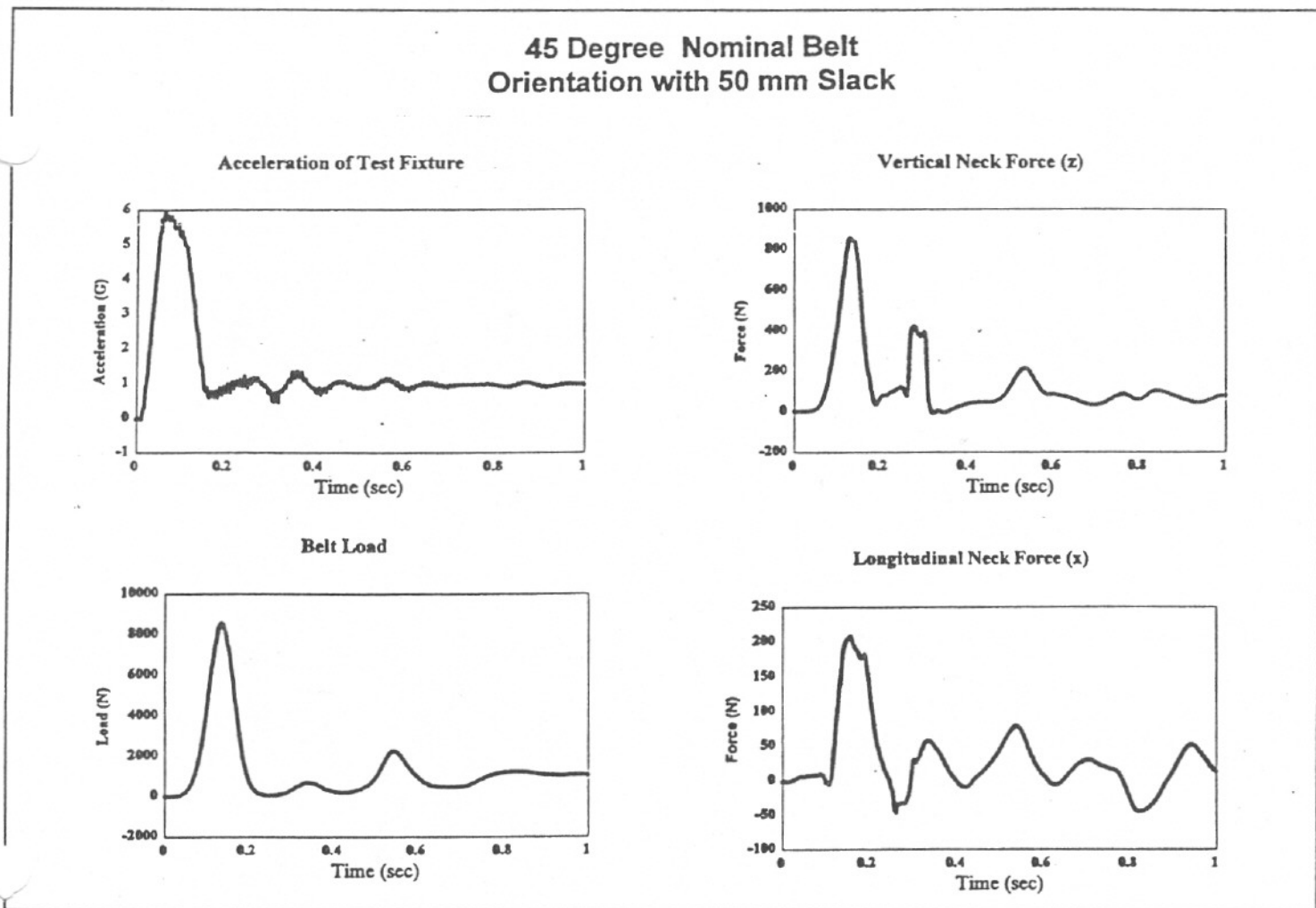

Figure 7: 45 degree nominal belt orientation with 50 mm slack

90 Degree Nominal Belt
Orientation with 444 N Adjustment Tension

Acceleration of Test Fixture

Vertical Neck Force (z)

Belt Load
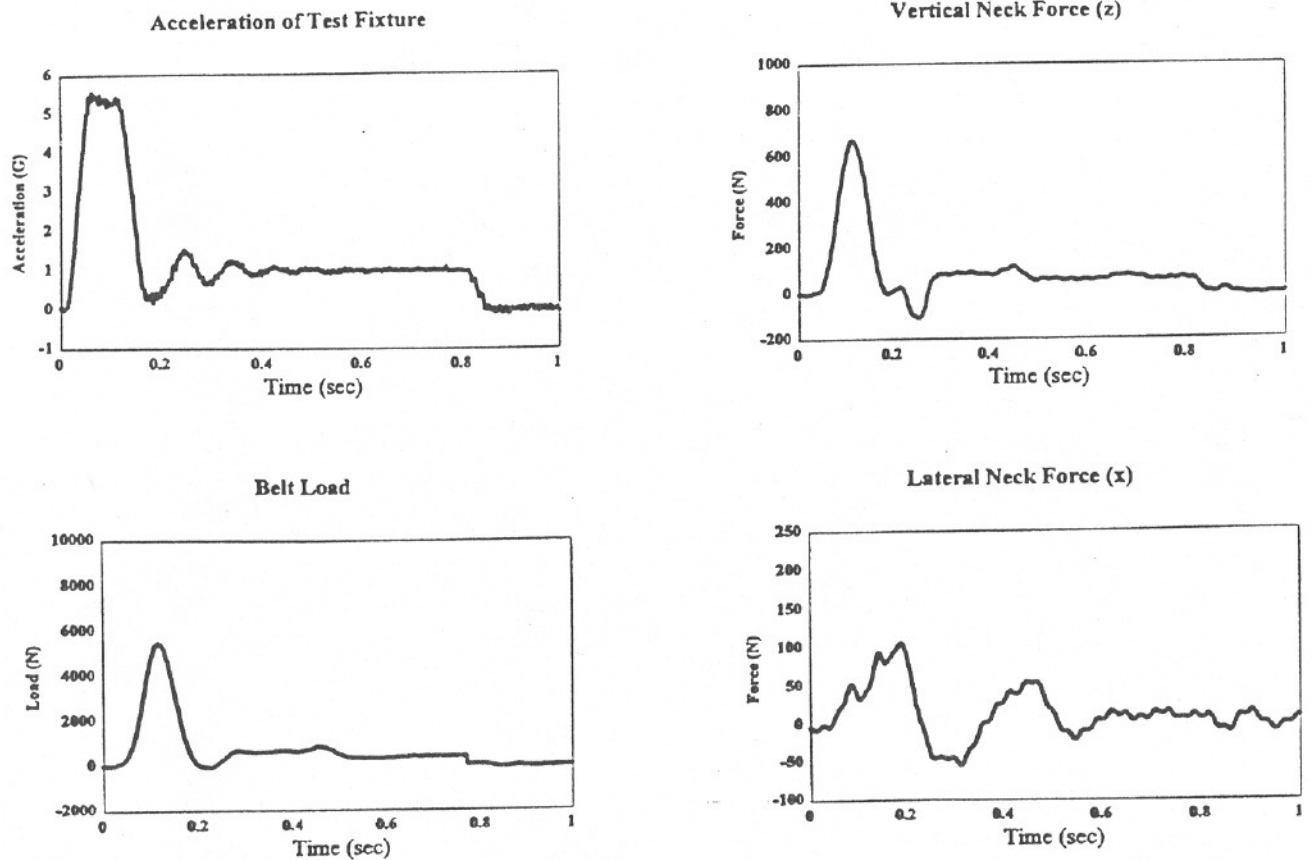
Lateral Neck Force (x)

Figure 8: 90 degree nominal belt orientation with 444 N adjustment tension

front-to-rear movement of the dummy head during rebound for the nominal 45-degree belt configuration. This effect is caused by the rearward component of force generated on the dummy by the angled belt. A corresponding effect of the nominal 45-degree belt angle was observed as significantly higher lap belt tension.

In the dynamic tests, the dummy's lower extremities are allowed to flail freely, which may be inconsistent with some occurrence in real motor vehicle rollover crashes in which for front occupants interference with lower dashboards and steering wheel may occur. The effect of the free flailing legs certainly increases the effective mass which must be restrained by the lap belt. The unrestrained lower extremities will also change the effective CG position of the dummy, influencing whole body flail. Overall, the longitudinal movement of the dummy may be greater in tests with Gx components of acceleration.

The tension response of the upper dummy neck is well within the human tolerance suggested by the discussion relative to the dynamic strength of the neck in Society of Automotive Engineers Information Report, "Human Tolerance to Impact Conditions as Related to Motor Vehicle Design—SAE J885." (16) Measurement of

dummy neck torque is possible, but probably not of additional interest in test without other dummy contacts. It is our hypothesis that neck torque in the tested conditions are below levels of human tolerance.

While not unexpectedly high, seat belt tensions recorded in the dynamic tests were at a magnitude that many motor vehicles develop permanent and possibly significant deformation of seat belt anchorages and other hardware due to seat belt loading. Deformation of seat belt mounting components due to seat belt tension is often minimal or unobservable in rollover crashes. This may be explained by the relative ineffectiveness of seat belts in limiting pelvic/torso vertical displacement, the role of other vehicle components (namely the roof) in limiting occupant whole body displacement, and/or a more aggressive test acceleration/condition than experienced in most rollover crashes. Considering deformation at seat belt anchorages is an important factor in seat belt controlled occupant flail.

The purpose of the test program was to provide some objective quantification of the effects of different restraint system variables. The relationship of the variations in lap belt slack to the effective slack that any pro-
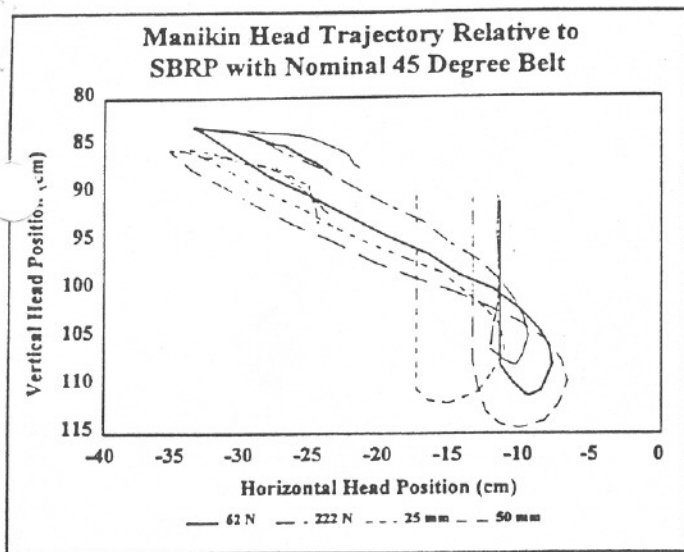
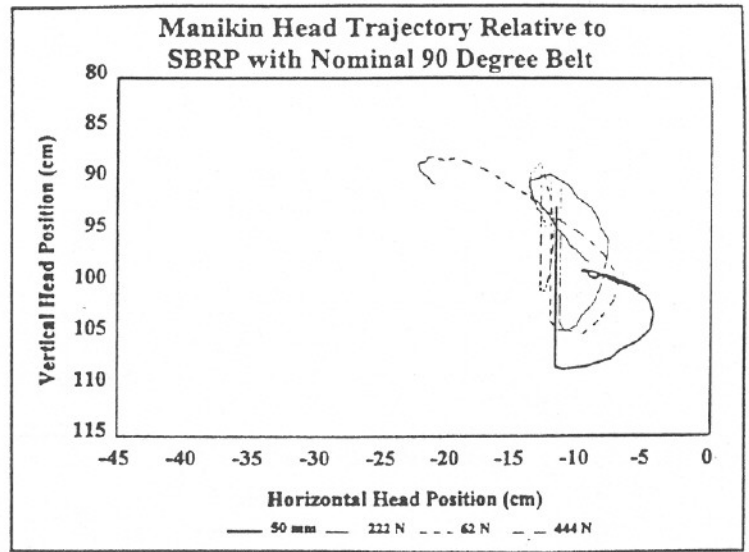**Figure 9:** Manikin head trajectory relative to SBRP with nominal 45 degree belt

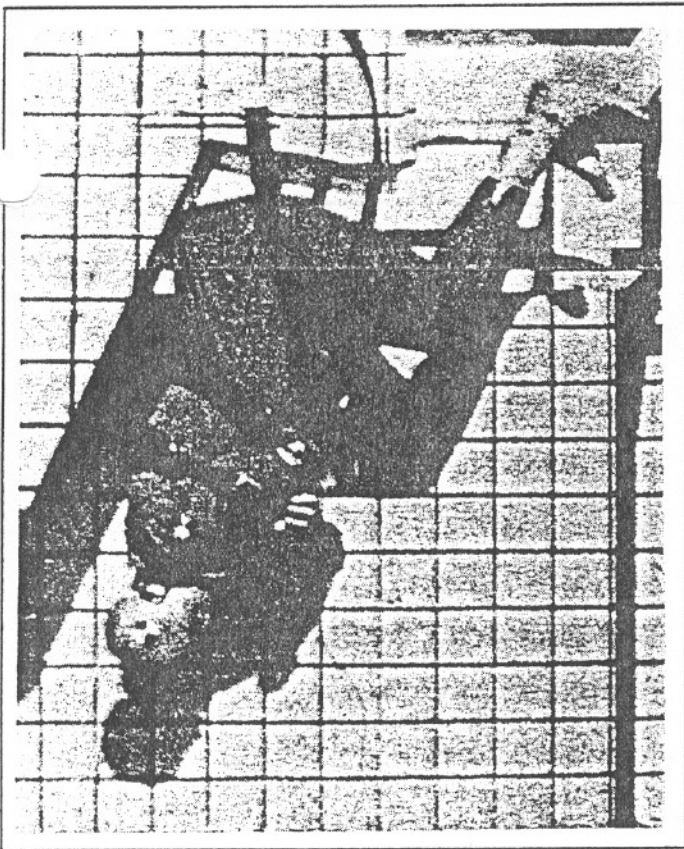**Figure 10:** Manikin head trajectory relative to SBRP with nominal 90 degree belt

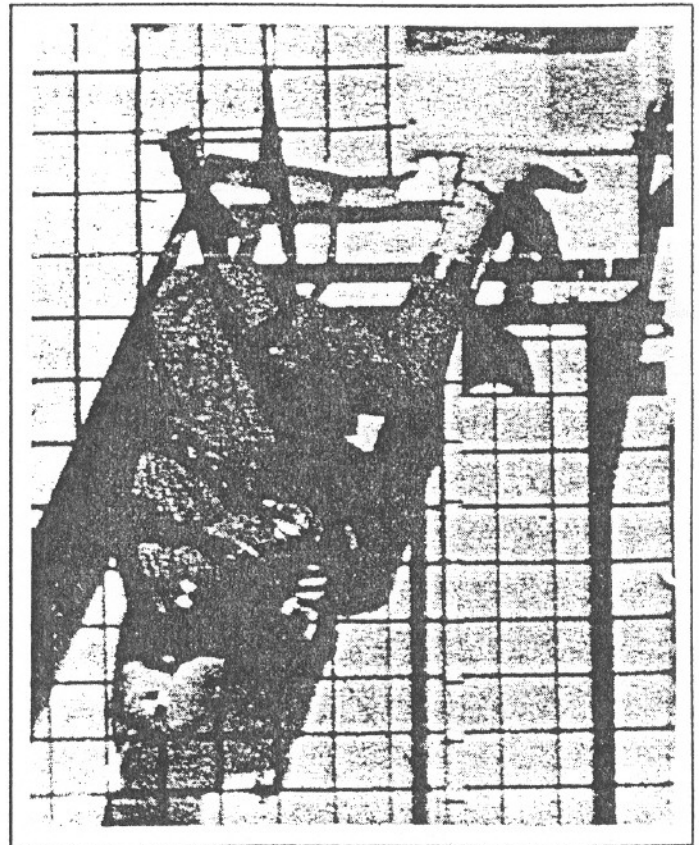**Figure 11:** 90 degree nominal belt orientation at 444N adjustment tension

Figure 12: 45 degree nominal belt orientation at 50 mm slack adjustment

duction vehicle may exhibit is undefined. When developing a vehicle rollover protection system, the amount of acceptable slack, if any, needs to be quantified. While it is clear that reducing effective slack reduces occupant displacement, useful means of determining the magnitude of a vehicle's seat belt system slack in rollover conditions needs to be developed.

Restraining the pelvis more closely to the seat may favorably affect the probability and magnitude of numerous rollover-related injuries. Addressing pelvis-to-roof relative displacement velocity may effectively limit the inertial loading of the neck by an occupant's body. Among many possible variables, pelvis-to-roof relative displacement during a rollover crash is a function of initial head to roof clearance, seat mounting height, occupant initial position, seat cushion stiffness, roof stiffness (crush), and seat belt (including anchorages) controlled occupant body flail.

CONCLUSION

The work presented in the paper shows that significant changes in vertical pelvic displacement are affected by different lap belt configurations. Vertical pelvic displacement can be significantly reduced by changing the lap belt configuration. In general, minimum vertical excursion occurred with a tight nominal 90-degree belt. Longitudinal excursion was also affected by belt angle and slack/tension.

Improvement to occupant protection needs to include aspects of the expected crash environment. A system approach to occupant protection in rollover crashes should include all rollover crash safety-related components and their relationship to one another, including, but not limited to, seat belt, seat, roof, and interior structures/components. It seems clear that for the greatest benefit in controlling occupant pelvic vertical displacement in rollover conditions, changes in presently manufactured seat belt systems may be required.

Lap belt slack significantly influences the excursion of the occupant from the seat. The actual effective slack of a production vehicle is undefined. Useful means of determining the magnitude of a vehicle's seat belt system slack in rollover conditions needs to be developed.

Effort is necessary to define longitudinal and lateral occupant flail envelope. Further definition of occupant exposure to injury in a rollover is required—expanding from probable occupant interior contact locations to probable contact velocity and body orientation.

The overall occupant protection components of a vehicle should be considered as a system. Changes which reduce the probability of one type of injury could affect the overall probability of another injury. With a more effective rollover protection system, an incremental improvement in motor vehicle safety seems probable.

BIBLIOGRAPHY

1. Johnson, Arnold K., Knapton, David A., "Occupant Motion During a Rollover Crash," National Highway Traffic Safety Administration, DOT HS-806 646, November 1984.

2. NHTSA Crashworthiness Staff, "Injury Contacts in Light Vehicle Rollovers," January 1983.

3. Bohlin, N.I., "A Statistical Analysis of 28,000 Accident Cases with Emphasis on Occupant Restraint Value," *11th Stapp Car Crash Conference*, October 1967.

4. Huelke, Donald F., Lawson, Robert Scott, And Marsh IV, Joseph C., "The Effectiveness of Belt Systems in Frontal and Rollover Crashes," SAE 770148.

5. Evans, Leonard, "Air Bag Effectiveness in Preventing Fatalities Predicted According to Type of Crash, Driver Age, and Blood Alcohol Concentration," *33rd Annual Proceedings of The Association for the Advancement of Automotive Medicine*, October 2-4, 1989, pp. 320.

6. Streff, F.M., "Field Effectiveness of Two Restraint Systems: The Three-point Manual Belt Versus the Two-point Motorized-Shoulder, Manual Lap belt," Advances in Occupant Restraint Technologies: Joint AAAM-IRCOBI Special Session, September 22, 1984, Lyon France, p. 9.

7. Orlowski, Kenneth F., Bandorf, Thomas R., Moffatt, Edward A., Rollover Crash Tests - "The Influence of Roof Strength on Injury Mechanics," *29th Stapp Car Crash Conference Proceedings*, October 1985, pp. 181-203.

8. Bahling, G.S., Bandorf, R.T., et al., "Rollover and Drop Tests – The Influence of Roof Strength on Injury Mechanics Using Belted Dummies," *Proceedings of the 34th Stapp Car Crash Conference*, November 1990, pp. 101-112.

9. Habush, Robert L., Slavik, Donald H., "The Anatomy of a Roof Crush Case," Paper by an attorney.

10. Huelke, D.F., Compton, C.P., "Injury Frequency and Severity in Rollover Car Crashes as Related to Occupant Ejection, Contacts and Roof Damage." *Accident Analysis and Prevention*, Vol. XIV, No. 5, 1983.

11. Fan, W.R.S. and Jettaer, E., "Light Vehicle Occupant Protection – Top and Rear Structures and Interiors," SAE 820244, *Crash Protection*, SP-513, 1982.

12. Yoganadan, Narayan, Almusallam, Abdullah, and Sances, Anthony, "Structural Dynamics – Head and Neck Dynamics in an Automobile Rollover," *Mathematical and Computer Modeling*, Great Britain, Vol. 14, 1990, pp. 947-952.

13. Strother, Charles E., Smith, Gregory C., James, Michael B., and Warner, Charles Y., "Injury and Intrusion in Side Impacts and Rollovers," SAE 840403.

14. Syson, Stephen R., "Occupant to Roof Contact: Rollovers and Drop Tests," SAE 950654, International Congress & Exposition, February 1995, p. 1.

15. National Highway Traffic Safety Administration, U.S. DOT, *Anthropometry of Motor Vehicle Occupants*, Volume 1, p. G-9.

16. "Human Tolerance to Impact Conditions as Related to Motor Vehicle Design," Human Injury Criteria Task Force of the Human Biomechanics and Simulation Subcommittee, SAE J885, July 1986.