A COMPARISON OF TWO AND THREE POINT BELT RESTRAINT SYSTEMS

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ABSTRACT

The performance of the two point belt/knee bolster restraint and the three point belt restraint systems were compared based upon vehicle crash cases, computer simulations, and frontal sled tests. The National Accident Sampling System data base files for frontal impacts indicated that drivers restrained with two point belt/knee bolster systems experience significantly more liver injuries than occupants restrained with three point belt systems. To verify these findings, forty-four sled tests with human cadavers and the Hybrid III dummy were conducted at 32 km/h and 48 km/h. Subject instrumentation included upper and lower chest bands and thoracic accelerometers. Following the sled tests, radiographs and autopsy results were used to correlate cadaver injury with measured engineering parameters. Analysis of occupant kinematics using high speed films indicated greater longitudinal excursion of the hips and pelvis and smaller rotations of the torso for the two point belt/knee bolster restraint. The kinematic differences resulted in loading of the lateral chest and abdomen in the region of the liver for the two point belt/knee bolster system and loading of the upper chest for the three point belt system. Occupants with two point belt/knee bolster restraints incurred more liver and visceral injuries while occupants with three point belt restraints experienced more sternal and clavicular fractures.

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THE THREE POINT BELT restraint system has proven to be an effective means of crash protection for vehicular occupants. Low usage rates of the manual three point belt system, however, prompted the United States Department of Transportation to adopt Federal Motor Vehicle Safety Standard No. 208 in 1977 [1]. This standard required passive restraint systems in passenger cars and resulted in the emergence of the automatic two point belt and knee bolster restraint system. This system uses a shoulder belt to restrain the torso and a knee bolster to absorb the kinetic energy of the lower extremities through the knee-thigh-hip complex.

The 1975 Volkswagen Rabbit [2] was the first production vehicle to use the two point belt system with a knee bolster. Since then, many vehicles have been equipped with automatic or motorized two point belts/knee bolster systems with supplemental manual lap belts. According to the National Highway Traffic Safety Administration (NHTSA), only 30% of Americans using automatic shoulder belts bother to fasten the manual lap belt. While use of the two point belt restraint is undeniably better than wearing no belts, this system may not afford the same level of occupant protection as the three point belt system. This paper compares the performance of the two point belt/knee bolster restraint system with that of the three point belt restraint system.

PREVIOUS STUDIES

In 1974, Schimkat et al. [3] conducted dummy and human cadaver sled tests at 50 km/h to compare the two point belt/knee restraint and three point belt restraint systems. Seven human cadavers were tested with the Volkswagen Rabbit two point belt/knee bolster restraint system and six human cadavers were tested with a production model three point belt restraint system. Minimal instrumentation and limited injury documentation hindered the correlation of observed trauma with recorded engineering parameters. Based on the limited data, however, Schimkat et al. concluded that the two point belt/knee bolster and three point belt restraint systems provided equivalent occupant protection.

In 1977, States et al. [4] examined automotive crashes in which the primary restraint was the original two point belt/knee restraint system designed by Volkswagen. For 59 cases, injuries were coded according to the Abbreviated Injury Scale (AIS). States et al. identified only three occupants with moderate injuries (AIS=3) and no occupants with severe or critical injuries (AIS≥4). Based on the data set, the authors concluded that the Volkswagen two point belt/knee bolster was a reliable and effective restraint system.

In 1979, Viano and Culver reported on seven human cadaver and four Hybrid III dummy sled tests in which a two point belt/knee bolster was used as the restraint system [5]. The experiments were conducted with a sled velocity of 48 km/hr. Viano and Culver observed that when the major component of the bolster force was directed below the knee joint, ligamentous tears were produced in the lower legs of the human cadavers. When the lower extremity restraining loads due to the bolster were directed along the axis of the femur, the restraint system provided adequate occupant protection.

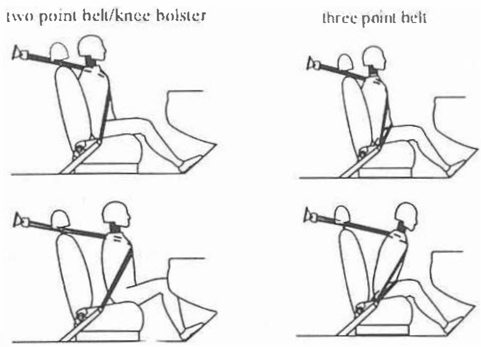

Figure 1. Typical overall occupant kinematics for belt restraint systems.

In 1988, Robbins [6] used the MVMA2D crash victim simulation program to examine the differences in occupant response between the two point belt/knee bolster restraint and the three point belt restraint systems. The study concluded that the occupant kinematics with the two point belt/knee bolster restraints depend heavily on the initial distance of the knee from the knee bolster. Robbins found the longitudinal movement of the H-point, the torso rotation, the shoulder belt and knee loads, the chest deformation, and the chest acceleration to be higher with two point belt/knee bolster restraints than with three point belt restraints. Typical occupant kinematics for the restraint systems are shown in Figure 1.

DATA BASE SURVEY METHOD

The 1984 to 1986 and 1988 to 1992 National Accident Sampling System (NASS) accident data bases were examined for cases satisfying seven conditions: (1) frontal collision, (2) occupant was older than 15 years of age, (3) occupant was either a driver or a right front seat occupant, (4) vehicle was a passenger car, light truck, or van, (5) occupant was not ejected, (6) the vehicle did not roll over, and (7) the occupant was using either a two point torso belt/knee bolster without a lap belt or a three point belt restraint system.

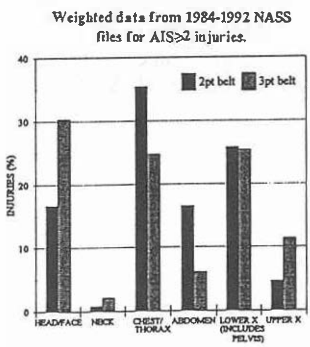

Figure 2

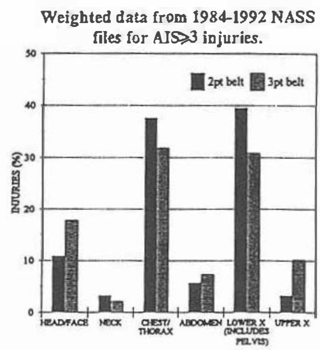

Figure 3

DATA BASE SURVEY RESULTS

The results of the injury survey for two point belt/knee bolster restraints and three point belt restraints are shown in Figures 2 and 3. The injury counts have been weighted by a national expansion factor to make the NASS files representative of the population of crashes that occur in the United States. Since the total number of injuries rather than the number of injured occupants was counted, multiple injuries for an individual were possible. The figures indicate that a higher percentage of chest and abdominal injuries with AIS≥2 occur for occupants restrained with two point belt/knee bolster systems than with three point belt systems. A breakdown of the abdominal injuries by organ indicates that liver injuries account for approximately 60% of the abdominal injuries for occupants restrained by the two point belt/knee bolster system and only 20% of the abdominal injuries for occupants with the three point belt system (Figures 4 and 5). The data also indicate that 12% of all injured occupants with two point belt/knee bolster restraints had liver injuries while only 3% of all injured occupants with three point belt restraints had liver injuries.

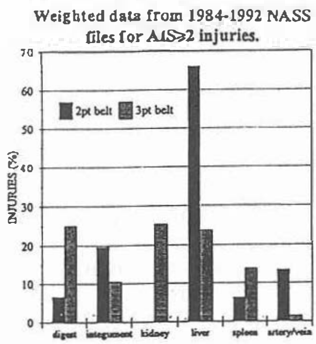

Figure 4

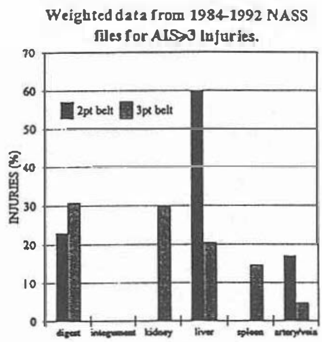

Figure 5

Based on the trauma information found in the NASS files, the injury distribution, severity, and patterns appear different for occupants restrained by the two point belt/knee bolster and the three point belt restraint systems. In order to check the statistical significance of these perceived differences, the survey data analysis software SUDAAN was used to analyze the 1988-1992 NASS data.

Table I. Percentage of AIS≥2 and AIS≥3 injuries
Sample Size (n), Standard Error (SE)

Body Region	Three Point Belt					
	Percent of AIS≥2			Percent of AIS≥3		
	%	SE	n	%	SE	n
head/face	12.0	0.85	1384	1.73	0.25	342
neck	1.98	0.46	127	0.53	0.21	40
chest	12.7	1.10	1155	4.09	0.51	502
abdomen	18.8	2.63	350	4.08	1.14	132
lower ext.	8.66	0.70	1355	2.69	0.38	489
upper ext.	10.1	1.25	598	2.19	0.41	146

Body Region	Two Point Belt/knee Bolster					
	Percent of AIS≥2			Percent of AIS≥3		
	%	SE	n	%	SE	n
head/face	14.9	2.93	48	2.38	1.25	10
neck	2.1	1.59	5	2.11	1.57	4
chest	20.1	6.03	76	5.31	1.48	31
abdomen	58.7	14.8	37	3.26	1.62	7
lower ext.	15.5	4.52	91	5.94	2.65	30
upper ext.	9.5	3.22	17	1.63	1.37	3

Table I shows the percentage of AIS≥2 and AIS≥3 injuries for each body region along with the associated standard errors and sample sizes. The statistical significance of the results was calculated using 95% confidence intervals, the *t* statistic (test), and the degrees of freedom (d.o.f) based on the Satterthwaite approximation (Table II). If zero was not contained within the confidence interval range, the difference in trauma for that particular body region was considered statistically significant at the 0.05 error level.

Table II. Confidence Intervals of AIS≥2 and AIS≥3 injuries in two point belt and three point belt restraints (1988-1992 NASS files).

Body Region	AIS≥2		AIS≥3	
	dof	95% interval	dof	95% interval
head/face	28	-3.3 to 9.1	26	-1.5 to 3.3
neck	28	-3.2 to 3.6	25	-1.7 to 4.8
chest	26	-5.1 to 20.1	30	-1.9 to 4.4
abdomen	25	9.0 to 70.7	43	-4.8 to 3.2
lower ext.	25	-2.6 to 16.3	25	-2.3 to 8.8
upper ext.	31	-7.6 to 6.5	28	-3.5 to 2.4

The results in Table II indicate that occupants restrained with two point belt/knee bolster systems experience significantly more AIS≥2 liver injuries than occupants restrained with three point belt systems [6]. None of the other differences in injury were found to be significant between the two restraint types. Despite loading of the knee bolster through the knee-femur-hip complex, no increase in lower extremity injury was noted for the two point belt system.

EXPERIMENTAL METHODS

A laboratory comparison of the safety performance of the two point belt/knee bolster and the three point belt restraint systems was based upon sled tests with human cadavers and the fiftieth percentile male Hybrid III dummy. Sled tests were conducted at Impact Trauma Laboratories at the University of Virginia (UVA) and the Medical College of Wisconsin [9]. From the NHTSA Biomechanics Data Base, twelve sled tests conducted by Wayne State University [10] in 1983 were also included in the study. The total combined experimental data set for human subjects consisted of twenty-two sled tests with two point belt/knee bolster restraints and twenty-two sled tests with three point belt restraints. Details of these tests, including anthropomorphic information for the subjects, are presented in Appendix A.

The experimental setup for the two Impact Trauma Laboratories is shown in Figure 6. Sled tests were conducted at 32 km/h and 48 km/h in order to produce moderate and severe occupant injuries. A typical deceleration pulse for a sled velocity of 48 km/h is shown in Figure 7. The interior components and dimensions of the sled buck were configured to replicate a 1990 Ford Tempo. For the two point belt tests, production model Volkswagen knee bolsters were used. All tests were conducted with the shoulder belt configured on the subjects as though they were drivers. Load cells to measure belt tension were connected near the upper and lower anchorage points of the shoulder belt and, for the three point belt system, near the inboard and outboard anchorage points of the lap belt. Initial positioning of the occupants set the initial chest to steering wheel, head to windshield, and knee to knee bolster distances. The minimum initial knee to knee bolster distance was 5 cm.

Fresh, frozen, and biofidelic embalmed cadavers were used in the sled tests. Pressurization of the arterial and pulmonary systems was accomplished using an apparatus that maintained constant arterial and pulmonary pressures prior to impact. Triaxial accelerometers were mounted on the cadavers at the first and the twelfth thoracic vertebrae. In order to obtain continuous measurements of chest deformations during impact, chest bands [11,12] were wrapped around the chest at the level of the lateral fourth and the eighth ribs (Figure 8); thus, chest deformation measurements near the heart, liver, and the spleen were possible. Chest deformations at locations along the chest contour were obtained by tracking the distance between pairs of gages (Figure 9).

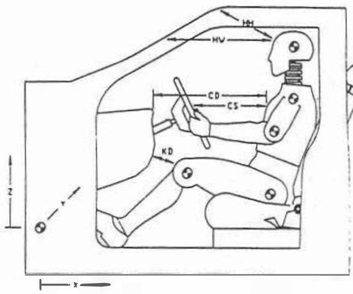

Figure 6
Sled configuration at UVA.

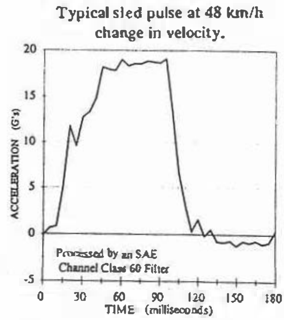

Figure 7

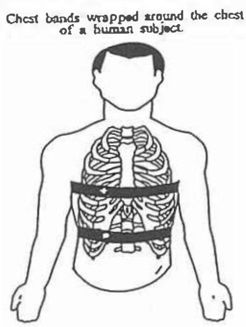

Figure 8

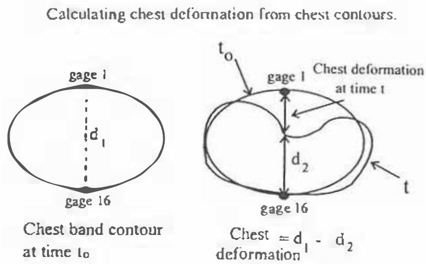

Figure 9

The sled buck at Wayne State University was configured to replicate a Volkswagen Rabbit. All tests were conducted with the shoulder belt configured on the subject as though they were the driver. The arterial systems of the unembalmed cadavers were pressurized by normal saline but the pulmonary systems were not pressurized. The subjects were fitted with triaxial accelerometers at the first and the twelfth vertebrae and uniaxial accelerometers at the fourth and the eighth ribs. No chest deformation measurement devices were used. Initial knee to knee bolster distances averaged nearly 13 cm. and were substantially greater than those in the sled tests performed at the Impact Trauma Laboratories.

EXPERIMENTAL RESULTS

The differences in occupant kinematics, applied belt loading, torso deformation, and induced trauma were evaluated for the sled tests with the two point belt/knee bolster and three point belt restraint systems.

OCCUPANT KINEMATICS - The occupant kinematics for the sled tests were compared using high speed films. For a given restraint system considerable variability in the pelvic, torso, and head trajectories was attributed to variations in subject anthropometry and differences in initial positioning.

The average and standard deviations for the measured kinematic variables are shown in Table III. Although the standard deviations of some parameters were large, differences in the trends were evident between the two restraint systems. For example, Table II indicates that occupants restrained with the two point belt/knee bolster system experienced larger longitudinal hip motion and smaller torso rotation than those occupants restrained with the three point belt system.

Table III. Kinematic parameters of occupants in cadaver sled tests conducted at UVA.

Kinematic Parameters (Average Excursions)	3 pt. belt 48 km/h	2 pt. belt 48 km/h	3 pt. belt 32 km/h	2 pt. belt 32 km/h
long. head (cm)	22.3±3.0	19.2±0.8	21.2±0.7	17.0±3.6
long. hip (cm)	9.1±2.7	13.3±1.1	9.0±1.8	12.8±3.0
long. torso (cm)	13.6±1.8	10.9±0.2	12.1±0.4	10.7±1.5
vertical head (cm)	10.5±2.0	-8.7±0.3	-8.7±0.3	-4.3±1.2
vertical hip (cm)	0.9±2.8	2.7±0.5	-1.9±0.1	2.1±2.3
vertical torso (cm)	-3.4±1.2	3.6±0.6	-3.4±0.3	5.6±1.4
torso rotation (degrees)	12.1±3.7	5.0±0.3	11.5±1.3	3.0±1.4

Hypothesis testing with the *t* statistic (test) was conducted to determine whether or not the differences in kinematics between the two restraint systems were significant. The results indicate significant differences in longitudinal hip excursion, torso rotation, and vertical motion of the hip between the two restraint systems. The average longitudinal hip movement was 4 cm greater with the two point belt/knee bolster than with the three point belt restraints. The rotation of the torso about the hip was approximately 9 degrees greater with three point belts than with two point belts. The vertical motion of the hip averaged 2 cm upward for occupants restrained with two point belt/knee bolster restraints and 0.5 cm downward for occupants restrained with three point belt restraints. No significant differences in the longitudinal motion of the torso or the head existed between the two restraint systems.

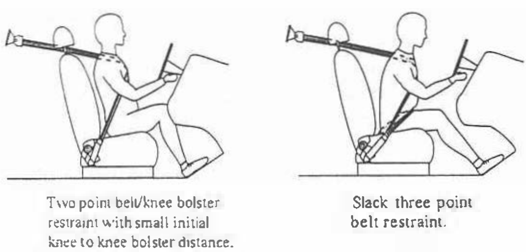

Figure 10. Occupant kinematics with two point belt/knee bolster and three point belt restraints.

The knee bolster in the sled tests conducted at the Impact Trauma Laboratories was relatively close to the knees (approximately 5 cm) and stiff. The proximity of the bolster to the cadaver prevented large relative velocities from developing between the knee and the bolster; which, coupled with the stiffness of the bolster, prevented large longitudinal motion of the hip in the sled tests. This led to little flexion of the knee and caused the pelvis and torso of the occupant to rise off of the seat. A sketch of the occupant kinematics in a two point belt/knee bolster restraint relative to the kinematics of an occupant in a three point belt restraint system is shown in Figure 10.

The overall Hybrid III dummy kinematics (head, torso, and H-point trajectories), while generally similar to the cadavers, exhibited several differences. For a given restraint type and sled velocity, the cadaver chests deformed more than the dummy chests. In addition, knee bolster deformations were higher in the dummy tests than in the cadaver tests in spite of the cadavers generally weighing more than the dummy.

In order to conduct a parametric study with initial positioning of the dummy and stiffness characteristics of the vehicle components (e.g., the knee bolster and seat), the Articulated Total Body (ATB) occupant simulator was used to model the sled tests for both types of restraint. The ATB simulations showed kinematic trends similar to those observed in the Hybrid III sled tests for the two point belt/knee bolster and three point belt systems. Occupant kinematics similar to those simulated by Robbins [6] were obtained using a softer bolster and a greater initial knee to knee bolster distance.

KINETICS - The degree and manner in which occupant kinematics lead to local response differences in torso deformation and loading applied to the human cadaver and to the Hybrid III dummy were analyzed. The sled tests with cadavers indicated no significant differences in the average thoracic accelerations, belt loads, and the maximum upper and lower chest deformations between the two point belt/knee bolster and the three point belt restraint systems (Figure 11). The maximum upper and lower chest deformations in the anterior-posterior and lateral directions were calculated at the equivalent locations of the chest deformation measuring devices on the Hybrid III dummy (Figure 12).

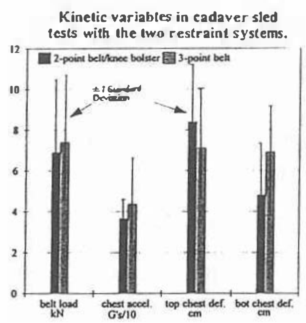

Figure 11

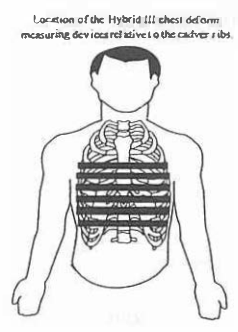

Figure 12

Figures 13 and 14 show typical chest contours obtained from the top and bottom chest bands for occupants restrained with a two point belt/knee bolster restraint and a three point belt restraint system. The view of the transverse plane is from the superior to the inferior direction with the spine positioned at the origin (0,0). Chest contours for the top band appear similar for two point belt restrained occupants and for three point belt restrained occupants. The chest contours from the bottom band, however, show greater lateral deformation of the chest for the occupants restrained by the two point belt than for those restrained by the three point belt. The high speed films of the sled tests indicate that the shoulder belt in cadaver sled tests with two point belt restraints moves up the torso as the lower extremities move forward into the knee bolster. Sliding of the shoulder belt was more pronounced in the two point belt restrained occupants where the shoulder belt went behind the equivalent location of the H-point (Figure 16). Movement of the shoulder belt during impact caused the belt to load the chest at a more lateral location of the lower chest band directly over the occupant's liver. Upward movement of the shoulder belt was not observed in any of the cadaver sled tests with three point belt restraints. Since the shoulder belt went over the equivalent H-point location of the occupant in all of the Hybrid III sled tests, the belt did not move up the torso of the dummy for any restraint configuration.

For the tests where there was an initial offset of the equivalent H-point from the shoulder belt, the offset was added to the longitudinal hip excursions to obtain the total expected longitudinal hip motion. The lateral distance of the maximum chest deformation from the mid-sagittal plane was closely correlated with the total hip excursions for the tests conducted at UVA (Figure 16). The lateral chest deformations and hip point excursions are greater in two point belt/knee bolster tests than in three point belt tests.

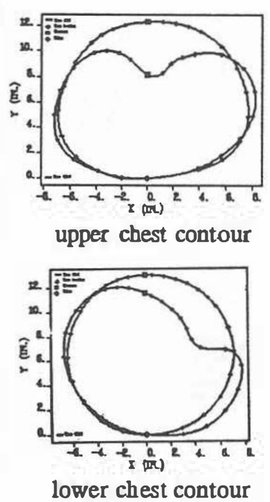

Figure 13
Chest contours of human subject with two point belt/knee bolster.

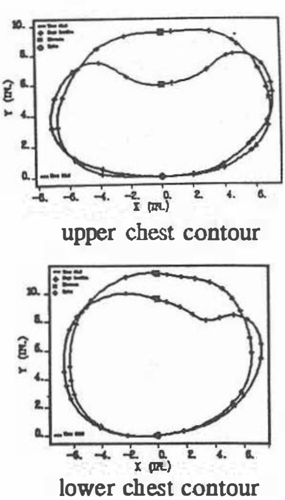

Figure 14
Chest contours of a human subject with three point belt restraints.

The sled tests showed no remarkable differences in the maximum chest velocities for occupants restrained by two point belt/knee bolster or three point belt restraints. Chest velocities were obtained by differentiating the chest deformations derived from the chest band curvature data. Using the chest band deformation and velocity data, no remarkable differences in the Viscous Criterion (VC) were identified between the two point belt sled tests and the three point belt sled tests. According to Lau et al. [13], VC is the best indicator of soft tissue injury for chest velocities between 3 and 30 m/s with the critical VC value for thoracic trauma occurring at a value of 1 m/s. Although, the chest velocity was greater than 3 m/s in most of the sled tests conducted at UVA, the VC values were typically less than 1 m/s. Consequently, the VC which was developed for blunt impacts, may not be a valid indicator of soft tissue trauma for these tests using belt restraints.

Figure 15. Occupant kinematics with two point/knee bolster system.

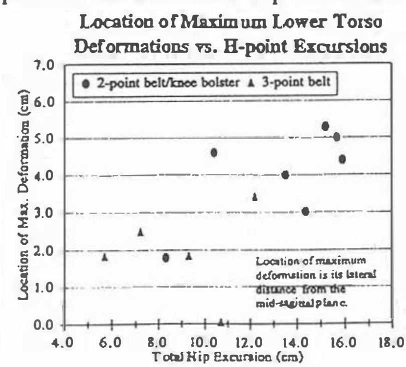

Figure 16

TRAUMA - Following the sled tests with cadavers, injuries were identified using radiographs and autopsy results. Observed trauma was correlated with the localized chest and abdomen deformations for each restraint type. The occupants with two point belt restraints incurred more soft tissue damage (minor lacerations of spleen and liver (AIS=2), and tears in the visceral pleura (AIS=4)). Figure 17 indicates differences in the abdominal trauma produced by the two point belt/knee bolster and the three point belt restraint systems. At a 95% confidence level, however, hypothesis testing indicated that the perceived differences in abdominal injuries were not significant.

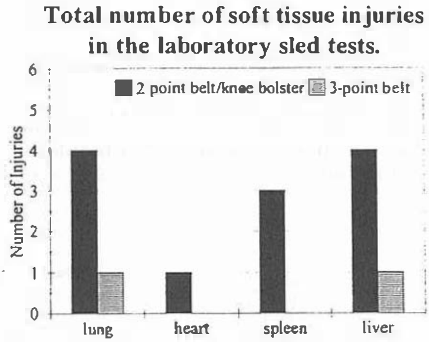

Figure 17

The most common injury, regardless of restraint type, was fractured ribs. The total number of fractures in each rib for the right and left aspects is shown in Figure 18. The data indicate more left rib fractures with two point belt restraints and more right rib fractures with three point belt restraints. The average location (lateral distance from the mid-sagittal plane) of fractures in each rib on the left and right side for the twenty-two two point belt restraint/knee bolster sled tests and the twenty-two three point belt restraint sled tests are shown in Figure 19.

Figure 19 shows that the locations of lower rib fractures with the two point belt/knee bolster restraints are more lateral (from the mid-sagittal plane) than with the three point belt restraints. This result conforms with the chest band data and the high speed film observations that indicate the maximum deformation and loading of the lower ribs are more lateral (from the mid-sagittal plane) in two point belt restraints than in three point belt restraints. Occupants with three point belt restraints had more clavicular and sternal fractures than those in two point belt/knee bolster restraints. Greater rotation of the torso in the three point belt tests caused the shoulder belt to bear a proportionately larger percentage of the overall belt loading.

To verify that the laboratory experiments were representative of real life vehicle crashes, the injuries obtained from the sled tests were categorized in a manner comparable to the NASS percentage results (Figures 20 and 21). The sled tests show more abdominal and lower extremity injuries of AIS≥2 with the two point belt/knee bolster restraints than with three point belt restraints. However, there were more chest injuries with three point belt restraints than with two point belt restraints. A complete description of the observed trauma in the sled tests used in this paper is presented in Appendix B.

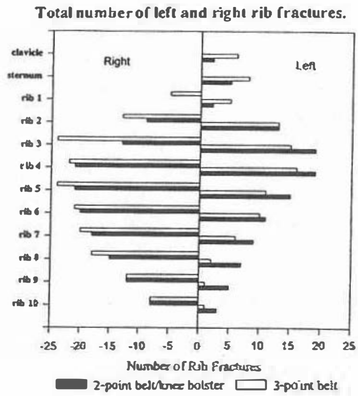

Figure 18

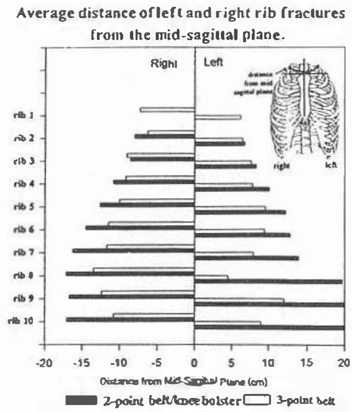

Figure 19

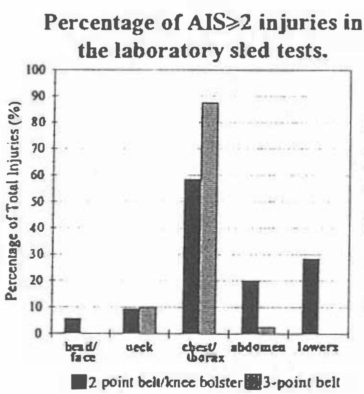

Figure 20

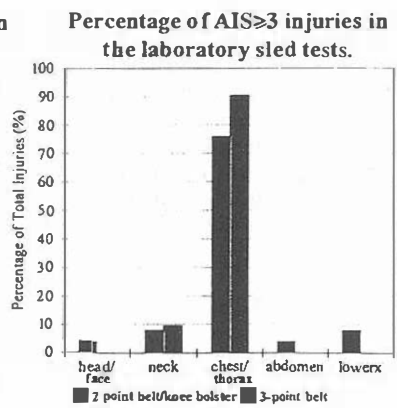

Figure 21

CONCLUSIONS

Sled tests and accident data base results indicate greater likelihood of liver injuries for occupants restrained with two point belt/knee bolster restraints than for occupants restrained with three point belt restraints in frontal collisions. The NASS data base files show that liver injuries account for approximately 60% of the abdominal injuries in two point belt/knee bolster restrained occupants while only 20% of the abdominal injuries in three point belt restrained occupants. Hypothesis testing identified significantly more AIS≥2 abdominal injuries for occupants using the two point belt/knee bolster restraint. Differences in injury to other body regions were not found to be significant between the restraint types.

In the cadaver sled tests, occupants restrained with the two point belt/knee bolster system incurred more abdominal soft tissue damage than occupants restrained with the three point belt system. Significant differences in occupant kinematics and kinetics were also identified between the two restraint systems. Analysis of the high speed films indicated larger hip excursions and smaller torso rotations with two point belt/knee bolster restraints than with three point belt restraints. The shoulder belt moved up the lower torso of cadavers restrained with the two point belt/knee bolster system but did not move with the three point belt restraint system. Subjects with three point belt restraints had more clavicle and sternal fractures than subjects with two point belt/knee bolster restraints. Greater rotation of the torso for these occupants concentrated the belt loading in the shoulder complex.

Torso contours obtained from the lower chest band at the level of the eighth rib indicated that the location of maximum chest deformation was more lateral from the mid-sagittal plane with two point belt/knee bolster restraints than with three point belt restraints. The lateral lower torso deformations were attributed to the upward motion of the shoulder belt identified with high speed films. Greater longitudinal movement of the hips for occupants restrained with the two point belt restraints positioned the belt on the rib cage directly over the liver. Radiographs and autopsy results confirmed that rib fractures occurred closer to the mid-sagittal plane for occupants restrained with the three point belt system.

For the sled tests with the Hybrid III dummy, there were no significant differences in the kinetic parameters (belt loads, chest acceleration, and maximum chest deformation) between the two point belt/knee bolster and three point belt restraints. The chest deformation gages in the Hybrid III dummy are unable to detect the lateral deformation of the lower torso that was observed in sled tests with cadavers in two point belt/knee bolster restraints. The phenomenon of the shoulder belt loading the chest laterally and causing lateral rib fractures would go undetected in a test with the Hybrid III dummy that did not use the chest bands. Response differences between the dummy and cadavers were attributed to the stiffer chest and knee-femur complex of the Hybrid III dummy.

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References

1. Federal Register, 49 CFR Part 571 Federal Motor Vehicle Safety Standards: Occupant Restraint Systems, Vol. 42, No. 128, July 1977.

2. Johannessen, H. G., "Historical Review of Automatic Seat Belt Restraint System," Restraint Technologies: Front Seat Occupant Protection, SAE Publication SP-690, February 1987.

3. Schimkat, H., Weissner, R., and Schmidt, G., "A Comparison between Volkswagen Automatic Restraint and Three-Point Automatic Belt on the Basis of Dummy and Cadaver Tests," Proceedings of the 18th Stapp Car Crash Conference, December, 1974, SAE paper no. 741183.

4. States, J. D., Miller, S. R., and Seiffert, U. W., " Volkswagen's Passive Seat Belt/Knee Bolster Restraint, VWRA: A Preliminary Field Performance Evaluation," Twenty-First Stapp Car Crash Conference, October 1977.

5. Viano, D.C., and Culver, C. C., "Performance of a Shoulder Belt and Knee Restraint in Barrier Crash Simulations," Twenty-Third Stapp Car Crash Conference, SAE paper no. 791006, October, 1979.

6. Robbins, D.H., "Study of Differences in Hybrid III Chest Deflections due to Three and Two Point Belt Loadings," DOT HS807 275, PB 88-238365/WTS.

7. Bross, I. D. J., "How to Use RIDIT Analysis," Biometrics, Vol 14, pp 18-38, March, 1988.

8. Fleiss, J. L., "Statistical Methods for Rates and Proportions," John Wiley and Sons, 1973.

9. Yoganandan, N., Skrade, D., Pintar, F. A., Reinartz, J., Sances Jr., A., "Thoracic Deformation Contours in a Frontal Impact," Thirty-Fifth Stapp Car Crash Conference, November 1991.

10. Cheng, R., King, H. Y., Levine, R. S., and King, A. I., "Dynamic Impact Loading of the Femur under Passive Restrained Condition," Twenty-Eighth Stapp Car Crash Conference, October 1984.

11. Eppinger, R. H., "On the Development of a Deformation Measurement System and Its Application Toward Developing Mechanically Based Injury Indices," Thirty-Third Stapp Car Crash Conference, October 1989.

12. Hagedorn, A. V., Eppinger, R. H., Morgan, R. M., Pritz, H. B., and Khaewpong, N., "Application of a Deformation Measurement System to Biomechanical Systems," International IRCOBI Conference on the Biomechanics of Impact, September 1991.

13. Lau, V. I., and Viano, D. C., "The Viscous Criterion--Bases and Applications of an Injury Severity Index for Soft Tissues," Thirtieth Stapp Car Crash Conference, October, 1986.

APPENDIX A - Experimental Sled Test Results

Two Point Belt/Knee Bolster Restraint Tests

Test Ref.	Vel. km/h	Occupant Information				Chest Acc. (G's)	Max. Chest Def. (cm)		Should. Belt Load (N)	
		type	age	sex	wt. kg.		upper	lower	upper	lower
Sled Tests Conducted at University of Virginia										
ASTS53	35	cadaver	61	F	61	38.0	7.4	2.2	7927	7131
ASTS55	37	cadaver	62	F	90	NA	NA	NA	9364	NA
ASTS 102	33	cadaver	60	M	95	25.3	9.6	5.6	8550	6775
ASTS 103	33	cadaver	57	M	102	NA	4.3	3.2	3640	1653
ASTS 104	32	cadaver	66	F	104	28.2	12.9	8.9	7279	4632
ASTS 113	48	cadaver	24	F	57	43.4	8.0	4.2	16095	6311
ASTS 114	48	cadaver	60	F	65	NA	NA	NA	5208	4279
ASTS 223	34	cadaver	51	M	61	72.8	8.2	5.9	7508	7361
ASTS 224	34	cadaver	58	M	65	46.2	9.0	6.0	7326	5596
ASTS 225	34	cadaver	36	M	68	82.6	5.7	9.1	8851	6846
ASTS52	32	dummy	NA	M	74	20.4	8.1	3.8	12344	10172
ASTS54	32	dummy	NA	M	74	32.6	8.5	4.1	13087	11063
ASTS 101	32	dummy	NA	M	74	57.5	6.6	2.2	9409	7351
Sled Tests Conducted at Wayne State University										
DOT IIF18	50	cadaver	21	M	60	NA	NA	NA	5149	5709
DOT IIF19	50	cadaver	65	M	56	57.9	NA	NA	4980	5154
DOT IIF20	50	cadaver	29	M	96	26.9	NA	NA	7575	5374
DOT IIF21	50	cadaver	56	F	50	28.6	NA	NA	5897	3762
DOT IIF22	50	cadaver	50	M	91	30.7	NA	NA	NA	NA
DOT IIF23	50	cadaver	63	M	69	41.2	NA	NA	9729	4338
DOT IIF24	50	cadaver	58	M	78	34.4	NA	NA	1402	5499
DOT IIF25	50	cadaver	58	M	73	51.0	NA	NA	7693	5661
DOT IIF15	50	cadaver	46	F	66	37.0	NA	NA	6332	4467
DOT IIF16	50	cadaver	60	M	79	34.8	NA	NA	5085	5720
DOT IIF26	50	cadaver	63	M	51	NA	NA	NA	3652	6942
DOT IIF27	50	cadaver	61	M	75	NA	NA	NA	15002	5519

Three point Belt Tests

Test Ref.	Vel. km/h	Occupant Information				Chest Accel. (G's)	Max. Chest Defl. (cm)		Shlder Belt Load N	Lap Belt Load N
		type	age	sex	wt. kg.		upper	lower		
Sled Tests Conducted at the University of Virginia										
ASTS 25	47	cadaver	63	M	75	NA	NA	NA	NA	NA
ASTS 47	32	cadaver	65	M	66	NA	5.8	4.0	9120	9024
ASTS 48	32	cadaver	75	M	99	NA	10.3	6.3	10740	9892
ASTS 61	48	cadaver	62	M	67	NA	7.0	9.5	10377	3563
ASTS 66	48	cadaver	57	M	51	NA	5.9	6.4	10931	4188
ASTS 79	48	cadaver	68	M	67	42.36	2.5	13.5	10735	5543
Sled Tests Conducted at the Medical College of Wisconsin										
RC101	49	cadaver	58	M	82	39.92	2.9	9.1	7326	5133
RC102	48	cadaver	57	M	73	89.53	5.0	9.7	6129	3834
RC103	48	cadaver	66	M	77	NA	10.4	5.3	8771	5133
RC104	48	cadaver	58	M	70	39.86	4.6	5.3	7299	5035
RC105	48	cadaver	67	M	73	71.02	9.7	7.1	6596	3554
RC106	48	cadaver	44	M	86	53	8.9	6.9	8211	4533
RC107	48	cadaver	63	F	77	47.1	10.2	10.7	6781	3870
RC108	48	cadaver	57	M	73	52.2	7.4	2.8	6377	3930
RC109	48	cadaver	59	M	91	32.3	13.0	7.9	8454	6275
RC110	48	cadaver	63	F	61	54.4	9.1	9.9	6807	4523
RC111	34	cadaver	65	F	75	34	NA	NA	5323	2935
RC117	23	cadaver	76	M	58	23.5	2.82	1.88	4021	2726
RC120	23	cadaver	51	M	66	12.4	3.96	5.06	4167	1543
RC121	24	cadaver	67	M	66	16.2	5.7	2.5	NA	NA
RC122	25	cadaver	81	F	60	15.2	5.5	3.4	3240	1270
RC123	24	cadaver	67	F	68	15.8	5.7	3.5	NA	NA

APPENDIX B - Injury Information

Detail of injuries in the two point belt/knee bolster sled tests

Test No.	Max AIS	Left Rib FX	Right Rib FX	Sternum FX	Clavicle FX	Soft Tissue	Lower Extrem.
ASTS53	4	4	15	N	N	none	none
ASTS55	3	2	10	N	N	liver lacer. AIS=2 spleen lacer. AIS=2	none
ASTS102	5	6	12	N	N	spleen lacer. AIS=2	none
ASTS103	5	7	7	N	N	pneumothorax AIS=5	AIS=2
ASTS104	5	4	5	Y	N	pneumothorax AIS=5	none
ASTS113	5	5	7	Y	N	pneumothorax AIS=5	none
ASTS114	5	7	16	N	N	pneumo thorax AIS=5, liver la er. AIS=2	AIS=2
ASTS223	4	5	11	N	N	none	none
ASTS224	4	4	9	Y	N	liver lacer. AIS=2	none
ASTS225	4	4	12	Y	N	liver lacer. AIS=2	none
DOTIIF18	3	0	0	N	N	none	none
DOTIIF19	2	2	2	N	N	none	none
DOTIIF20	3	1	6	Y	N	none	none
DOTIIF21	2	3	1	N	N	none	none
DOTIIF22	2	0	2	N	N	none	none
DOTIIF23	2	2	1	N	Y	none	none
DOTIIF24	5	8	0	N	N	lacer. of heart AIS=5, spleen AIS=4	patella femur FX AIS=3
DOTIIF25	4	10	7	N	N	none	none
DOTIIF15	2	3	3	N	Y	none	none
DOTIIF16	4	7	4	N	N	none	none
DOTIIF26	3	4	3	N	N	none	none
DOTIIF27	4	10	4	N	N	none	tibia FX AIS=2

Detail of injuries in the three point belt sled tests

Test No.	Max AIS	Left Rib FX	Right Rib FX	Sternum FX	Clavicle FX	Soft Tissue	Lower Extrem.
ASTS25	4	5	8	n	y	none	none
ASTS61	4	5	14	n	n	none	none
ASTS66	4	3	14	n	n	none	none
ASTS79	3	7	12	n	n	none	none
ASTS47	3	0	1	n	n	none	none
ASTS48	3	2	6	y	n	spleen lacer. AIS=2	none
RC101	4	6	4	y	y	none	none
RC102	4	6	6	y	n	lung lacer. AIS=3	none
RC103	3	3	5	n	n	none	none
RC104	3	3	10	y	y	none	none
RC105	3	2	17	n	n	none	none
RC106	4	5	4	y	n	none	none
RC107	6	11	11	y	y	none	none
RC108	4	4	4	n	y	none	none
RC109	3	1	11	n	n	none	none
RC110	4	7	17	n	n	none	none
RC111	4	5	9	n	y	none	none
RC117	3	0	9	n	n	none	none
RC120	3	2	6	n	y	none	none
RC121	0	0	0	n	n	none	none
RC122	2	1	3	y	n	none	none
RC123	1	1	0	y	n	none	none