RESPONSE OF THOR IN FRONTAL SLED TESTING IN DIFFERENT RESTRAINT CONDITIONS

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ABSTRACT

Thor, the NHTSA Advanced Frontal Dummy, has been tested at Volvo and Autoliv to evaluate its response in different restraint conditions. The Hybrid III dummy has also been tested under the same conditions. At Volvo, a series of eight sled tests was conducted with Thor and Hybrid III seated side by side. Four of the tests were at 56 kph, while four were at 48 kph, with maximum decelerations of 30 G and 26 G respectively. At each speed, the dummy was seated in both the driver and passenger side positions. At the higher speed, on the driver side, the dummy was restrained by a 3-pt belt and airbag, while on the passenger side, it was restrained by a 3-pt belt only. At the lower speed, the dummy was restrained only by an airbag for both driver and passenger positions.

At Autoliv, twelve tests were conducted with the dummy in the driver position and with a sled velocity of 56 kph and peak deceleration of 25 G. A 3-pt belt system with and without force-limiting features were used in conjunction with an airbag. Each configuration was repeated three times.

In this paper we will: (1) analyze the ability of THOR to discriminate between belt and belt/bag restraint environments and also standard belt vs. force-limiting belt designs; (2) compare THOR responses and capabilities to those of HIII in equivalent environments; and (3) compare kinematics of the two dummies and evaluate repeatability based on the available tests.

IN 1994, THE NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION (NHTSA) began a major effort to develop an advanced frontal crash test dummy. The scope of the effort included refinement of the torso design, development of advanced representations of the face, neck, abdomen, pelvis, and femur. Improvements to various instrumentation systems were also to be investigated, and incorporation of additional sensors accomplished, so that the correlation of dummy responses to estimates of human injury potential could be achieved with greater confidence.

At present, two dummies have been fabricated and they have been undergoing extensive testing at a number of different laboratories under various test conditions. Figure 1 shows the principal components of the new advanced frontal crash test dummy which has been named THOR (Test Device for Human Occupant Restraint). More detailed discussion of Thor has been presented by White (1996), and Rangarajan (1998). Recently, it has been tested in Sweden, where it went through a test round-robin, being first tested at the Volvo Safety Center (VSC) sled facility followed by testing at Autoliv Research. A series of eight sled tests were conducted by Volvo and twelve sled tests conducted at Autoliv.

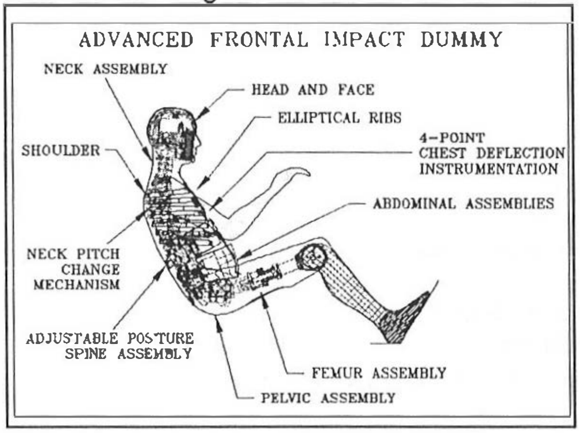


Figure 1. Principal features of THOR

TESTS AT VOLVO

DESCRIPTION OF TESTS - The tests at Volvo were meant to evaluate Thor from the perspective of a car crash laboratory. The following table summarizes the test conditions, each test condition being repeated twice.

Table 1. Summary of Tests at Volvo Safety Center (VSC)

Test No.	Speed	Driver	Drv Restraint	Pass	Pass Restraint
1 2	56 kph	Thor	Airbag+3-pt belt	Hybrid III	3-pt belt
3 4	56 kph	Hybrid III	Airbag+3-pt belt	Thor	3-pt belt
5 6	48 kph	Hybrid III	Airbag	Thor	Airbag
7 8	48 kph	Thor	Airbag	Hybrid III	Airbag

The tests were conducted with a Volvo 850 car body on the Hyge sled. Interior components such as seats, dashboard, steering system, sun visors, etc. were mounted on the car body. The energy absorbers in the steering column were blocked to minimize variation that may arise from column deformation.

The peak deceleration achieved with the 56 kph initial velocity was about 30 G, while the peak deceleration with the 48 kph velocity was about 26 G. The duration of both pulses was about 100 msec. The Hybrid III dummy was tested in the same configuration as Thor.

Initial Positioning - The dummy was positioned on the seat such that the lower body matched as closely as possible the Hybrid III position and the upper body was approximately aligned with the seat back with the head and neck in an erect position. In the resulting configuration, the Thor dummy was slightly more erect and a little to the rear with respect to the Hybrid III position.

TEST RESULTS - Table 2 shows the differences in the peak values for selected quantities in Thor and Hybrid III for the different test configurations. These values were obtained by averaging the results from the two similar tests performed with each configuration.

Table 2. Comparison of peak values from Thor and Hybrid III

Quantity	Driver				Passenger			
	3pt + bag		bag only		3pt only		bag only	
	Thor	Hyb III	Thor	Hyb III	Thor	Hyb III	Thor †	Hyb III
HIC	568	542	250	224	846	918	207	93
Chest acc (g)	46	51	38	38	46	44	43	33
Pelvis acc (g)	68	69	58	57	68	63	47	45
Chest defl (mm)	UL=-26 UR=-44 LL= * LR=-23	- 46	UL=-56 UR=-51 LL= * LR=-28	-51	UL=-46 UR=-23 LL= * LR=-12	-44	UL=-18 UR=-14 LL= * LR= -9	-15
Abdomen defl (mm)	L= -24 R= -30	-	L= +13 R= +15	-	L= -30 R= -23	-	L= +11 R= +10	-
Neck My (N-m)	6	54	28	84	40	110	46	125
Neck Fx (kN)	0.2	*	0.8	*	1.6	*	1.0	*
Neck Fz (kN)	2.4	1.7	3.4	2.8	2.9	2.7	1.9	1.2
Femur Fz (kN)	L=2.9 R=2.9	L=2.2 R=1.9	L=4.7 R=4.7	L=5.2 R=5.0	L=0.9 R=2.9	L=1.6 R=1.7	L=3.8 R=5.0	L=4.5 R=4.5
Shldr belt (kN)	6.6	6.8	-	-	8.0	8.2	-	-
Lap belt (kN)	4.1	6.2	-	-	5.9	6.4	-	-

* channel failure - no measurement † head contact with sun visor in one test

Figure 2 shows a plot comparing the head accelerations of Thor and Hybrid III for the case of the 56 kph pulse, with driver side airbag and 3-pt belt. Figure 3 shows the same for the passenger side with 3-pt belt only.

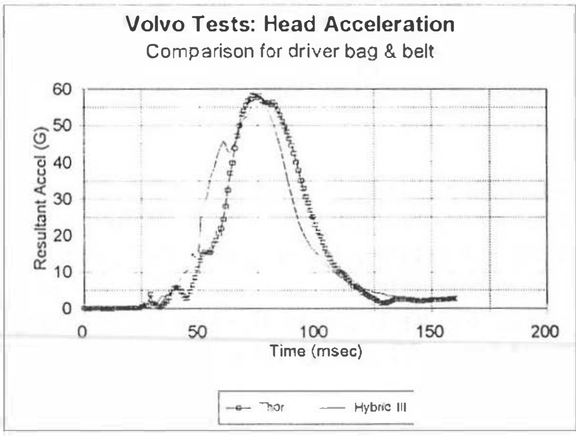


Figure 2. Comparison of Thor and Hybrid III head accelerations for airbag and 3-pt belt (driver).

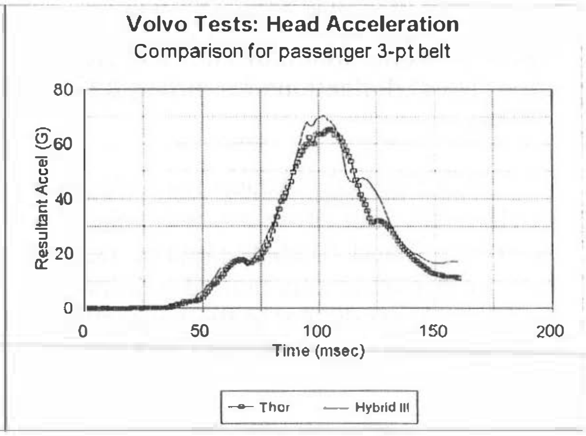


Figure 3. Comparison of Thor and Hybrid III head accelerations for 3-pt belt only only (passenger).

Figures 4 and 5 compare chest accelerations for the same test configurations.

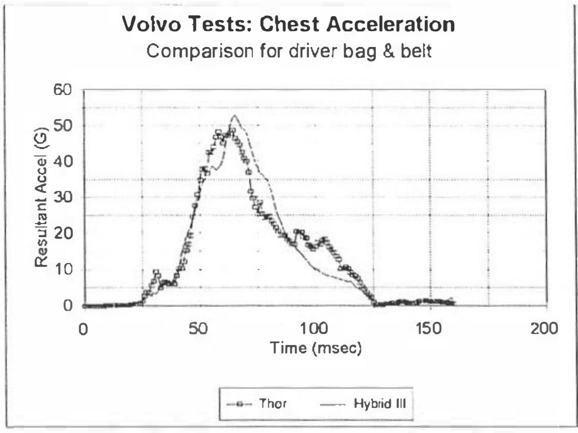


Figure 4. Comparison of Thor and Hybrid III chest accelerations for airbag and 3-pt belt.

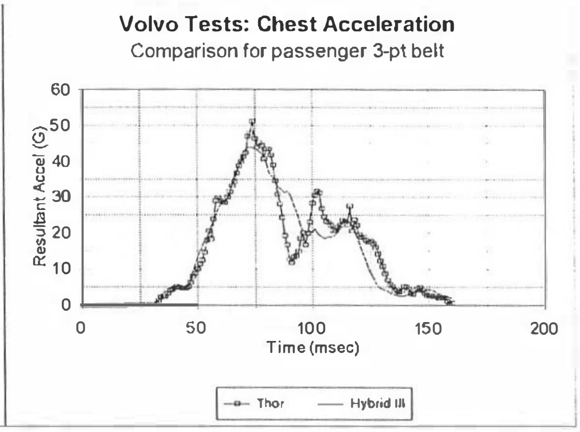


Figure 5. Comparison of Thor and Hybrid III chest accelerations for 3-pt belt only.

Figure 6 shows the chest deflections for the bag and belt restraint configuration. It shows that the Hybrid III deflection was similar to the X deflection of the right side CRUX unit, i.e. the unit with the greatest deflection. Figure 7 shows the chest deflections for the belt only configuration, and in this case the Hybrid III deflection lies between the right side and left side deflections seen in Thor.

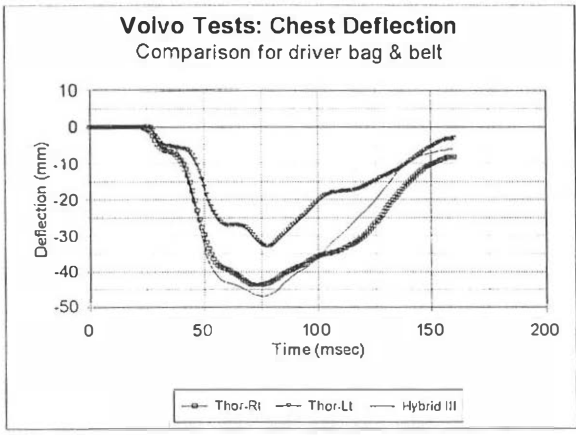


Figure 6. Comparison of Thor and Hybrid III upper chest deflections for airbag &3-pt belt (driver).

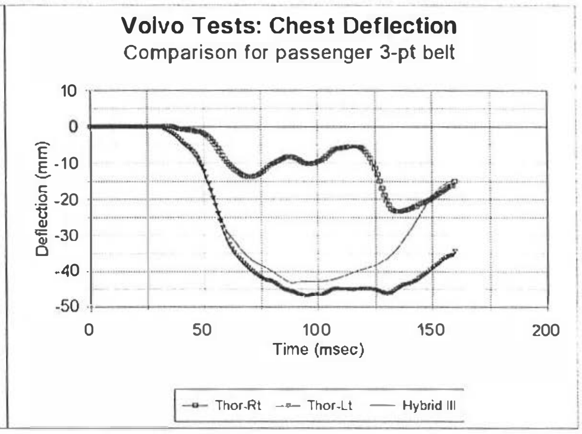
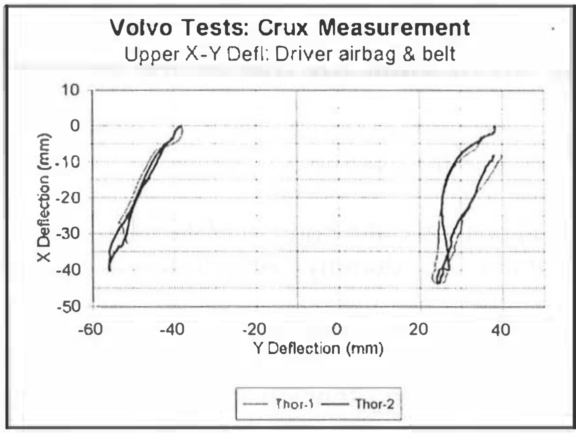


Figure 7. Comparison of Thor and Hybrid III upper chest deflections for 3-pt belt only (passenger).

Thor Chest Deflections and Restraint Conditions - The chest deflections at the four locations on Thor show characteristic differences depending on the restraint configuration. Figures 8, 9 and 10 show plots of the deflections of the upper left and right CRUX units in the X and Y directions plotted together. These represent the deflections in the X-Y plane which is perpendicular to the lower thoracic spine. Figure 8 shows the plot for the airbag and belt case, figure 9 for the belt only case, and figure 10 shows the plot for the bag only case.



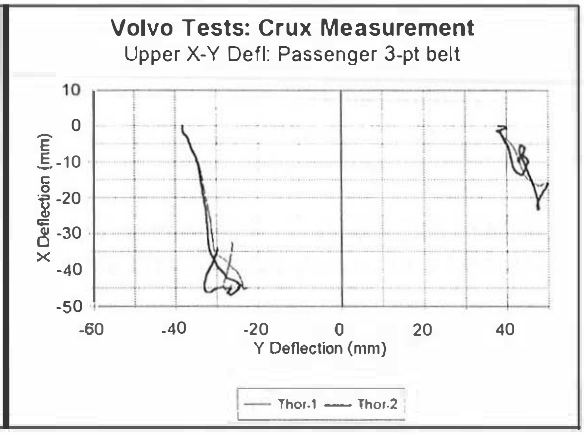


Figure 8. X-Y plot of displacements of upper CRUX units for airbag & belt configuration.

Figure 9. X-Y plot of displacements of upper CRUX units for belt only configuration.

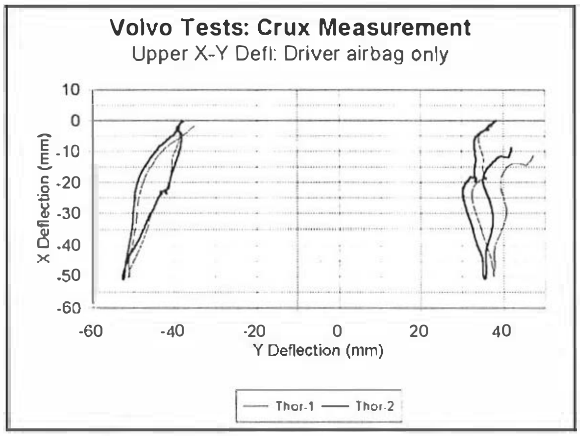


Figure 10. X-Y plots of displacement of upper CRUX units for bag only configuration (driver).

The airbag only case shows relatively close agreement between the left and right side deflection measurements along the X direction (perpendicular to the lower thoracic spine) while the belt only case shows the largest deviation between the X deflections on the left and the right. The plots also show the greater Y deflections for the cases where belts were present.

Comparison of Dummy Responses - The general kinematics showed similar motions of the Thor and Hybrid III dummies. The head, chest and pelvis accelerations were similar in magnitude and overall shape for the different restraint configurations. There were small differences in the specific shape of the chest acceleration. Some of this difference may be explained by the presence of the flexible element in the thoracic spine. The maximum chest deflection obtained from the CRUX units within Thor were similar in magnitude to that obtained from Hybrid III, except for the airbag only tests, where Thor showed higher deflections (about 5 mm greater).

The main differences noticed in the response of Thor and Hybrid III from comparable sensors were:

- Neck moments measured at the upper neck load cell are significantly lower in Thor. The X and Z forces measured at the load cell are higher for Thor. These differences are due to the additional load paths that are generated in the Thor neck through the neck springs. This is discussed in the DISCUSSION section.

- The peak lap belt force was significantly lower (by 30%) with Thor for the airbag and belt combination, but were only slightly lower (by 5%) for the belt only configuration.
- The femur forces were appreciably higher in Thor for the belt only and belt and bag configurations, but were lower or comparable for the bag only tests.

DUMMY USE ISSUES - The staff at Volvo (1997) pointed out a number of items that were of interest concerning the use and setting up of the Thor dummy. Among these were:

- Addition of H-point tool for positioning. (NOTE: This tool has been added since the Swedish tests.)
- A more reliable procedure for adjusting the spring tension in the neck spring assembly.
- An estimation of the effect on the chest deflection measured by the CRUX units due to bending the upper thoracic spine relative to the lower thoracic spine. GESAC had previously carried out an initial bending test which indicated that the deflection in the X direction measured by the CRUX units increased by about 1mm for a bending angle of about 25°. Another series of tests will be performed in the near future to fully quantify this effect.
- Procedure for making it easier to lift the dummy.

TESTS AT AUTOLIV

DESCRIPTION OF TESTS - A series of twelve sled tests were performed at the Autoliv Research crash laboratory. The objective of these tests was to compare the chest response of the Thor and Hybrid III to combined airbag and belt loading. Of particular interest was the performance of the dummies in a force limiting belt system. Two different belt systems were tested. The first was a standard belt system (with nominal stretch of 6 - 8% for 10kN applied tension) and the second was a force limiting belt with a shoulder belt limiting force of about 4 kN. The tests were done without pyrotechnic pretensioning of the seat belts.

The sled tests were performed using the white body of a large size 4-door sedan. The tests were run with a driver side air bag (US size) in all the tests. The steering column was reinforced and not allowed to deform during the tests. A reinforced, standard car seat was used and the knee bolster consisted of a piece of steel with a 25 mm thick padding (Ethafoam 400) and an outside cover of 1mm polyethylene sheet. The padding was replaced when permanent crush was seen. The tests were run at 56 kph (35 mph) with a crash pulse with peak deceleration of about 22 - 24 G and duration of 100 msec. In order to evaluate the repeatability of the Thor and Hybrid III dummies, three tests were performed for each of the two restraint configurations.

Positioning of Dummies - The Thor dummy was initially positioned in the seat so that its pelvis corresponded to the pelvis position of the Hybrid III as closely as possible. The upper torso of Thor was placed in an orientation similar to that of the Hybrid III dummy.

TEST RESULTS - The overall kinematics of the Thor and Hybrid III dummies were again fairly similar. A summary of the peak values obtained for selected sensors are given in Table 3 (values are averaged over three repeat tests).

Table 3. Summary Comparison of Thor and Hybrid III Response for Autoliv Tests

	Stand. Belt + Airbag		Force Limit Belt + Airbag	
	Thor	Hybrid III	Thor	Hybrid III
HIC	637	886	528	813
Chest acc (3ms) (g)	52	60	39	47
Pelvis acc (3ms) (g)	63	70	64	62
Chest Defl (mm)	UL= -39 UR= -49 LL = +5 LR= -25	- 44	UL=-41 UR=-48 LL= +3 LR= -25	-40
Abdomen Defl (mm)	L = -12 R = -19	-	Left= -13 Right=-19	-
Neck My (N-m)	12	35	11	73
Neck Fx (kN)	0.3	0.1	0.2	0.8
Neck Fz (kN)	2.0	1.7	1.6	1.0
Femur Fz (kN)	L= -2.4 R= -1.4	L= -1.2 R= -0.6	L= -1.8 R= -1.2	L= -0.4 R= -0.6
Shoulder Belt (kN)	9.0	9.3	5.6	5.6
Lap Belt (kN)	7.7	10.2	7.9	9.7

- No measurement

Figures 11 and 12 show the comparisons of the resultant head accelerations seen in Thor and Hybrid III for the airbag with standard belt and with force limiting belt cases. Figures 13 and 14 show the comparisons for the chest resultant accelerations.

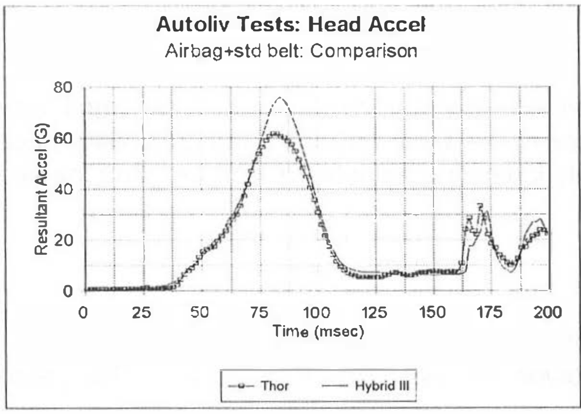


Figure 11. Comparison of head accelerations for Thor and Hybrid III with airbag & standard belt.

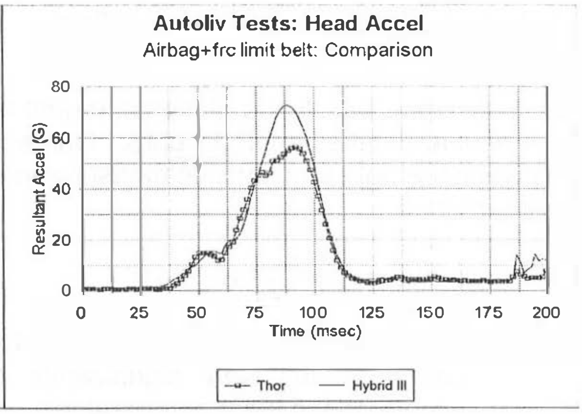


Figure 12. Comparison of head accelerations for Thor and Hybrid III with airbag and force limiting belt

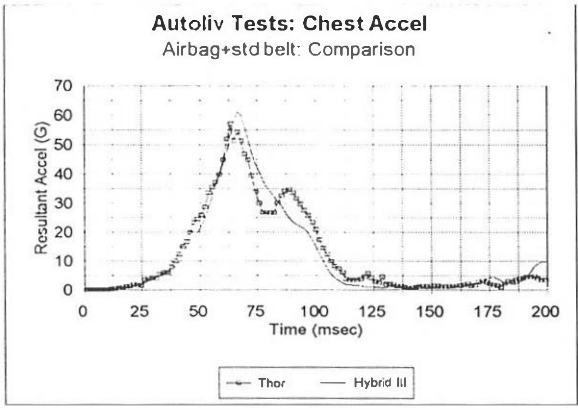


Figure 13. Comparison of chest accelerations for Thor and Hybrid III with airbag & standard belt.

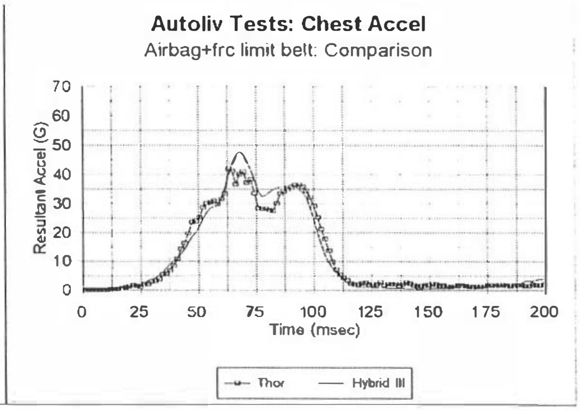


Figure 14. Comparison of chest accelerations accelerations for Thor and Hybrid III with airbag and force limiting belt.

Figures 15 and 16 show the chest deflections measured by Thor and Hybrid III.

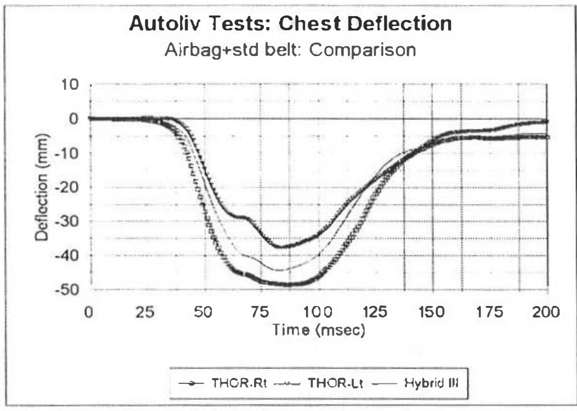


Figure 15. Comparison of chest deflection in Thor and Hybrid III with airbag and standard belt.

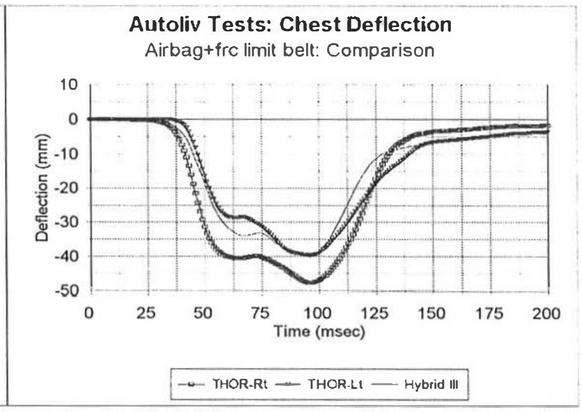


Figure 16. Comparison of chest deflection in Thor and Hybrid III with airbag and force limiting belt.

In these tests, the Hybrid III measurement fell in between the measured deflections from the right and left side CRUX units. One sees in the Thor response, the clear difference between the right and left side measurements indicating the influence of the strip loading from the belt.

The main differences were:

- The head and chest accelerations for both the standard belt and force limiting belt configurations were significantly lower for Thor (by 15%-25%). The pelvis accelerations were comparable.
- The shoulder belt loads were very similar, but the lap belt loads were lower in Thor (by about 20%).
- The neck Y-moment measured at the upper neck load cell was significantly lower in Thor compared to Hybrid III. The X and Z forces measured at the load cell were higher in Thor. The reason for differences are discussed in the DISCUSSION section of this paper.
- The maximum chest deflection in Hybrid III fell in between the maximum X deflections for the right and left sides. There was a reduction in the Hybrid III chest

deflection with the force limiting belt. This was not seen in the Thor upper chest deflections. The possible reasons for the difference in response is presented in the DISCUSSION section.

- The femur forces were higher in Thor for both the left and right femurs.

Influence of Force Limiting Belts - In tests with both Thor and Hybrid III, the shoulder belt loads showed the effect of the force limiting. These are shown in figures 17 and 18.

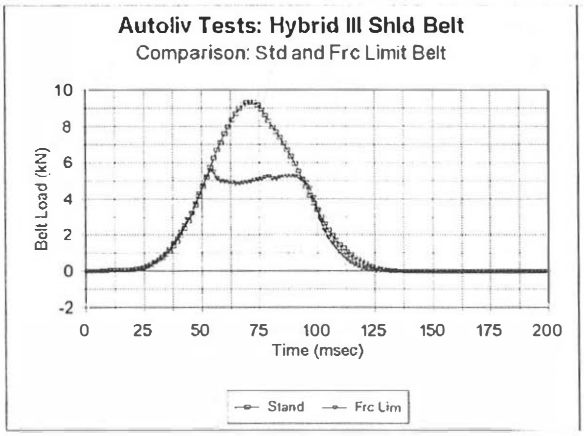


Figure 17. Comparison of shoulder belt loads in in Hybrid III for standard and force limiting belts with airbag.

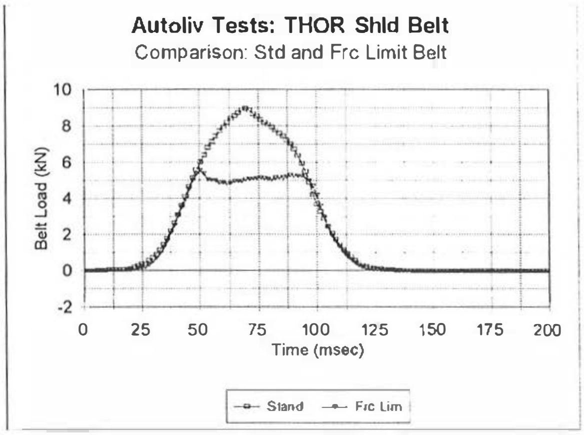


Figure 18. Comparison of shoulder belt loads Thor for standard and force limiting belts with airbag.

Both Thor and Hybrid III showed reductions in head and chest accelerations with the force limiting belt system. For Thor there was a 20% reduction in HIC and a 33% reduction in the peak chest acceleration. On the other hand, for Hybrid III, there was a 9% reduction in HIC and a 26% reduction in peak chest acceleration. With respect to chest deflection, Thor did not show any significant change, while Hybrid III showed a reduction of 11%. There were reductions in neck forces and neck Y-moment seen in both dummies, as well as, reductions in femur forces, though Thor always showed lower upper neck Y-moment and higher femur forces.

Repeatability - One of the objectives of the testing was to evaluate the repeatability of the response in Thor in multiple tests and compare it with the response of Hybrid III. The responses for both dummies were quite consistent for repeated tests. Though only three tests were carried out for each condition, there was indication of better repeatability inThor, for most of the principal output quantities such as HIC and chest acceleration. Only for the upper neck force in the Z-direction, Thor showed lower repeatability than Hybrid III. Figure 19 shows the percentage standard error (defined as sample standard deviation over sample average expressed as a percentage) in the peak values of five selected quantities. The chart shows that except for the case of the upper neck force in the Z-direction, the standard error was usually about 5% or less.

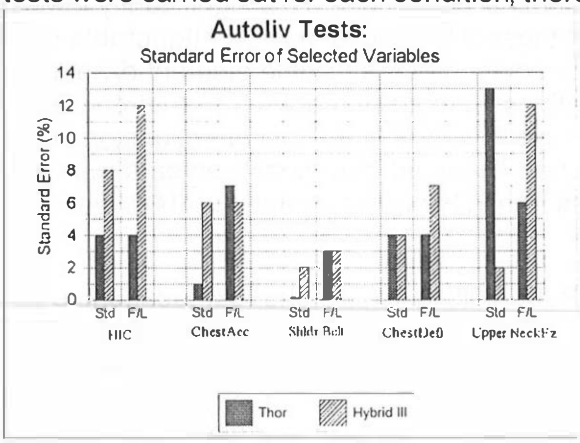


Figure 19. Standard error of selected output quantities (from three repeat tests).

The repeatability of the response over time is shown in Figures 20 and 21. Figure 20 shows the head acceleration time histories for the three repeat tests for Hybrid III and Figure 21 shows the corresponding curves for Thor.

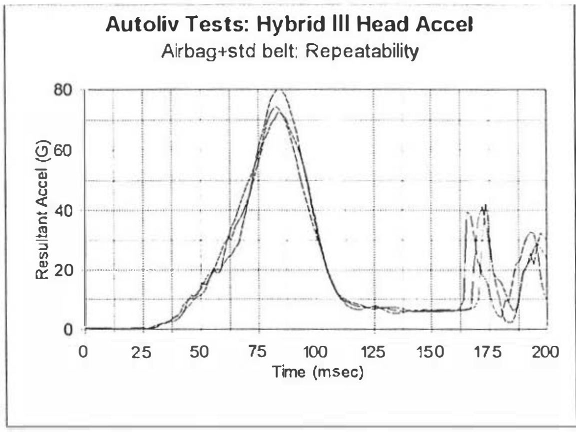


Figure 20. Hybrid III head accelerations with airbag and standard belt from three repeat tests.

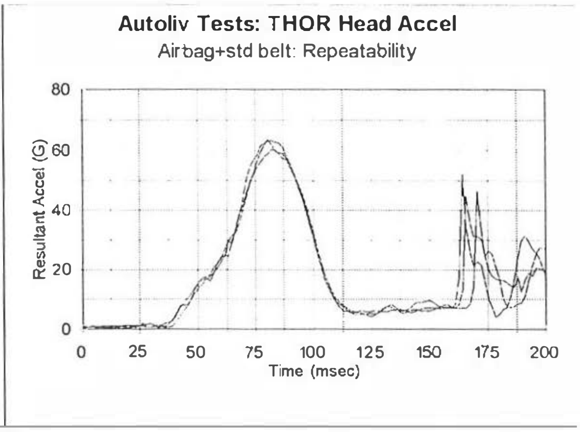


Figure 21. Thor head accelerations with airbag and standard belt from three repeat tests.

DISCUSSION

The new advanced frontal crash test dummy developed by NHTSA has been tested in a series of tests at Volvo and Autoliv. The principal aim of the testing at both facilities was to examine the responses of Thor in frontal crash testing to various bag and belt configurations and compare them to the responses of Hybrid III under the same conditions. At Autoliv, the change in response between standard and force limiting belts in the two dummies were also compared. Finally, an initial examination of the repeatability of the dummy responses was made.

The main results from the two series of tests were:

- There was general agreement in the overall kinematics of the two dummies in the same test conditions. In the Volvo tests, there was close agreement in the peak head and chest accelerations in the two dummies, except for the passenger side airbag case, where Thor showed higher peaks due to contact of the head with the sun visor. At Autoliv, the head and chest accelerations were significantly lower in Thor for all test conditions. Some of these differences may be attributable to the different neck design in Thor and the addition of the flexible element dividing the thoracic spine. The pelvic accelerations were comparable in all test conditions. The equivalent or lower readings for the head and chest accelerations, indicated that in a typical test of a well restrained occupant, the measurements from Thor would be below the Injury Assessment Reference Values (IARV) for these quantities.

- The deflections measured by the CRUX units in Thor at the four locations on the ribcage could differentiate between the different loading conditions. When the 3-pt belt was present, there was a clear asymmetry in the peak deflections seen on the left and right sides, with the belt only case providing the greatest asymmetry. With the bag only case, the upper deflections were more symmetrical.

In the Volvo tests where a belt was present, the Hybrid III chest deflections matched the upper Thor CRUX unit with the greater deflection, whereas for the bag only cases, Thor showed greater deflections than Hybrid III. In the Autoliv tests, the Hybrid III deflection fell between the left and right side deflections. Part of the difference in the relative responses of the two dummies in different restraint conditions may be due to the relative contributions of the bag and the belt to the overall deflection.

- In the Autoliv tests, a reduction (9%) in the chest deflection was seen in Hybrid III when the force limiting belt was used. In Thor, no visible reduction was seen. The reason behind this may lie with the relative importance of the bag and belt effects when compressing the chest. Autoliv Research (1998) performed an analysis on the relative importance of the belt and bag loads to chest acceleration and chest deflection. Figures 22 and 23 show the magnitude and time of the belt and bag peak loads with respect to the peak chest deflection in Hybrid III and Thor respectively. It is seen that the belt loads are about the same for the two dummies, but there is 15% greater bag pressure in the case of Thor. We believe that the increased contribution of the bag load in Thor offset the potential reduction in peak chest deflection, which might be expended, due to the lower belt load. The increased bag contribution also led to a slight decrease in the difference between the right side and left side chest deflections.

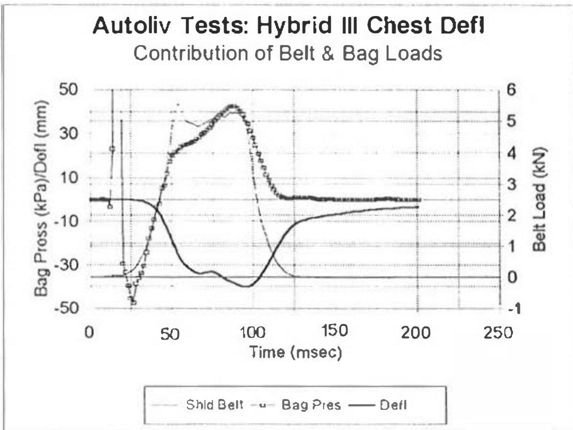


Figure 22. Relative contributions of belt and bag loads with respect to Hybrid III chest deflections.

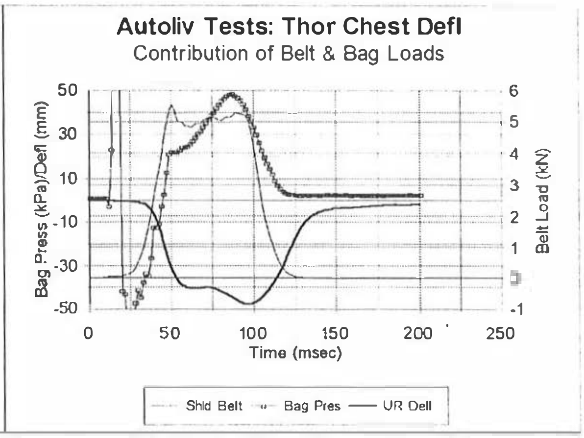


Figure 23. Relative contributions of belt and bag loads with respect to Thor chest deflections.

Interestingly, a study by Kallieris, etal (1995) on the combined effects of bag and belt systems in cadavers, found that the maximum chest deflection was approximately the same for both standard 3-pt belt/airbag system and a force limited belt/airbag system, a behavior similar to that seen with Thor. He concluded that with the force limited belts, the bag played a more important role than with a standard belt counteracting the reduced loads from the force limiting belt. The additional influence of the bag also resulted in reducing the difference in the deflections between the right and left sides of the chest.

- The shoulder belt forces were quite similar in both dummies for all test conditions. The lap belt forces tended to be significantly lower in Thor. This probably arose from the lower pelvic flesh stiffness in Thor, as well as, the different segmentation at the pelvis in Thor. Since the upper femur flesh is no longer part of the pelvic assembly, as in Hybrid III, a smaller effective mass is being accelerated, leading to a lower force, since the kinematics stay the same. Also, a greater share of the resistive force is taken by the femurs, which show typically higher values in Thor. Only in the 3-pt belt only case, were the lap belt loads comparable, and the femur loads were slightly higher in Hybrid III.

- The measured neck moments at the upper neck load cell were consistently lower in Thor than in Hybrid III. This difference arises from the new neck assembly in Thor and the different location of the upper neck load cell. In Thor, load paths are also present along the neck springs and cables at the front and rear, which by pass the upper neck load cell. Also the load cell is placed below the pin joint representing the occipital condyle in Thor, and above the joint in Hybrid III. Thus, when moments are computed about the occipital condyles themselves, additional contributions will come from the Fx force and the rear spring force (the front spring will not be usually active during frontal flexion). Since the testing in Sweden, additional instrumentation has been added which permits measurement of these additional contributions. These include load cells at the front and rear springs to measure the spring loads along the cable, and a rotary potentiometer at the occipital condyle to measure the relative angle between the head and top of the neck.

  An estimate of the additional contribution can be made for one of the tests done at Volvo with the airbag and belt combination. The Y-moment measured at the load cell was about 8 N-m in Thor and 50 N-m in Hybrid III. The Fx force at this time was 125 N in Thor (with a moment arm of .025 m), and almost 0 in Hybrid III. An estimate of neck spring force can be made by comparing the Fz forces in Thor and Hybrid III. The Thor showed a peak of 2250 N while Hybrid III showed a peak of 1750 N. Since the head accelerations were very similar, one can hypothesize, that the higher value resulted from the neck force (so that the total force on the head is about the same). Assuming then a neck spring force of 500 N with an average moment arm of .05 m, the total moment about the O.C. increases to about 35 N-m, which is still less but comparable to the Hybrid III moment. The Thor neck has been designed to be softer than Hybrid III in dynamic loading, and the final lower value probably reflects this lower stiffness.

- In the three repeat tests performed at Autoliv for each dummy and restraint configuration, Thor showed equal or better repeatability than the Hybrid III dummy for most of the important output parameters, such as head and chest accelerations, belt loads and chest deflections. The exception was the upper neck force, which showed less repeatability than the Hybrid III.

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