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Assessing Child Belt Fit, Volume II: Effect of Restraint Configuration, Booster Seat Designs, Seating Procedure, and Belt Fit on the Dynamic Response of the Hybrid III 10YO ATD in Sled Tests

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16. Abstract

A total of 49 dynamic sled tests were performed with the Hybrid III 10YO to examine issues relating to child belt fit. The goals of these tests were to evaluate ATD response to realistic belt geometries and belt fit, develop methods for accurate, repeatable evaluation of restraint conditions for older children, identify dependent measures that differentiate between good and poor restraint performance, and relate ATD performance to static belt fit with children. The first series of tests examined the effects of lap belt tension, belt configuration, and seating procedure on dynamic responses of the ATD. The second series of tests examined how different designs of booster seat lap belt guides and shoulder belt guides affect performance. In addition, the ATD's response to different shoulder belt and lap belt geometries was evaluated.

With regard to test procedures, use of a lap/shoulder belt with a sliding latchplate produced similar results to using a lap/shoulder belt with fixed anchorages. Use of a production retractor reduced shoulder belt load, as well as head, neck, and chest measures. Reducing lap belt tension to a more realistic 2 lb (rather than 15 lb) did not have a pronounced effect on ATD kinematics with two different booster seats. The UMTRI seating procedure, which produces ATD postures closer to those measured in real children, also prevents the lap belt from being trapped in the gap between the pelvis and the thigh. Use of the UMTRI seating procedure produces more reclined initial postures and more pronounced chin-to-chest contact. A well-designed booster lap belt guide can maintain good belt position dynamically, even with poor lap belt geometry. Shoulder belt guide designs affect ATD kinematics. However, preventing the shoulder belt from coming out of the shoulder belt guide does not necessarily produce better restraint performance, because the belt can still come off of the ATD shoulder during the event, and stiffening booster seats does not necessarily produce better routing of the shoulder belt dynamically. Shoulder belt scores less than 70 mm produce good torso kinematics with the 10YO ATD, but use of HIC as an injury criterion tends to discourage booster seat designs that produce good belt fit on the 10YO ATD. Lap belt angle affects torso kinematics, with shallower lap belt angles leading to submarining and more vertical lap belt angles leading to rollout. Wider spacing of lap belt anchorages leads to submarining, while narrowing spacing leads to rollout.

Both upper and lower belt anchorage locations have a strong effect on ATD kinematics. Although good booster designs can mitigate the consequences of poor vehicle lap belt geometry, boosters cannot always overcome poor shoulder belt geometry to keep the belt on the ATD shoulder dynamically, even when they are able to create good static belt fit. This finding suggests that more attention should be focused on the effects of the wide variability in vehicle upper anchorage locations on belt restraint performance for children. Also, because HIC scores are decreased when the torso belt fit is degraded, use of HIC as an injury criterion for booster testing may lead to worse rather than better booster designs.

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Metric Conversion Chart

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
In	inches	25.4	millimeters	mm
Ft	feet	0.305	meters	m
Yd	yards	0.914	meters	m
Mi	miles	1.61	kilometers	km
AREA				
in^2	squareinches	645.2	square millimeters	mm^2
ft^2	squarefeet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
Ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N

lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
FORCE and PRESSURE or STRESS				
N	Newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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1.0 Overview

1.1 Introduction

The National Highway Traffic Safety Administration has undertaken a variety of activities to improve crash safety for children. Among other actions in the last few years, NHTSA has expanded the scope of FMVSS 213 to include restraints for children up to 65 lb using the Hybrid III 6YO ATD, added the Hybrid III 10YO ATD to 49 CFR Part 572, and most recently proposed to use the Hybrid III 10YO as part of an expansion of FMVSS 213 to evaluate restraints for children up to 80 lb.

NHTSA has proposed to add the Hybrid III 10YO to FMVSS 213 to provide for testing restraints with a simulated occupant that weighs more than 75 lb (the nominal weight of the Hybrid III 10YO is 77 lb). If these tests are to provide meaningful assessments of the belt-positioning effectiveness of booster seats, one requirement is that the sensitivity of the ATDs' response to changes in belt fit produced by boosters be similar to changes in belt fit produced on children under the same conditions. More generally, the utility of the HIII 10YO for assessing restraint conditions is based substantially on whether this ATD can discriminate between good and bad belt fit.

UMTRI has completed a two-phase research program for NHTSA to evaluate the performance of the Hybrid III 10YO across a range of belt-fit conditions. In the first phase described in Volume I of this report, the effects of vehicle belt system geometry, booster design, and vehicle seat conditions on static belt fit were evaluated through laboratory testing of 44 children with body weights from 40 to 100 lb. Four booster configurations were tested with a range of vehicle seat conditions and belt anchorage locations. These data quantify the effects of the belt-restraint configuration on belt routing with respect to the pelvis, chest, and shoulders of the volunteers.

Results of the study with volunteer children provided input for test conditions of the second phase of the study, which involved dynamic testing of the Hybrid III 10YO. A total of 49 sled tests were performed with the Hybrid III 10YO to examine issues relating to child belt fit. The goals of these tests were to:

- Evaluate ATD response to realistic belt geometries and belt fit,
- Develop methods for accurate, repeatable evaluation of restraint conditions for older children,
- Identify dependent measures that differentiate between good and poor restraint performance, and
- Relate ATD performance to static belt fit with children.

The first series of tests examined the effects of lap belt tension, belt configuration, and seating procedure on dynamic responses. The second series of tests examined how different designs of booster seat lap belt guides and shoulder belt guides affect performance. In addition, the dummy's response to different shoulder belt and lap belt geometries was evaluated.

1.1.1 Evaluation of Test procedures

FMVSS 213 specifies 53-67 N (12-15 lbf) of tension in the lap portion of the belt and 7-18 N (2-4 lbf) in the torso portion of the belt. The lap-belt tension is carried over from earlier FMVSS 213 procedures for testing harness restraints and is unrealistically high for children who don the belt themselves. During the child belt-fit testing in the laboratory, the belt tensions the children produced when they donned the belt themselves were measured. These results showed that a tension near 8 N (2 lbf) is more realistic. Sled tests were performed using two different booster seat designs to assess the effects of reducing the lap belt tension.

The current FMVSS 213 testing uses belt webbing attached to fixed shoulder and lap belt anchorages to simulate the lap and torso portions of the vehicle belt. In most vehicle seating positions, the belt is equipped with a sliding latch plate and an emergency locking retractor (ELR). ELR retractors generally produce “softer” force/deflection characteristics for the upper anchorage than does the fixed-length 213 system because a small amount of webbing spools out from the retractor as the belt load increases. The effect on dynamic performance of using a production belt system, or a fixed anchorage system with a sliding latchplate, was evaluated.

UMTRI has developed a new ATD installation procedure, based on child posture data, which produces more representative hip and head CG locations (Reed et al. 2006). The procedure uses several positioning aids to achieve these postures. The effects of using the UMTRI seating procedure with the 10YO, compared to results using standard 213 seating procedures, were assessed for two boosters. The repeatability of the UMTRI seating procedure in multiple belt and booster conditions was also evaluated.

1.1.2 Assessing ATD Response to Variations in Belt and Booster Geometry

Recent studies at UMTRI have shown that the static routing of belt restraints relative to the Hybrid-III ATDs is significantly different from the belt fit on similar-size children in the same seat and for the same belt geometry. The most dramatic difference is at the pelvis, where the iliac spine landmarks of the ATDs protrude much higher above the thigh-abdominal junction than is the case with children.

A test series was conducted at UMTRI in 2005 to investigate the sensitivity of the HIII-6YO and HIII-10YO to belt geometry. Tests were conducted using the FMVSS 213 seating buck with a range of lap belt and torso belt anchorage locations. The tests included an extreme range of lap belt angles, including a lap belt configuration that placed the belt on the abdomen, one placing the belt at the top of the ATD pelvis, and one placing the belt on the thighs. As expected, both ATDs submarined with the high lap belt position, and did not submarine with the low belt position. The middle position was chosen based on previous UMTRI volunteer data to represent a belt position that engaged the ATD pelvis but would not likely engage the pelvis of children. In this configuration, the 10YO ATD submarined but the 6YO did not. This suggests that (1) the 6YO is insufficiently sensitive to poor lap belt configurations, and that (2) some aspect of the 10YO pelvis/lumbar design makes it more appropriately sensitive to poor lap belt geometry. However, ATD performance data were needed for more realistic belt conditions.

In the current study, a series of sled tests was conducted with the 10YO Hybrid-III ATD and a more refined set of test conditions to determine the effects of belt fit on ATD kinematics and injury measures. The test conditions were selected to span a range around the possible submarining and torso rollout thresholds identified in the human-subject data and explored in the 2005 test series. Child belt-fit data were used to identify a lap belt angle that corresponds to approximately half of the lap belt lying below the top of the pelvis. This belt position is considered to represent the static-fit threshold for submarining. Tests were performed with lap belt angles above and below this threshold. With the ATD seated on a backless belt-positioning booster, tests were also conducted with variable upper belt anchorage locations that span a location that is identified in the static child belt-fit data as the likely threshold for rollout.

In addition to performing tests to evaluate the Hybrid III 10YO response to variable belt anchorage geometry, tests were run to evaluate the effect of different types of lap belt guides present on booster seats. Boosters with two different styles of lap belt guides were evaluated with poor and favorable lap belt geometry to identify whether static belt fit provided by the guides can predict dynamic performance.

The ability of different booster shoulder belt guides to reroute shoulder belts dynamically was also evaluated. While belt-routing features on boosters can improve the static belt fit relative to the occupant’s torso, the results of dynamic testing in vehicles suggest that these features may not be capable of maintaining good belt fit during ridedown. In this test block, several boosters with different styles of shoulder belt guides were evaluated using less favorable shoulder belt geometry than is normally used in FMVSS 213 testing. In addition, the effects of several modifications to one of the boosters intended to improve performance were evaluated.

1.2 General Methods

All testing was performed on a standard FMVSS 213 sled buck using the Hybrid III 10-year-old ATD. The lumbar spine was adjusted to standard posture (not slouched) and the neck was adjusted to the 8-degree angle position. In the 07 series of tests (see Table 1), each booster seat was used for two tests, while each booster seat was used only once in the 08 series of tests.

Prior to each test, a FARO arm 3-D coordinate measurement system was used to record the posture of the ATD and the position of the booster seat and belt restraints. Some of these measurements were used to calculate a shoulder belt score (SBS), and lap belt score (LBS), which quantify the position of the belt relative to ATD landmarks. The shoulder belt score (SBS), illustrated in Figure 1, is defined as the lateral distance between inboard edge of the shoulder belt and the centerline of the neck/bib landmark at the height of the centerline landmark. The lap belt score, illustrated in Figure 2, is the distance from the ASIS to the top of the lap belt, measured at the same lateral location of the ASIS. Results present the mean of the left and right lap belt scores for each test condition.

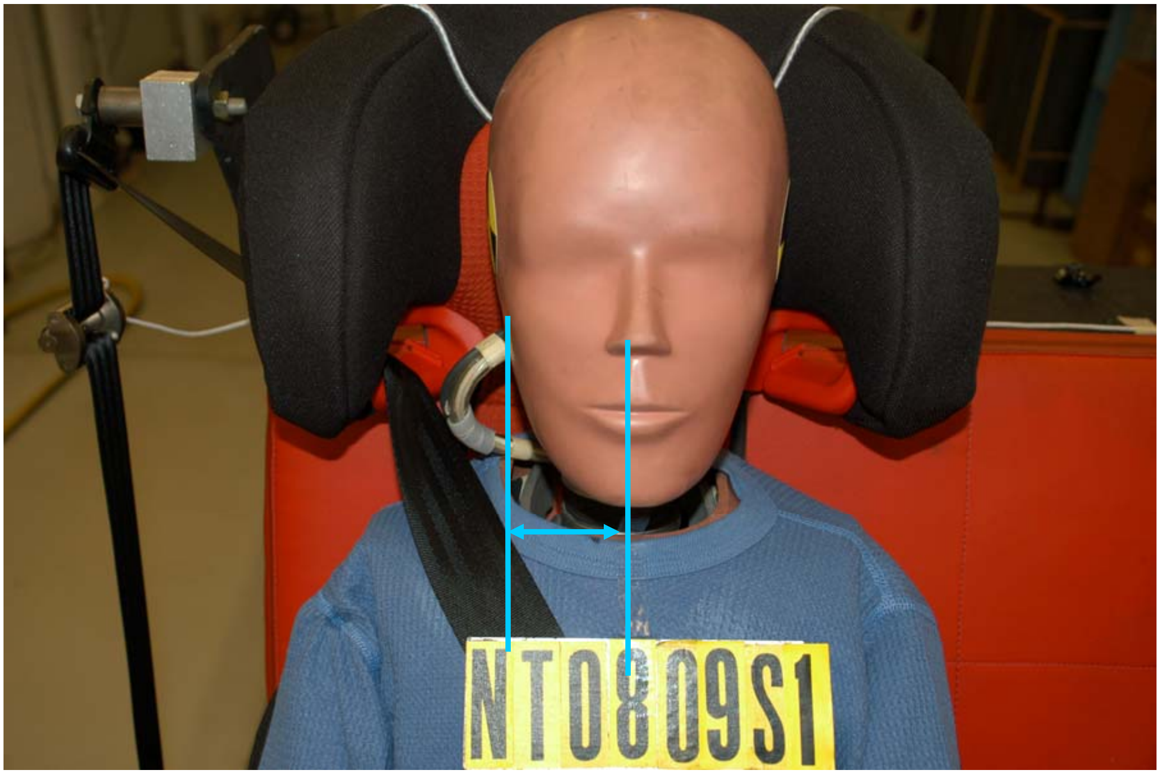


Figure 1. Illustration of shoulder belt score (SBS) measurement.

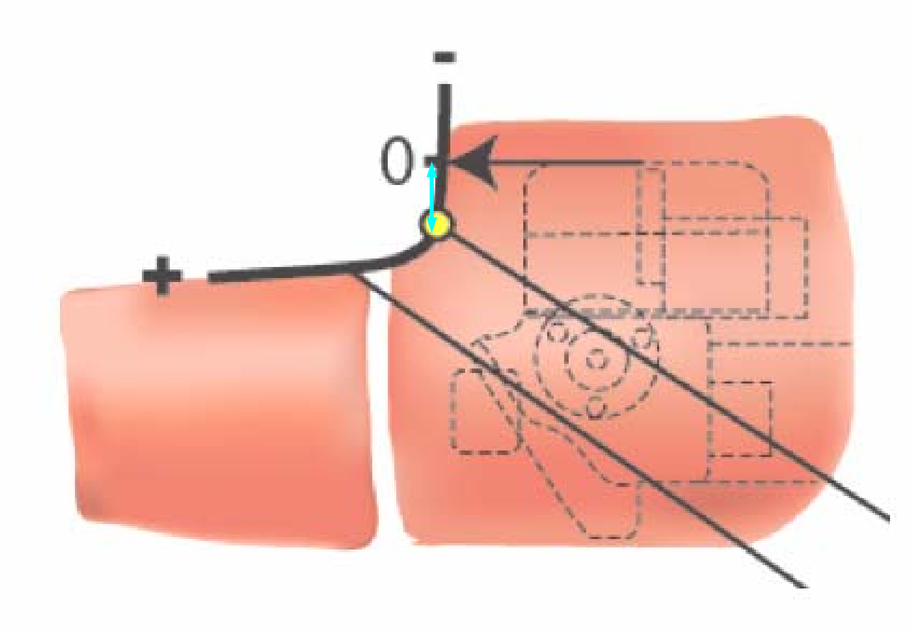


Figure 2. Illustration of lap belt score (LBS) measurement.

In all tests using the UMTRI seating procedure, hip offset tools shown in Figure 3 were inserted in the pelvis to allow reliable measurement of pelvis position and orientation. These tools did not interfere with belt routing, and remained in place during dynamic testing. They did not have any discernable effect on instrumentation signals, including pelvis acceleration.

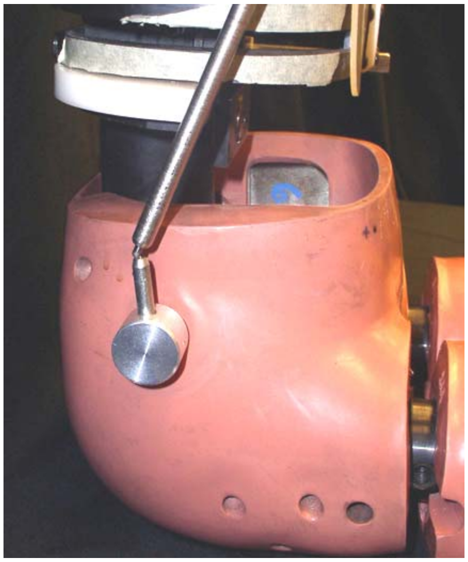


Figure 3. Illustration of hip offset tool to facilitate measurement of pelvis orientation using the FARO arm.

The test conditions for the entire matrix are listed in Table 1. The following sections report detailed methods and results for each series of tests.

Table 1. Test Matrix

Test	*Seating Procedure*	*Lap belt tension*	*Belt Type*	*Booster*	*Lower anchorage*	*Upper anchorage*
NT0701	213	~60 N	Fixed, 2-piece	TB/ back/low guides	50 deg (~213)	213 (.5" spacer)
NT0702	213	~8 N	Fixed, 2-piece	TB/ back/low guides	50 deg (~213)	213 (.5" spacer)
NT0703	213	~8 N	Fixed, 2-piece	TB/ back/low guides	50 deg (~213)	213 (.5" spacer)
NT0704	UMTRI	~8 N	Fixed, 2-piece	TB/ back/low guides	50 deg (~213)	213 (.5" spacer)
NT0705	UMTRI	~8 N	Fixed, 2-piece	TB/ back/low guides	50 deg (~213)	213 (.5" spacer)
NT0706	UMTRI	~8 N	Retractor+ continuous	TB/ back/low guides	50 deg (~213)	213 (.5" spacer)
NT0707	UMTRI	~8 N	Fixed, continuous	TB/ back/low guides	50 deg (~213)	213 (.5" spacer)
NT0708	UMTRI	~8 N	Retractor+ continuous	TB/ back/low guides	50 deg (~213)	213 (.5" spacer)
NT0709	UMTRI	~8 N	Fixed, 2-piece	TB/back/no guides	50 deg (~213)	213 (.5" spacer)
NT0710	213	~60 N	Fixed, 2-piece	Generations	50 deg (~213)	213 (.5" spacer)
NT0711	213	~8 N	Fixed, 2-piece	Generations	50 deg (~213)	213 (.5" spacer)
NT0712	UMTRI	~8 N	Fixed, 2-piece	Generations	50 deg (~213)	213 (.5" spacer)
NT0713	UMTRI	~8 N	Fixed, 2-piece	Generations	50 deg (~213)	213 (.5" spacer)
NT0714	UMTRI	~8 N	Fixed, 2-piece	TB/back/no guides	50 deg (~213)	213 (.5" spacer)
NT0715	UMTRI	~8 N	Fixed, continuous	TB/ back/low guides	50 deg (~213)	213 (.5" spacer)
NT0716	213	~8 N	Fixed, 2-piece	Generations	50 deg (~213)	213 (.5" spacer)
NT0717	213	~60 N	Fixed, 2-piece	TB/ back/low guides	50 deg (~213)	213 (.5" spacer)
NT0801	UMTRI	~8 N	Fixed, 2-piece	Generations	15 deg (high)	213 (.5" spacer)
NT0802	UMTRI	~8 N	Fixed, 2-piece	Generations	15 deg (high)	213 (.5" spacer)
NT0803	UMTRI	~8 N	Fixed, 2-piece	TB/ back/low guides	15 deg (high)	213 (.5" spacer)
NT0804	UMTRI	~8 N	Fixed, 2-piece	TB/ back/low guides	15 deg (high)	213 (.5" spacer)
NT0805	UMTRI	~8 N	Fixed, 2-piece	Compass	50 deg (~213)	Outboard (2.5" spacer)
NT0806	UMTRI	~8 N	Fixed, 2-piece	Recaro Vivo	50 deg (~213)	Outboard (2.5" spacer)
NT0807	UMTRI	~8 N	Fixed, 2-piece	TB/ back/low guides	50 deg (~213)	Outboard (2.5" spacer)
NT0808	UMTRI	~8 N	Fixed, 2-piece	TB/ back/low guides	50 deg (~213)	Outboard (2.5" spacer)
NT0809	UMTRI	~8 N	Fixed, 2-piece	Recaro	50 deg (~213)	Outboard (2.5" spacer)

NT0810	UMTRI	~8 N	Fixed, 2-piece	Compass	50 deg (~213)	Outboard (2.5” spacer)
NT0811	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	50 deg (~213)	213 (.5” spacer), SBS ~47
NT0812	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	50 deg (~213)	Mid ++ (1.5” spacer), SBS~80
NT0813	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	50 deg (~213)	Mid + (1” spacer), SBS~70
NT0814	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	50 deg (~213)	Mid + (1” spacer), SBS~70
NT0815	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	50 deg (~213)	Mid ++ (1.5” spacer), SBS~80
NT0816	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	50 deg (~213)	213 (.5” spacer), SBS ~47
NT0817	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	60 deg	213 (.5” spacer)
NT0818	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	60 deg	213 (.5” spacer)
NT0819	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	70 deg	213 (.5” spacer)
NT0820	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	70 deg	213 (.5” spacer)
NT0821	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	30 deg	213 (.5” spacer)
NT0822	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	30 deg	213 (.5” spacer)
NT0823	UMTRI	~8 N	Fixed, 2-piece	Modified TB 1	50 deg (~213)	Outboard (2.5” spacer)
NT0824	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	50 deg (~213)	Mid +++ (2” spacer)
NT0825	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	50 deg (~213)	Mid +++ (2” spacer)
NT0826	UMTRI	~8 N	Fixed, 2-piece	Stiffened TB 1	50 deg (~213)	Outboard (2.5” spacer)
NT0827	UMTRI	~8 N	Fixed, 2-piece	Modified TB 2	50 deg (~213)	Outboard (2.5” spacer)
NT0828	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	50 deg, inboard anchor shifted +75	Mid + (1” spacer), SBS~70
NT0829	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	50 deg, inboard anchor shifted +75	Mid + (1” spacer), SBS~70
NT0830	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	50 deg, inboard anchor shifted -75	Mid + (1” spacer), SBS~70
NT0831	UMTRI	~8 N	Fixed, 2-piece	TB/no back/no guides	50 deg, inboard anchor shifted -75	Mid + (1” spacer), SBS~70
NT0832	UMTRI	~8 N	Fixed, 2-piece	Stiffened TB 2	50 deg (~213)	Outboard (2.5” spacer)

In subsequent graphs, booster A refers to TurboBooster and Booster B refers to Generations.

2.0 Evaluation of Test Procedures

2.1 Lap Belt Tension

Seven tests were used to examine the effect of lap belt tension using two different booster seats (NT0701 and NT0717 vs. NT0702 and NT0703; NT0710 vs. NT0711 and NT0716). All tests used FMVSS 213 belts and belt geometry, and the ATD was positioned using normal 213 procedures. Baseline tests were run using the ~60 N lap belt tension specified in FMVSS 213, while comparison tests used a lap belt tension of ~8 N. This tension was selected based on measures of lap belt tension in volunteer children who applied the belt themselves.

A summary of results is shown in Table 2, and a comparison of the ATD kinematics at peak excursion is shown in Figure 4. Overall, lowering lap belt tension did not have a substantial effect on ATD measures. For example, as shown in Figure 5 and Figure 6, mean head excursion increased by 6 to 11 mm when lap belt tension was lower, while mean knee excursion increased by 25 to 32 mm. Repeatability in standard FMVSS 213 conditions is considered acceptable if it varies less than 15 mm, so these changes are not considered substantial.

Table 2. Summary of results for tests to evaluate the effect of lap belt tension.

Test	*Lap Belt Tension*	*Booster*	*Head R (g)*	*HIC 36*	*Chest clip (g)*	*Pelvis R (g)*	*Head ex (mm)*	*Knee ex (mm)*	*Torso angle (deg)*	*LBS (mm)*	*SBS (mm)*
NT0701	~60 N	TB/ back/low guides	64	692	38	40	672	674	14.8	70	59
NT0717	~60 N	TB/ back/low guides	58	633	37	45	675	675	14.1	64	56
NT0702	~8 N	TB/ back/low guides	64	681	45	51	686	710	14.1	68	68
NT0703	~8 N	TB/ back/low guides	62	591	41	50	682	703	12.3	66	66
NT0710	~60 N	Generations	68	760	43	41	669	717	15.0	47	58
NT0711	~8 N	Generations	71	915	43	41	677	750	15.9	42	51
NT0716	~8 N	Generations	67	796	48	43	674	735	14.5	51	49

Figure 4. Comparison of peak excursions. Top row: booster A, bottom row, booster B. Left: ~60 N lap belt tension, right: ~8 N lap belt tension.

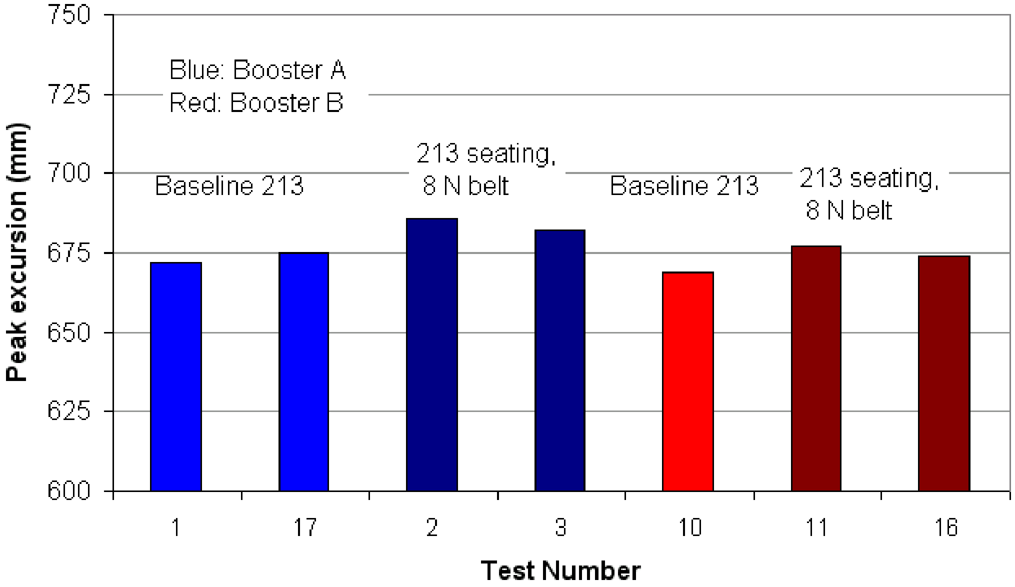


Figure 5. Head excursions with two different boosters, with standard 213 and realistic belt tension (for reference, head excursion limit is 813 mm).

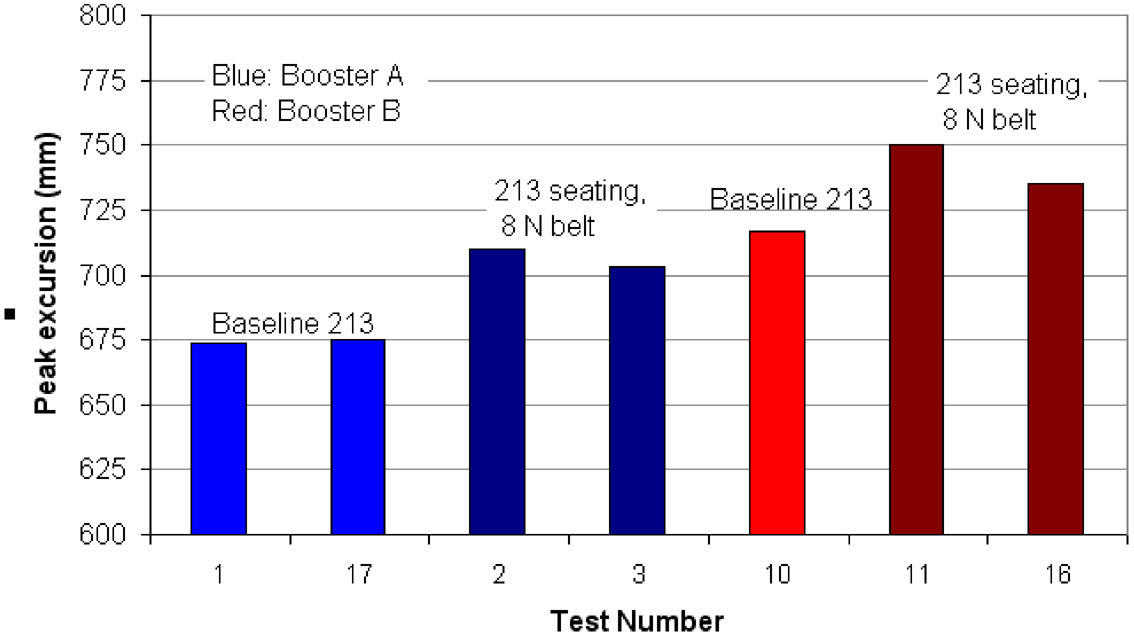


Figure 6. Knee excursions with two different boosters, with standard 213 and realistic belt tension (for reference, head excursion limit is 914 mm).

2.2 Belt Type

Results from six tests were used to examine the effect of different belt configurations on ATD dynamic response. All of these tests were run using standard FMVSS 213 belt anchorages, UMTRI seating procedure, the highback TurboBooster, and ~8 N lap belt tension. NT0704 and NT0705 used a lap/shoulder belt with fixed anchorages, as is specified in FMVSS 213, which essentially makes the lap/shoulder belt function as two separate pieces of webbing. NT0707 and NT0715 used a continuous piece of webbing routed through a sliding latchplate, but with the outboard shoulder and lap anchorages fixed. NT0706 and NT0708 used a seatbelt and retractor from a production seatbelt mounted to the FMVSS 213 anchor points.

Table 3 summarizes results from these tests, while Figure 7 and Figure 8 shows plots of the head and knee excursions. Peak head and knee excursions are similar for all three belt configurations. Other results were also quite similar for the tests run with the fixed, 2-piece belt and the continuous, fixed belt. When the retractor was used, most head, neck, and chest measures decreased by approximately 10% compared to the other belt configurations. Figure 9 shows the shoulder belt force measured in these tests, with peak values of shoulder belt load with the retractor approximately 25% lower than those without. The difference in shoulder belt loading likely resulted in the other differences seen in these tests. When reviewing videos of the two tests with the retractor, the first test appeared to allow slightly more spoolout than the second one. Conditioning the retractor by pulling it in and out several times before testing may be desirable.

.

Table 3. Summary of results for tests to evaluate the effect of belt configuration

Test	***Belt Config***	***Head R (g)***	***HIC 36***	***Chest clip (g)***	***Pelvis R (g)***	***Head ex (mm)***	***Knee ex (mm)***	***Torso angle (deg)***	***LBS (mm)***	***SBS (mm)***
NT0704	Fixed, 2-piece	73	953	47	57	642	736	19.0	48	51
NT0705	Fixed, 2-piece	68	764	45	52	641	716	17.9	46	52
NT0707	Fixed, continuous	68	798	46	58	654	732	17.9	43	45
NT0715	Fixed, continuous	75	874	44	57	641	735	19.9	45	57
NT0706	Retractor+ continuous	61	661	42	49	634	724	19.7	44	49
NT0708	Retractor+ continuous	71	739	47	54	647	739	18.2	42	43

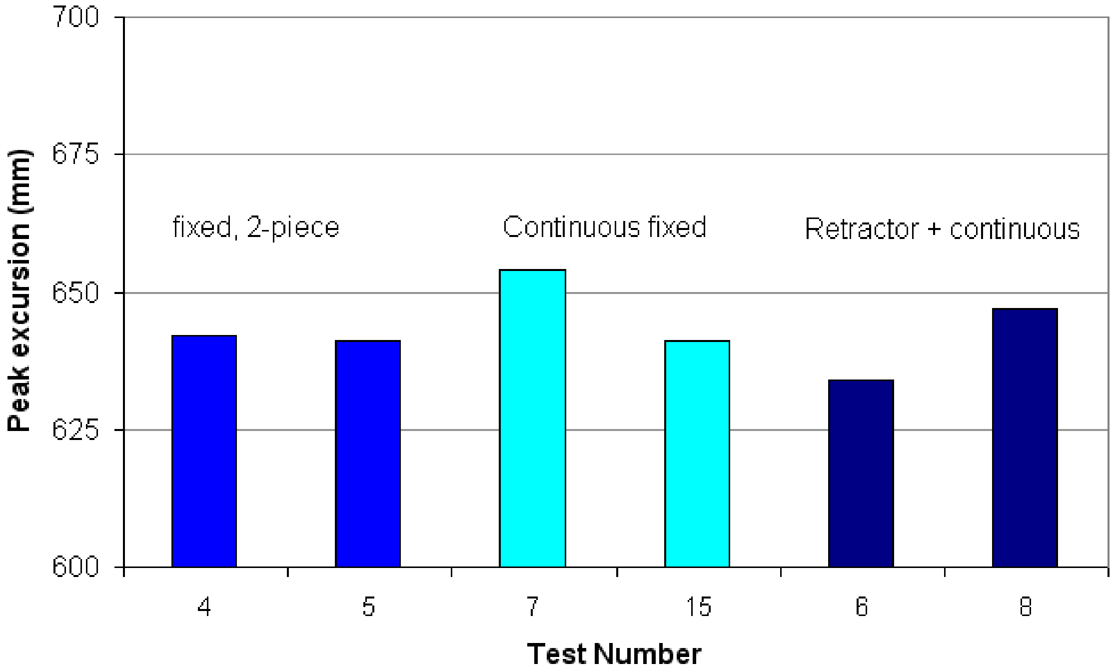


Figure 7. Peak head excursions in tests run with three different belt configurations.

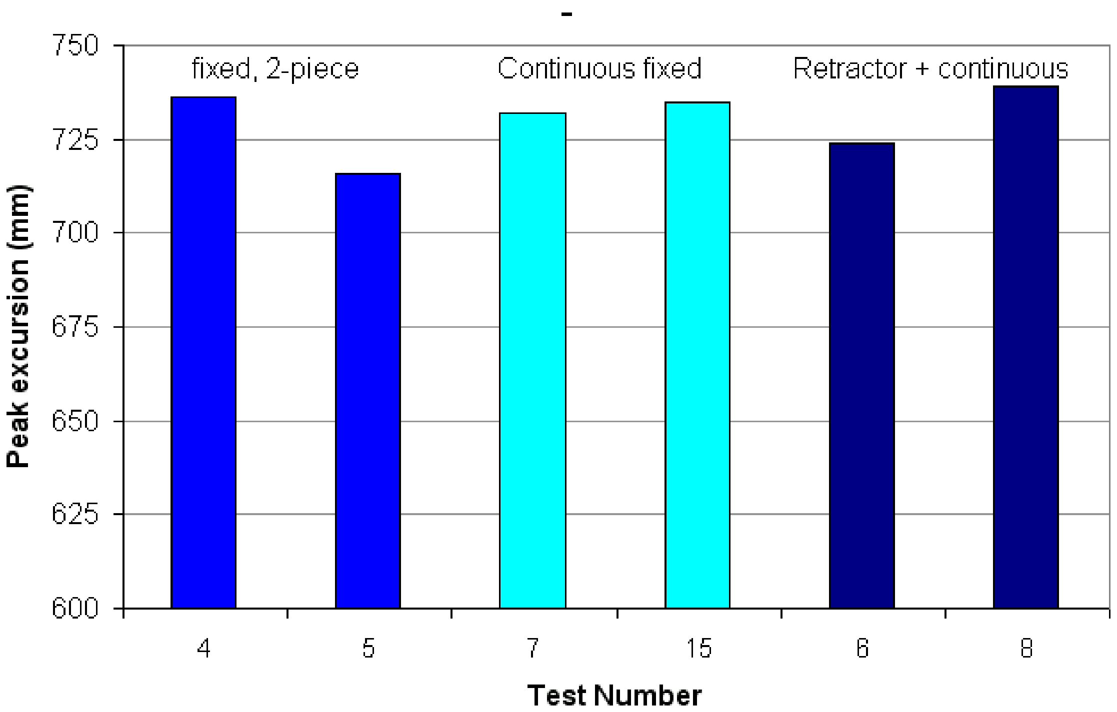


Figure 8. Peak knee excursions in tests run with three different belt configurations.

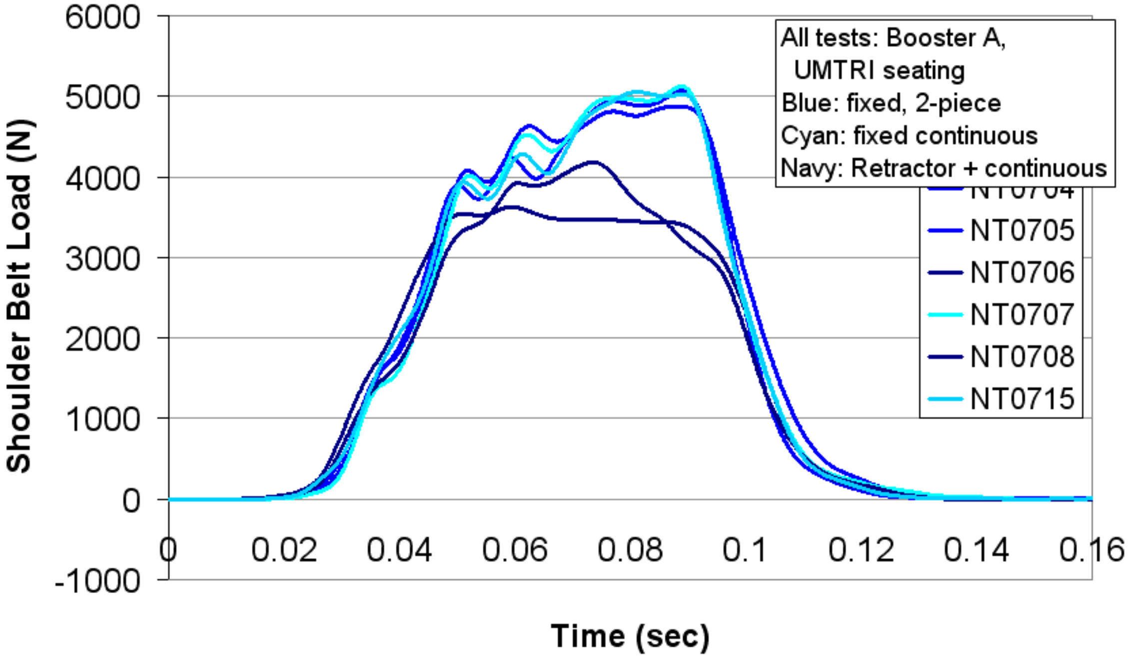


Figure 9. Shoulder belt force in tests run with three different belt configurations.

2.3 Seating Procedure

The 213 seating procedure involves placing the ATD in the booster and pushing the dummy torso and pelvis back into the seat. The UMTRI seating procedure positions the hips and heads of the ATDs in the positions where hips and heads of real children would be (reference 2006 stapp paper? reference procedure in docket?). The geometry of the booster seat controls the posture and belt routing over the dummy. The resulting postures are usually more reclined than those produced by the FMVSS 213 seating procedure.

To achieve a more realistic posture, the UMTRI seating procedure uses a 20-mm thick pelvis positioning pad that is attached to the back of the pelvis and a silicone lap shield placed on top of the pelvis, shown in Figure 10. In addition, use of the flexible lap shield also shown in Figure 10 allows the lap belt to be placed without catching in the pelvis-thigh gap of the ATD. The UMTRI seating procedure uses a realistic lap belt tension near 8 N.

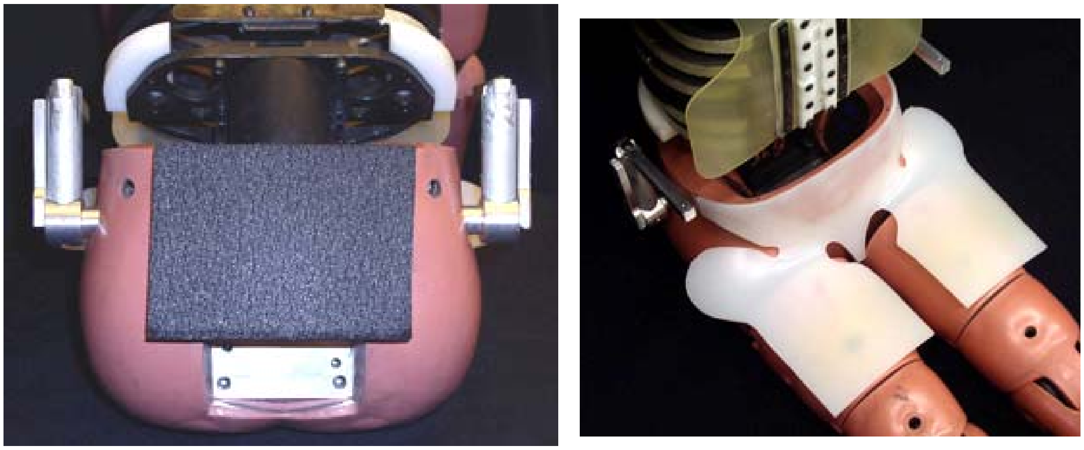


Figure 10. Illustration of positioning devices used with UMTRI seating procedure.

Eight tests were run with two boosters to examine the effect of seating procedure (NT0702 and NT0703 vs. NT0704 and NT0705; NT0711 and NT0716 vs. NT0712 and NT0713). Variations in lap belt routing with seating procedure and booster are shown in Figure 11. The TurboBooster, shown in the top row, routes the belt low over the ATD’s thighs. When the 213 seating procedure is used as shown on the left, the lap belt becomes trapped in the gap between the pelvis and the thigh. When the UMTRI seating procedure is used, the lap belt shield keeps the belt out of the gap, both statically and during dynamic testing. With the Generations, shown in the top row, the booster positions the belt higher over the pelvis, so the belt being trapped in the pelvis/thigh gap is not an issue.

Figure 11. Initial lap belt position on TurboBooster (top row) and Generations (bottom row) using FMVSS 213 seating procedure (left) and UMTRI seating procedure (right). The front edge of the belt is trapped in the gap in test NT0702.

Table 4 summarizes results from these tests. Most differences in tests with the TurboBooster using the 213 and UMTRI seating procedures result from the belt not being trapped in the gap rather than a change in posture. For the Generations tests, the lap belt was not trapped in the gap during any tests, so changes with UMTRI seating procedure result primarily from a shift in posture. The peak head and knee excursions from these tests are shown in Figure 12 and Figure 13. For the TurboBooster, head excursions decrease and knee excursions increase with the UMTRI seating procedure. For the Generations, head excursions are similar, while knee excursions increase slightly.

Table 4. Summary of results for tests to evaluate the effect of seating procedure

Test	***Seating Proc.***	***Booster***	***Head R (g)***	***HIC 36***	***Chest clip (g)***	***Pelvis R (g)***	***Head ex (mm)***	***Knee ex (mm)***	***Torso angle (deg)***	***LBS (mm)***	***SBS (mm)***
NT0702	213	TB/ back/low guides	64	681	45	51	686	710	14.1	68	68
NT0703	213	TB/ back/low guides	62	591	41	50	682	703	12.3	66	66
NT0704	UMTRI	TB/ back/low guides	73	953	47	57	642	736	19.0	48	51
NT0705	UMTRI	TB/ back/low guides	68	764	45	52	641	716	17.9	46	52
NT0711	213	Generations	71	915	43	41	677	750	15.9	42	51
NT0716	213	Generations	67	796	48	43	674	735	14.5	51	49
NT0712	UMTRI	Generations	82	1312	41	43	677	763	17.4	26	53
NT0713	UMTRI	Generations	95	1664	46	48	656	773	21	29	44

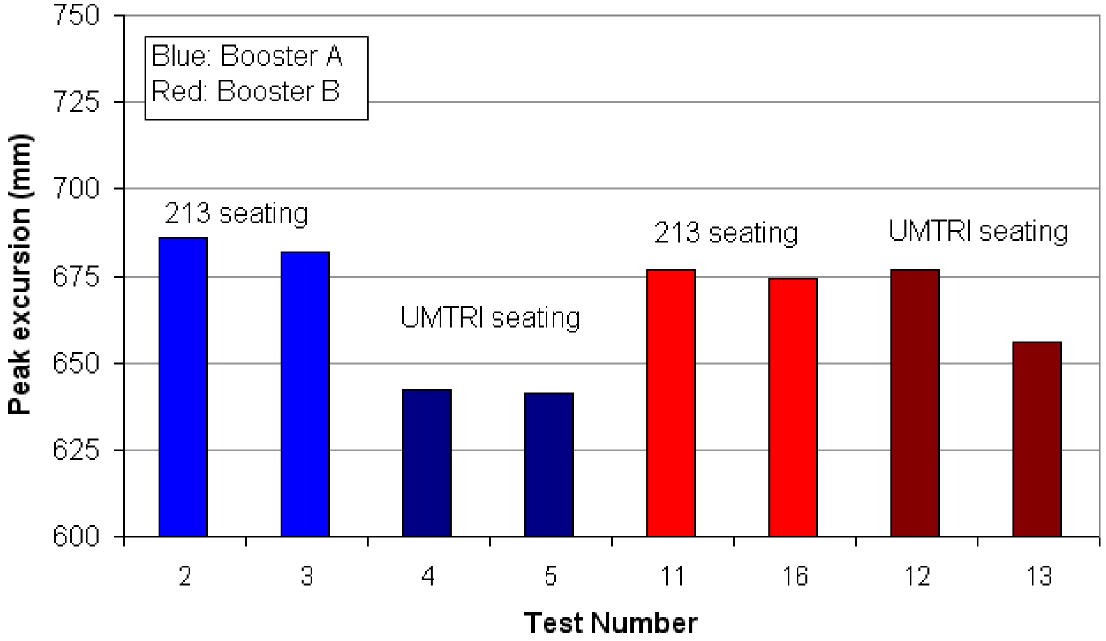


Figure 12. Peak head excursions for TurboBooster and Generations using FMVSS 213 and UMTRI seating procedures.

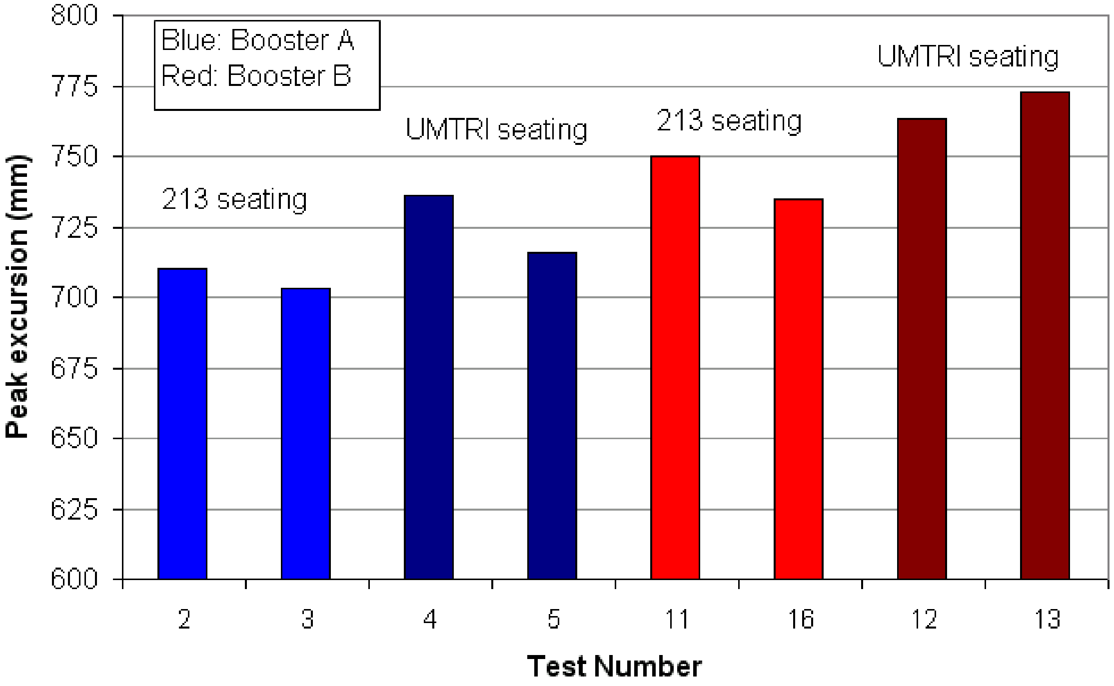


Figure 13. Peak knee excursions for TurboBooster and Generations using FMVSS 213 and UMTRI seating procedures.

The resultant head accelerations for these tests are shown in Figure 14. For both booster seats, use of the UMTRI seating procedure produces a larger second peak that results from chin-to-chest contact. The variability in the second peak contributes to the variations in HIC among these tests.

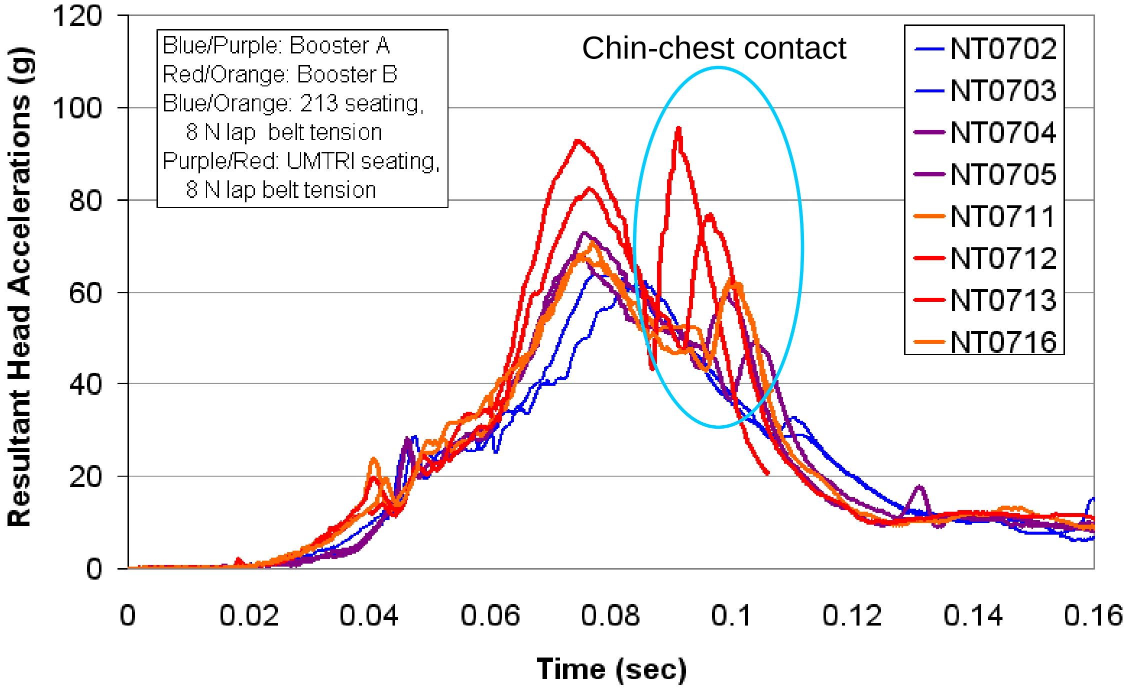


Figure 14. Resultant head accelerations for tests using 213 seating procedure and UMTRI seating procedure with two different boosters.

The initial tests performed with the UMTRI seating procedure showed differences in ATD posture repeatability between the two booster seats. In subsequent testing, the UMTRI seating procedure was first used to perform three static installations with each booster seat/belt geometry being tested. The averages of the three head, hip, shoulder belt, and lap belt locations in the static installations were used to define a target ATD and belt position for dynamic testing for each combination of booster seat and belt geometry tested. A tolerance of +/- 6 mm to the static targets was achieved in remaining tests. Figure 15 shows the absolute difference in torso angle, shoulder belt score, and lap belt score between paired tests run in the same condition in chronological order. The strategy of using a target position based on static installations, as well as increased familiarity with the procedure, resulted in improved posture and belt position repeatability over time.

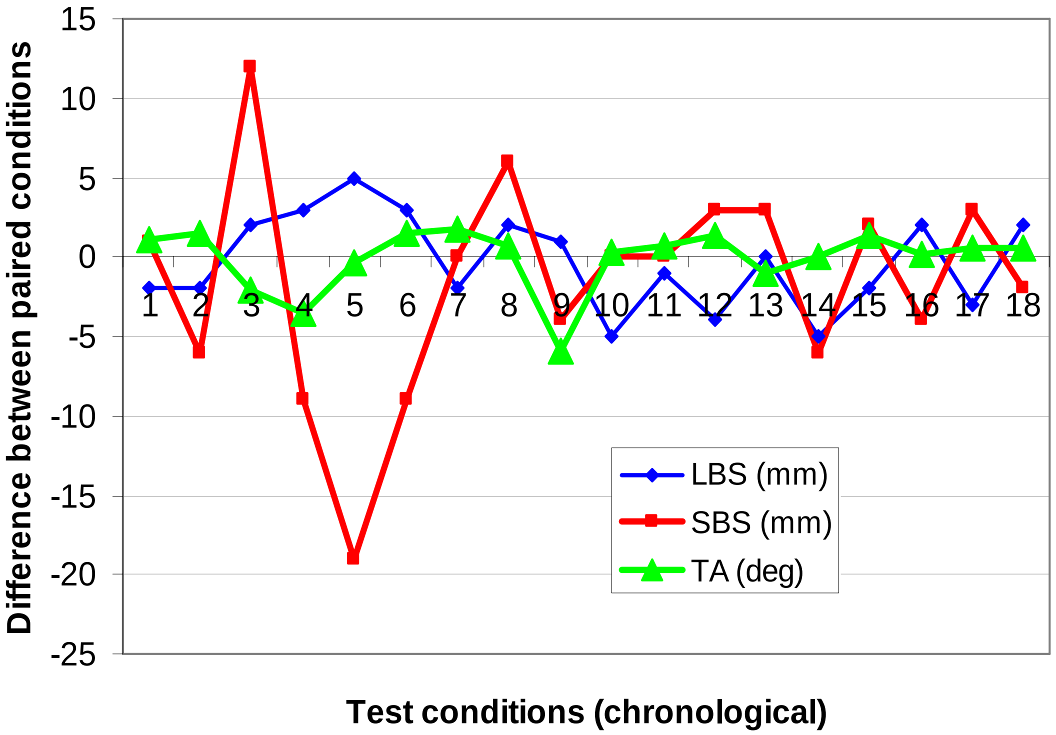


Figure 15. Differences in lap belt score (LBS), shoulder belt score (SBS), and torso angle (TA) for paired test conditions over time.

In the originally proposed test matrix, tests were planned to evaluate the effect of the positioning pad and lap shield on the dynamic performance of the ATD by first using the UMTRI seating procedure to position the ATD, then running a test where the dummy is placed in the same position (judged by comparison of FARO arm data) without using the pad or shield. These tests were not performed, because the same Z-coordinate measurements could not be achieved without the pad even when the X-coordinates matched. The tests that were conducted inadvertently showed that the UMTRI seating procedure devices have a positive effect on dynamic response because the lap shield prevents the lap belt from being trapped in the unrealistic pelvis/thigh gap.

3.0 Assessing Belt Guides on Booster Seats

3.1 Lap Belt Guide Assessment

Ten tests were run to assess the effect of booster lap belt guides on dynamic performance. All of these tests used the UMTRI seating procedure, which eliminated the lap belt being trapped in the pelvis/thigh gap as a contributor to dummy response. Two boosters were selected for testing that had lap belt guide designs producing substantially different lap belt fit with the ATD. First, tests were performed using normal FMVSS 213 lap belt anchor point geometry with each booster seat (NT0704, NT0705, NT0712, NT0713). An additional pair of tests were run with the lap belt guides removed from the TurboBooster (NT0709, NT0714). As shown by the peak excursion frames in Figure 16, differences using the TurboBooster with and without the lap belt guides indicated that the guides are effective in maintaining good belt routing during dynamic tests. Without lap belt guides (lower picture), the dummy is approaching submarining as the pelvis moves forward more and the torso rotates forward by a smaller amount. In contrast, the relatively high lap belt guide on the Generations booster had no contact with the lap belt during the test, and thus did not have any effect on the lap belt routing.

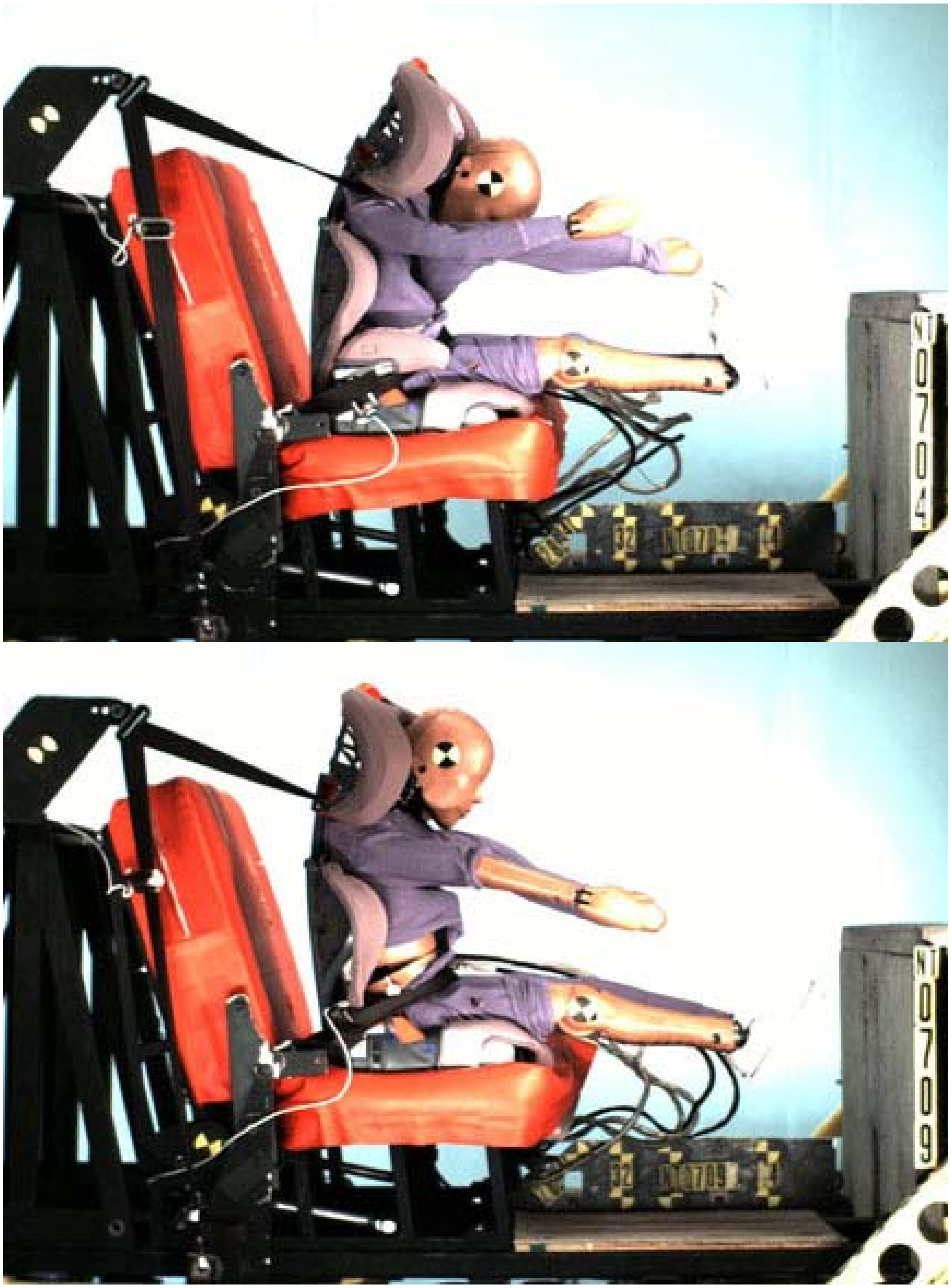


Figure 16. Frame of peak head excursion for TurboBooster with (top) and without (bottom) lap belt guides.

The remaining four tests in this series (NT0801, NT0802, NT0803, NT0804) quantified the effects of different lap belt guide designs using disadvantageous lap belt geometry. The lap belt anchorages were high, producing a very shallow lap belt angle of 15 degrees.

Figure 17 shows the peak head excursion frame from one of these tests with the TurboBooster, while Figure 18 shows the peak head excursion from one of the these tests with the Generations. The lap belt guides on the TurboBooster were effective dynamically and prevented the dummy from submarining. With the Generations, the lap belt guides again had no effect on the belt routing during the test, and the dummy submarined with this lap belt geometry. This set of tests provides a good demonstration of how a well-designed lap belt guide can maintain good belt position, even with poor lap belt geometry. They also indicate that static lap belt fit matters dynamically.

Figure 17. Peak excursion in test using TurboBooster and poor lap belt geometry.

Figure 18. Peak excursion in test using Generations and poor lap belt geometry.

Table 5 summarizes the results from tests used to assess the effect of lap belt guides. HIC values were highest in the tests where submarining occurred (NT0801 and NT0802).

Table 5. Summary of results for tests to evaluate the effect of lap belt guides

Test	*Lap belt geometry*	*Booster*	*Head R (g)*	*HIC 36*	*Chest clip (g)*	*Pelvis R (g)*	*Head ex (mm)*	*Knee ex (mm)*	*Torso angle (deg)*	*LBS (mm)*	*SBS (mm)*
NT0704	213	TB/ back/low guides	73	953	47	57	642	736	19.0	48	51
NT0705	213	TB/ back/low guides	68	764	45	52	641	716	17.9	46	52
NT0709	213	TB/ back/no guides	76	1110	49	51	602	731	18.3	44	28
NT0714	213	TB/ back/no guides	76	1054	47	55	616	718	17.4	41	43
NT0803	15°	TB/ back/low guides	84	1097	41	53	658	713	18.8	42	53
NT0804	15°	TB/ back/low guides	79	1131	41	55	672	718	17.3	45	44
NT0712	213	Generations	82	1312	41	43	677	763	17.4	26	53
NT0713	213	Generations	95	1664	46	48	656	773	21	29	44
NT0801	15°	Generations	119	1758	41	45	662	912	19.6	14	42
NT0802	15°	Generations	135	1846	41	44	607	857	19.9	19	23

3.2 Shoulder Belt Guide Assessment

Six tests were run (NT0805-NT0810) to examine how different styles of shoulder belt guides and booster seatbacks affected the shoulder belt routing during dynamic tests. Testing was conducted with three boosters selected to have different types of belt-guide and back component construction. The mid lap belt anchorage locations and an outboard shoulder belt position (shifted 2 inches outboard relative to normal 213 geometry) were used in these tests. The outboard anchorage was chosen to challenge the shoulder-belt-routing capability of the booster.

Illustrations of the kinematics with these three boosters are shown in Figure 19. Of the three boosters, the Compass (left column) was most effective at rerouting the belt and keeping it on the shoulder, possibly because the Compass had the most rigid connection between the back and base of the booster and an open belt guide structure that retained the belt. The back of this booster had the least amount of forward rotation. The Recaro (center column) had the most rigid overall construction, but the shoulder belt came out of the guide within 45-55 ms. (Peak excursion occurred around 110 ms). However, the shoulder belt seemed to stay on the shoulder somewhat better when it came out of the guide early in the impact event. In tests with the TurboBooster (right column), which had the least rigid construction, the belt stayed within the guide until about 60-70 ms, but the belt "landed" further out on the ATD shoulder and slipped farther off when it came out of the guide later in the event.

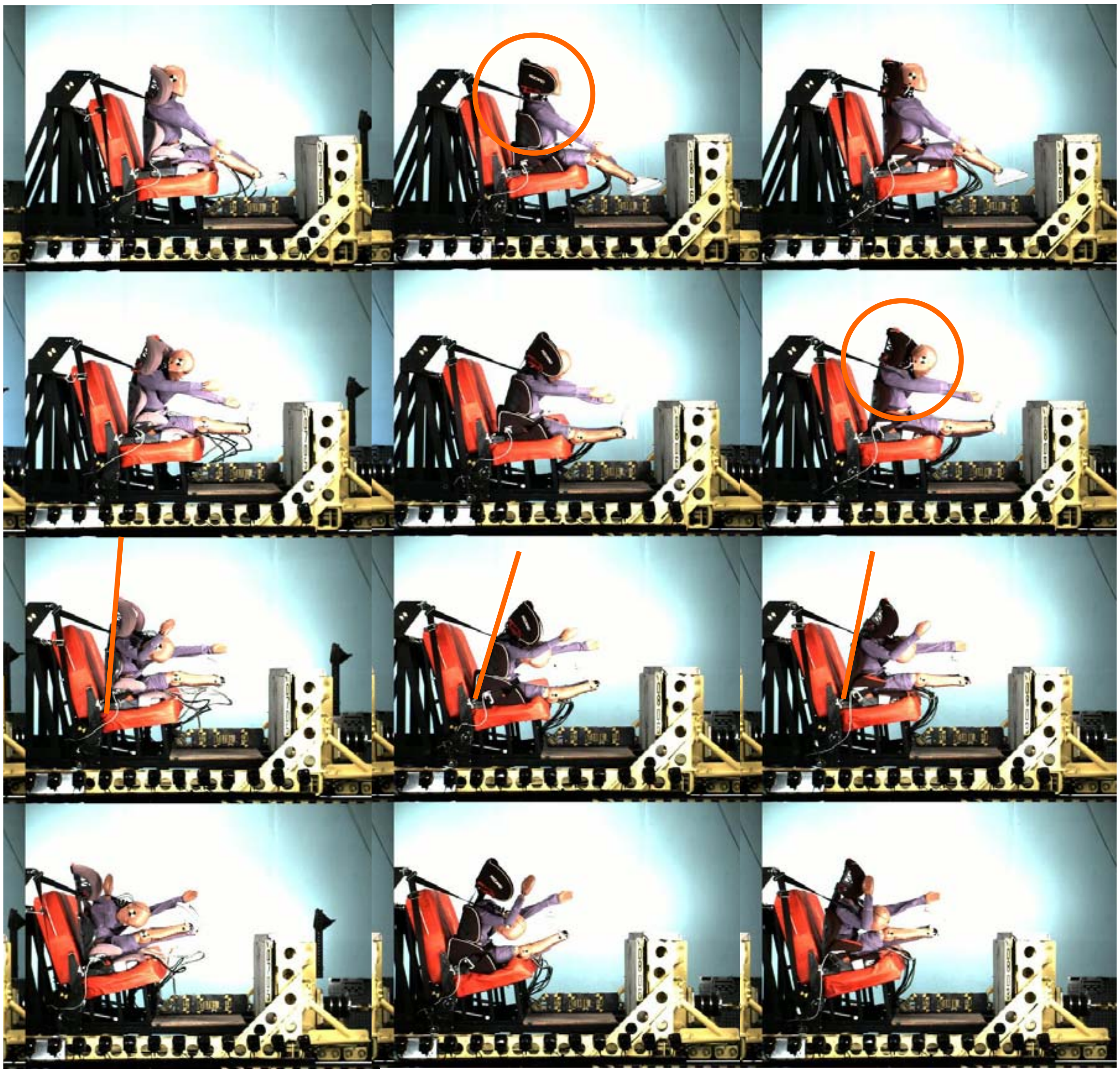


Figure 19. Kinematics using outboard shoulder belt anchorages and three different booster seat designs: Compass 530 (left), Recaro Vivo (center), and TurboBooster (right). Frames from top to bottom are from times 80, 100, 120, and 140 ms.

Table 6 summarizes results from these tests and Figure 20 shows the resultant head accelerations. The variability in HIC seems primarily to result from different levels of chin-to-chest contact visible in the second peak of the resultant accelerations. Although the 3-ms chest clip accelerations are similar in value for all of these tests, the chest resultant accelerations shown in Figure 21 indicate that the Compass booster, with the most favorable kinematics, allows the shoulder belt to begin loading the chest 3 ms sooner than the other two boosters. When reviewing the differences in the style of the shoulder belt guide illustrated in Figure 22, the Compass does not have any structure between the belt and shoulder through which to route the belt, and the shoulder belt first comes in contact with the top part of the booster seatback. The shoulder belt guide on the headrest affects lateral position. For the Recaro and TurboBooster, the shoulder belt routes through a belt guide component that is part of the headrest structure, which has more of an effect on the vertical routing of the shoulder belt through the guide.

Table 6. Summary of results for tests to evaluate the effect of shoulder belt guides

Test	***Shoulder belt geometry***	***Booster***	***Head R (g)***	***HIC 36***	***Chest clip (g)***	***Pelvis R (g)***	***Head ex (mm)***	***Knee ex (mm)***	***Torso angle (deg)***	***LBS (mm)***	***SBS (mm)***
NT0805	50 mm outboard	Compass 530	76	1043	42	43	677	758	17.2	29	69
NT0810	50 mm outboard	Compass 530	69	804	42	41	693	750	15.4	27	69
NT0806	50 mm outboard	Recaro Vivo	76	969	45	53	690	749	20.1	41	37
NT0809	50 mm outboard	Recaro Vivo	72	788	41	54	695	752	19.4	43	43
NT0807	50 mm outboard	TB/ back/ low guides	103	865	40	51	714	716	16.1	42	46
NT0808	50 mm outboard	TB/ back/ low guides	82	1082	42	51	671	737	22	43	42

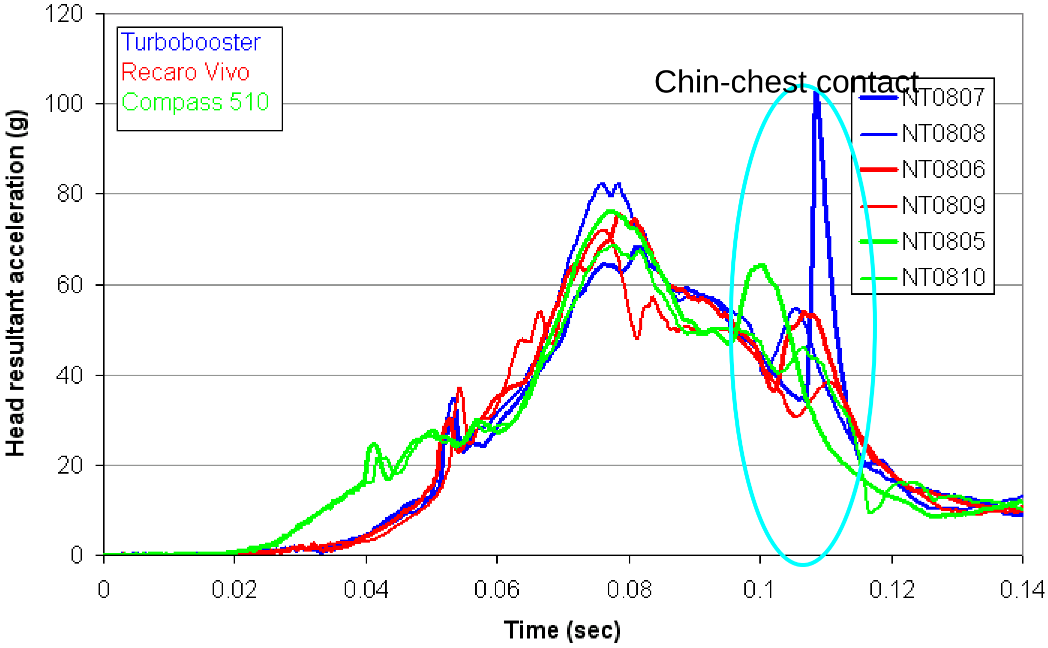


Figure 20. Head resultant accelerations using outboard shoulder belt anchorages and three different booster seat designs: Compass 530, Recaro Vivo, and TurboBooster.

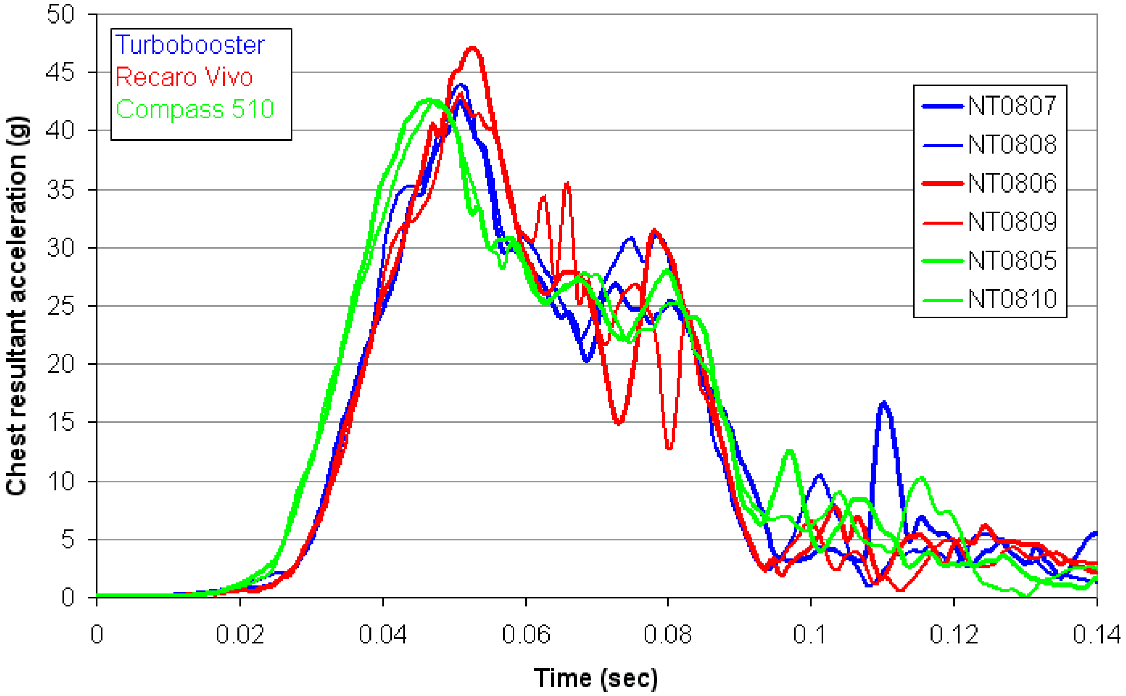


Figure 21. Chest resultant accelerations using outboard shoulder belt anchorages and three different booster seat designs: Compass 530, Recaro Vivo, and TurboBooster.

Figure 22. Difference in shoulder belt guide structures in the Compass, Recaro, and TurboBooster (left to right). The Compass (left) retained the belt most successfully in this test series.

3.3 Effect of Modified Shoulder Belt Guides

Additional tests were then run with modified versions of the TurboBooster (NT0823, NT0826, NT0827, NT0832) to determine if different shoulder belt slot geometry or a stiffer back and connection to the base would improve performance. Figure 23 shows the modified slot design, while Figure 24 shows the stiffened back and base connection plus a close-up of the slot modification for those tests. With the two modified slot tests, the modifications to the booster were the same in each test. However, in the first test, the headrest was in the highest position, while in the second test, it was shifted to the next lowest position so the slot geometry was closer to the original configuration. For the two tests with the rigid modifications, the seatback was stiffened with the steel angle stock, the back was bolted to the base, and a metal strap was placed on the shoulder belt guide to prevent it from releasing the belt. In the second test, additional metal plate was bolted to the seatback was shown, and the attachment between the base and back was reinforced further.

Figure 23. TurboBooster with modified slot design.

Figure 24. TurboBooster with structure modified to be more rigid, plus close-up of "closed" shoulder belt guide.

Table 7 summarizes the results of tests with modified boosters compared to the baseline tests run with the TurboBooster. Although both modified designs retained the belt within the shoulder belt guide, neither resulted in substantially improved performance. Figure 25 shows illustrations of the kinematics of the ATD during the latter part of the test. For the standard TB shown on the left, the shoulder belt has come out of the slot, and the seatback moves forward with the ATD since the shoulder belt is not in contact with the seatback. For the TB with the modified slot shown in the middle, the shoulder belt continues to be routed through the slot, which causes the whole seatback to flex toward the belt. With the stiffened TB shown on the right, the whole booster tips toward the belt, which is retained in the routing slot. For each of these tests, the shoulder belt ends up just off the shoulder in the final frame. These test results indicate that keeping the belt within the shoulder belt guide is not sufficient for achieving good dynamic position of the shoulder belt during impact. Stiffening the booster is also not sufficient; the booster cannot resist moving toward the outboard shoulder belt location if it is not secured to the vehicle seat. Future testing could investigate the effect of using a tether or lower LATCH attachments on the booster's ability to maintain effective shoulder belt routing.

Table 7. Summary of results for tests to evaluate the effect of modified shoulder belt guides

Test	***Booster***	***Head R (g)***	***HIC 36***	***Chest clip (g)***	***Pelvis R (g)***	***Head ex (mm)***	***Knee ex (mm)***	***Torso angle (deg)***	***LBS (mm)***	***SBS (mm)***
NT0807	TB/ back/ low guides	103	865	40	51	714	716	16.1	42	46
NT0808	TB/ back/ low guides	82	1082	42	51	671	737	22	43	42
NT0823	TB, modified slot	72	964	44	51	674	710	14.1	40	25
NT0827	TB, lower modified slot	65	905	42	54	705	705	11.9	35	29
NT0826	TB, stiffer back	62	828	46	50	713	709	13.6	43	39
NT0832	TB, extra stiff back	64	650	41	55	710	721	12.9	40	50

Figure 25. Kinematics of TurboBooster (left), TB with modified slot (middle), and rigid TB. Frames from top to bottom are from times 80, 100, and 120 ms.

4.0 Effects of Belt Anchorage Locations on ATD Outcomes

4.1 Shoulder Belt Rollout Threshold

Rollout is a term used to describe torso kinematics that occur when the torso portion of the belt does not remain engaged with the shoulder during ridedown. As the torso belt slides outward on the shoulder, the dummy torso rotates away from the belt and the head moves through a larger arc than would be the case if the belt remained engaged with the shoulder. Rollout is considered an adverse outcome indicative of poor torso restraint.

The objective of this test series was to examine ATD torso kinematics when varying shoulder belt position over a range of values expected to correspond to the rollout threshold for real children, based on shoulder belt score. Four pairs of tests (NT0811 to NT0816, NT0824, NT0825) were run using four different shoulder belt anchorage locations and mid lap belt geometry. The anchorages were varied using 0.5" (normal 213), 1", 1.5", and 2" spacers at the D-ring (larger spacers move the D-ring more outboard).

Table 8 summarizes the results of tests to evaluate shoulder belt geometry. The average SBS in the four conditions was 47 mm, 70 mm, 80 mm, and 86 mm. Kinematics for the 47 and 70 mm SBS were very similar, while in the 80 and 86 mm conditions, the torso rotated further forward and more outboard. Results were less repeatable in the more outboard belt conditions. As shown in Figure 26 and Figure 27, peak lumbar X moments (lateral bending) and change in thorax angle were most effective at differentiating between acceptable and less desirable kinematics. These results may provide some initial guidance in developing a definition of rollout that could be used to identify zones of torso belt fit that provide good kinematics on the 10YO ATD. However, a potential issue with using torso angle as a criterion is that the peak value of the torso angle may not always correspond with the peak forward motion of the torso. In some test conditions, the peak angle occurs late in the event because of artifacts from integrating an angular rate sensor to determine torso angle.

Table 8. Summary of results for tests to evaluate the effect of shoulder belt geometry.

Test	*Shoulder Belt Geometry*	*Head R (g)*	*HIC 36*	*Chest clip (g)*	*Pelvis R (g)*	*Head ex (mm)*	*Knee ex (mm)*	*Torso angle (deg)*	*LBS (mm)*	*SBS (mm)*
NT0811	Mid (.5")	75	1054	44	52	540	701	16.4	21	47
NT0816	Mid (.5")	79	1116	51	56	544	711	16.1	16	47
NT0813	Mid+ (1")	72	1051	45	51	537	701	16.5	16	70
NT0814	Mid+ (1")	77	1055	47	52	543	707	15.8	15	70
NT0812	Mid++ (1.5")	74	1008	44	56	627	697	16.9	19	78
NT0815	Mid++ (1.5")	69	818	47	57	583	712	15.6	15	81
NT0825	Mid+++ (2”)	66	835	42	52	598	680	14.7	29	88
NT0826	Mid+++ (2”)	92	950	43	51	561	697	13.6	43	84

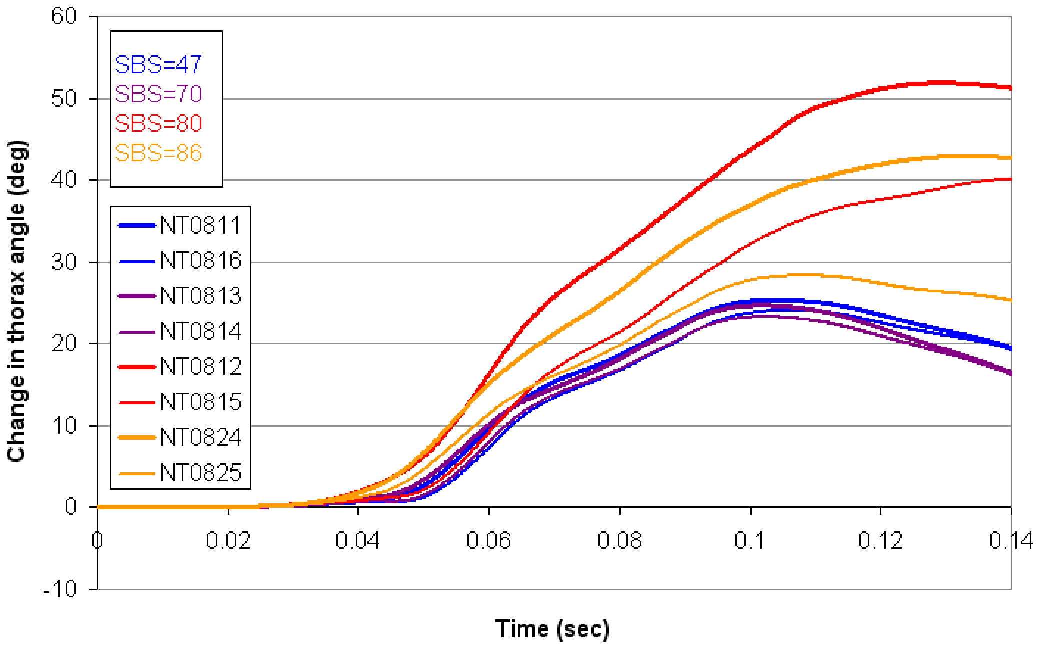


Figure 26. Change in thorax angle with variations in shoulder belt position.

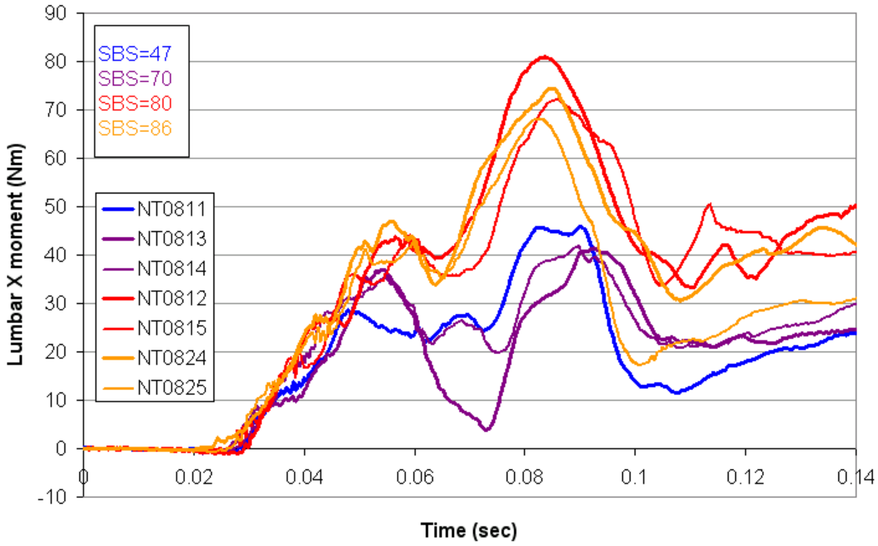


Figure 27. Lumbar X moment with variations in shoulder belt position.

Figure 28 shows examples of the kinematics in the latter part of the impact event for four initial SBS. The belt stayed on the shoulder with SBS of 47 and 70 (left two images). With an initial SBS of 78 shown in the third column, the belt ended up near the upper arm joint. An SBS of 88 resulted in the belt off the shoulder, lying against the arm.

Figure 29 and Figure 30 show HIC and head excursion as a function of SBS. The blue zones indicate a range of good torso restraint and the red zones show the regions of failing HIC(36) and head excursion. HIC decreases as the shoulder belt score is increased, but the two conditions with good torso restraint do not pass the HIC criterion. All of the conditions fall well within the acceptable range of head excursion. These data suggest that use of HIC in evaluating booster seats may inadvertently provide an advantage to designs that produce poor belt fit on children.

Static testing with the 10YO reported in Volume I showed that an ATDSBS10C of 70 corresponds to SBS of 80.6 mm for children. This value is identified as providing poor static belt fit on volunteer children. Biofidelity issues with the ATD shoulder may contribute to the difference between “good fit” measured statically vs. dynamically with this ATD. Although an ATD SBS of 70 mm produced good torso restraint with the 10YO ATD, the ATD shoulder may not interact realistically with the belt. These tests indicate that limiting ATD SBS to no more than 70 mm could be considered as a first step in providing improved belt fit, but the child belt fit data in Volume I of this report suggest a more restrictive SBS criterion may be appropriate.

Figure 28. Variation in torso rollout with shoulder belt position. From left, shoulder belt scores of 47, 70, 79, 87 mm. From top to bottom, frames are from elapsed time of approximately 80, 100, 120, and 140 ms.

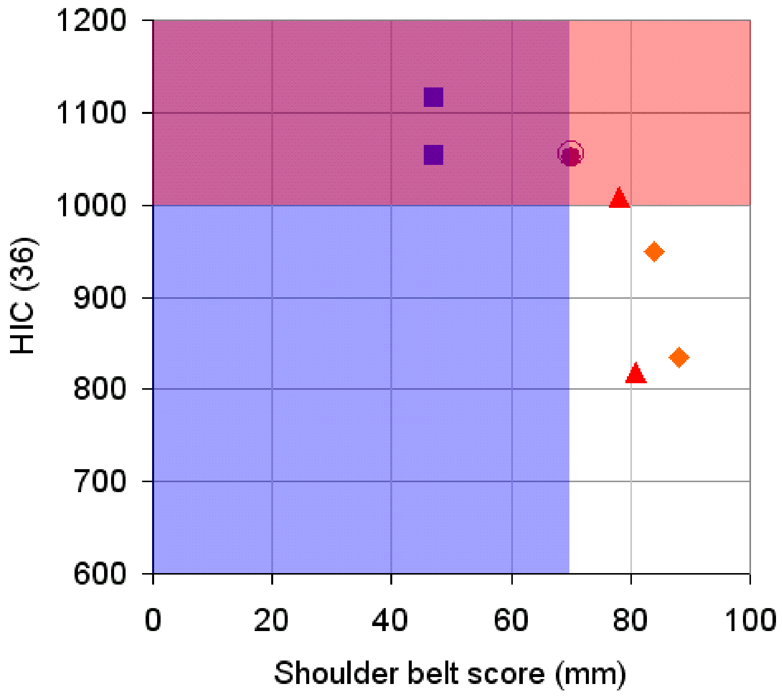


Figure 29. HIC (36) as a function of shoulder belt score. Blue zone indicates good torso restraint while red zone indicates excessive HIC values.

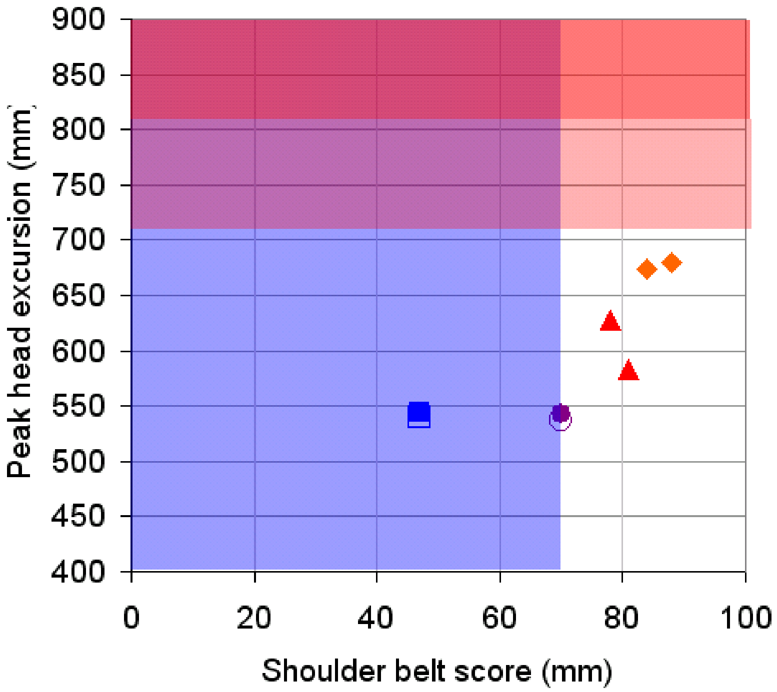
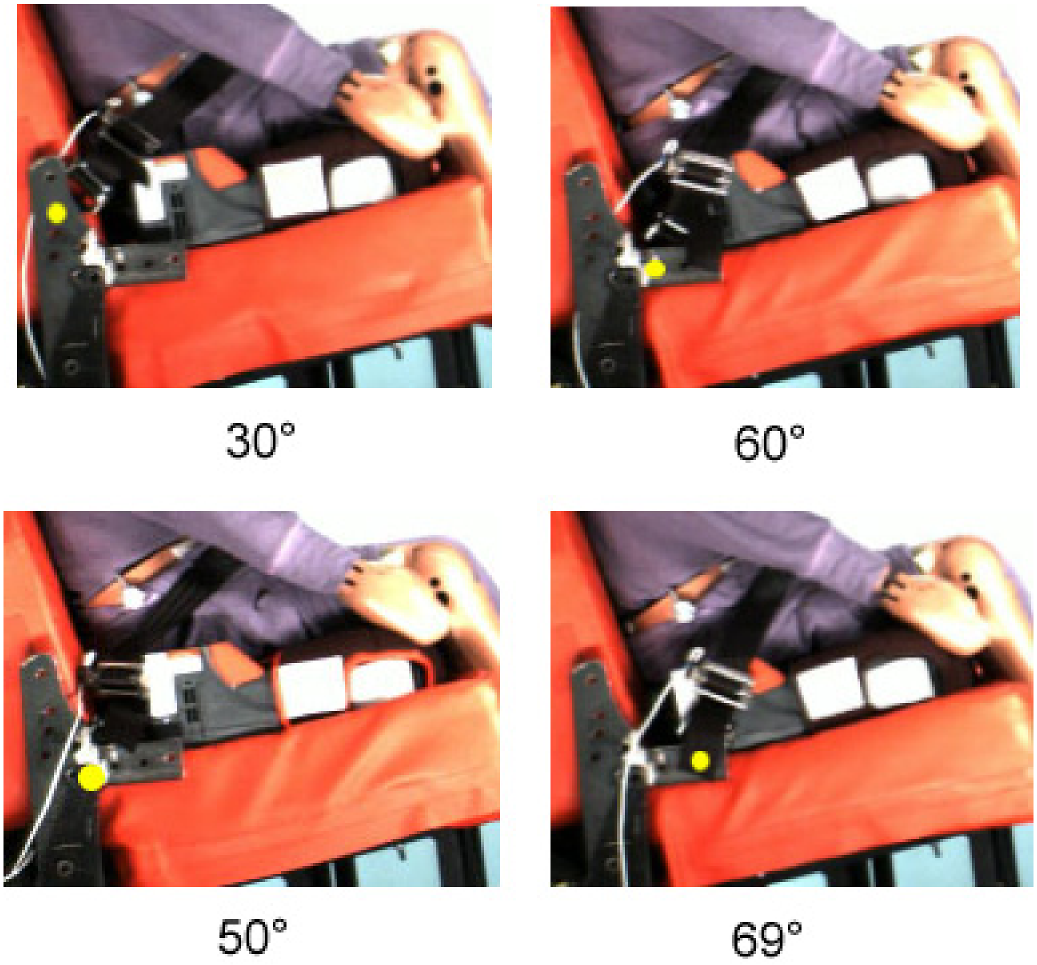


Figure 30. Peak head excursion as a function of shoulder belt score. Blue zone indicates good torso restraint and red zone peak head excursion limits from FMVSS 213.

4.2 Variations with Lap Belt Position

The objective of these tests (NT0811, NT0816, NT0817-NT0822) was to examine ATD kinematics when varying lap belt position above and below where the ASIS would be located on real children who are the size of the 10YO ATD. As shown in Figure 31, the buck was modified with additional lap belt anchors that resulted in nominal lap belt angles of 30, 40, 50, 60, and 70 degrees with respect to the H-point of the 10YO ATD when seated on the backless, armless TurboBooster on the 213 bench seat. Angles were defined relative to the 10YO H-point, rather than the H-point location on the bench seat, to facilitate construction of appropriate anchor locations on the inboard side of the seat. The 60 and 70 degree anchors are located forward of the 50 degree anchor, while the 30 and 40 degree anchors are superior to the 50 degree anchor.


30°

60°

50°

69°

Figure 31. Illustrations of different lap belt anchorage locations.

A summary of test results is shown in Table 9. Although head excursions are fairly consistent in sets of paired tests, HIC(36) varies considerably in the steeper lap belt angles where rollout occurred.

Table 9. Summary of results for tests to evaluate the effect of lap belt geometry.

Test	*Lap Belt Geometry*	*Head R (g)*	*HIC 36*	*Chest clip (g)*	*Pelvis R (g)*	*Head ex (mm)*	*Knee ex (mm)*	*Torso angle (deg)*	*LBS (mm)*	*SBS (mm)*
NT0821	30°	89	1315	45	52	511	653	16.6	22	46
NT0822	30°	83	1313	43	51	527	634	15.3	20	48
NT0811	50°	75	1054	44	52	540	701	16.4	21	47
NT0816	50°	79	1116	51	56	544	711	16.1	16	47
NT0817	60°	50	458	41	49	606	713	15.7	41	45
NT0818	60°	66	810	50	58	598	735	16.7	41	48
NT0819	69°	62	637	47	60	600	756	15.9	48	51
NT0820	69°	54	447	44	56	611	734	15.9	43	45

Surprisingly, lap belt angle had a larger effect on torso rollout kinematics than it had on submarining. In the 60- and 70-degree lap belt conditions, the torso of the dummy rolled out of the belt, with change in torso angle varying from 39 to 50 degrees among the four tests. Rollout did not occur in the 50 and 30 degree configurations, with change in torso angle varying from 24 to 29 degrees among these four tests. The lap belt remained on the pelvis throughout all test conditions. As shown in Figure 32, the knee excursions increased with lap belt angle, while head excursion increased from the 30 through the 60 degree conditions, but was similar for the 60 and 70 degree conditions. ASIS loads decreased with increasing lap belt angle.

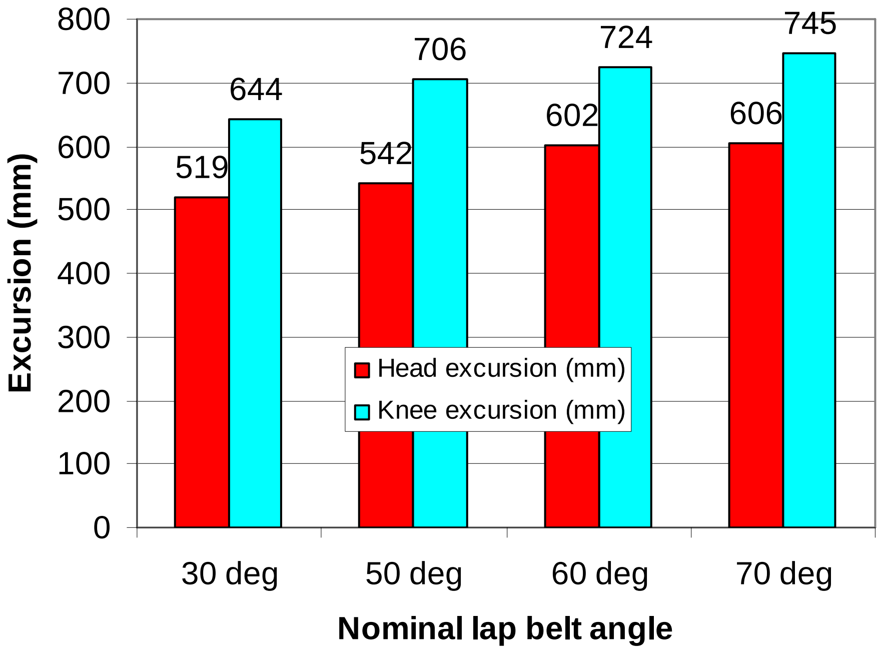


Figure 32. Variation in head and knee excursions with varying lap belt angle (mean value of two tests at each condition).

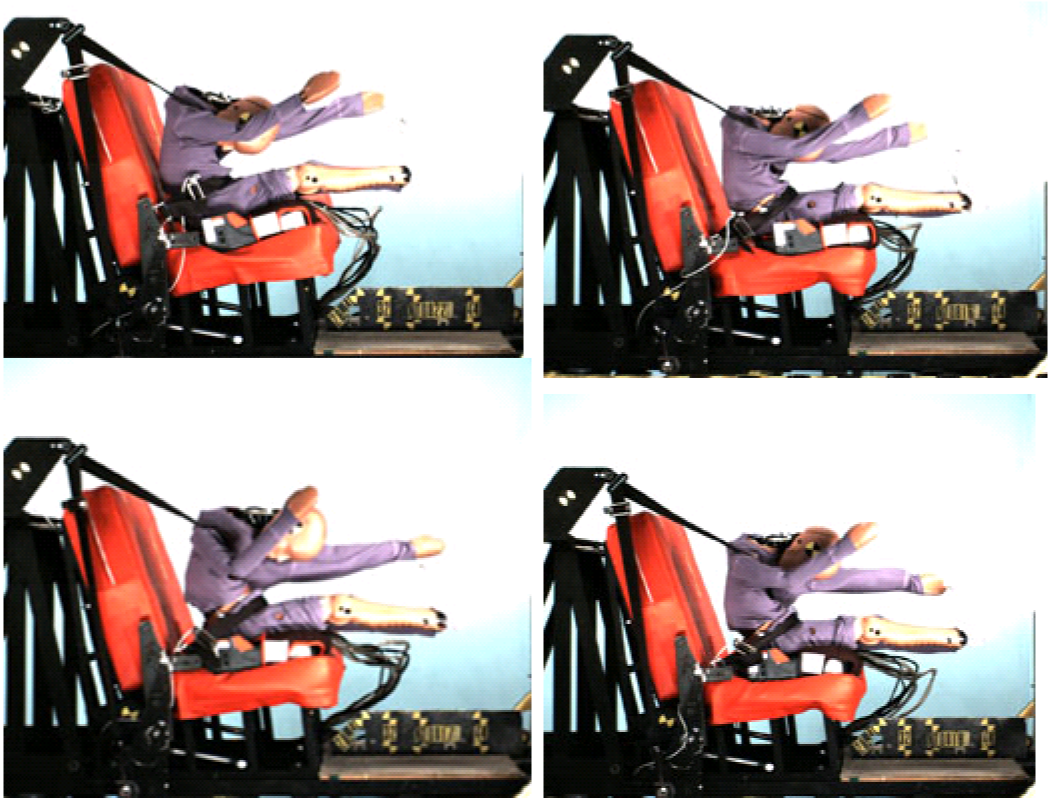


Figure 33. Kinematics with variation in lap belt angle (30˚ upper left, 50˚ upper right, 60˚ lower left, 70˚ lower right.)

Some of these effects likely result from differences in fore/aft location of the anchorages used to achieve the different lap belt angles. In addition, moving the inboard anchor can change the way the shoulder belt is routed across the torso. Two more test configurations were run to examine the effect of moving the inboard lap belt anchorage while maintaining the shoulder belt anchorage position near the threshold of rollout (SBS ~70) and same sideview lap belt angle. NT0828 and NT0829 used an inboard lap belt anchorage shifted 75 mm inboard (away from the ATD) from the standard FMVSS 213 location, while NT0830 and NT0831 used an inboard lap belt anchorage shifted 75 mm outboard (towards the ATD) from the standard location. The ATD approached submarining with a wider spacing between the anchorages, and exhibited rollout tendencies with a narrower spacing between the anchorages.

Table 10. Summary of results for tests to evaluate the effect of lap belt spacing

Test	*Lap Belt Spacing*	*Head R (g)*	*HIC 36*	*Chest clip (g)*	*Pelvis R (g)*	*Head ex (mm)*	*Knee ex (mm)*	*Torso angle (deg)*	*LBS (mm)*	*SBS (mm)*
NT0813	213	72	1051	45	51	537	701	16.5	16	70
NT0814	213	77	1055	47	52	543	707	15.8	15	70
NT0828	75 mm >	123	1344	44	45	500	680	15.5	28	69
NT0829	75 mm >	119	1465	48	*	514	671	15.0	25	72
NT0830	75 mm <	89	867	38	47	535	698	15.2	21	71
NT0831	75 mm <	82	837	39	53	548	699	14.7	23	69

* pelvis instrumentation cable unplugged during test

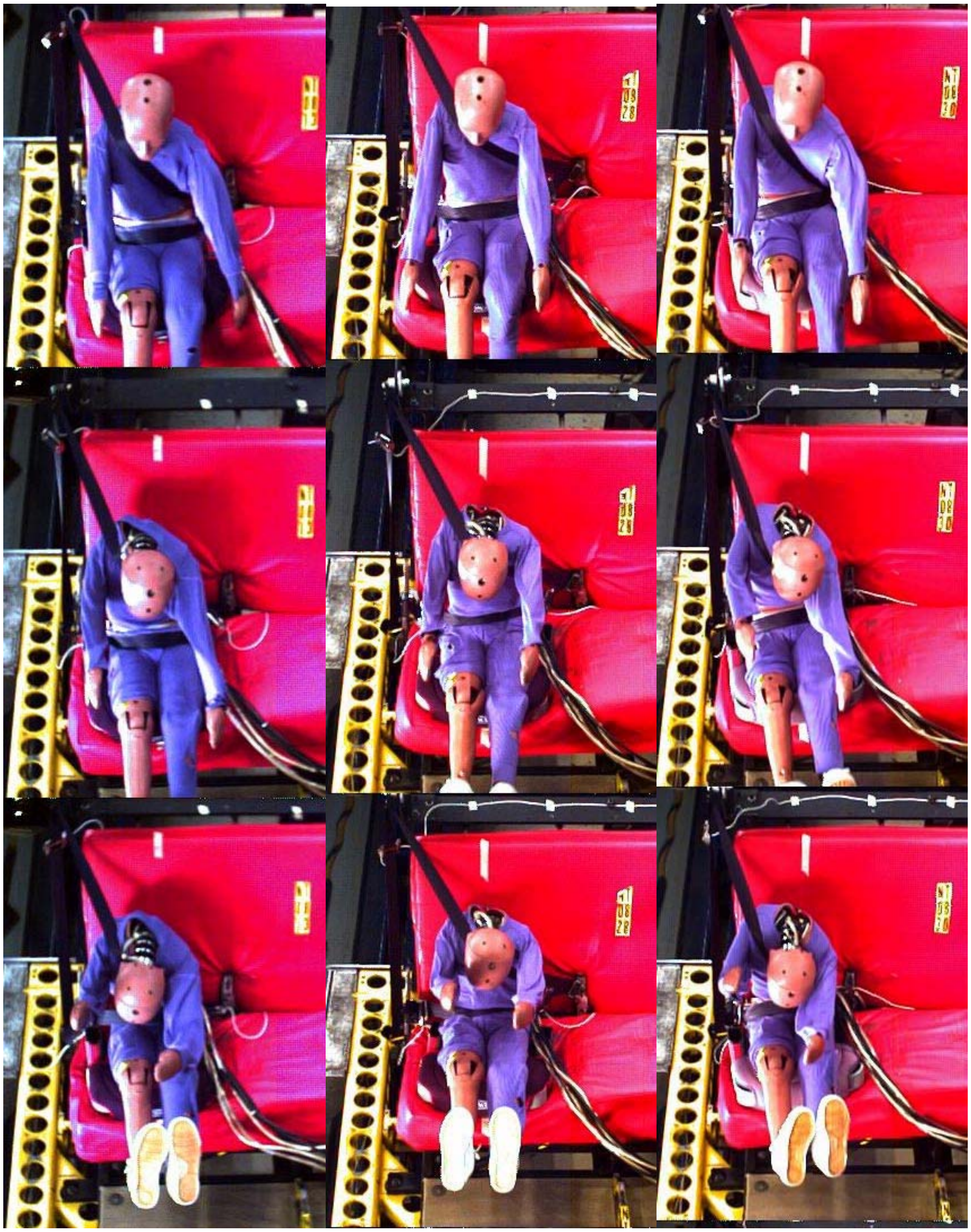


Figure 34. Kinematics with variation in lap belt spacing (from left: normal 213, 75 mm wider, 75 mm narrower). Frames from top to bottom are from times 80, 100, and 120 ms.

5.0 Summary and Discussion

5.1 Test Procedures

- Reducing lap belt tension to a realistic 2 lb (rather than 15 lb) did not have a pronounced effect on kinematics with two different booster seats.
- Use of a lap/shoulder belt with a sliding latchplate produces similar results to using a lap/shoulder belt with fixed anchorages. Use of a production retractor reduces shoulder belt load, as well as head, neck, and chest measures.
- Use of the UMTRI seating procedure prevents the lap belt from being trapped in the gap between the pelvis and the thigh.
- Use of the UMTRI seating procedure produces more reclined initial postures and more pronounced chin-to-chest contact.

This test series demonstrated that the realism of the FMVSS 213 procedures can be improved without dramatic changes in ATD outcomes. The FMVSS 213 belt tension for booster testing, which is a carryover from procedures originally developed for harness restraint testing, is much higher than the typical values children produce when they don the belt themselves. These test results indicate that switching to the more realistic 8 N tension would not change the evaluation of most boosters, since increases in head and knee excursion are modest.

In real vehicles, shoulder belt loads are exerted through retractors, and these results suggest that retractors may act to reduce peak loads and slightly increase head excursions. Given the importance of head excursion in injury risk (head injuries are the most common serious and fatal injuries among booster-seated children), more research should be conducted on the real-world performance of rear-seat retractors.

The UMTRI child ATD seating procedure was developed to place the ATDs in more realistic positions than the FMVSS 213 procedures. The lap shield added as part of the procedure has an important effect of preventing the lap portion of the belt from sliding into the unrealistic thigh-pelvis gap during testing. The increased recline angles in the UMTRI procedure and the reduced lap belt tension tend to produce greater head excursions, and chin-chest contact becomes more likely.

5.2 Evaluation of Belt Guides

- A well-designed lap belt guide can maintain good belt position dynamically, even with poor lap belt geometry, but poorly designed lap belt guides have little effect.
- Shoulder belt guide designs affect ATD kinematics.

- Preventing the shoulder belt from coming out of the shoulder belt guide does not necessarily produce better routing of the shoulder belt under dynamic loading conditions.

- Stiffening booster seats does not necessarily produce better routing of the shoulder belt during the crash event.

- Shoulder belt scores less than 70 mm produce good kinematics with the 10YO ATD.

- Use of HIC may encourage outboard shoulder belt routing that leads to an undesirable level of ATD rollout but can dramatically reduce HIC values.

- Lap belt angle affects torso kinematics, with shallower lap belt angles leading to increased knee excursion and submarining and more vertical lap belt angles leading to rollout.

- Shifting the inboard lap belt anchorage, while maintaining the same shoulder belt anchorage location and lap belt angle, affects kinematics. Wider spacing leads to submarining, while narrowing spacing leads to rollout.

- Booster seats seem to be more effective at mitigating poor lap belt fit than at overcoming poor shoulder belt fit.

Because most testing of boosters is conducted using FMVSS-213 conditions, relatively little is known about how boosters affect ATD outcomes for other conditions, particularly when belt anchorage locations are changed. FMVSS 210, which regulates anchorage locations, permits a large range of upper and lower anchorage locations, and measurements of vehicle second-row seating positions at UMTRI have shown that current vehicle designs span a large percentage of the permissible range.

This test series demonstrated that changes in belt anchorage location have substantial effects on ATD kinematics. The data also show that boosters differ substantially in their ability to compensate for poor belt geometry. The lap belt guides on the TurboBooster were able to prevent submarining with poor lap belt geometry, but the lap belt guides on the Generations booster had almost no dynamic effect on belt routing, permitting the dummy to submarine when tested with poor lap belt geometry.

Upper anchorage location has a strong affect on torso kinematics. The development of the shoulder belt score in previous research allowed the determination of the relationship between shoulder belt score (SBS) and the rollout threshold. However, subsequent testing revealed that the location of the lower anchors also influences the relationship between SBS and the rollout threshold, such that a SBS of 70, the suggested upper limit based on dynamic testing, may still lead to rollout if lower anchorages are spaced more narrowly than those specified in FMVSS 213. More work will be necessary to understand these relationships.

The spacing of lower anchors in current vehicles varies widely, and FMVSS 210 requires only that the anchorages be at least 165 mm apart. Consultation with vehicle manufacturers indicated that lateral belt spacing is primarily based on available geometry in the vehicle seat relative to other requirements such as LATCH anchorages, and is rarely an explicit design target.

The effectiveness of the shoulder belt routing features on boosters was ambiguous. Three boosters that produced similar static belt fit produced different outcomes with respect to maintaining the belt on the shoulder with a moderately disadvantageous upper anchorage location. Experimental modifications to one booster failed to clarify particular features that would keep the belt on the shoulder. However, one reasonable conclusion is that boosters cannot be relied upon to maintain good shoulder belt position in the presence of poor upper anchorage locations. The consequence for child occupants would be greater head excursions, belt loading across the chest rather than through the clavicle, and an increased risk of head injury.

More research is needed to determine whether alternative booster designs might better control the shoulder belt. It may be possible to reroute poor shoulder belt geometry with a booster, but the booster would likely need to be anchored to the vehicle, and the shoulder belt routing features must be strong enough to withstand forces near 4 kN. This type of approach would likely result in heavier boosters that would need to be installed with LATCH. Instead, it may be more constructive to improve vehicle shoulder belt anchorage geometry, which would also benefit children who use backless boosters or no booster.

Lap belt angles were changed from 30 degrees to 69 degrees by moving anchorage locations downward and forward, which seemed to increase rollout even as it minimized submarining tendencies. Changing the lap belt angle from 50 to 60 degrees made LBS shift from near 19 to 41. As a result, the current test series does not provide dynamic data for the intermediate range that would allow us to set a range of acceptable lap belt scores based on dynamic considerations.

Conceptually, a threshold-level submarining configuration could be defined as one at which submarining occurs 50% of the time. Based on the results of the current testing, many different combinations of upper and lower anchorage locations would produce this threshold behavior, and this would further depend on the performance of the booster. As noted above, wider spacing of lap belt anchorages leads to submarining and narrower spacing leads to rollout in certain test conditions. Additional tests with a larger number of anchorage locations are needed to clarify these effects. The current testing demonstrates that ATD kinematics in boosters tested with a realistic range of anchorage locations are likely to differ substantially from those obtained with the FMVSS 213 anchorages.

5.3 UMTRI Seating Procedure and HIC

One of the objectives of this program was to evaluate ATD response using the UMTRI seating procedure, which positions the hips and heads of the ATD in locations where the hips and head of children the sizes of the dummies would be. Use of the UMTRI procedure produces more reclined initial postures, and tends to lead to more pronounced chin-to-chest contact, which can lead to increased variability in HIC. For each test condition using the UMTRI seating procedure, Figure 35 shows the absolute difference in HIC vs. the absolute difference in head excursion for paired test conditions. The blue shaded area shows a region where head excursion is repeatable within 16 mm, which is considered an acceptable level of repeatability with the current ATD and seating procedure. The red shaded area shows a region where HIC repeats within 100, which was selected arbitrarily as being an acceptable level of repeatability. For the 18 test conditions shown on this plot, 13 of them have an acceptable level of repeatability on head excursion. Only seven of those 13 test conditions have acceptable repeatability for HIC. The conditions where head excursion does not repeat well are either more extreme conditions of torso rollout or submarining, or where there was a substantial difference in initial torso angle during test setup. Head excursion repeats well in all conditions approaching a “normal” FMVSS 213 tests, whereas this is not the case with HIC. The variation in HIC, even when initial ATD posture is well controlled, indicates HIC is not the best measure for assessment of booster seat performance.

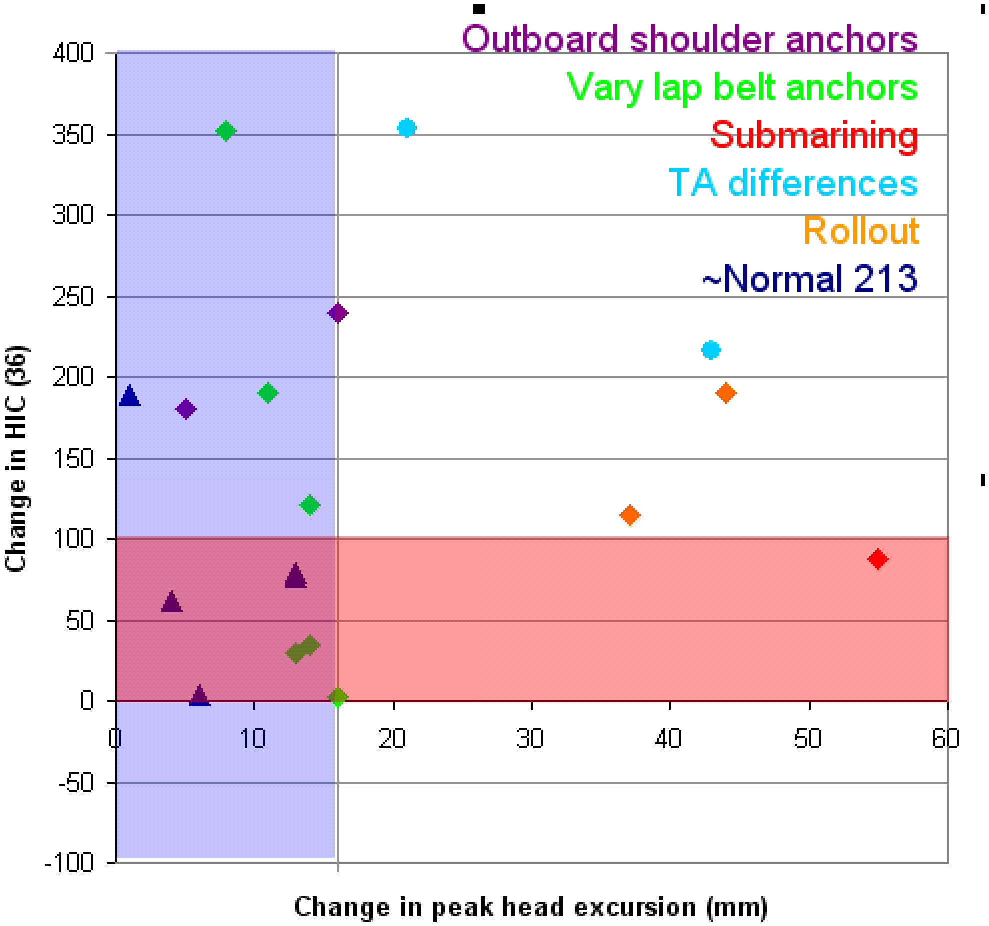


Figure 35. Change in HIC (36) vs. change in peak head excursion for paired test conditions using the UMTRI seating procedure. (TA=initial torso angle)

6.0 References

Reed, M. P., Ebert-Hamilton, S.M., Manary, M.A., Klinich, K.D., and Schneider, L.W. (2006). Improved positioning procedures for 6YO and 10YO ATDs based on child occupant postures. Technical Paper 2006-22-0014. *Stapp Car Crash Journal* 50:337-388.