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CHILD POSTURE AND BELT FIT IN SECOND ROW VEHICLE SEATS

KATHLEEN D. KLINICH, SHEILA EBERT, MATTHEW P. REED

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16. Abstract

Posture and belt fit were measured for 40 children ages 5 to 12 years across two phases of testing involving six vehicles and six boosters, including one integrated booster. The three-dimensional locations of landmarks on the children, belt, and seat were recorded in each condition. Belt anchorage locations and other vehicle dimensions were recorded to characterize the seating environments. Lap belt fit was quantified by the location of the edge of the belt relative to the anterior-superior iliac spine landmark on the pelvis. Shoulder belt fit was measured as the lateral distance of the belt from the occupant centerline at the height of the suprasternale landmark. Lap belt fit without a booster was generally poor, with the belt lying fully above the pelvis for most children in most conditions. Belt positioning boosters improved lap belt fit in all conditions and improved shoulder belt fit for many combinations of children and vehicle. Taller children generally experienced better belt fit, but the effects were small compared to the benefits of using a booster. Belt fit scores were correlated with predictions based on previous laboratory studies using child stature and vehicle geometry as inputs. Mean belt fit scores were well correlated across conditions with predictions based on ATD measurements.

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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	square inches	645.2	square millimeters	mm^2
ft^2	square feet	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	pound force	4.45	newtons	N
lbf/in^2	pound force 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)				
°C	Celsius	1.8C+32	Fahrenheit	°F
FORCE and PRESSURE or STRESS				
N	Newtons	0.225	pound force	lbf
kPa	Kilopascals	0.145	pound force 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)

ACKNOWLEDGMENTS

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INTRODUCTION

In a series of laboratory studies, researchers at the University of Michigan Transportation Research Institute (UMTRI) have quantified the belt fit that children experience across a range of booster configurations (Reed et al. 2005a, Reed et al. 2008, Reed et al. 2009). Important conclusions from these laboratory studies include:

- The belt fit provided by belt-positioning boosters differs substantially across booster models.
- On average, larger children experience better belt fit than smaller children when sitting without a booster, but children the size of a typical three-year-old experience better lap belt fit in a booster than a typical twelve-year-old sitting without a booster.
- Shorter seat cushion lengths are associated with less-slouched postures and better lap belt fit.

UMTRI research has also shown that the seat cushions in rear seats are generally much longer than the thighs of children under age 12 (Reed and Huang 2006). Longer seat cushions are associated with more-slouched postures for both adults and children (Reed et al. 2005b, Reed et al. 2008).

The objectives of the current study were:

- Gather data to quantify the posture and belt fit that children experience in vehicle second-row seats with and without belt-positioning boosters.
- Gather data to improve quantification of the effects of seat cushion length on child posture and belt fit.
- Compare the results to predictions based on laboratory data.

METHODS

Vehicles

Six vehicles were chosen for testing. Half of subjects were tested in three vehicles each. Figure 1 shows the vehicles used in the first phase of testing, while Figure 2 shows those tested in Phase II. The vehicles were chosen to span a range of size and body style. Additional requirements included a readily accessible second-row seat and rental availability in Ann Arbor. One vehicle (Volvo) was provided by the manufacturer. The minivan and the large SUV were equipped with second-row captain's chairs that could be adjusted fore-aft. Because the outboard belt anchorage locations were fixed to the vehicle, changes in seat position affected belt angles. Consequently, these seats were tested in two fore-aft positions. The Volvo XC60 was equipped with a two-position integrated booster (see Figure 5). Along with the booster-stowed condition, this vehicle provided three test conditions. The Traverse was equipped with a shoulder belt router pictured in Figure 3.

Figure 1. Vehicles used in Phase I testing.

Figure 2. Vehicles used in phase II testing.

Figure 3. Traverse has an add-on “comfort guide” for the rear seat positions, which is a piece of elastic from the pillar to a plastic sleeve that that the shoulder belt slides through.

Table 1 summarizes the key dimensions and specific seat features in each vehicle, as well as the code used to identify the vehicle conditions tested in this study. Table 2 describes characteristics of the vehicle belt systems in each vehicle.

Table 1. Vehicle Seat Details

Condition	Vehicle	Seat Position	Seat Type	Seat Back Angle (˚)	Seat Cushion Angle (˚)	H30 (mm)	Cushion Length (mm)	Seat surface
Pas1C1	Altima	NA	Bench	28	14	330	474	Leather
Mnv1C1	Caravan	Aft	Captain	23	18	300	470	Cloth
Mnv1C2	Caravan	Fore	Captain	23	18	316	470	Cloth
Suv1C1	Traverse	Aft	Bench	23	17	295	425	Cloth
Suv1C2	Traverse	Fore	Bench	23	17	297	425	Cloth
Pas2C1	Civic	NA	Bench	27	16	320	463	Cloth
Pas3C1	Taurus	NA	Bench	28	18	310	475	Cloth
Suv2C1	Volvo	NA	Integrated	29	15	340	454	Leather

Table 2. Vehicle Belt Details

	H-pt to Anchor XZ Angle Rel. Horizontal (˚)		Anchor Y Distance Rel. Seat Centerline (mm)		D-ring to H-pt. Angles Rel. Vertical (˚)		Buckle Information		
ID	OB	IB	OB	IB	XZ	YZ	Location	Stalk	D-Ring Condition
Pas1C1	53	45	245	148	38	22	Bight	Webbing	+Guide
Mnv1C1	55	51	282	220	31	24	Lateral	Rigid	Low
Mnv1C2	45	51	282	220	34	20	Lateral	Rigid	High
Suv1C1	69	51	300	169	var.	var.	Bight	Rigid	+Guide
Suv1C2	53	51	300	169	28	22	Bight	Rigid	-Guide
Pas2C1	52	42	226	182	43	23	Bight	Webbing	NA
Pas3C1	34	42	353	154	32	22	Fwd. Bight	Webbing	NA
Suv2C1	73	59	237	220	42	26	Bight	In seat	NA

Boosters

Six boosters were selected for testing in this study. The boosters were chosen from those used in previous studies to provide a wide range of belt-fit performance. Details about each booster are listed in Table 3. Figure 4 shows the boosters used in Phase 1 and Figure 5 shows the Phase-2 boosters.

Table 3. Boosters

Booster Number:	**B12H**	**B12L**	**B32H**	**B34H**	**B35H**	**B36H**	**B37L**	**B37H**
Model	Turbo Booster	Turbo Booster	Alpha Omega	Generations	Frontier 85	ProBooster	Stage 1	Stage 2
Manufacturer	Graco	Graco	Safety 1st	Evenflo	Britax	Recaro	Volvo	Volvo
Configuration	High Back	Low Back	High Back	High Back	High Back	High Back	Low Back	Low Back
Type	Booster Only	Booster Only	Combo	Combo	Combo	Booster Only	Integrated Booster	Integrated Booster
Child Weight limit (lb)	30-100	40-100	40-100	30-100	40-120	30-120	49-79	33-55
Child Stature Limit (in)	38-57	40-57	43-52	37-57	42-65	37-61	45 - 55	37- 47

Figure 4. Boosters used in Phase I testing: Generations (left), Frontier (center), and the Turbo Booster (right).

Figure 5. Boosters used in Phase II: ProBooster (left), Alpha Omega (left center), Volvo Integrated at the “Low” position (right center), and the Volvo Integrated at the “High” position (right).

Vehicle Test Matrix

Testing was conducted in two phases to achieve a wide range of booster/vehicle combinations. Table 4 lists the allocation of participants by phase, vehicle, and booster/seat configuration.

Table 4. Allocation of Participants by Vehicle and Booster/Seat Configuration

	PHASE 1					PHASE 2		
Vehicle:	Nissan Altima Pas1	Dodge Caravan Mnv1		Chevy Traverse Suv1		Honda Civic Pas2	Ford Taurus Pas3	Volvo XC60 Suv2
Vehicle Condition Level:		C1	C2	C1	C2			
Booster Conditions								
TurboBooster BB *(B12L)*	10	10	10	10		10	10	10
Alpha Omega *(B32H)*	10	10		10		10	10	10
Frontier 85 *(B35H)*	10	10		10		10	10	10
TurboBooster HB *(B12H)*	10	10		10		10	10	10
Generations *(B24H)*	10	10		10		10	10	10
ProBooster *(B26H)*	10	10		10		10	10	10
No booster	20*	20*	10	20*	10	20*	20*	20*
Integrated Low *(B37L)*								20**
Integrated High *(B27H)*								20**

*Two repetitions per participant,
**Two repetitions for half of the participants
Grey and white = blocked "groups" 1 and 2 respectively

In Phase 1, testing was conducted with the Nissan Altima, Dodge Caravan, and Chevrolet Traverse, and Phase-2 testing was conducted with the Honda Civic, Ford Taurus, and Volvo XC60. All testing used the second-row, left (driver-side) outboard seating position. With each phase, participants were tested in one of two blocks of booster conditions. Half the participants in each phase were tested in the TurboBooster backless, Alpha Omega, and Frontier 85, while the other half were tested in the TurboBooster highback, Generations, or ProBooster. All participants were tested in the no-booster condition twice for each vehicle in their phase. The Caravan and Traverse seats were equipped with fore-aft adjustment. Most of the testing was conducted with these seats full-rear, but additional trials were conducted with the seat full-forward (see Table 1). In the Caravan, the testing included the TurboBooster backless configuration. In all cases, the vehicle D-rings were adjusted to their lowest positions, except that in conditions C2, with the seats full-forward, the adjustable D-rings were set to their highest positions. In Phase 2, participants were tested in the low and high integrated-booster configurations available in the Volvo. Repeated measurements were made in each of the no-booster conditions and in the integrated (Volvo) booster conditions. For each subjects' test sessions, the order of vehicles was randomized, as were all trials within each vehicle, both with and without booster.

Subject Recruitment

For this study, 20 boys and 20 girls aged 5 to 12 whose stature and weight span the range of the Hybrid III 6YO and 10YO ATDs were recruited. The weight-by-stature distribution of subjects for each phase and group are shown in Figure 6. All test procedures were approved by an Institutional Review Board at the University of Michigan (HUM00008969).

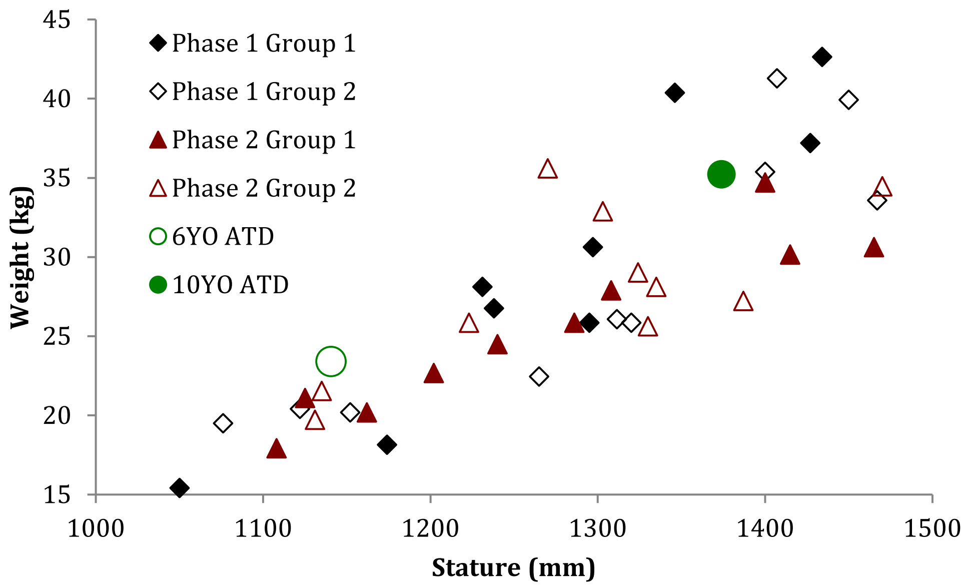


Figure 6. Participant weight and stature distribution.

Participant Body Dimensions

Each participant wore loose-fitting clothing provided by the experimenters that was open in the back to facilitate access. Initial testing included the standard anthropometric measures listed in Table 5. Figure 7 shows an example of the type of calipers used in anthropometric measurement.

Table 5. Standard Anthropometric Measures

Stature	Hip Breadth
Weight	Shoulder Elbow Length
Head Length	Elbow Fingertip Length
Erect Sitting Height	Buttock-Knee Length
Shoulder Height	Buttock-Popliteal Length
Acromion Height	Chest Depth
Knee Height	Abdomen Depth
Popliteal Height	Chest Width
Bideltoid Breadth	Abdomen Width
Bi-acromial Breadth	Popliteal Depth
Bispinous Breadth	Waist circumference, seated

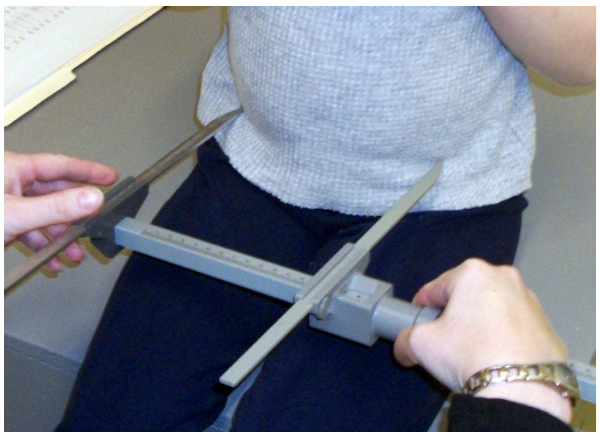


Figure 7. Measuring bispinous breadth as part of standard anthropometry.

Key landmarks were marked on each subject using washable marker as shown in Figure 8. Body landmark locations were recorded using a FARO Arm coordinate digitizer (FARO Technologies, Lake Mary, FL) as each participant sat in laboratory hardseat, shown in Figure 9, which provides access to posterior landmarks on the spine and pelvis. Figure 10 shows the landmarks that were recorded in the hardseat.

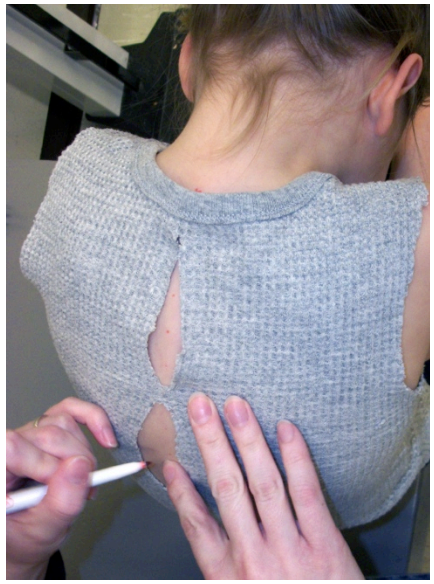


Figure 8. Locating and marking spinous process landmarks prior to hardseat measurement.

Figure 9. Measuring body landmark locations in the hardseat.

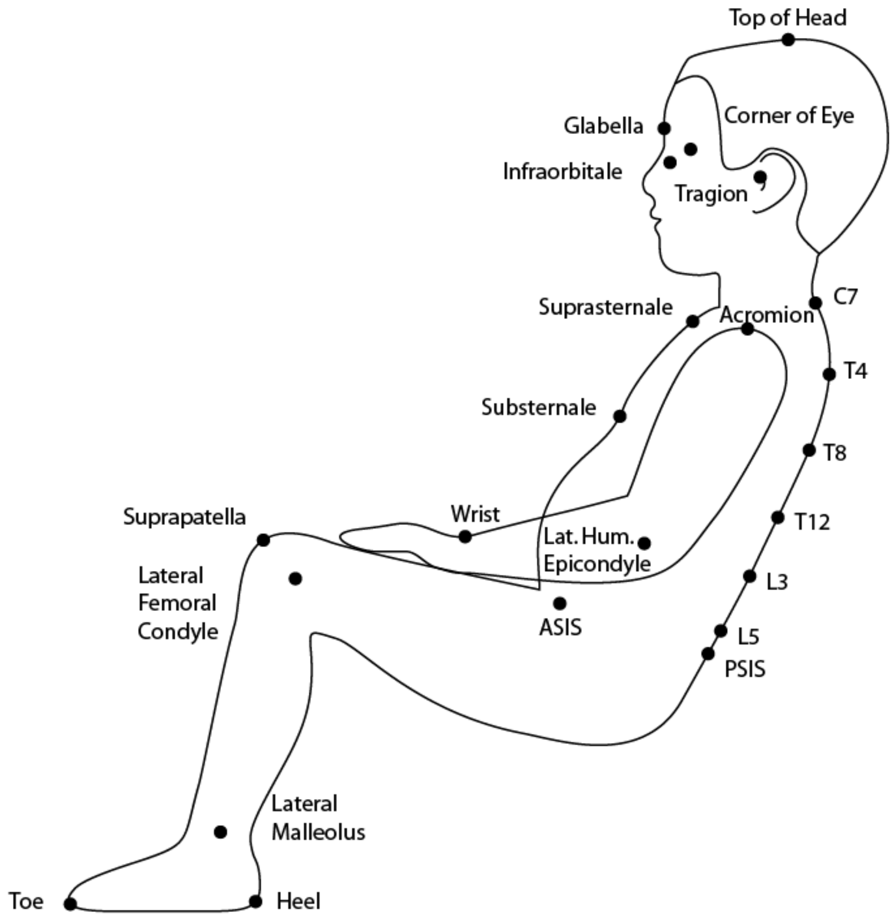


Figure 10. Landmarks recorded for each participant in the hardseat.

Laboratory Test Conditions

Following anthropometry measurement, subject posture and belt fit were measured as each child sat in a reconfigurable mockup of a rear seat. This mockup was used in previous UMTRI studies (Reed et al. 2005a, Reed et al. 2008, Reed et al. 2009). The objective of this testing was to quantify the effects of seat cushion length on posture and belt fit. Body and belt landmarks were recorded while the participant sat in each of five conditions distinguished by seat cushion lengths of 325, 360, 400, 435, 471, and 504 mm. Seat cushion length was measured as described in Huang and Reed (2006). The seat back angle (SAE A40) was 23 degrees and seat cushion angle (SAE A27) was 14.5 degrees as measured by the SAE J826 manikin. The seats was mounted high enough from the floor (SAE H30 = 400 mm) that most of the children were not able to touch the floor while sitting all the way back on the seat, reproducing the typical situation for children in rear vehicle seats. Subjects chose their own posture and donned the belt themselves as shown in Figure 11.

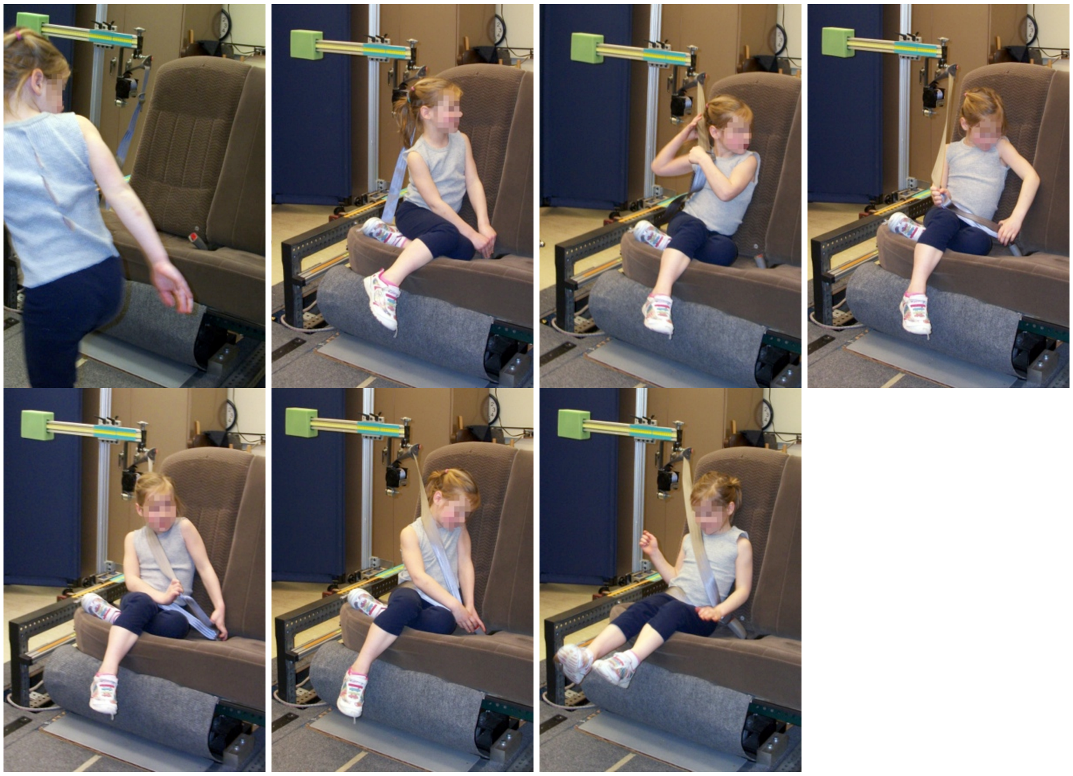


Figure 11. Subject choosing posture and donning belt in reconfigurable vehicle seat mockup.

Vehicle Measurements

The FARO arm was used to record subject and vehicle landmark locations listed in Table 6 for each in-vehicle test condition. The FARO arm was also used in its streaming mode to record the position of the shoulder and lap belt across the subject. In addition, a sagittal stream at the left and right ASIS lateral position was recorded from the substernale height to mid thigh.

Table 6. Recorded Points

Torso Belt Points	Child Landmarks Left and Right	Booster
Dring Pivot Dring (or guide) Fore Dring (or guide) Aft	Acromion Suprapatella Infrapatella Femoral Condyle, Lateral Femoral Condyle, Medial ASIS	Shell Reference Points (3) ** Headrest Reference Points (3)** Vehicle Reference Points (3) **
Torso Belt Relative to Child	Child Landmarks D-ring Side (Outboard)	Streams of Continuous Points
Clavicle Outboard Clavicle Inboard Leaves Shoulder Suprasternale Height Outboard Suprasternale Height Inboard Sternum Top Sternum Bottom	Infraorbitale at pupil Ectoorbitale Tragion Clavicle, Medial Clavicle, Lateral Humeral Epicondyle, Lateral Wrist Malleolus Lateral Heel Ball of Foot Toe	Sagittal stream at ASIS lateral position from substernale height to mid thigh (left and right) Stream along top of shoulder (outboard)
Lap Belt Points		
Latchplate Fore/Aft Buckle-latchplate opening Buckle/seat plane fore and aft Outboard anchor/seat contact		
Lap Belt Points Relative to Child, Left and Right	Child Landmarks Centerline	
Hip Contact Fore and Aft Child ASIS Fore, Mid, Aft	Suprasternale Substernale Glabella	

**** Digitized with and without child on booster**

Prior to testing, each booster seat was adjusted outside the vehicle to fit each participant according to child restraint manufacturers' directions as shown in Figure 12. Figure 13 shows a typical sequence of in-vehicle measurement, where the adjusted booster location is measured before the child enters the vehicle, the child sits in the booster and dons the seat belt, measurements with the belt in place are taken, and then additional body landmarks are recorded with the belt taken off. A close-up of the points used to document lap belt position relative to the ASIS is shown in Figure 14; the top and bottom of the lap belt at the lateral location of the left and right ASIS are recorded.

Figure 12. Adjusting booster seat to fit each child.

Figure 13. Typical sequence of in-vehicle test measurements.

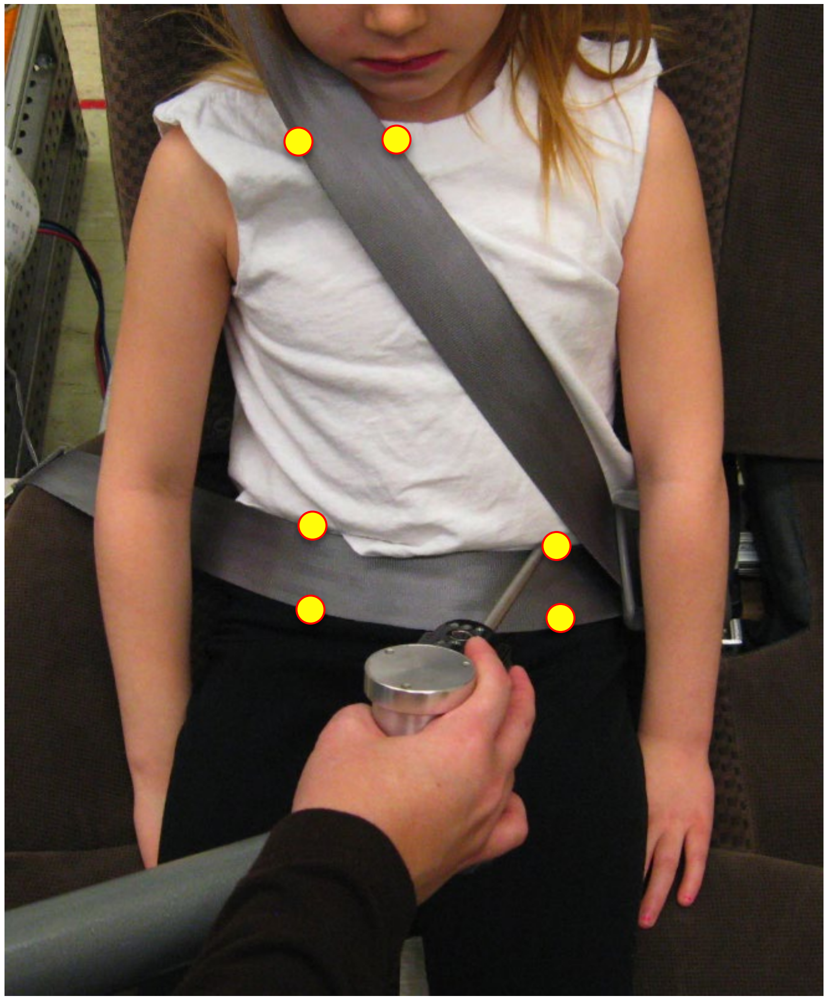


Figure 14. Points used to characterize lap belt location with respect to the pelvis and suprasternale.

Calculations

A method of quantifying lap belt and shoulder belt position was developed in previous UMTRI research studies (Reed et al. 2005a, Reed et al. 2008, Reed et al. 2009). Shoulder belt score, illustrated in Figure 15, is defined as the lateral measurement between the suprasternale and the nearest point on the shoulder belt at the height of the suprasternale. Negative values indicate the belt passes to the right (buckle side) of the suprasternale landmark.

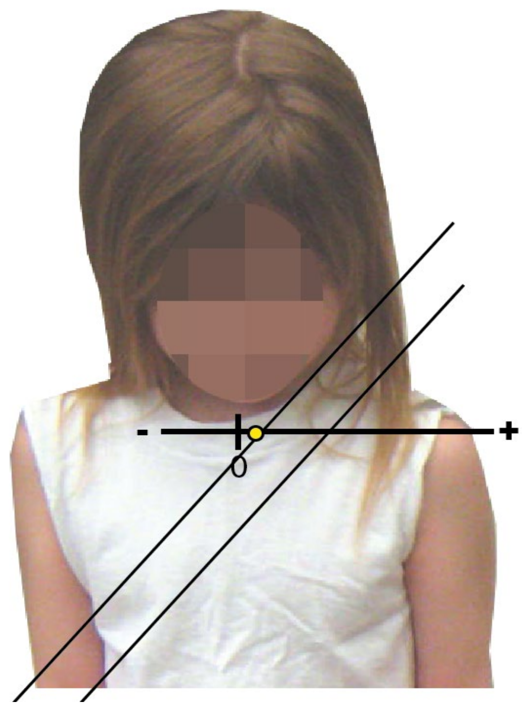


Figure 15. Shoulder belt score.

Calculation of lap belt score is shown in Figure 16. Using a spline fit along the stream taken at the lateral ASIS location, the distance from the projection of the ASIS to the top of the lap belt is the lap belt score. Positive values indicate that the belt lies below the ASIS, while negative scores indicate that the top of the belt lies above the ASIS towards the abdomen.

As shown in Figure 17, the location of the D-ring is characterized by the angular relationship between the D-ring and the seat H-point in front (YZ) view. Using as an origin the vehicle seat H-point on the vehicle seat centerline, the angle from the vehicle seat centerline to a line between the origin and the D-ring is defined as the frontal D-ring angle.

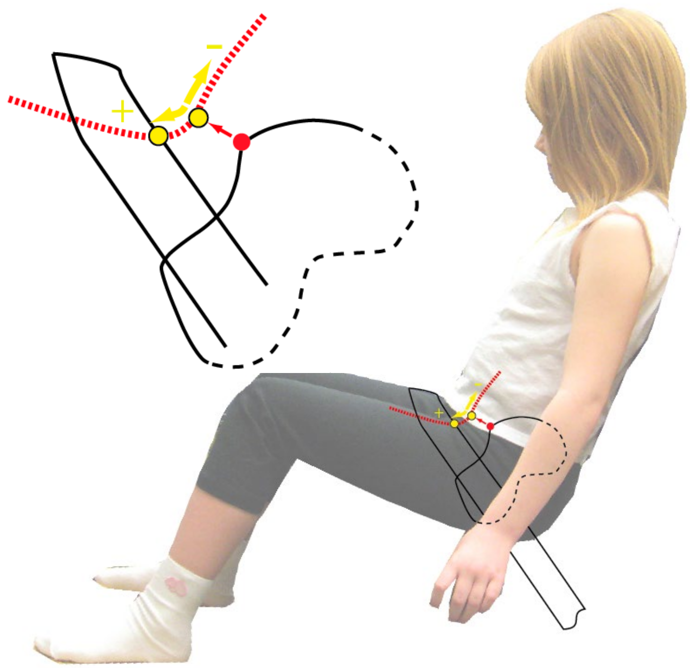


Figure 16. Calculating lap belt score.

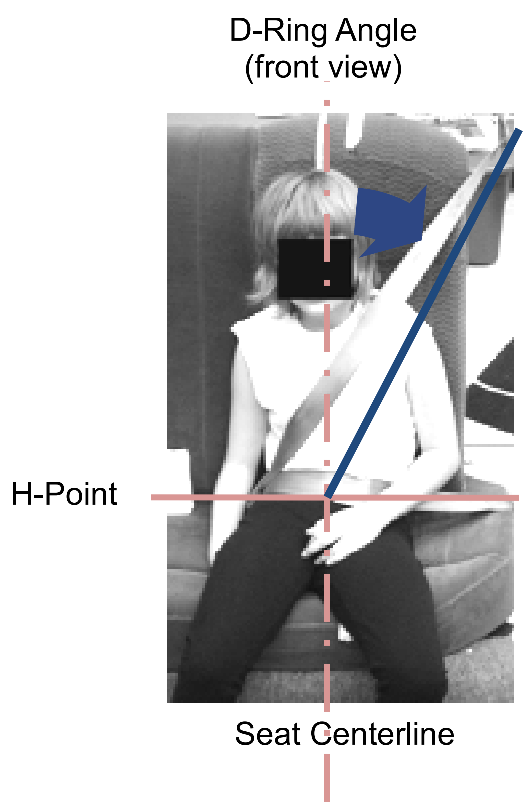


Figure 17. Calculating D-ring angle in YZ plane.

Measurement of Vehicle Belt Fit Using 6YO ATD

A critical component of this research task is to establish the relationships between vehicle belt fit, as measured by belt fit on the 6YO Hybrid-III ATD, and child belt fit under the same conditions. Previous procedures used to install the ATD and measure belt fit in boosters are inadequate, because children seated without a booster tend to slump considerably. To address this need, a new ATD positioning procedure was developed for situations in which children are seated without a booster (Reed et al. 2011).

Figure 18 shows the results of applying this procedure in two vehicles. The ATD pelvis does not contact the seat back and the lap portion of the belt is routed over the abdomen. The torso is propped up slightly to eliminate head contact with the seat back (Reed et al. 2011).

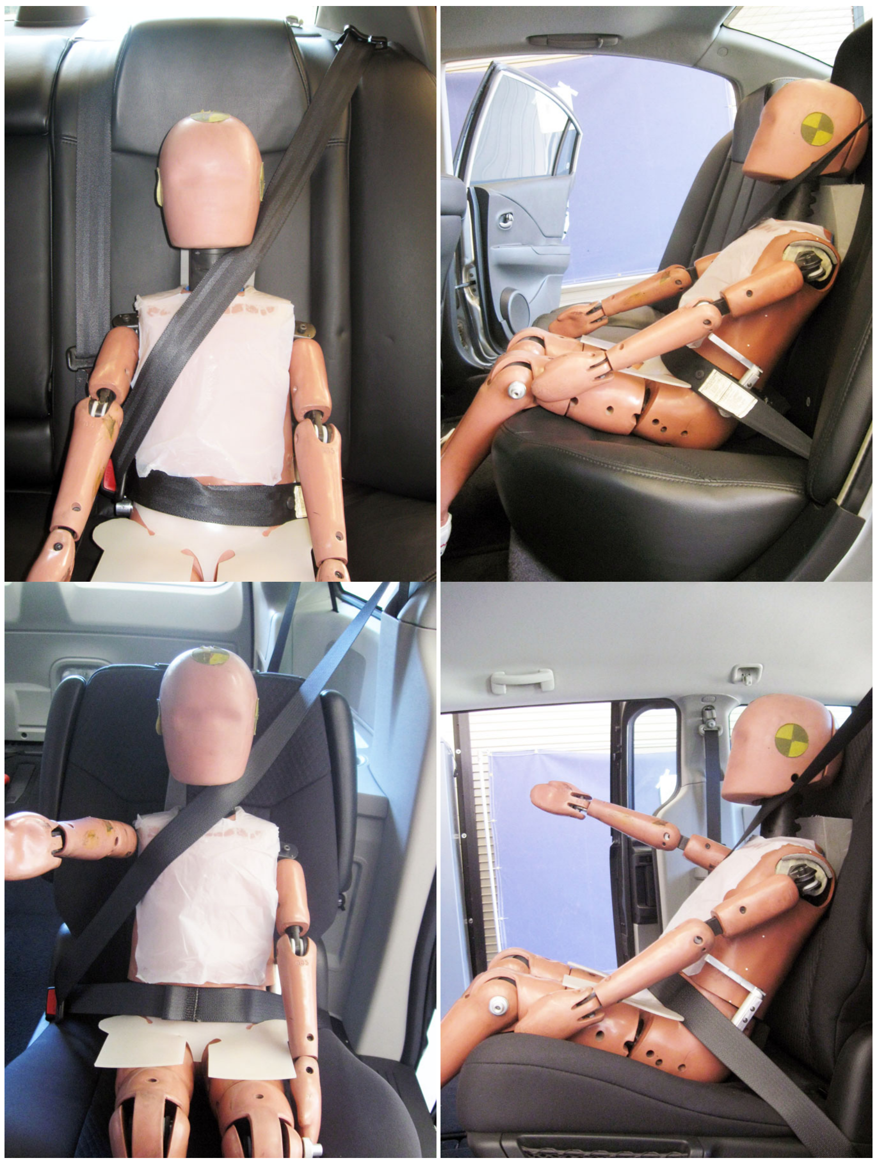
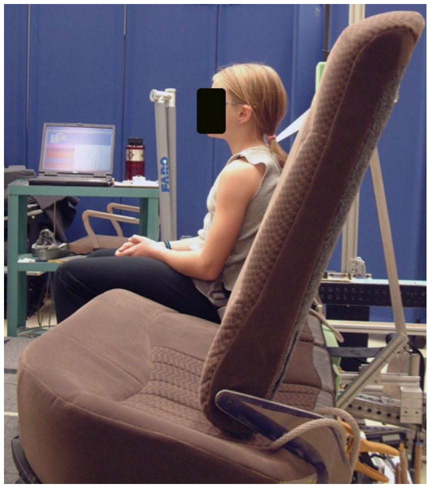


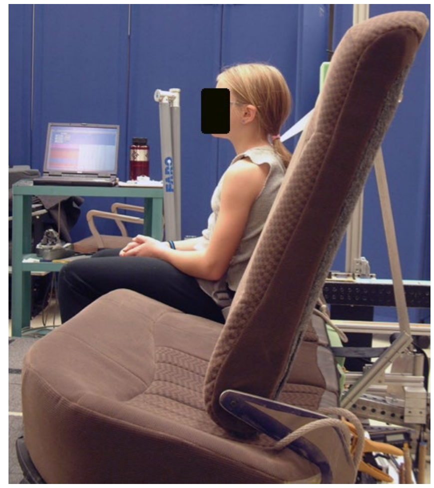
Figure 18. Belt fit obtained with 6YO ATD in Nissan Altima (top) and Dodge Caravan (bottom) using new ATD positioning/belt fit measurement procedures.

RESULTS

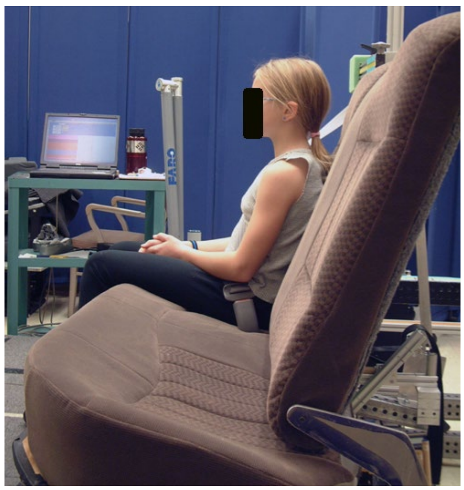
Effects of Seat Cushion Length on Posture

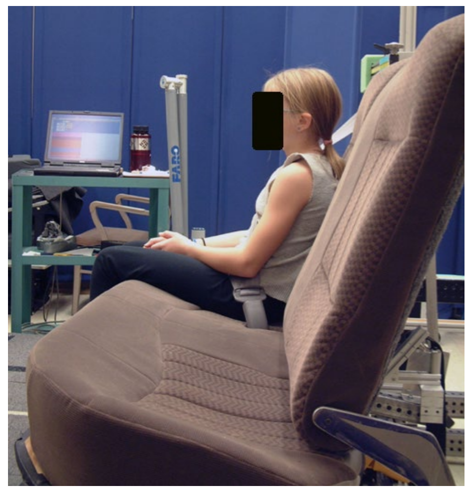
Figure 19 shows the posture of one subject as the seat cushion length is varied from 325 to 504 mm. The child's posture becomes visibly more slumped with longer cushion settings, with a gap opening up behind the child's pelvis. Longer seat cushions produced slightly lower lap belt scores, as shown in Figure 20. The mean lap belt score drops by 4.8 mm for each 100-mm increase in cushion length. An effective lap belt angle was calculated as the angle of the side view vector from the outboard anchorage to the measured lap belt point on the right (outboard) side with respect to horizontal. The effective lap belt angle shown in Figure 21 was slightly flatter (lower) with longer seat cushion due to greater slumping and more-forward hip locations. Figure 22 shows the distribution of calculated hip locations relative to seat H-point. On average, increasing the seat cushion length by 100 mm shifted the children's hips 35 mm further forward on the seat. Figure 23 illustrates the increased slumping associated with longer cushions by showing eye height above seat H-point. On average, increasing the seat cushion length from 325 to 500 mm lowered the children's eyes by 36 mm.



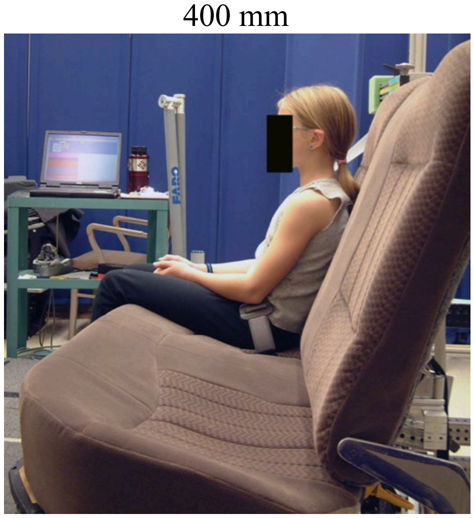


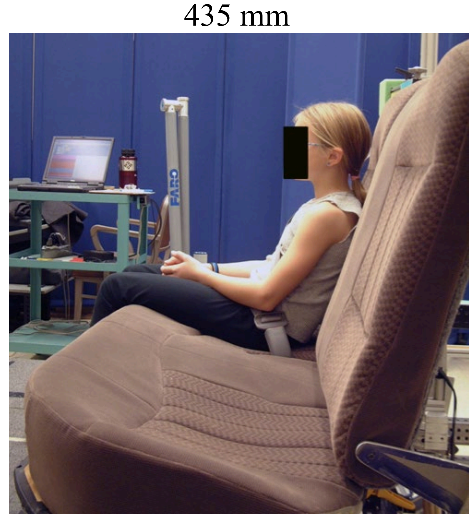
325 mm 360 mm





400 mm 435 mm





471 mm 504 mm

Figure 19. Qualitative variation in posture with cushion length for one subject.

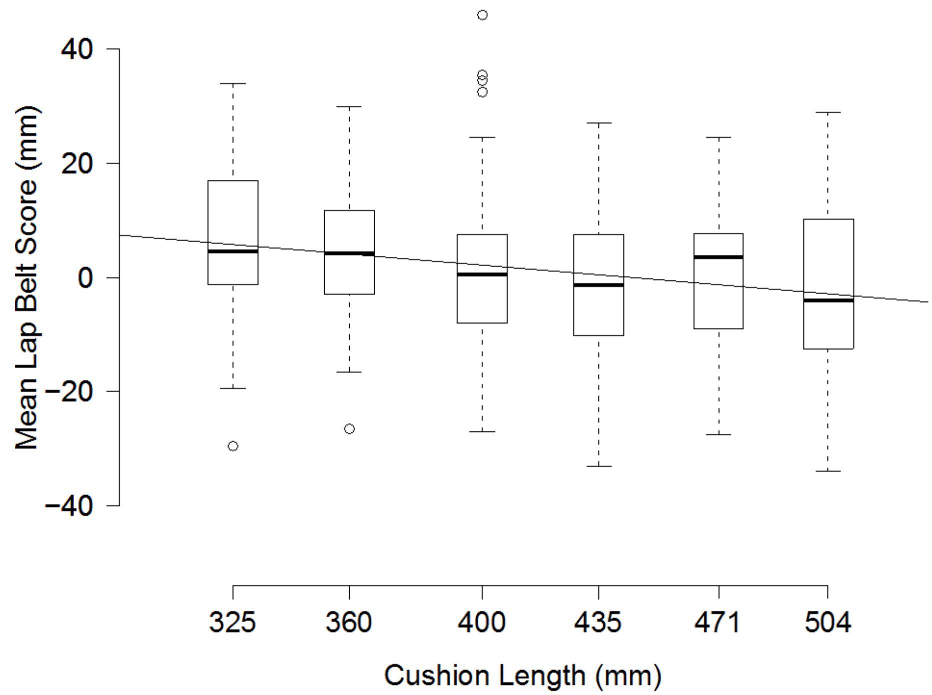


Figure 20. Variation in mean lap belt score with cushion length.

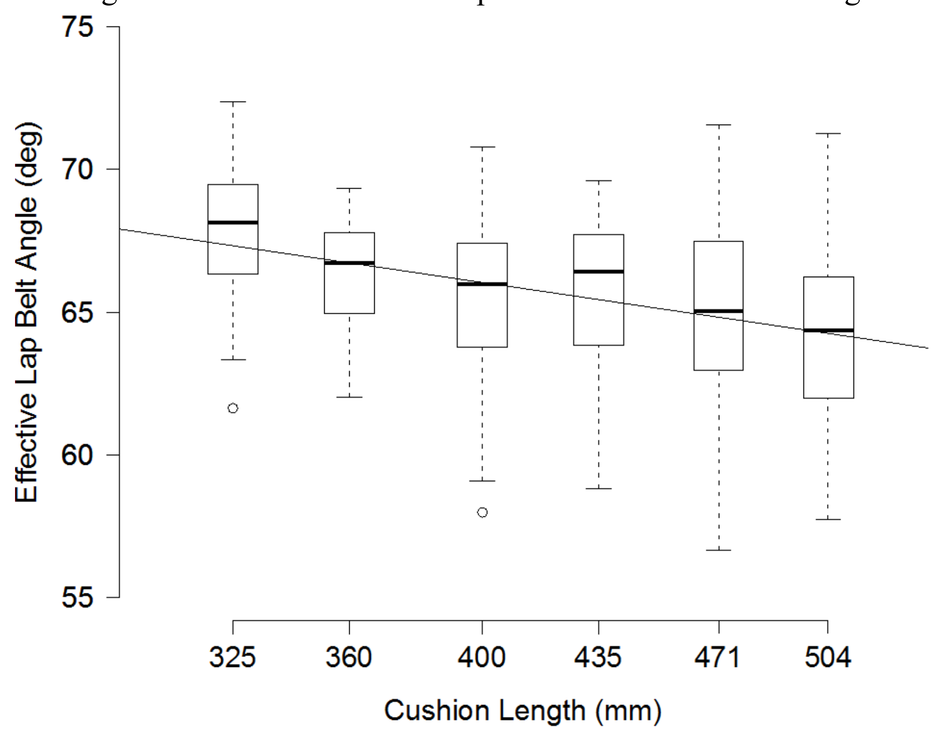


Figure 21. Variation in effective lap belt angle with cushion length.

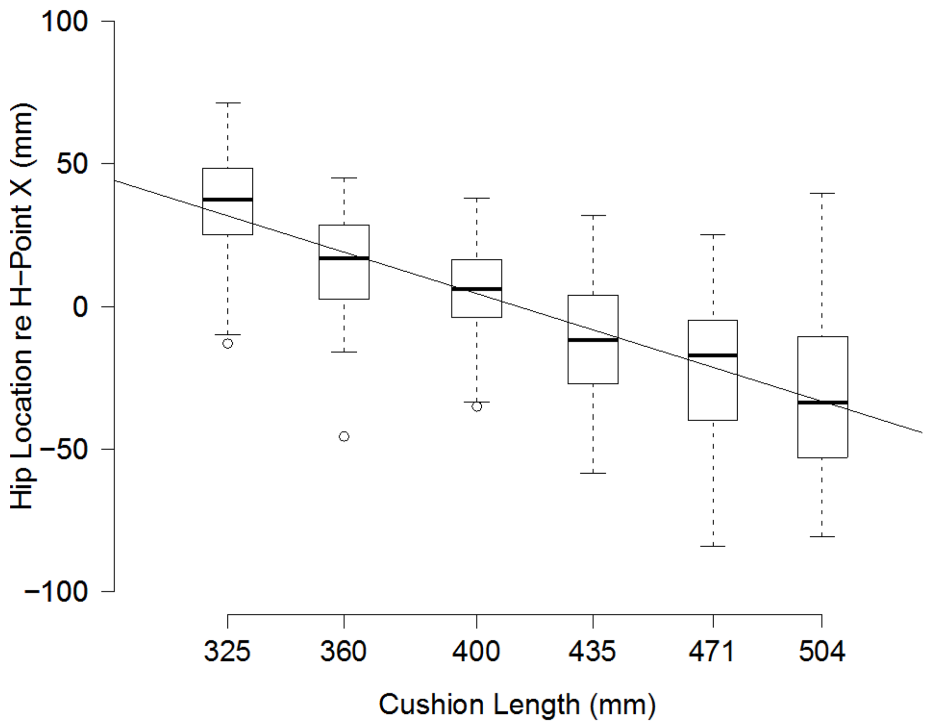


Figure 22. Variation in hip fore-aft location relative to seat H-point with cushion length.

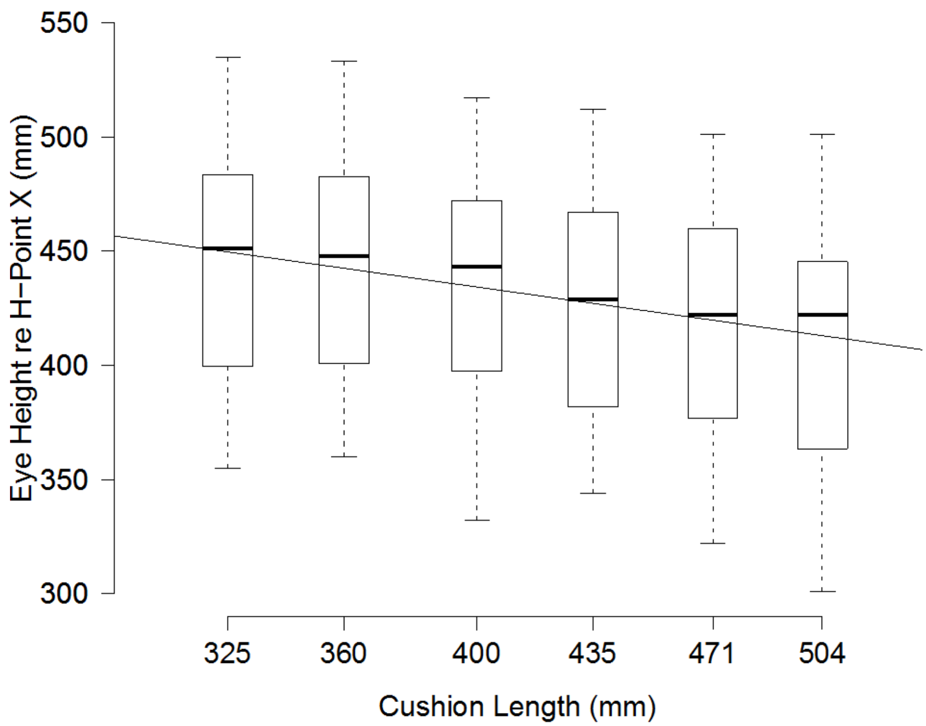


Figure 23. Variation in eye height relative to seat H-point with cushion length.

In-Vehicle Posture

Qualitative

Figure 24 through Figure 26 show images of a 1400-mm-tall child sitting in the rear seat of three vehicles with and without an add-on booster. In the Caravan, the child's feet rested on the floor while sitting on the vehicle seat, but were above the floor when sitting on the booster. The outboard lap belt angles were visibly different across the three vehicles.

Figure 26 and Figure 27 show two children sitting in the Volvo with the integrated booster stowed and at the two height settings. The images show an apparent increase in lap belt angle relative to horizontal at higher booster settings.

Figure 24. An 11YO subject, stature 1400 mm, seated in Dodge Caravan with and without a booster.

Figure 25. An 11YO participant with stature 1400 mm seated in Nissan Altima with and without a booster.

Figure 26. An 11YO subject with stature 1400 mm seated in Chevy Traverse with and without a booster.

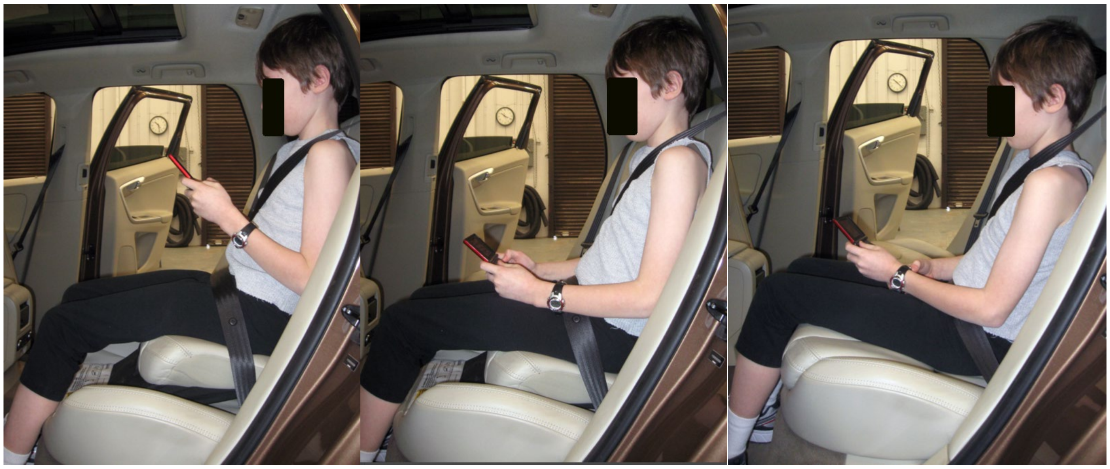


Figure 27. 9YO subject with stature 1297 seated in Volvo in integrated booster with high, low, and stowed positions.

Figure 28. 6YO subject with stature 1131 seated in Volvo with the integrated booster in the high, low, and stowed positions.

Belt Fit: Variation with Test Condition

Box plots of the lap belt score in each vehicle without the booster are shown in Figure 29. Scores in the two seat positions (C1 and C2) in Mnv1 and Suv1 were not significantly different and so were pooled. Lap belt score in Pas1 is lower than in the other vehicles, which have a similar range of scores. None of the vehicles had a mean value of lap belt score that was positive, indicating that on average, for the range of 5-to-12 year old subjects tested in this study, vehicle seat belts alone do not produce good lap belt fit, where good fit is defined as a belt resting fully below or forward of the ASIS landmarks.

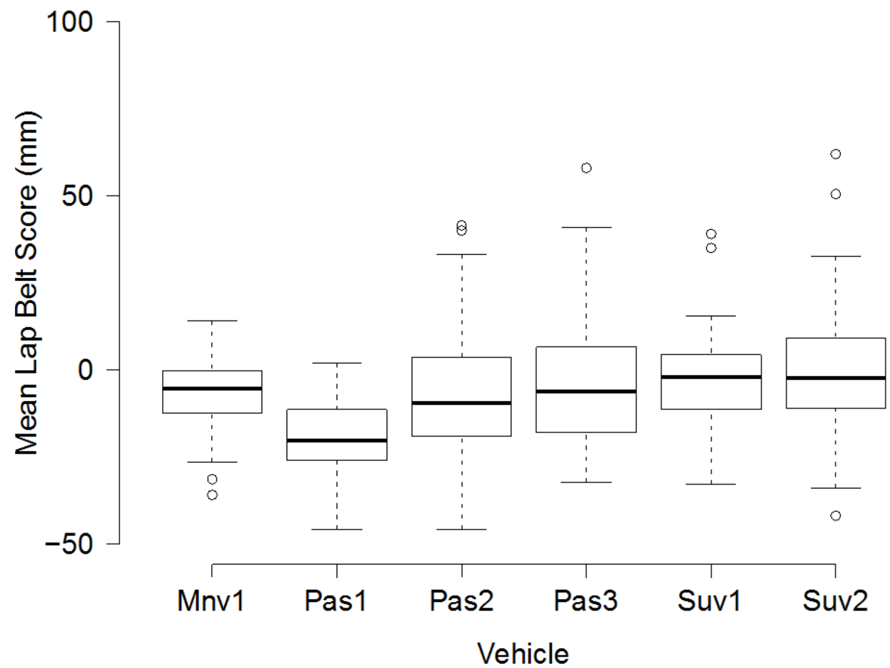


Figure 29. Lap belt score box plots for each vehicle without booster. C1 and C2 are pooled for Mnv1 and Suv1.

Shoulder-belt score box plots are shown in Figure 29. Seat positions C1 and C2 produced different scores for Suv1, so C1 and C2 are shown separately. On average, the minivan and three passenger vehicles produce belt shoulder belt fits that cross close to the child's suprasternale without using a booster. SUV1 shoulder belts cross further outboard on the child's shoulder, while SUV2 shoulder belts cross further inboard.

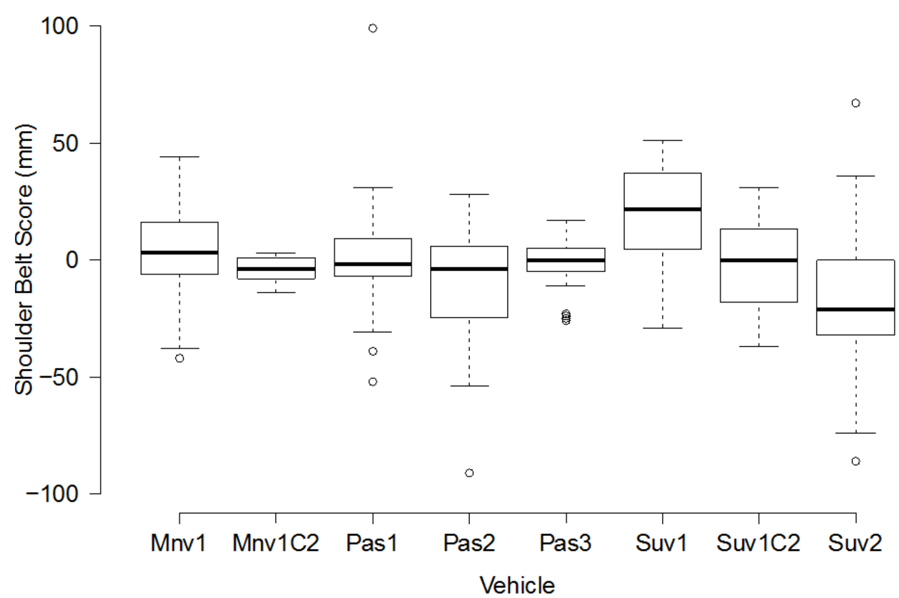


Figure 30. Shoulder belt score box plots for each vehicle condition without booster.

Figure 28 shows box plots of lap belt score for each vehicle and booster seat condition. Across vehicles, the two conditions with booster 12 and conditions with booster 36 produced the best lap belt scores. Test conditions with boosters generally showed greater differences with the no-booster condition in the three passenger vehicles, and the least amount of difference in the minivan. In all vehicles, median lap belt scores for the booster conditions were better than in the no-booster condition.

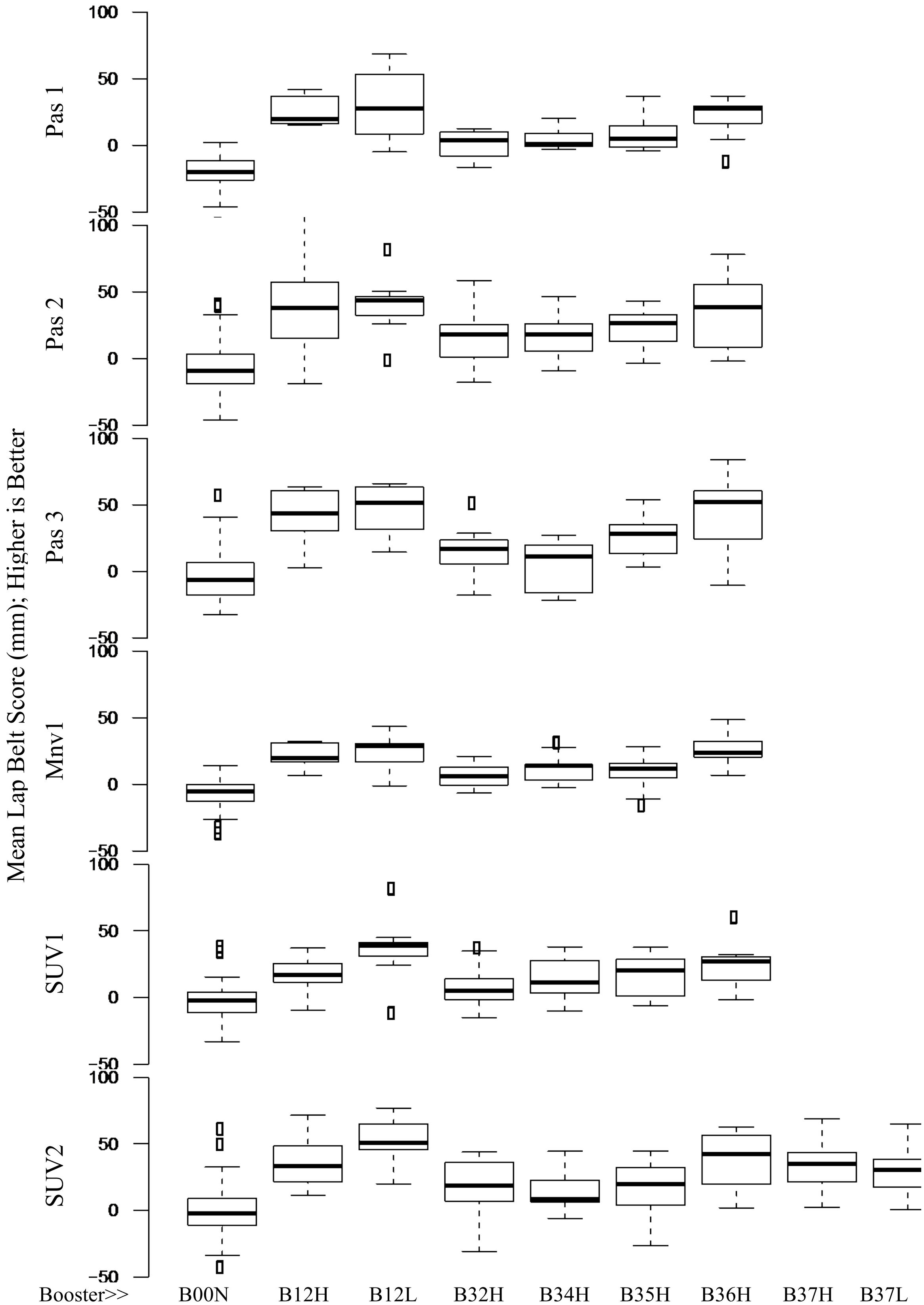


Figure 31. Lap belt score box plots for each booster condition and vehicle.

Figure 32 shows the distribution of mean lap belt score across vehicles and boosters. The boosters show a fairly consistent rank across vehicles, with booster B12 generally having the best scores. However, the vehicle also has an effect, with better median scores in Pas2 and Pas3 for booster conditions than in Mnv1, Pas1, and Suv1. All booster conditions produced mean lap belt scores substantially better than were obtained without any booster. B00N conditions are pooled in Mnv1 and Suv1 across seat positions C1 and C2.

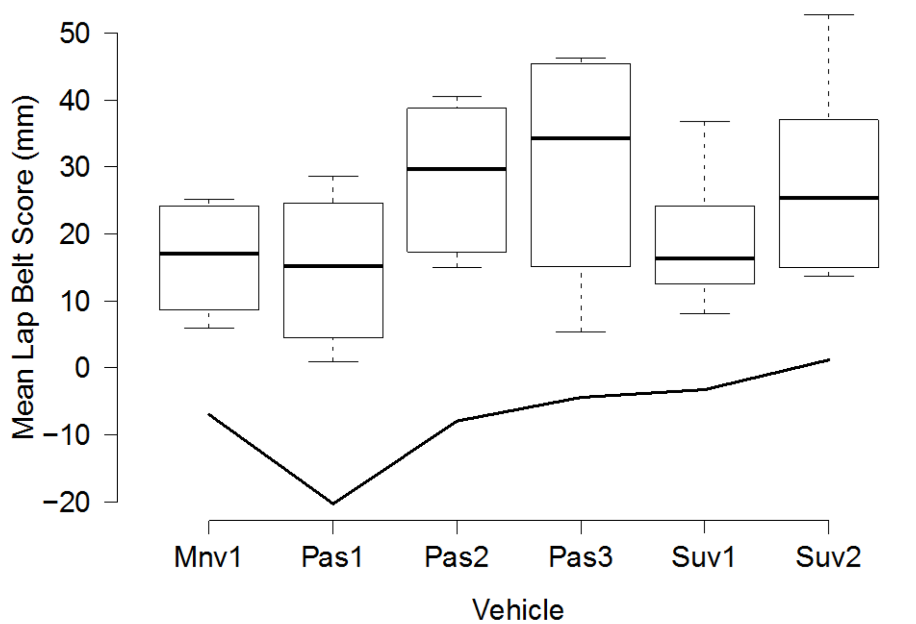


Figure 32. Mean lap belt score by vehicle and booster. Top figure shows boxplots of mean lap belt score for booster conditions and a line for no-booster conditions. Bottom figure shows individual lines for each booster condition. Data are shown for seat position C1 only for Mnv1 and Suv1.

Figure 33 shows boxplots of shoulder belt scores by booster and vehicle. The data show that boosters differ fairly widely in the distribution of shoulder belt scores, and the differences between the boosters are similar across vehicles. Figure 34 shows box and line plots for mean shoulder belt scores across booster and vehicle conditions. In all vehicles, the shoulder belt score was much lower with no booster, with a mean value of 1.5 mm indicating that the inner edge of the shoulder belt passed over the suprasternale landmark, on average. In contrast, the mean score for all booster conditions was 37 mm, indicating that the belt was substantially further outboard. The line plot shows that the rank order of shoulder belt score across boosters was similar across vehicles, demonstrating that the booster belt routing was usually more important than the vehicle belt geometry in determining shoulder belt score.

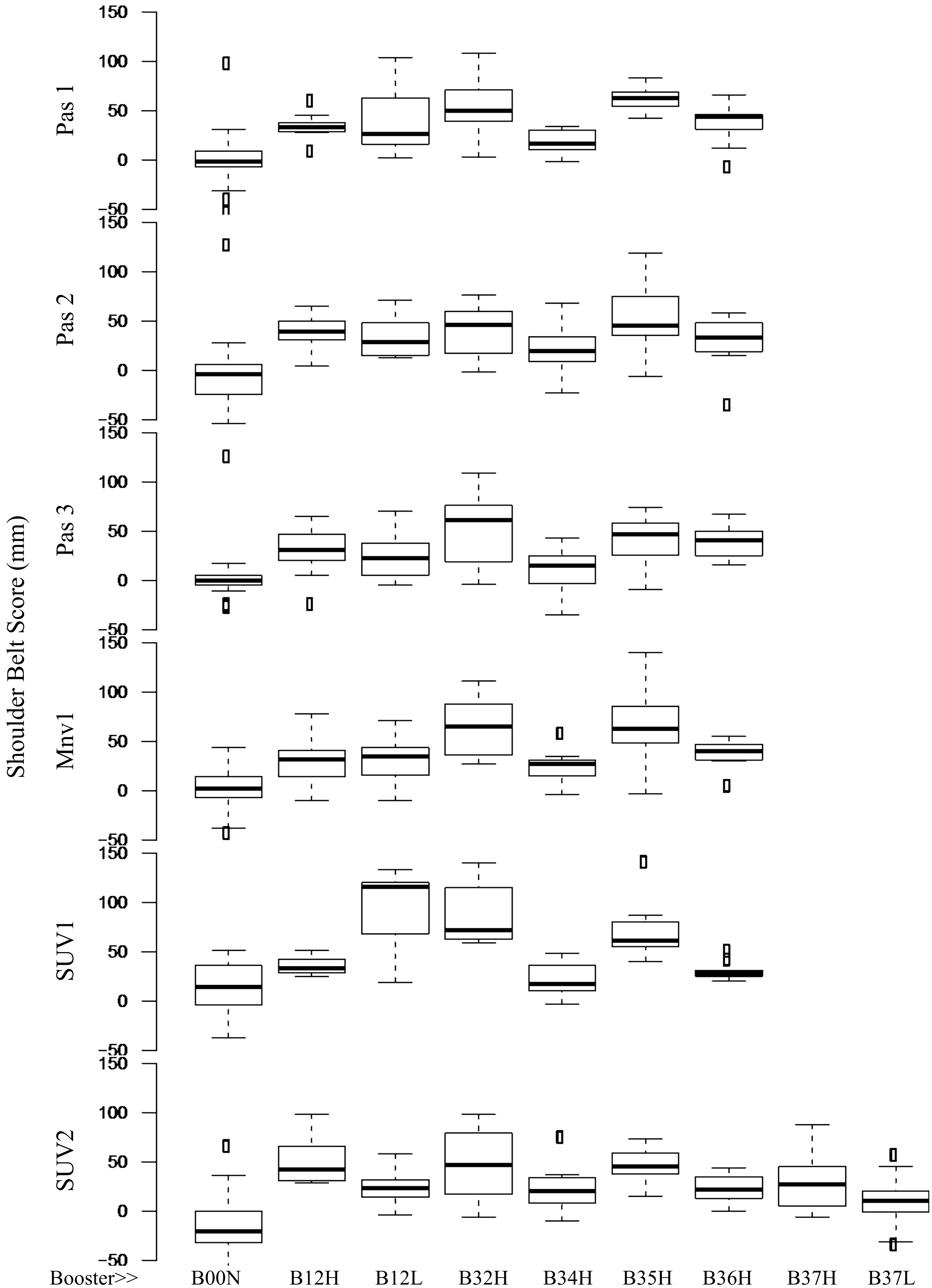


Figure 33. Shoulder belt score box plots for each booster condition and vehicle.

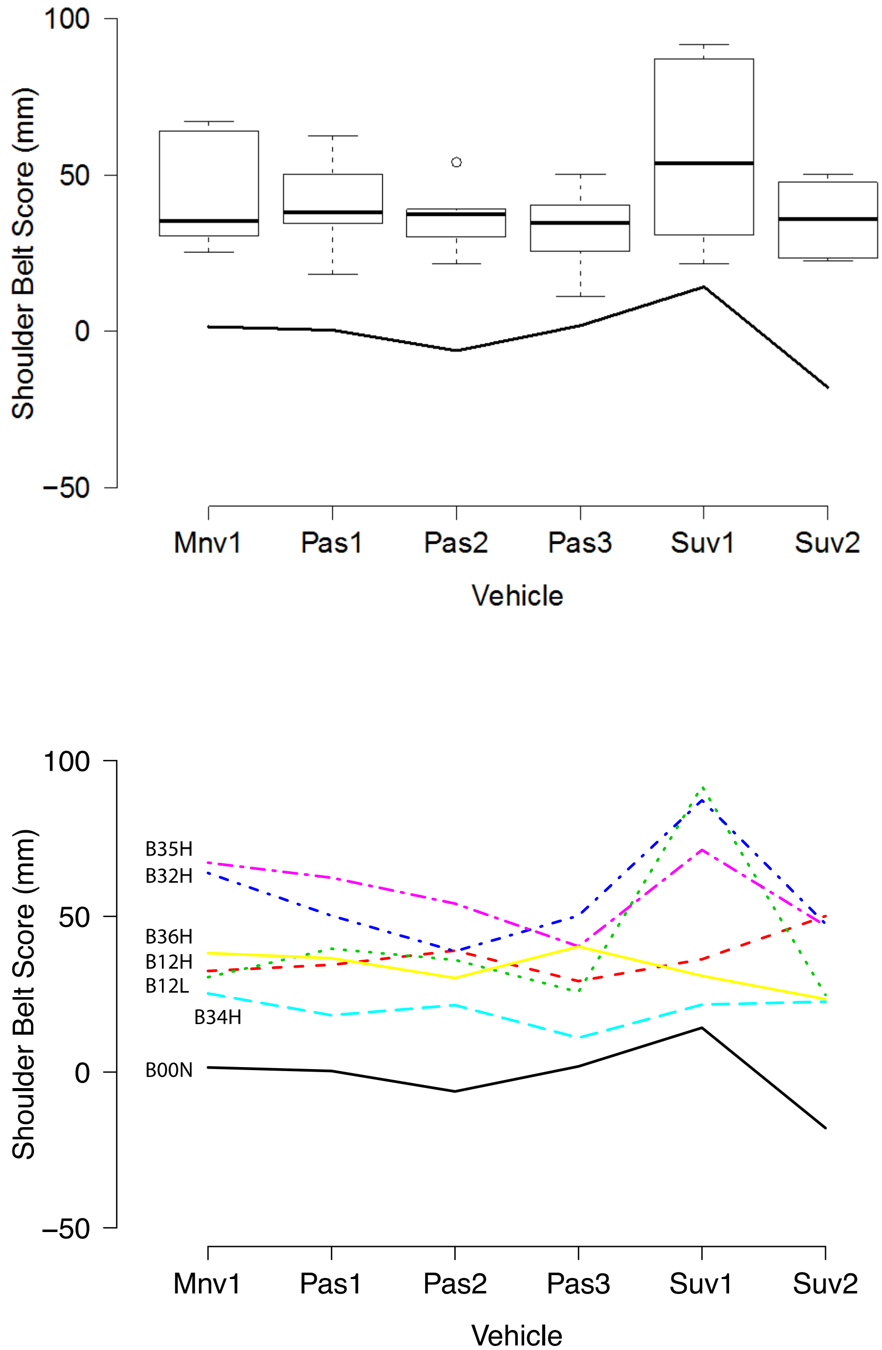


Figure 34. Shoulder belt score by vehicle and booster. Top figure shows boxplots of shoulder belt score for booster conditions and a line for no-booster conditions. Bottom figure shows individual lines for each booster condition. Data are from C1 only for Mnv1 and Suv1.

Belt Fit: Variation with Vehicle and Subject Anthropometry

Lap Belt Fit

In the no-booster condition, mean lap belt score was significantly related to stature ($p<0.001$) across vehicles, but the relationship was weak:

Mean LBS (mm) = -74 + 0.053 Stature, R^2=0.12, RMSE = 17.2, $p<0.001$

On average, taller children experienced better lap belt fit. Across the approximately 400 mm range of stature in the dataset, mean lap belt score differed by 21 mm, on average, or about half of the belt width. Mean lap belt score in the no-booster condition was significantly poorer in Pas1 compared with the other vehicles ($p<0.001$), but no other between-vehicle comparisons were significant in this condition.

ANOVA showed no significant interactions between boosters and vehicles for mean lap belt score. That is, differences across boosters in mean lap belt score were not significantly affected by the vehicle in which the booster was placed. Lap belt fit was significantly better than the average across vehicles in Pas2, Pas3, and Suv2 ($p<0.001$), and significantly worse than the average across boosters in B32H, B34H, and B35H ($p<0.001$). Lap belt fit in the integrated booster levels (B37H and B37L) was not significantly different from the mean.

Shoulder Belt Fit

In the no-booster condition, the mean shoulder belt score was significantly lower in Suv2 than in the other vehicles; no other significant differences across vehicles were observed. Shoulder belt score was significantly related to stature:

Shoulder Belt Score, No Booster (mm) = -100 + 0.078 Stature, R^2=0.12, RMSE = 25.4, $p<0.001$

but the relationship was fairly weak. On average, shoulder belt score was higher for taller children (belt further outboard on the shoulder), with the approximate stature range in the data of 400 mm corresponding to a mean difference in shoulder belt score of 31 mm. After accounting for stature, no other anthropometric variables were significantly related to shoulder belt score in the no-booster condition.

In the no-booster condition, shoulder belt scores were significantly higher (indicating more-outboard belt placement on the child's shoulder) than the average across vehicles in Suv1.

Across the booster conditions, shoulder belt scores were significantly but weakly related to stature:

Shoulder Belt Score, Booster (mm) = -42.8 + 0.052 Stature, R^2=0.07, RMSE = 21.4, $p<0.001$

After accounting for stature, no other anthropometric variables had significant effects. Shoulder belt scores were significantly higher in booster conditions B32H and B35H and significantly lower in B34H. No significant interactions between booster and vehicle were observed.

Posture: Variation with Vehicle

In the no-booster condition, child posture varied significantly across vehicles. Figure 35 shows box plots of the fore-aft locations of the children's hip joint center locations (mean of left and right) and head CG locations. On average, hip locations are forward of seat H-point, but a substantial amount of variability is observed within vehicle. The relationship between hip and head CG, expressed as a torso recline angle, is also significantly different among vehicles, as shown in Figure 36.

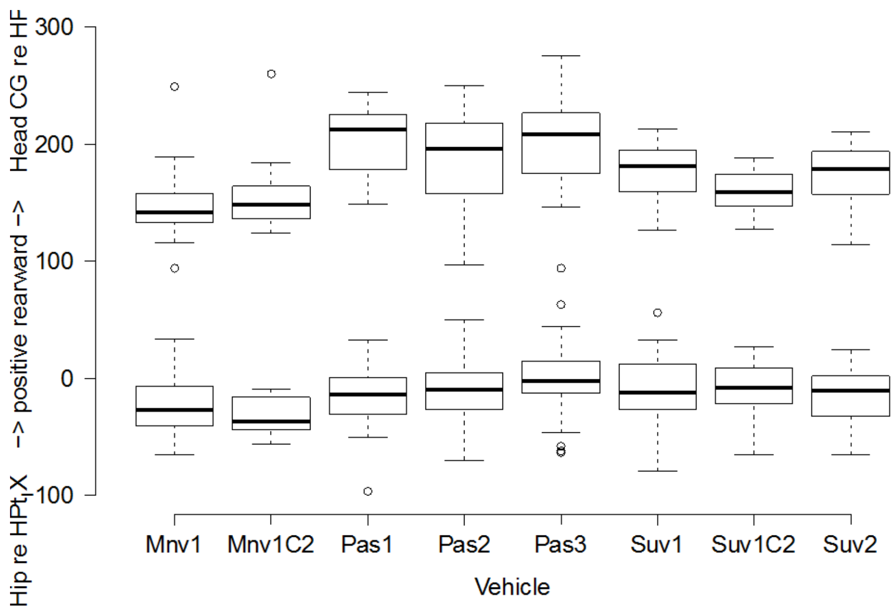


Figure 35. Hip and head CG location with respect to seat H-point for no-booster condition across vehicles.

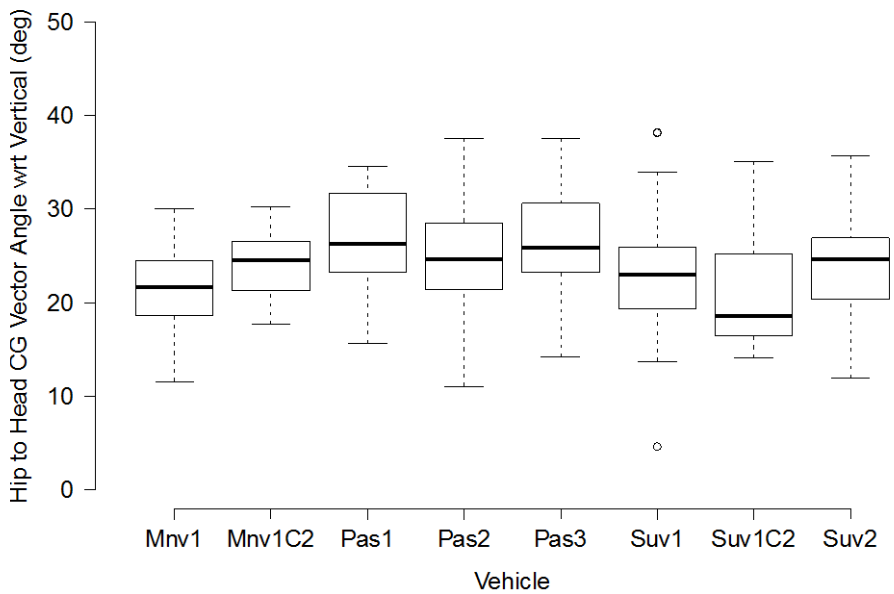


Figure 36. Angle of hip-to-head-CG vector with respect to vertical for the no-booster condition across vehicles.

Comparison of Predicted and Observed Child Belt Fit

One goal of the current study was to assess the extent to which belt-fit predictions based on laboratory studies match in-vehicle data. The regression models used for this analysis were obtained in Reed et al. (2008), a laboratory study of forty-four boys and girls ages 5 to 12 in a wide range of vehicle seat and booster conditions. For the no-booster conditions, a regression analysis gave

$$\text{Lap Belt Score, No Booster (mm)} = -93.8 + 0.0388\ \text{Stature} + 0.455\ \text{LBA},\quad R^2\text{adj} = 0.34,\ \text{RMSE} = 11.5$$

and

$$\text{Shoulder Belt Score, No Booster (mm)} = -144.9 + 0.0824\ \text{Stature} + 2.731\ \text{DRingYZAngle},\quad R^2_{adj} = 0.31,\ \text{RMSE} = 25.3$$

The seat cushion length in these conditions was 471 mm, measured using the same techniques that were applied in the current study. Shortening the seat cushion to 400 mm improved lap belt fit by an average of 4 mm.

Figure 37 shows a plot of predicted lap belt score versus the mean observed score for no-booster conditions across vehicles. The correlation is 0.35, showing a statistically significant but relatively weak relationship. The slope of the linear regression is 1.05, essentially parallel to the 1:1 line shown in the figure. The data show an approximately constant offset of 15 mm, with the observed lap belt scores better (higher) than predicted based on lap belt angle and occupant stature. Note that the predicted scores are expected to have a smaller range than the observed because the regression model used for prediction captured only about a third of the variance measured in the lab study. That is, in both the lab and in-vehicle studies, most of the variance in lap belt score for no-booster conditions is not accounted for by body size or the belt angle (or any other available predictors).

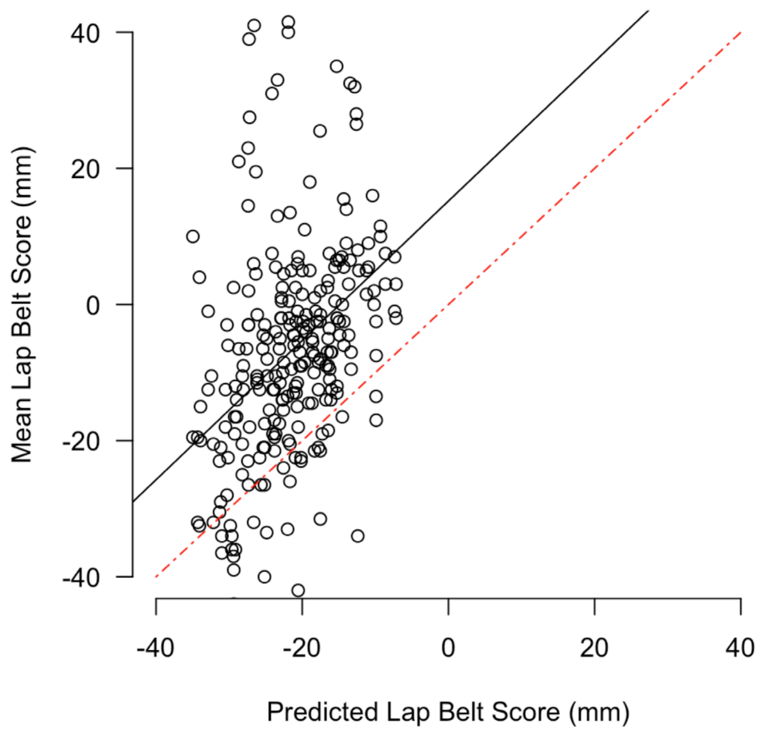


Figure 37. Observed mean lap belt score as a function of predicted **lap belt score** for no-booster conditions. Solid line is linear regression. Dashed line is 1:1.

Figure 38 shows a similar plot for shoulder belt score. In this case, the observed values are nearly all outboard (larger) than the predicted values, an average difference of 25 mm and a correlation of 0.35. The regression line is approximately parallel to the 1:1 line.

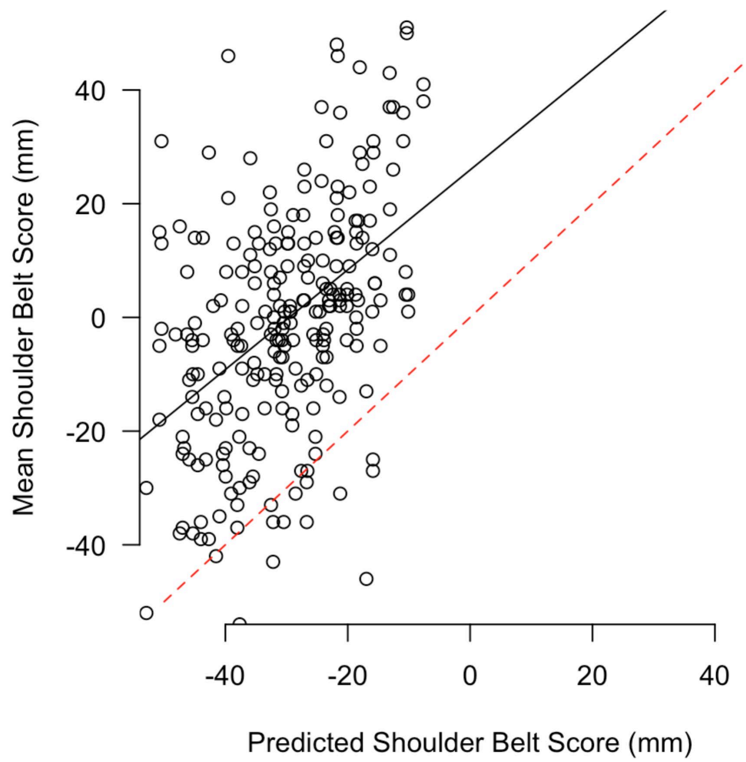


Figure 38. Observed mean lap belt score as a function of predicted **shoulder belt score** for no-booster conditions. Solid line is linear regression. Dashed line is 1:1.

ATD Belt Fit in Vehicle and Booster Conditions

Reed et al. (2008) demonstrated significant relationships between belt fit measured using the 6YO and 10YO Hybrid-III ATDs and belt fit measured on children. In the current study, belt fit was measured with the 6YO ATD in both booster and no-booster conditions. The 10YO was used only in no-booster conditions. Table 7 and Table 8s how the ATD lap and shoulder belt scores, respectively. Note that not all boosters were measured in all vehicles.

Table 7. Mean Lap Belt Scores from ATD Belt Fit Measurements*

Booster	Vehicle					
	Mnv1	Pas1	Pas2	Pas3	Suv1	Suv2
B00N	-8	-19	-46	-37	-9	-12
B00N (10YO*)	-5	-9	NA	-12	-16	-4
B12H	NA	NA	-3	19	NA	12
B12L	23	26	24	21	NA	8
B32H	-2	-2	-6	-3	-2	1
B34H	-3	4	-14	-2	0	10
B35H	8	7	24	-10	14	1
B36H	15	14	0	17	17	20
B37H	NA	NA	NA	NA	NA	27
B37L	NA	NA	NA	NA	NA	14

* 6YO except where noted; 10YO data gathered only in no-booster condition

Table 8. Mean Shoulder Belt Scores from ATD Belt Fit Measurements*

Booster	Vehicle					
	Mnv1	Pas1	Pas2	Pas3	Suv1	Suv2
B00N	55	38	40	-1	47	64
B00N (10YO*)	42	26	NA	14	-15	67
B12H	NA	NA	-17	-17	NA	-18
B12L	-15	11	-29	10	NA	31
B32H	-43	-47	-48	-65	-36	-58
B34H	37	35	32	25	31	45
B35H	-4	7	-25	-7	-28	-13
B36H	-18	-3	4	-17	3	1
B37H	NA	NA	NA	NA	NA	-14
B37L	NA	NA	NA	NA	NA	5

* 6YO except where noted; 10YO data gathered only in no-booster condition

Relationships Between Child and ATD Belt Fit

Figure 39 shows a plot of the observed mean child lap belt score across conditions as a function of the score predicted from 6YO ATD belt fit scores based on the relationships in Reed et al. (2008). The correlation is 0.69. The plot also shows the regression lines from Reed et al. (2008) for booster and no-booster conditions. The lap belt scores are consistently higher than predicted by an average of 15 mm. Note that this is the same discrepancy noted in the prediction of lap belt score from occupant stature and vehicle lap belt angle.

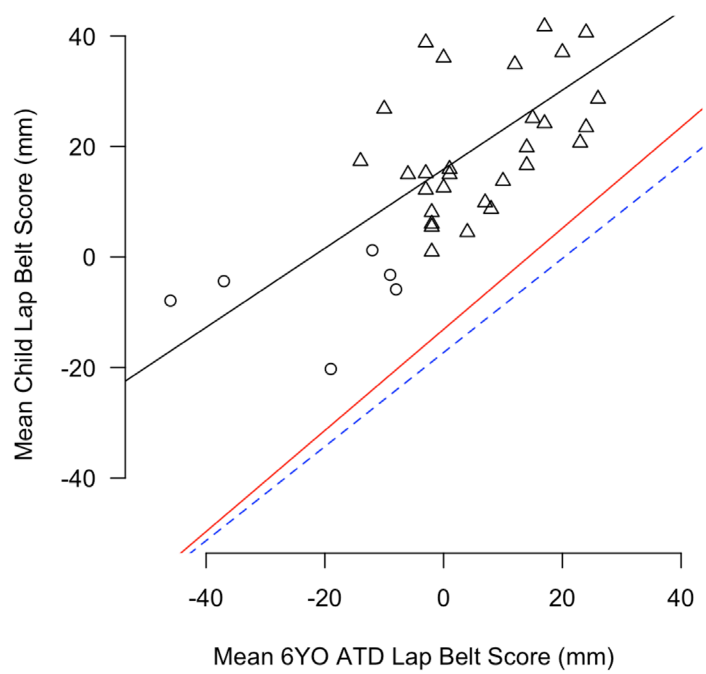


Figure 39. Observed mean child **lap belt score** as a function of 6YO ATD lap belt score. Each combination of vehicle and booster (triangle) and no-booster conditions (circles) are shown. Black line is linear regression. Red and blue lines are prediction models from Reed et al. (2008) for booster and no-booster conditions, respectively.

Figure 40 shows the relationship between shoulder belt score measured by the 6YO ATD and the mean child shoulder belt score across conditions. The correlation was 0.73, indicating a strong positive relationship. The regression relationship from Reed et al. (2008) predicting child shoulder belt score for boosters lies within the data observed in the current study. The observed mean scores for the no-booster conditions are slightly higher (more outboard) than predicted.

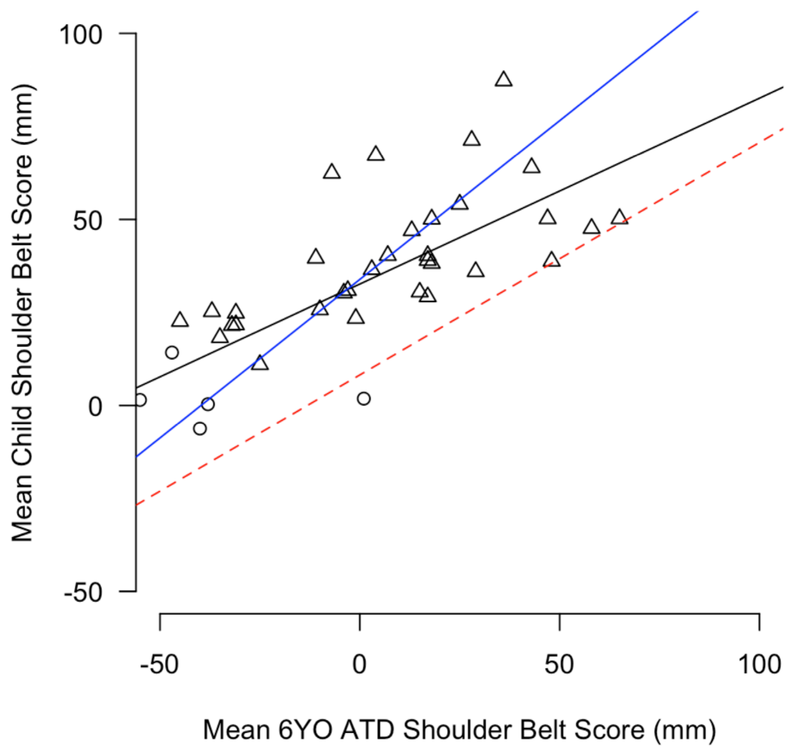


Figure 40. Observed mean child **shoulder belt score** as a function of 6YO ATD shoulder belt score. Each combination of vehicle and booster (triangle) and no-booster conditions (circles) are shown. Black line is linear regression. Red and blue lines are prediction models from Reed et al. (2008) for booster and no-booster conditions, respectively.

DISCUSSION

Summary

This study is the first to quantify belt fit for children in a large range of in-vehicle conditions with and without belt-positioning boosters. Boosters improved the average lap belt fit in all vehicles tested. However, the improvement in lap belt fit varied widely among boosters.

Although taller children on average experience better lap belt fit than shorter children, the effect is small compared to the improvement achieved by using a booster. In this study, an integrated booster seat produced belt fit comparable to the belt-fit observed with the add-on boosters that produced the best lap belt fit.

The trends in posture and belt fit among child volunteers were generally comparable to those observed in previous laboratory studies. In particular, longer seat cushions were associated with more slouched postures, with hip positions more forward on the seat and lower head positions.

The associations between belt fit and potential predictors, such as stature and belt anchorage locations, were similar to those observed in the previous laboratory studies. The most important difference concerned lap belt scores, which were systematically higher (better) by about 15 mm in the current study compared with Reed et al. (2008). Although we have not been able to definitively identify the reason for this difference, we believe that it is attributable to the use of three-dimensional, rather than planar, calculations for belt locations relative to the pelvis.

Limitations

This study had several limitations. Subjects were seated in each condition for only a short period of time in stationary vehicles. Postures would likely vary over longer time periods and in vehicles drive on-road. The study captures “in-position” postures and belt fit; the current results do not consider the effect on child posture from vehicle maneuvers, sleeping, or fidgeting. Results are based on only six vehicles (one with integrated booster) and six add-on boosters, and may vary for other vehicles and booster seats. The lap belt fit would be expected to be somewhat worse if the children wore clothing that was thicker than the standardized test garments used in this study.

Conclusions

1. Belt fit for children ages 5 to 12 in vehicle rear seats is generally poor unless they are seated on belt-positioning boosters. Specifically, hip locations tend to be well forward of the seat H-point, resulting in the lap belt being positioned over the abdomen rather than on the thighs. Shoulder belt fit without a booster varies widely depending on the locations of the belt anchorage.

2. All boosters improved belt fit, but the level of improvement differed markedly across boosters. The best-performing boosters produced similar belt fit regardless of the vehicle configuration.

3. An integrated booster in one vehicle produced belt fit comparable to the best-performing add-on boosters.

4. Child body size was only weakly associated with belt fit — even the largest children experienced improved belt fit when using boosters.

5. The study confirmed that measures of belt fit obtained using the 6YO Hybrid-III ATD are strong predictors of mean belt fit scores across vehicle seating conditions and boosters, with correlations of 0.69 and 0.73 for lap and shoulder belt scores, respectively.

REFERENCES

Reed, M.P., Ebert-Hamilton, S.M., Manary, M.A., Klinich, K.D., and Schneider, L.W. (2005a). A new database of child anthropometry and seated posture for automotive safety applications. *SAE Transactions: Journal of Passenger Cars - Mechanical Systems,* 114: 2222-2235

Reed, M.P., Ebert-Hamilton, S.M., and Schneider, L.W. (2005b). Development of ATD installation procedures based on rear-seat occupant postures. *Stapp Car Crash Journal*, 49: 381-421.

Reed, M.P., Ebert-Hamilton, S.M., Klinich, K.D., Manary, M.A., and Rupp, J.D. (2008a). Assessing Child Belt Fit, Volume I: Effects of Vehicle Seat and Belt Geometry on Belt Fit for Children with and without Belt Positioning Booster Seats. Technical Report UMTRI-2008-49-1. University of Michigan Transportation Research Institute, Ann Arbor, MI.

Reed, M.P., Ebert, S.M., Sherwood, C.P., Klinich, K.D., and Manary, M.A. (2009). Evaluation of the static belt fit provided by belt-positioning boosters. *Accident Analysis and Prevention*, 41:598-607.

Reed, M.P., Ebert-Hamilton, S.M., and Flannagan, C.A.C. (2011). Improving the Repeatability and Reproducibility of Belt Fit Measurement with 6YO and 10YO ATDs. Technical Report 2011-4. University of Michigan Transportation Research Institute, Ann Arbor, MI.

APPENDIX A: INSTRUCTIONS FOR EACH BOOSTER

Table A1 High Back Turbo Booster Instructions

<table>
<tr><th colspan="3">MANUAL INSTRUCTIONS</th></tr>
<tr><th>TurboBooster</th><th>Item</th><th>Action</th></tr>
<tr><td rowspan="3"></td><td>Component Adjustments</td><td>To ensure the correct head support height is obtained, the bottom of the headrest MUST be even with the top of child's shoulders as and the shoulder belt must be positioned in the red zone. If the belt lays across child's neck, head or face, readjust head support height.</td></tr>
<tr><td>Shoulder Belt</td><td>Belt must pass underneath the armrests. Position shoulder belt through the shoulder belt guide. Fasten buckle and pull up on the shoulder belt to tighten. If the belt lays across child's neck, head or face, readjust support height.</td></tr>
<tr><td>Lap Belt</td><td>Lap portion of lap/shoulder belt MUST be low and snug on hips, just touching thighs. The lap belt portion MUST pass under the armrests and be positioned low on the hips.</td></tr>
<tr><th colspan="3">IN LAB INSTRUCTIONS</th></tr>
<tr><td colspan="2"></td><td>Adjust headrest so that it looks like this image.</td></tr>
<tr><td colspan="2"></td><td>Check belt fit at mid settings.
Shoulder belt must be in router.
Lap belt must be under armrests.
Shoulder belt must be under inboard armrest.
If child does not try to tighten belt, ask them to do so.
If lap belt has more than 2 inches of slack, ask the child to tighten it again.</td></tr>
<tr><td colspan="3">Script:
• On your right side the lap belt goes under the armrest.
• On your left side both the lap and shoulder belt goes under the armrest.
• Make sure the shoulder belt goes through this guide. (It will be in the guide already)
• Pull up on the shoulder belt to tighten.</td></tr>
</table>

Table A2 Backless Turbo Booster Instructions

<table>
<tr><th colspan="3">MANUAL INSTRUCTIONS</th></tr>
<tr><th>TurboBooster</th><th>Item</th><th>Action</th></tr>
<tr><td rowspan="3"></td><td>Component Adjustments</td><td></td></tr>
<tr><td>Shoulder Belt</td><td>The shoulder belt MUST lay across the child's shoulders in red zone as shown. IF shoulder belt lays outside this zone, the shoulder belt positioning clip MUST be used.</td></tr>
<tr><td>Lap Belt</td><td>The lap belt position MUST pass under the armrest and be positioned low on the hips. The belt MUST NOT be twisted.</td></tr>
<tr><th colspan="3">IN LAB INSTRUCTIONS</th></tr>
<tr><td colspan="2"></td><td>Lap belt must be under armrests.
Shoulder belt must be under inboard armrest.
Do not use the shoulder belt clip.
If child does not try to tighten belt, ask them to do so.
If lap belt has more than 2 inches of slack, ask the child to tighten it again.
If the child cannot tighten the belt on their own, help – but let the child select the final tightness.</td></tr>
<tr><td colspan="3">Script:
On your right side the lap belt goes under the armrest.
On your left side both the lap and shoulder belt goes under the armrest.
Pull up on the shoulder belt to tighten.</td></tr>
</table>

Table A3 Generations Instructions

MANUAL INSTRUCTIONS		
Generations	Item	Action
	Component Adjustments	Place the shoulder belt in the belt guide and adjust the headrest so its bottom is near, but above, the top of your child's shoulders. NOTE: If the vehicle's shoulder belt naturally crosses midway between your child's shoulder and neck, you do not need to use the belt guide.
	Shoulder Belt	The shoulder belt must cross midway between child's shoulder and neck. The shoulder belt MUST NOT cross the child's neck or fall off the child's shoulder. If you can not adjust the shoulder belt to properly lay midway between the child's shoulder and neck, try another seating location or do not use the booster seat.
	Lap Belt	Placed low and snug across the child's hips, beneath the armrests, and fastened into the buckle.
IN LAB INSTRUCTIONS		
		Adjust headrest so that it looks like this image. Check belt fit at mid settings. Shoulder belt must cross midway between child's shoulder and neck. Lap belt must be under armrests. Shoulder belt must be under inboard armrest. If child does not try to tighten belt, ask them to do so. If lap belt has more than 2 inches of slack, ask the child to tighten it again.
Script: • On your right side in this area (point to depression) • On your left side in this area (point to depression) • Pull up on the shoulder belt to tighten.		

Table A4 Frontier 85 Instructions

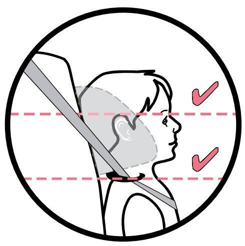
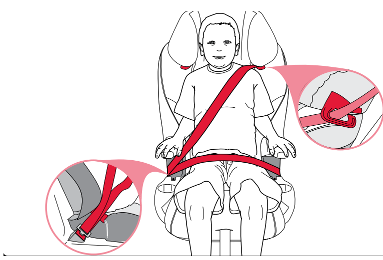
<table>
<tr><th colspan="3">MANUAL INSTRUCTIONS</th></tr>
<tr><th>Frontier 85</th><th>Item</th><th>Action</th></tr>
<tr><td rowspan="3"></td><td>Component Adjustments</td><td>Adjust the head restraint so the shoulder belt guides position the vehicle belt at or just above the child's shoulders. The child's ears should be below the top of the head restraint.</td></tr>
<tr><td>Shoulder Belt</td><td>Shoulder part of belt is routed through upper belt guide at or above the child's shoulder and does not contact the child's neck.</td></tr>
<tr><td>Lap Belt</td><td>Lap part of the vehicle belt must be routed low across the child's hips.</td></tr>
<tr><th colspan="3">IN LAB INSTRUCTIONS</th></tr>
<tr><td colspan="2"></td><td>Adjust head rest so that it looks like this image.</td></tr>
<tr><td colspan="2"></td><td>Check belt fit at mid settings.
Shoulder belt must be in router.
Lap belt must be under arm rests.
Shoulder belt must be under inboard arm rest.
If child does not try to tighten belt, ask them to do so.
If lap belt has more than 2 inches of slack, ask the child to tighten it again.</td></tr>
<tr><td colspan="3">Script:
On your right side the lap belt goes under the armrest.
On your left side both the lap and shoulder belt go under the armrest.
Make sure the shoulder belt goes through this guide. (It will be in the guide already)
Pull up on the shoulder belt to tighten.</td></tr>
</table>

Table A5 ProBooster Instructions

MANUAL INSTRUCTIONS		
ProBOOSTER	Item	Action
	Component Adjustments	Your child's head must be centered vertically between the top and bottom of the head restraint. The red shoulder belt guide must be above the child's shoulder to allow for correct vehicle belt positioning.
	Shoulder Belt	Route the lower portion of the vehicle belt closest to the vehicle buckle under the arm rest. Position the top portion of the shoulder belt into the red shoulder belt routing guide near the child’s ear. The shoulder belt should be flat against the child’s chest and collarbone. The shoulder portion of the vehicle seat belt system should NEVER be located across the child’s neck.
	Lap Belt	Position the lap portion of the vehicle seat belt system through the red lower lap belt guides. Fasten the vehicle seat belt to the vehicle buckle. The vehicle buckle should be below the red lap belt guide. The lap belt should be positioned flat across the child’s lap or thigh area. It should not be lying against the child’s abdomen or ‘belly’. NEVER use a buckle that is too long and interferes with the red lap belt guide.
IN LAB INSTRUCTIONS		
		Adjust head rest so that it looks like this image.
 		Check belt fit at mid settings. Shoulder belt must be in router. Lap belt must be under arm rests. Shoulder belt must be under inboard arm rest. If child does not try to tighten belt, ask them to do so. If lap belt has more than 2 inches of slack, ask the child to tighten it again.

Script:
- On your right side the lap belt goes under the armrest.
- On your left side both the lap and shoulder belt go under the armrest.
- Make sure the shoulder belt goes through this guide. (It will be in the guide already)
- Pull up on the shoulder belt to tighten.

Table A6 Alpha Omega Instructions

MANUAL INSTRUCTIONS		
Alpha Omega Elite	Item	Action
	Component Adjustments	To help position the shoulder belt, you may need to secure the shoulder belt through one of the notches in the shoulder belt-positioning guide.
	Shoulder Belt	The shoulder belt should lay snugly across the center of the child's shoulders and across the chest (not on the face or neck).
	Lap Belt	Lap belt should cross the child's thighs.
IN LAB INSTRUCTIONS		
		Check belt fit at mid settings. Lap belt must be under arm rests. Shoulder belt must be under inboard arm rest. If child does not try to tighten belt, ask them to do so. If lap belt has more than 2 inches of slack, ask the child to tighten it again.
Script: • On your right side in this area (point to depression) • On your left side in this area (point to depression) • Pull up on the shoulder belt to tighten.		