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Evaluation of the static belt fit provided by belt-positioning booster seats

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ABSTRACT

Belt-positioning booster seats are recommended for children who use vehicle seat belts as primary restraints but who are too small to obtain good belt fit. Previous research has shown that belt-positioning boosters reduce injury risk, but the belt fit produced by the wide range of boosters in the US market has not previously been assessed. The present study describes the development of a method for quantifying static belt fit with a Hybrid-III 6-year-old test dummy. The measurement method was applied in a laboratory seat mockup to 31 boosters (10 in both backless and highback modes) across a range of belt geometries obtained from in-vehicle measurements. Belt fit varied widely across boosters. Backless boosters generally produced better lap belt fit than highback boosters, largely because adding the back component moved the dummy forward with respect to the lap belt routing guides. However, highback boosters produced more consistent shoulder belt fit because of the presence of belt routing guides near the shoulder. Some boosters performed well on both lap belt and shoulder belt fit. Lap belt fit in dedicated boosters was generally better than in combination restraints that also can be used with an integrated harness. Results demonstrate that certain booster design features produce better belt fit across a wide range of belt geometries. Lap belt guides that hold the belt down, rather than up, and shoulder belt guides integrated into the booster backrest provided better belt fit.

1. Introduction

Belt-positioning booster seats are intended to improve the performance of vehicle seat belts by changing the occupant position relative to the belt and by routing the belt more advantageously with respect to the occupant. The U.S. National Highway Traffic Safety Administration (NHTSA, 2007a) recommends that children less than 1450 mm (57 in.) tall who are not using a harness restraint use a belt-positioning booster. Durbin et al. (2003), in an analysis of data from a field survey of crash-involved child passengers, found that children ages 4–7 using belt-positioning boosters were 59% less likely to be injured than children in seat belts alone, after adjusting for driver, vehicle, and crash characteristics. Elliot et al. (2006) found that children 2–6 years old in child restraints, including harness restraints, shield boosters, and belt-positioning boosters, are about 28% less likely to be fatally injured than those using belts alone.

In U.S. vehicles, children sitting in second- or third-row vehicle seats usually experience seat cushions that are longer than their thighs (Huang and Reed, 2006). Children in this situation often slouch, sliding forward and rolling their pelvises rearward, causing the lap portion of a three-point belt to ride up on the abdomen. In a frontal crash the lap belt will load the abdomen rather than the pelvis, leading to a kinematic phenomenon known as submarining, in which the pelvis slides down and under the belt and the body is restrained through abdominal soft tissue, rather than through loads applied to the bony pelvis. Belt loading to the abdomen produces a constellation of injuries to the abdominal region and lumbar spine known as seat belt syndrome. Boosters improve the performance of vehicle seat belts in several ways:

1. Boosters raise a child relative to the seat, typically by about 100 mm (Reed et al., 2006). This improves the lap belt angle, making it more vertical, so the belt is less likely to slide off the pelvis and onto the abdomen during a crash. It also reduces the likelihood that the shoulder belt will interact uncomfortably with the neck, a situation that can lead to a child leaning away from the belt or tucking the belt under an arm or behind the back.
2. Boosters include features to improve the routing of the belt with respect to the child. Nearly all boosters include lap belt routing guides that affect the positioning of the belt relative to a

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child's pelvis, and most boosters also include features intended to control the positioning of the belt relative to the shoulder.
3. Boosters control child posture by restricting the range of possible postures with respect to the belt and by allowing more comfortable postures than those available on the vehicle seat without the booster. In particular, highback boosters control lateral torso lean, and the shorter seat pan of most boosters, relative to the vehicle seat, allows a child to sit with more comfortable knee flexion.

Boosters sold in the United States are subject to the dynamic testing and other requirements of Federal Motor Vehicle Safety Standard (FMVSS) 213. Among other criteria, boosters must pass dynamic frontal impact sled testing with one or more crash dummies (depending on the manufacturer's specified weight range for children) on a standard seating buck. The largest anthropomorphic test device (ATD) currently used in the standard is the 6-year-old Hybrid-III.

ECE Regulation 44 specifies booster design requirements test procedures using the P3, P6, and P10 ATDs. Unlike FMVSS 213, R44 includes requirements for belt routing, but does not provide a quantitative method for determining compliance. For example, Section 6.2 specifies that the lap portion of the belt should apply loads to the pelvis without specifying a measurement method. Australian/New Zealand Standard (AS/NZS) 1754:2004 includes dummy retention requirements for dynamic testing of boosters using the P3, P6, and P10 ATDs, but does not include either static or dynamic fit requirements.

The dynamic tests of boosters in R44 and FMVSS 213 assess belt fit indirectly through ATD performance measures in dynamic tests, but the 6-year-old ATD may not interact realistically with the belt. Chamouard et al. (1996) compared the geometry of the P- and Hybrid-III-series ATDs representing 3–6-year-old children with data from radiographic images of similar size children and concluded that the substantial differences between ATDs and children in the pelvis area made the ATDs insufficiently sensitive to submarining. Moreover, the FMVSS 213 and R44 test procedures each use a single midrange belt and seat geometry that does not evaluate the ability of boosters to produce good belt fit in the disadvantageous conditions often found in rear seats.

Few studies have examined belt fit in belt-positioning boosters. Using categorical scales, Klinich et al. (1994) coded belt fit using video data of children sitting on each of three boosters and on a vehicle seat without a booster. The boosters improved belt fit significantly, but the analysis did not quantify the location of the belt with respect to a child's skeleton. A small-scale photographic study evaluated seat belt fit among children ages 4–7 and a Hybrid-III 6-year-old ATD with and without boosters in the rear seats of three different vehicles chosen to represent a variety of vehicle seats (Insurance Institute for Highway Safety, 2001). Only a few boosters routed the lap belt properly, and some actually worsened the fit of the lap belt. As part of a large-scale study of child posture, Reed et al. (2005) measured belt fit for 62 children in a range of vehicle seats and in four boosters. Differences in belt fit across boosters were noted that appeared to be related to the booster design. Bilston and Sagar (2007) compared the locations of the upper (shoulder or sash) belt routing slots in six boosters to published shoulder height distributions of U.S. children. The boosters fit children from 4 to 6 years of age well, but larger children were often not accommodated. The authors recommended harness restraints rather than boosters for children below 4 years of age, and noted that the disaccommodation of larger children was expected because the regulatory requirements in Australia, where the research was conducted, focus on protection for children up to 26 kg, approximately the median body mass for an 8-year-old child. The authors did not address lap belt fit.

Good belt fit is characterized by positioning of the lap and shoulder portions of a three-point belt over skeletal structures that can bear relatively high loads without injury. The shoulder belt should pass over the clavicle as close to the occupant centerline as possible without contacting the neck. The upper belt anchor should be at or above the shoulder level to avoid excessive downward load on the shoulder and spine during crashes. If the shoulder belt lies too far outboard, excessive forward excursion of the head and upper torso may occur, increasing the risk of head injury due to contact with the vehicle interior. If the shoulder belt lies against the neck, the resulting discomfort may lead the occupant to put the belt behind the back or under the arm, increasing the risk of belt-induced injury. The lap portion of a three-point belt is intended to direct restraint force onto the pelvis during a crash. If the belt is placed too high and fails to engage the pelvis, the occupant is likely to submarine, directing belt loads onto the abdominal organs. The optimal position for the lap belt therefore is below or forward of the anterior-superior iliac spines (ASIS) of the pelvis. In both adults and children, the ASIS landmarks lie approximately at the thigh/abdominal junction, so a belt that is below or forward of ASIS landmarks must lie predominantly on the thighs, not on the lower abdomen (Chamouard et al., 1996). A belt positioned farther forward on the thighs than is necessary to engage the pelvis effectively introduces slack into the belt, allowing greater occupant excursion and producing higher peak forces and accelerations on the occupant.

The objectives of the present study were (1) to develop a repeatable and reproducible method of assessing the static belt fit produced by belt-positioning boosters and (2) to quantify the belt fit provided by a large number of boosters available in the US market.

2. Methods

2.1. ATD preparation

The Hybrid-III 6-year-old ATD was chosen as the primary human surrogate because it is widely used for impact testing and has dimensions near the middle of the stature and body-weight distributions for booster-age children. However, the Hybrid-III 6-year-old has an unrealistic flesh contour in the lap area that complicates the measurement of belt routing. The large gap between the pelvis flesh and thigh flesh can catch the lap belt.

To eliminate this problem, a flexible lap form was developed and attached to the upper edge of the pelvis flesh using double-sided tape. Constructed from 50A-durometer, 1/8-in. thick silicone rubber, the lap form provides a smooth contour and uniform friction in the critical area at the thigh/abdomen junction. The portions of the lap form over the thigh flesh were not attached to the ATD. To improve repeatability, the ATD was tested without clothing. A 20-mm-thick foam pad was attached to the back of the ATD pelvis with double-sided tape to assist in ATD positioning (Reed et al., 2006).

2.2. Booster belt-fit measurement procedure

The booster belt-fit measurement procedure is described in detail in Reed et al. (2008). Each booster was adjusted according to the manufacturer's instructions for a child the size of the ATD and placed on the seat with the centerline aligned with the centerline of the seat.

A piece of tape was placed on the thorax of the ATD to mark the measurement location for shoulder belt fit. The lap/shoulder belt was placed on the ATD using a method developed to approximate the donning procedure a child would use while also producing repeatable and reproducible routing. If the booster back was equipped with a belt-routing feature, the belt was placed through the guide. The latchplate was inserted into the buckle and the slack in the lap belt was controlled by the investigator's left hand while

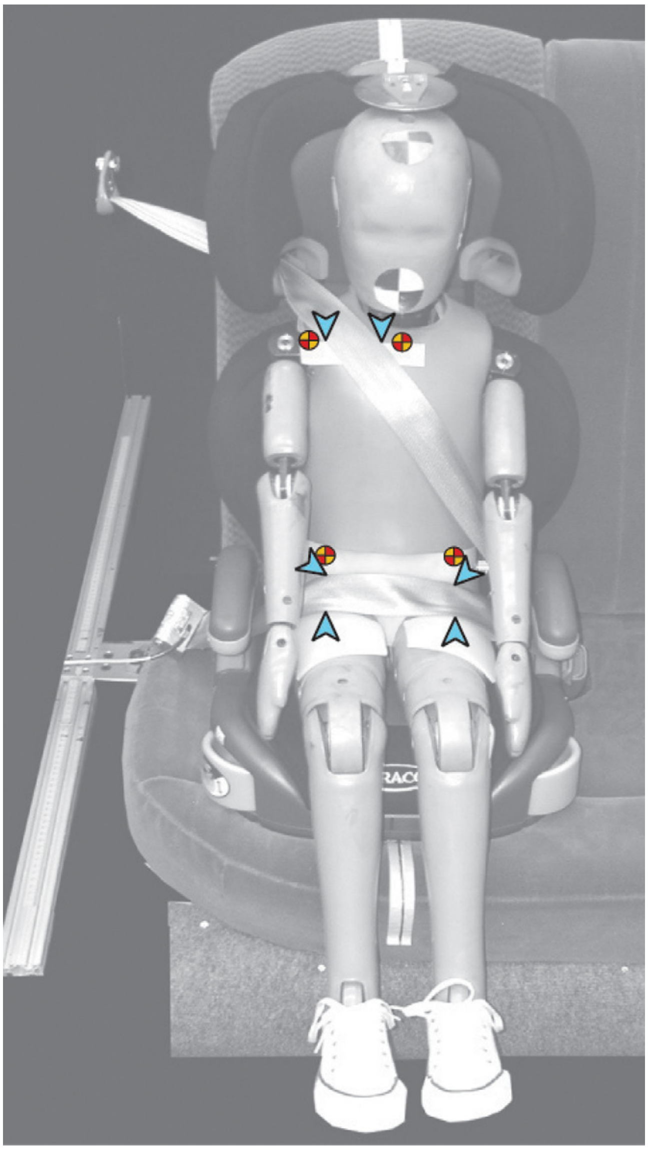

Fig. 1. Landmarks (arrows) indicate inboard/outboard locations of shoulder belt on the chest and upper/lower edges of lap belt on the pelvis. Reference points (circles) indicate locations from which belt fit was measured.

the right hand pulled the belt through the latchplate to tighten the lap belt. The belt was pulled only until it stopped moving against the lap form. The shoulder belt then was placed snugly against the chest by pulling the belt outward at the upper anchorage (D-ring) while gently adjusting the belt position against the chest. The goal was to achieve the belt routing requiring the least belt webbing (i.e., minimum distance routing).

A portable coordinate digitizer (FARO Technologies, Lake Mary, FL, USA) was used to record belt routing at the chest and pelvis. The inboard and outboard edges of the shoulder belt were digitized where they passed over the tape on the chest. The upper and lower edges of the lap belt were recorded where the belt passed over the lateral positions of the ASIS landmarks of the pelvis bone (Fig. 1). The locations of landmarks on the pelvis, chest, head, and extremities were recorded to quantify the posture and position of the ATD, and reference points on the booster were digitized.

2.3. Booster sample

Boosters sold in the US market were identified through retailers and online, including lists from NHTSA (2007b) and SafetyBeltSafe (http://www.carseat.org). Boosters were purchased retail. A total of 31 boosters were tested in 41 modes (see Appendix A); 10 boosters had removable back components, allowing them to be used in either highback or backless modes. Five boosters were backless only, and 16 were highback only. Ten highback boosters (two of which can also be used as a backless booster) were combination restraints that also could be used as forward-facing harness restraints; these were tested only as boosters. Additionally, one backless booster could also be used as a forward-facing harness restraint with the addition of other components. This seat was tested only as a backless booster.

2.4. Laboratory test conditions

Boosters were tested in a laboratory mockup of the rear seat from a 2002 Pontiac Grand Am. The outboard bolster on the seat back was removed to reduce interference with belt routing. The retractor, D-ring, and buckle assembly from the outboard front seat of a 2001 Ford Taurus were installed using adjustable anchors (the second-row belt from the same vehicle model was not used because the webbing was too short to accommodate all test conditions). The buckle anchorage could be moved fore-aft in a slot in the seat to achieve a range of lap belt angles. The lower outboard anchorage was similarly adjustable fore-aft. The retractor and D-ring were mounted on a fixture that allowed fore-aft, vertical, and lateral adjustment. The D-ring pivoted about a laterally oriented bolt, equivalent to typical D-rings in vehicles.

Table 1 lists the test conditions for each booster. All testing was conducted with the seat cushion angle set to 14.5°, as measured by the Society of Automotive Engineers (SAE) J826 procedure (SAE, 2004). Seat back angle (SAE dimension A40) was set to 23°. Belt configurations were based on an analysis of second-row belt anchorage locations in 31 2001-06 model year vehicles including passenger cars, minivans, and SUVs. Anchorage locations were chosen to span approximately 90% of the range of the in-vehicle data. All of the D-ring anchorage locations were consistent with the requirements of FMVSS 210. Following the definitions in FMVSS 210, lap belt

Table 1
Test matrix.

Test condition	D-ring (upper anchor) location[a]			Lap belt angle (inboard, outboard)[a]
	X	Y	Z	
1	Fore (248)	Outboard (312)	Low (494)	Mid (63°, 52°)
2	Mid (399)	Mid (263)	Mid (566)	Mid (63°, 52°)
3	Aft (550)	Inboard (214)	High (638)	Mid (63°, 52°)
4	Mid (399)	Mid (263)	Mid (566)	Min (41°, 35°)
5	Fore (248)	Outboard (312)	Low (494)	Min (41°, 35°)
6	Mid (399)	Mid (263)	Mid (566)	Max (83°, 63°)
7	Aft (550)	Inboard (214)	High (638)	Max (83°, 63°)

[a] Numeric values are mm with respect to seat H-point on occupant centerline. X is positive rearward, Y is positive to the right (outboard), and Z is positive upward. Lap belt angles are measured with respect to forward horizontal per FMVSS 210.

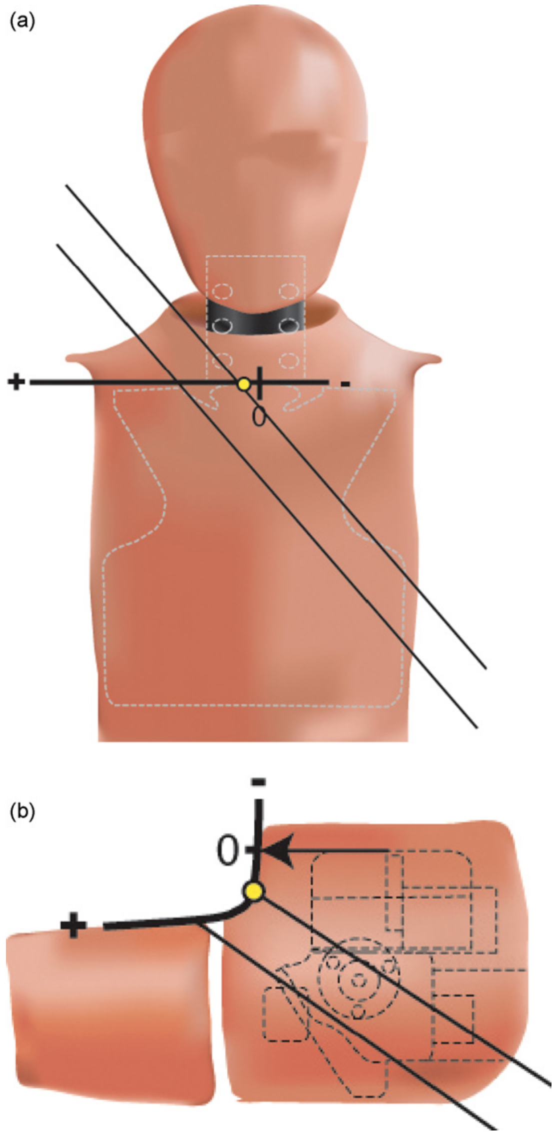

Fig. 2. Diagrams showing calculation of scores for shoulder and lap belt fit. Small circles indicate digitized landmark used to compute scores; belt scores were defined as the distance (mm) along the indicated contour from the origin (marked with 0). The origin for the lap belt fit is the top of the ATD pelvis. The origin for the shoulder belt fit is the ATD centerline at the height of the neck/chest-bib junction.

angles were defined as the side-view angle of the vector from the anchorage to the seating reference point (H-point) with respect to horizontal. Tests were conducted with inboard belt angles of 41°, 63°, and 83° (min, mid, and max, respectively, in Table 1) and outboard angles of 35°, 52°, and 68°.

Some backless boosters are supplied with a clip on a flexible strap to improve routing of the shoulder belt. These boosters were tested in a manner that followed the manufacturer's instructions for use of the clip.

2.5. Dependent measures

Lap belt fit was quantified relative to the projection of the ASIS of the ATD pelvis bone onto the surface of the ATD skin. The lap belt score was computed as the distance below/forward of the ASIS of the upper/rearward edge of the belt along the side-view profile of the pelvis and thighs at the lateral position of the ASIS (Fig. 2). The distance was taken along the curved profile and was computed rather than directly measured. A value of zero indicates that the upper edge of the belt is at the height of the ASIS landmark on the ATD pelvis bone. Separate scores were computed for the inboard (buckle) and outboard sides. A score was considered *fair* if the belt lay fully below the expected ASIS location for a child the size of the ATD sitting with the same posture (score 10–20 mm). Chamouard et al. (1996) found that the iliac crest of the Hybrid-III 6-year-old ATD was higher than the corresponding dimension in children by about 10 mm, so the *fair* belt fit zone starts at 10 mm. Recognizing that the best lap belt fit is obtained when the belt lies flat on the thighs, rather than partly on the lower abdomen, a *good* belt fit zone was established for belt scores equal to or greater than 20 mm. A score of approximately 35 mm indicates that the belt was lying fully on the thighs at the thigh abdominal junction. Higher scores indicate further-forward belt positions that may degrade performance for children the size of the ATD, so the range of *good* scores is defined to be 20–50 mm. Scores 50–60 mm are considered *fair*, and scores higher than 60 mm indicate that the belt is too far forward.

The correlation across boosters and test conditions between inboard and outboard lap belt scores was 0.98. On average, the inboard lap belt score was 1.5 mm higher than the outboard score (standard deviation of the difference was 3.4 mm). To simplify presentation, the mean of the inboard and outboard scores for each test condition was analyzed.

Shoulder belt fit was quantified as the distance between the ATD centerline and the inboard edge of the belt where it passed over the tape on the upper chest (Fig. 2). A value of zero indicated the belt was optimally positioned over the center of the shoulder, whereas a higher value indicated the belt was more lateral (outboard). Scores from −10 to 10 mm were considered to represent *good* shoulder belt fit; this is approximately the optimal range for children the size

Table 2
Repeatability and reproducibility of belt-fit measurement procedure: mean and range values from three installations of booster and ATD followed by three trials with repeated belt donning (mm).

Booster[a]	Investigator	Lap belt score				Shoulder belt score			
		Full install		Belt only		Full install		Belt only	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range
B12B[b]	1	39	8	36	1	4	8	2	11
B12B[b]	2	37	4	40	6	−1	5	−1	4
B12B	1	36	1	36	1	−19	5	−17	3
B12B	2	33	3	35	2	−11	8	−11	10
B12	1	31	6	29	1	−5	4	−5	8
B12	2	25	2	27	1	−1	2	−4	8
B24	1	4	2	4	2	−24	14	−27	3
B24	2	3	1	2	1	−34	7	−34	5

[a] B12 = Graco Turbobooster, B12B = Graco Turbobooster backless, B24 = Cosco (Dorel) Alpha Omega highback.
[b] Tested with positioning clip for shoulder belt.

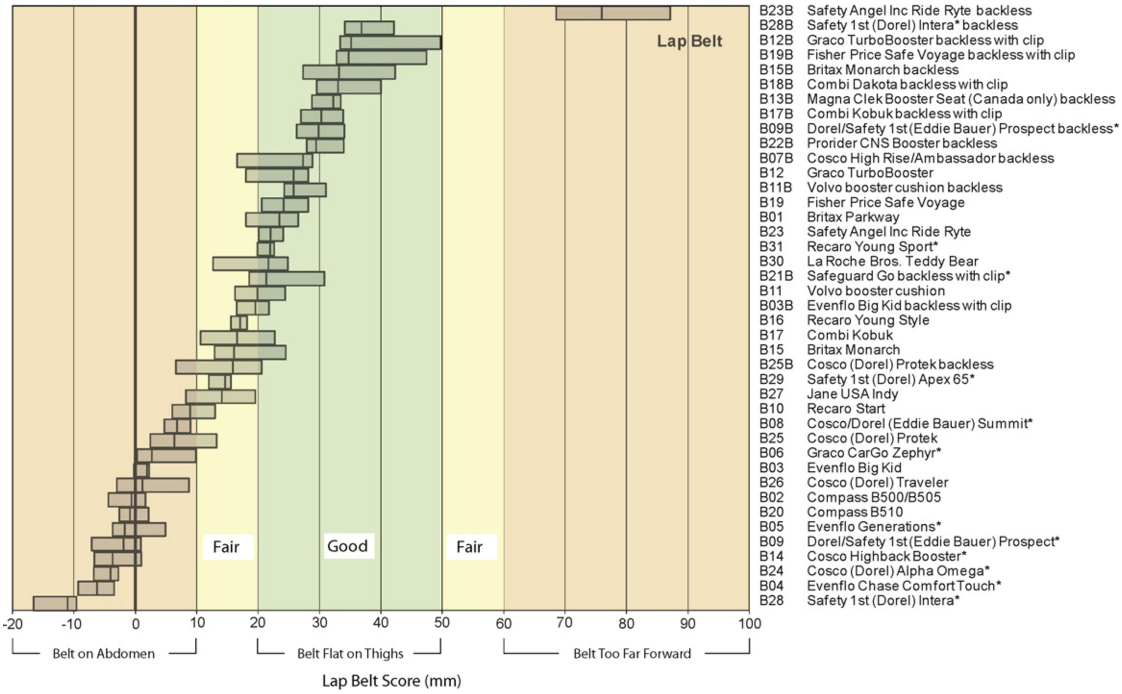

Fig. 3. Median and range of lap belt scores (average of left and right sides), rank ordered by median score.

of the ATD. A score was considered *fair* if the belt was positioned within 10 mm on either side of the *good* zone.

3. Results

3.1. Repeatability and reproducibility of measurement procedure

Prior to full-scale testing, the repeatability and reproducibility of the measurement procedure were evaluated using two investigators and two boosters selected to represent the extremes of the range of lap belt fit. During this test series, one booster was tested in highback and backless modes with and without a clip to position the shoulder belt. Results are listed in Table 2. Each investigator conducted three measurements on each booster, reinstalling the booster and ATD each time. Following the last installation, the belt was routed over the ATD repeatedly to obtain an estimate of variability for belt routing alone. For most conditions, the range of both lap and shoulder belt scores within and between investigators was less than 10 mm. Variation between investigators was greater for the shoulder belt scores than for the lap belt scores.

3.2. Lap belt fit

Fig. 3 shows the ranges of lap belt scores for all boosters across test conditions, rank ordered by median value, and the fair and good belt fit zones. Backless booster B23B had an outlying belt score (median 76 mm), larger than the optimal value for children the size of the ATD.

Of the 15 boosters tested in the backless mode, 10 provided good lap belt fit and three provided fair lap belt fit. Eleven of the 26 highback boosters had fair or good lap belt fit scores.

Boosters that could be converted between backless and highback modes produced better lap belt fit in backless mode (Fig. 3). The lower scores in highback mode occurred primarily because the addition of the back component pushed the ATD farther forward relative to the lap belt routing guides. Fig. 4 shows the relatively good and poor lap belt fits in booster B09 in both backless and highback modes. In backless mode the lap belt lay nearly flat on the tops of the

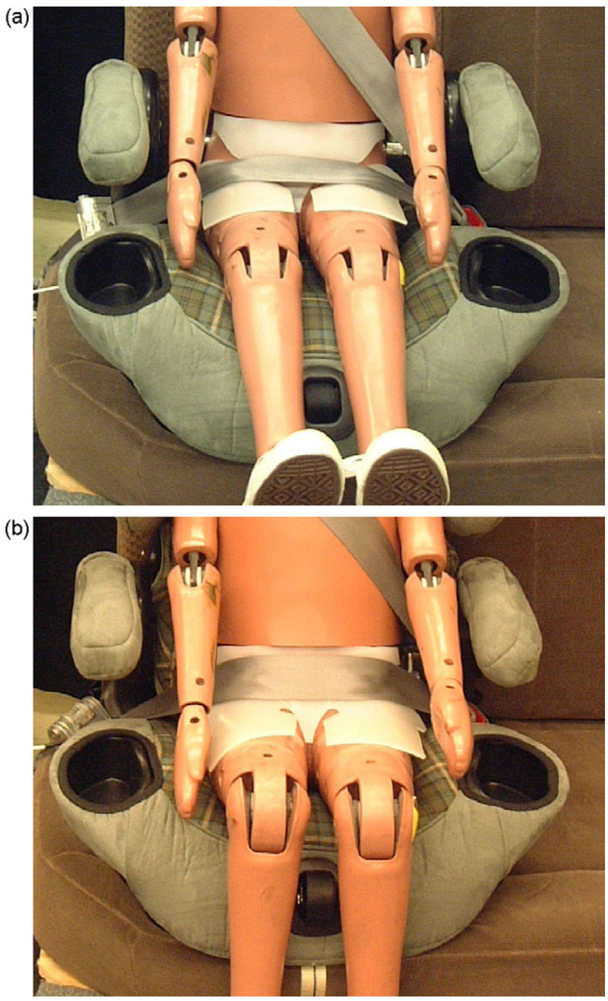

Fig. 4. Booster B09 in test condition 2 in backless mode (left) and highback mode (right).

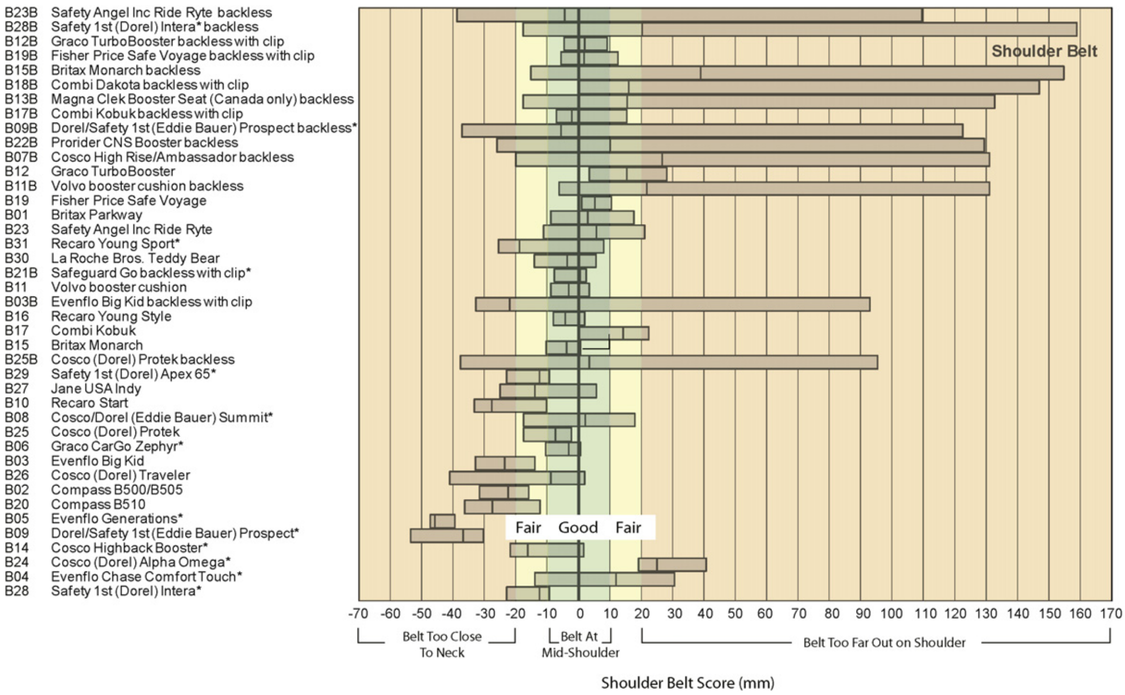

Fig. 5. Median and range of shoulder belt scores rank ordered by median lap belt score (see Fig. 3).

thighs, whereas in highback mode the booster placed the belt vertically on the front surface of the ATD pelvis. With the addition of the back component, the ATD's knees were substantially more flexed and indicative of the more forward positioning of the ATD relative to the lap belt guides that results in poorer lap belt fit. Boosters with thin back components (e.g., B11 and B25) had the smallest decrement in lap belt fit when the back components were added. Booster B28 was effectively two different boosters in highback and backless modes. The shell component used in highback mode produced the worst median lap belt score, whereas the median score produced by the base component used in backless mode was among the best.

3.3. Shoulder belt fit

Fig. 5 shows the median and range of shoulder belt scores for all boosters across test conditions, rank ordered by median value. Positive values indicate that the belt is further outboard on the shoulder.

For backless boosters, shoulder belt-positioning clips were used if available. Backless boosters without belt-positioning devices showed large ranges in belt fit as D-ring locations were varied, but good shoulder belt fit could be achieved with backless boosters when belt-positioning devices were used (boosters B12B and B21B). Manufacturers' instructions for these boosters specify that the belt should be placed to achieve good shoulder belt fit and then the positioning device should be used to maintain that position. Accordingly, results indicated that the positioning devices helped to maintain the belt on the ATD shoulder.

Shoulder belt fit varied over a relatively narrow range for highback boosters due to their belt-routing features, particularly when compared to the backless boosters without clips. Backless boosters had shoulder belt scores ranging from −39 to 159 mm, while highback booster scores ranged from −54 to 41 mm. Four highback boosters had fair shoulder belt scores and five had good scores.

Fig. 6 shows shoulder belt routing for three boosters in test condition 1, demonstrating belt fit that is too close to the neck (booster B05), centered on the shoulder (booster B11), and too far outboard (booster B24).

3.4. Booster design assessment

Differences in lap belt fit across boosters were readily explained by differences in the construction of the belt-routing features and the positions of these features with respect to the ATD. The lap belt guides on better-performing boosters hold the lap belt forward and down, rather than up. Fig. 7 shows side views of booster B19, which was among the best for lap belt fit, and booster B24, which was among the worst. The belt guides in booster B19 held the lap belt forward, and the lower edge of the belt path was at the same height as the booster seat surface, rather than above it. In contrast, in booster B24 the lap belt is routed through a channel in the plastic shell, which holds the belt above the booster seat surface and at an angle to the thighs.

Lap belt fit generally was poorer in combination boosters that also can be used as harness restraints. The six boosters with the worst lap belt scores (B05, B09, B14, B24, B04, B28) were combination boosters with rigid shells (nonpivoting nonremovable backs). The best shoulder belt fit was obtained with routing features similar to those shown for booster B19 in Fig. 7. These belt guides could be adjusted vertically with the back component and always could be located appropriately for the ATD. In contrast, the shoulder belt-positioning guides in the shell-type combination restraints typically were placed more outboard and had more limited adjustment, resulting in more outboard or inboard belt placement than desirable (booster B24 in Fig. 7, for example).

4. Discussion

Belt-positioning booster seats differ meaningfully in the lap and shoulder belt fit they provide children, as measured by a Hybrid-III 6-year-old ATD using repeatable and reproducible test procedures. The effect of test condition (belt and vehicle seat configuration) on lap belt scores generally was smaller than the

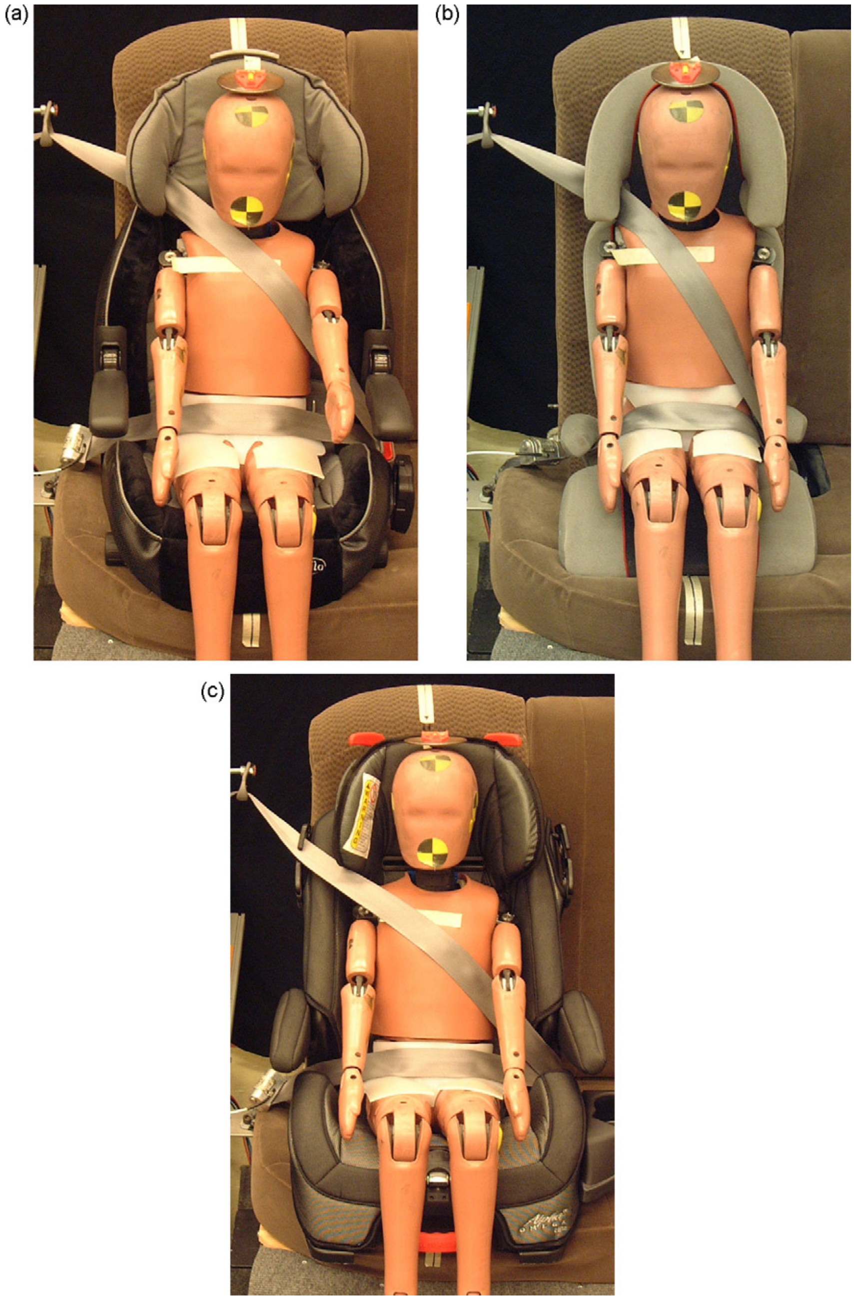

Fig. 6. Examples of shoulder belt fit in test condition 1.

differences across boosters, indicating that booster design, particularly the geometry of belt-routing features, is more important than vehicle belt and seat configuration in determining static lap belt fit.

The wide variation in lap belt fit across boosters deserves particular attention, given that a primary purpose of boosters is to improve lap belt fit to reduce the likelihood of submarining. In eight of 41 boosters studied (all eight were highback boosters, and six were combination shell boosters that also could be used as forward-facing child restraints with internal harnesses), the upper edge of the belt was above the top of the ATD pelvis bone (median lap belt score of less than 0). This position places the width of the belt vertically against the lower abdomen, rather than in the preferred position flat on the tops of the thighs. Boosters that produced good lap belt scores had belt-routing features that held the belt down and forward.

Backless boosters produced better lap belt fit, on average, than highback boosters. Some of this difference can be attributed to the relatively poor lap belt guides in the highback shell combination boosters. However, boosters that could be used in both backless and highback modes produced better lap belt fit without their back components, an effect that was due largely to more rearward positioning of the ATD. The importance of fore-aft occupant positioning for lap belt fit suggests that smaller children and those who sit more rearward in boosters will tend to obtain better belt fit in backless boosters than in highback boosters. However, the extended-knee postures produced by the more rearward seated position (Fig. 7) might cause smaller children to slouch more in backless boosters, creating a smaller difference in practice than is observed in ATD testing.

Even after installing and adjusting the boosters in close accordance with manufacturers' instructions, the shoulder belt fre-

(a) (b) (c) (d) (e) (f)

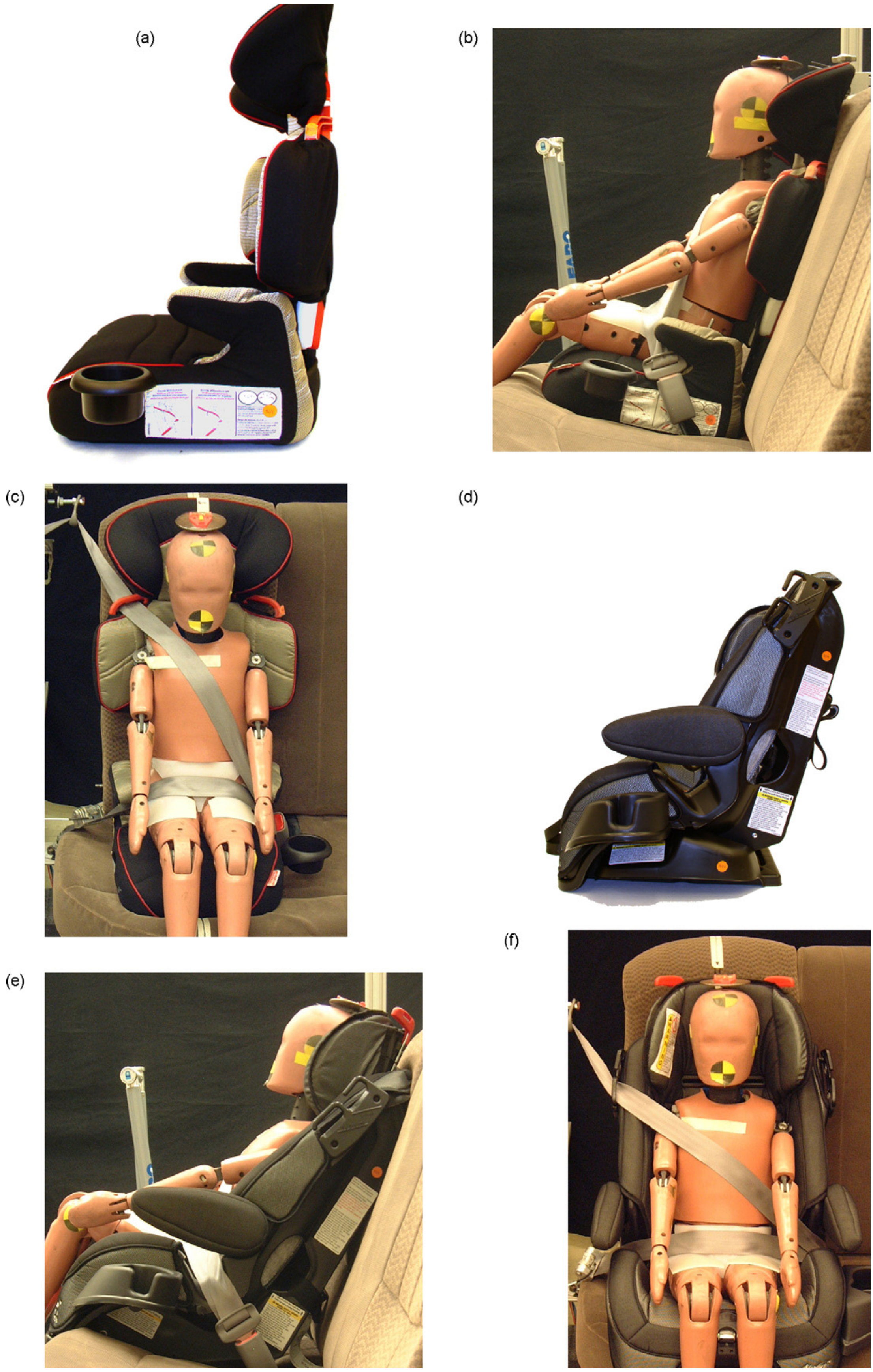

Fig. 7. Design differences in lap belt-routing features. Booster B19 (top) produced good lap and shoulder belt fit, whereas booster B24 (bottom) placed lap belt too high and shoulder belt too far outboard. Note placement of lap belt relative to ATD pelvis.

quently encroached on the neck or lay beyond the appropriate shoulder zone. Because the 6-year-old ATD is near the middle of the body size range of the 4–8-year-old children for whom boosters are intended, these results suggest that a large percentage of children would experience poor shoulder belt fit in these boosters. Shoulder belt fit in backless boosters was strongly affected by upper belt anchorage location, except that the positioning clips provided with some boosters were effective in maintaining the belt on the shoulder. Further research is needed to determine whether the belt routing in backless boosters using these clips is as effective as the routing provided by highback boosters in providing torso restraint. The real world use rates of these clips and their ability to maintain good static belt fit during normal riding motions also are important concerns.

Boosters can simultaneously achieve good lap and shoulder belt fit. Based on the full range of scores falling within the fair or good zones, 10 boosters provided fair or good belt fit scores for both the lap and shoulder belts (highback boosters B01, B11, B15, B16, B19, and B30; backless boosters with clips B12B, B17B, B19B, and B21B). The lap belt guides on these boosters (Fig. 7), which are similar to the design proposed by Chamouard et al. (1996), restrict the upward and rearward movement of the lap belt while allowing the belt to lie flat against the outer edge of the booster seat surface, rather than holding the belt above the seat.

Backless boosters without shoulder belt routing guides produced a large range of shoulder belt fit, as expected. Because the range of upper anchorage locations in vehicles is large, static belt fit that can be expected with a backless booster is much more dependent on the vehicle than is the case for highback boosters with integrated belt guides. These results suggest that increased attention to the belt fit that children are achieving with a particular booster/vehicle combination is warranted for backless boosters.

Booster designs vary considerably in their ability to accommodate children of different sizes, particularly with respect to shoulder belt positioning. The current procedures do not evaluate the belt fit of booster seats for children of different sizes, and the belt fit experienced by children using these boosters can be expected to vary more widely than the measurements reported here due to differences in posture and body dimensions. The belt-fit measurement methods presented here could readily be adapted to testing with any size dummy, including the P-series dummies used in European testing. Testing with 3-year-old and 10-year-old dummies could help to illuminate the effects of body size on belt fit, but belt fit data from children with a wide range of body size are also needed. Data from children in the same conditions tested with ATDs will provide the needed correlation between child and ATD belt fit. Based on the results of previous studies, lap belt fit is likely to improve as children get larger. The effects of increasing body size on shoulder belt fit will depend on the position and adjustability of the shoulder belt routing components (Reed et al., 2005, 2006).

The belt-fit measurement procedure developed in this study is substantially more precise than previous methods used to measure belt fit among children (e.g., Klinich et al., 1994). Although the repeatability values in Table 2 suggest that the rank ordering of boosters in Figs. 3 and 5 likely would be somewhat different if the testing were repeated with a different investigator, the overall conclusions with respect to the effects of booster features on belt fit would not be expected to differ. The procedures could be readily adapted for use with other dummies, including the Hybrid-III and P-series ATDs. The lap and shoulder belt fit scores would be different for each ATD, due to differences in geometry and posture, but the rank ordering of boosters would be expect to be similar. Testing with larger and smaller ATDs would provide the opportunity to assess the extent to which adjustable shoulder belt routing accommodates differences in child body size.

The ATD positioning procedure was based on the methods developed by Reed et al. (2006) using data on the postures of children sitting in boosters. The ATD position is approximately 20 mm farther forward than the position that would be obtained using FMVSS 213 procedures. Based on the differences in lap belt fit observed between backless and highback booster modes, the forward shift of the ATD to a more realistic position likely had a substantial negative effect on lap belt scores. That is, children in realistic postures are likely to experience less advantageous belt fit than would the ATD if positioned according to FMVSS 213 procedures. However, the ATD position used in this testing may vary relative to child postures across boosters. For example, boosters with unusually long seats may cause children to sit further forward than the ATD. Further research is needed to demonstrate the relationship between child belt fit and belt fit measured with the ATD across booster conditions.

The static belt fit measured in this study also may not be a good predictor of the dynamic performance of the booster. However, many researchers have identified the initial position of the lap belt with respect to the pelvis as critical for preventing submarining (e.g., Chamouard et al., 1996). If the belt starts out above the pelvis, submarining is inevitable in a frontal impact. The use of any booster is likely to be safer for most children in this age range than not using a booster, but the current results suggest that some boosters do a better job than others in placing the belt appropriately with respect to skeletal structures.

Additional research is needed to determine the extent to which the observed differences in static belt fit affect dynamic outcomes. Such efforts will be complicated by the limitations in the realism of the available crash dummies (Chamouard et al., 1996). In particular, the ATDs may be inadequately sensitive to poor lap belt fit. Further analysis of field data is also needed to monitor the incidence of injuries caused by poor belt fit.

5. Conclusions

Belt-positioning boosters produce a wide range of static belt fit. Differences across boosters appear large enough to produce differences in the level of occupant protection, particularly in preventing belt-induced abdominal injuries. The data indicate it is feasible to design boosters to produce better belt fit than many boosters currently provide. Limitations of current child test dummies and lack of field data showing differences in outcomes among booster models should not delay improvements in booster design that would improve static belt fit.

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Appendix A

Booster seats used in testing.

Make	Model	Mode	Code
Britax	Parkway	Highback	B01
Compass	B500/B505	Highback	B02
Evenflo	Big Kid Confidence	Highback	B03
Evenflo	Big Kid Confidence	Backless with clip	B03B
Evenflo	Chase Comfort Touch[a]	Highback	B04
Evenflo	Generations[a]	Highback	B05
Graco	CarGo Zephyr[a]	Highback	B06
Cosco	High Rise/Ambassador	Backless	B07B
Cosco/Dorel (Eddie Bauer)	Summit[a]	Highback	B08
Dorel/Safety 1st (Eddie Bauer)	Prospect[a]	Highback	B09
Dorel/Safety 1st (Eddie Bauer)	Prospect	Backless	B09B
Recaro	Start	Highback	B10
Volvo	Booster Cushion	Highback	B11
Volvo	Booster Cushion	Backless	B11B
Graco	TurboBooster	Highback	B12
Graco	TurboBooster	Backless with clip	B12B
Magna (Canada only)	Clek Booster Seat	Backless	B13B
Cosco	Highback Booster[a]	Highback	B14
Britax	Monarch	Highback	B15
Britax	Monarch	Backless	B15B
Recaro	Young Style	Highback	B16
Combi	Kobuk	Highback	B17
Combi	Kobuk	Backless with clip	B17B
Combi	Dakota	Backless with clip	B18B
Fisher-Price	Safe Voyage	Highback	B19
Fisher-Price	Safe Voyage	Backless with clip	B19B
Compass	B510	Highback	B20
Safeguard	Safeguard Go[a]	Backless with clip	B21B
Prorider	CNS Booster	Backless	B22B
Safety Angel Inc.	Ride Ryte	Highback	B23
Safety Angel Inc.	Ride Ryte	Backless	B23B
Cosco (Dorel)	Alpha Omega[a]	Highback	B24
Cosco (Dorel)	Protek	Highback	B25
Cosco (Dorel)	Protek	Backless	B25B
Cosco (Dorel)	Traveler	Highback	B26
Jane USA	Indy	Highback	B27
Safety 1st (Dorel)	Intera[a]	Highback	B28
Safety 1st (Dorel)	Intera	Backless	B28B
Safety 1st (Dorel)	Apex 65[a]	Highback	B29
La Roche Bros.	Teddy Bear	Highback	B30
Recaro	Young Sport[a]	Highback	B31

[a] Combination booster that also can be used as harness restraint.

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