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Effects of vehicle seat and belt geometry on belt fit for children with and without belt positioning booster seats

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ABSTRACT

A laboratory study was conducted to quantify the effects of belt-positioning boosters on lap and shoulder belt fit. Postures and belt fit were measured for forty-four boys and girls ages 5–12 in four highback boosters, one backless booster, and on a vehicle seat without a booster. Belt anchorage locations were varied over a wide range. Seat cushion angle, seat back angle, and seat cushion length were varied in the no-booster conditions.

All boosters produced better mean lap belt fit than was observed in the no-booster condition, but the differences among boosters were relatively large. With one midrange belt configuration, the lap belt was not fully below the anterior–superior iliac spine (ASIS) landmark on the front of the pelvis for 89% of children in one booster, and 75% of children failed to achieve that level of belt fit in another. In contrast, the lap belt was fully below the ASIS for all but two children in the best-performing booster. Child body size had a statistically significant but relatively small effect on lap belt fit. The largest children sitting without a booster had approximately the same lap belt fit as the smallest children experienced in the worst-performing booster. Increasing lap belt angle relative to horizontal produced significantly better lap belt fit in the no-booster condition, but the boosters isolated the children from the effects of lap belt angles. Reducing seat cushion length in the no-booster condition improved lap belt fit but changing cushion angle did not.

Belt upper anchorage (D-ring) location had a strong effect on shoulder belt fit in conditions without shoulder belt routing from the booster. Unexpectedly, the worst average shoulder belt fit was observed in one highback booster with a poorly positioned shoulder belt routing clip. The shoulder belt was routed more outboard, on average, with a backless booster than without a booster, but raising the child also amplified the effect of D-ring location, such that children were more likely to experience poor shoulder belt fit due to outboard and forward D-ring locations when sitting on the booster. Taller children experienced more-outboard shoulder belt fit in conditions without shoulder belt routing by the booster and in the one booster with poor shoulder belt routing. Adjustable shoulder belt routing on three of the highback boosters effectively eliminated stature effects, providing approximately the same shoulder belt fit for all children. Seat back angle did not have a significant effect on shoulder belt fit.

The results of this study have broad applicability toward the improvement of occupant restraints for children The data show substantial effects of booster design on belt fit, particularly the effects of alternative lap and torso belt routing approaches. The data quantify the critical importance of belt anchorage location for child belt fit, providing an important foundation for efforts to optimize belt geometry for children.

1. Introduction

Children who cannot achieve good belt fit with vehicle belts alone should be seated in an appropriately sized harness restraint or in a belt-positioning booster. Children heavier than 40 lb seated in booster with a three-point vehicle belt are considered to be

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appropriate restrained. NHTSA recommends that children continue to use boosters until they reach age 8 unless they are 57 in. (1450 mm) tall (NHTSA, 2007). Child restraints and belt-positioning boosters have been shown to be effective in reducing the risk of injury. Elliot et al. (2006) found that the use of child restraints reduces the risk of fatality by about 28% over seat belts alone for children from 2 to 6 years of age. Durbin et al. (2003), in an analysis of data from a field survey of crash-involved child passengers, found that children 4–7 years of age using a belt-positioning booster were 59% less likely to be injured than those using a vehicle belt alone, after adjusting for driver, vehicle, and crash characteristics. Jeremakian et al. (2007) analyzed an expanded set of data from the same survey and found that the risk of abdominal injury was significantly lower for children age 4–7 using boosters compared with those using vehicle belts alone, but identified three children who experienced abdominal injuries in frontal impact while using belt-positioning boosters. Arbogast et al. (2009), updating the Durbin et al. (2003) analysis, confirmed that belt-positioning boosters reduce injury risk for children ages 4–8 compared to seat belts alone.

Boosters are designed to improve belt fit by altering the seated position of the child and, in most cases, by changing the belt routing. Good belt fit is characterized by placement of the belt in anatomical regions where the restraint forces can be directed onto the skeleton rather than soft tissues. During a frontal crash, the lap portion of the belt should engage with the front of the pelvis and the shoulder portion of the belt should load the clavicle. To achieve this loading pattern, the pre-crash position of the lap portion of the belt needs to be below the anterior superior iliac spine (ASIS) landmark on the upper edge of the front of the pelvis bone. A lap belt that starts out too high can lead to a kinematic pattern 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 known as seat belt syndrome.

The shoulder portion of the belt must be centered on the shoulder, as inboard as possible without contacting the head or neck. If the belt is too far inboard, the associated discomfort may lead to misuse such as putting the belt behind the back or under the arm. If the belt is too far outboard, the belt may slide off the shoulder and fail to properly restraint the torso during a crash, leading to excessive head excursion and increased injury risk.

Most rear vehicle seats are too long for children and small adults (Huang and Reed, 2006; Bilston and Sagar, 2007), which can lead to slouching and poor belt fit (Klinich et al., 1994). A booster effectively shortens the seat cushion, allowing the child to sit comfortably with less slouching. A booster also raises the child by about 100 mm (Reed et al., 2006) which tends to improve both shoulder and lap belt fit, reducing neck interference and increasing the lap belt angle in side view relative to horizontal. Boosters also have features designed to alter the belt routing. Nearly all boosters have belt guides in the lap area, and many have guides to control shoulder belt position.

Boosters sold in the U.S. 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. Boosters are not required to meet static belt fit criteria. However, the dynamic testing does not adequately assess the belt fit provided by the boosters. Chamouard et al. (1996) compared the geometry of anthropomorphic test devices (ATDs) representing three- and six-year-old children to X-ray data 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 test procedures use a single, midrange belt and seat geometry that does not evaluate the ability of the booster to produce good belt fit in the disadvantageous conditions often found in vehicle rear seats.

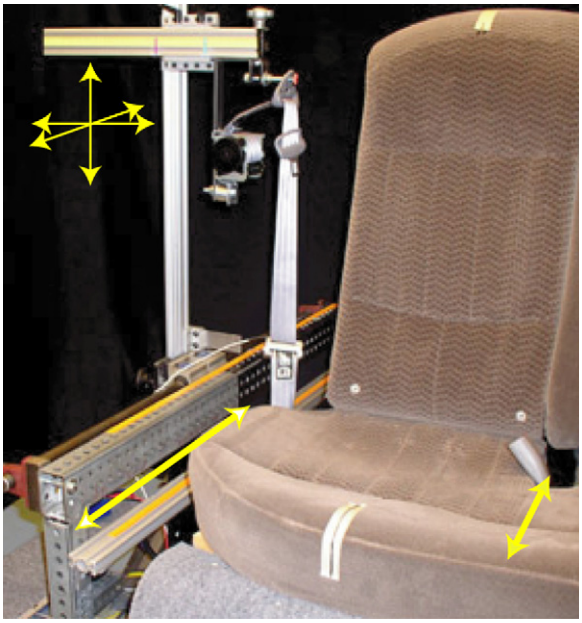

Fig. 1. Reconfigurable rear seat mock-up. The upper anchorage (D-ring) location can be adjusted on three axes and the lower anchorages can be adjusted fore-aft.

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 the child's skeleton. In another study with child volunteers, measurements of the belt fit in several boosters with markedly different construction indicated that some boosters may provide better belt fit than others (Reed et al., 2005). Reed et al. (2009) developed a method for using anthropomorphic test devices (ATDs) to quantify belt fit in belt-positioning boosters.

The current study examines the belt fit provided by four boosters in a wide range of vehicle belt conditions for children ages 5–12. The test conditions were selected to span a large range of the vehicle seat and belt configurations found in a survey of second-row seating positions in late-model vehicles. The booster belt fit is contrasted with the belt fit obtained without a booster.

2. Methods

2.1. Laboratory mockup

Testing was conducted using a reconfigurable mockup of a vehicle rear seating area shown in Fig. 1. The seat was mounted to fixtures that allowed the back angles, cushion angles, and cushion lengths to be varied over wide ranges. Testing was conducted in the right-most outboard seating position. The side bolster on the seat back was removed so that the shoulder belt would have minimal interaction with seat. The seats were mounted high enough from the floor that none of the children were able to touch the floor while sitting all the way back on the seat, reproducing the typical situation for children in rear vehicle seats. The H-point location, seat back angles, and seat cushion angles were measured using the procedures in SAE J826 (SAE, 2004).

The vehicle mockup was equipped with a three-point belt system with a sliding latchplate and emergency (inertial) locking retractor obtained from a late-model sedan. The retractor and