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Evaluation of Child Anthropometries in Relation to Modern Vehicle Seat and Booster Dimensions

Gretchen H. Baker[1], Rosalie R. Connell[1], Carrie A. Rhodes[2], Julie A. Mansfield[1]
[1] Injury Biomechanics Research Center, The Ohio State University
[2] Nationwide Children's Hospital

ABSTRACT – This study compared modern vehicle and booster geometries with relevant child anthropometries. Vehicle geometries (seat length, seat pan height, shoulder belt outlet height, and roof height) were obtained for 275 center and outboard rear seating positions of US vehicles (MY 2009–2022). Measurements of 85 US boosters (pan height and pan length) and anthropometries of 80 US children between 4–14yo (seated height, thigh length, leg length, and seated shoulder height) were also collected. Comparisons were made between vehicles, boosters, and child anthropometries. Average vehicle seat lengths exceeded child thigh lengths (+9.5cm). Only 16.4% of seating positions had seat lengths less than the child thigh length mean+1SD. Even for children at least 145cm, only 18.8% had thigh lengths greater than the average vehicle seat length. Child thigh lengths were more comparable with average booster seat pan lengths for all multi-mode and high-back designs (-2.0cm) and low-back boosters (+3.1cm). The average observed booster pan height (9.9cm) would help most children achieve seated shoulder heights similar to the Hybrid III 5th percentile Female ATD. Compared to vehicle seats, booster geometries were more compatible with child thigh lengths and assist children in achieving seated shoulder heights more comparable to the vehicle restraint system. This emphasizes the continued need for shorter vehicle seat cushion lengths for these occupants and the need to educate caregivers and promote booster recommendations which highlight the importance of achieving proper belt fit and avoiding slouched postures, even for children greater than 8 years and/or 145cm.

KEYWORDS –Vehicle Geometry, Belt-Positioning Booster, Child Anthropometry.

INTRODUCTION

In the US, many states utilize basic anthropometric thresholds to suggest when children can transition from utilizing a belt-positioning booster to sitting on the vehicle seat alone, including reaching 6 or 8 years of age, 22.7 or 36.3 kgs (60 or 80 lbs), or 145 cm (57 inches). Current best practice recommendations from the American Academy of Pediatrics (AAP) suggest that children should utilize boosters until the vehicle seat belt fits properly, which the AAP states as typically occurring once reaching 145 cm (57 inches) in stature and between 8 and 12 years (Durbin and Hoffman, 2018). In Europe, recommendations of 12 years of age, 135 cm stature, or 150 cm stature are utilized (European Union, 2014). The Centers for Disease Control (CDC) growth chart data suggest children will reach the US 145 cm booster transition threshold around 11 years of age (CDC, 2017). However, in the US in 2021, observed booster use was only 31.0% among 4–7yo's (16.1% were restrained by the seatbelt and 10.6% were unrestrained) and 12.5% among 8–12yo's (73.3% were restrained by the seatbelt and 13.2% were unrestrained) (Boyle, 2023). This suggests that many US children between 4–12 years may be prematurely transitioning from boosters based on their stature alone.

Best practice recommends that children should pass the "5-Step Test" to appropriately and safely sit on the

Address correspondence to: Gretchen Baker, The Ohio State University, 333 W. 10th Ave., Columbus, OH 43210. Electronic mail: Gretchen.Baker@osumc.edu

vehicle seat without a booster, which includes the child being able to sit with:

(1) their back fully against the vehicle seatback,

(2) knees bent comfortably over the vehicle seat,

(3) the shoulder belt over the center of the clavicle,

(4) the lap belt below the anterior superior iliac spine (ASIS), and

(5) the child is mature enough to sit properly for the entire trip (SafetyBeltSafe U.S.A., 2022).

Some versions of the 5-Step Test also include the child's ability to place their feet flat on the floor. Basic anthropometries (such as age or stature) have been shown to be inadequate predictors of proper belt fit in the rear seat for 7–12yo children (Parab et al., 2022), which also suggests children are likely prematurely transitioning from boosters based on the principles of good belt fit and the 5-Step Test if relying on age- and/or stature-based recommendations alone.

Prior studies have compared rear seat vehicle geometries (model year, "MY", 2005–2006) to historic child anthropometric data (Snyder et al., 1975, 1977) and found that vehicle seat cushion lengths were too long compared to the anthropometry of most children (Bilston and Sagar, 2007; Huang and Reed, 2006). Huang and Reed (Huang and Reed, 2006) analyzed child age distribution data from NASS-GES (crash years 1999–2002) and nationally representative anthropometric data from prior studies (Gordon et al., 1989; Snyder et al., 1975). They compared expected child buttock-popliteal lengths (BPL) to a convenience sample of 56 vehicles (described in 2006 as "late model") to assess child compatibility with vehicle rear seat geometries. They found the median second-row seat pan length to be 455 mm, which was longer than the expected thigh length of 83% of children and 24% of adult rear-seated occupants. Bilston and Sagar (Bilston and Sagar, 2007) evaluated 50 vehicles (MY 2005–2006) and compared their geometries to nationally representative anthropometric data and expected child BPL (Snyder et al., 1975, 1977; Steenbekkers, 1993). Similarly, they found the 50th percentile child's BPL would not accommodate the average vehicle seat cushion length of 453 mm until 14 years of age.

Previous research studies have recommended 44.0 cm as the maximum seat cushion length that small female occupants could reasonably accommodate based on their anthropometry (Pheasant and Alston, 1987; Reed et al., 1994). Additionally, many studies have recommended that shorter vehicle seat cushion lengths are necessary to accommodate children (the primary rear seat occupants) and may contribute to improvements in crash outcomes (Hu, Wu, Klinich, et al., 2013; Hu, Wu, Reed, et al., 2013; Huang and Reed, 2006; Klinich et al., 2013). Updated comparisons of vehicle geometries and child anthropometries would allow investigation on potential improvements to rear seat geometries in recent years to better accommodate children. Additionally, recent work has highlighted the reality of children assuming slouched postures on belt-positioning boosters as well, in some cases attributed to long booster seat pan lengths (Baker et al., 2021; Connell et al., 2024; Jones et al., 2020). This suggests that updated comparisons of booster geometries and child anthropometries are also warranted. Therefore, the purpose of this study was to compare modern vehicle and booster geometries with relevant child anthropometries in the context of expected child posture and belt fit.

METHODS

Vehicle geometries were obtained for 275 center and outboard rear seating positions (second and third row, if applicable) of vehicles on the US market with MY ranging from 2009–2022 (average 2015). Vehicles represent a convenience sample and were obtained from a large used vehicle retailer in the US. Vehicle measurements were obtained via manual measurements with rigid and/or flexible tape measures. First, the centerline of the seat pan was found by measuring the width of the flat part of the seat pan cushion and finding the center of this width. Then, the plane of the seatback was projected downwards using a rigid carpenter's level. The intersection of the seatback plane with the centerline of the seat pan was defined as the "origin." Seat pan length along the centerline ("seat length") was measured from the origin to the most curved point on the front edge of the vehicle seat cushion, following the plane of the seat pan cushion without applying any preload. "Seat pan height" was measured as the height from the upper front edge of the seat pan to the floor measured at 90° from the surface of the seat pan. The "shoulder belt outlet height" was measured from the origin to the D-Ring of seatbelt outlet in the vertical direction. Roof height was measured from the origin to the roof, along the plane of the vehicle seatback. More details about vehicle measurements are shown in Figure 1.

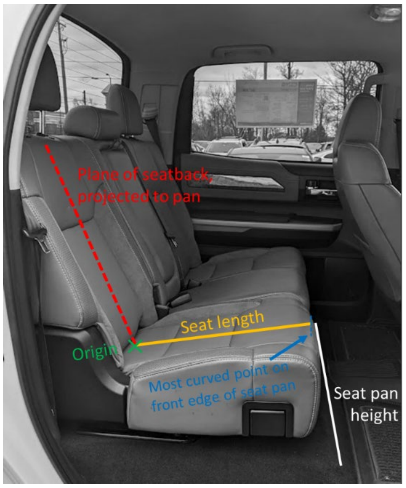

Figure 1: Vehicle Measurements

Measurements of 85 US boosters were also obtained, with manufacture dates from 2012–2022 (average 2017). Boosters also represent a convenience sample and were obtained from manual measurements obtained at large retailers of child restraint systems (CRS) in the US. Booster seat pan height was measured at the rear centerline of the booster ("booster pan height"). Booster seat pan length ("booster pan length") was defined as the length along the booster centerline from the booster rearmost point on the booster pan to the most curved point on the front edge of the booster. Finally, maximum booster shoulder belt guide height from the seating surface ("booster shoulder belt guide height") was obtained, if applicable, as the height of the center of the booster belt guide in its highest position with respect to the rear booster pan surface when measured along the booster seatback angle. Booster measurements are shown in (Figure 2).

Figure 2: Booster Measurements

Anthropometries of 80 US children (4–14 years, 18.1–54.4 kg, 83.8–160.0 cm) were collected as part of research projects targeting children of the age, mass, and stature to be appropriately restrained on boosters in the US (Institutional Review Board protocol numbers: 2019H0207 and 2022H0268) (Baker et al., 2021; Connell et al., 2024). Anthropometry measurements included seated head height ("seated height") which was defined at the height from the seating surface to the most superior point of the head, seated buttock to popliteal length ("BPL" or "thigh length") defined as the length from the most posterior part of the buttock to the popliteal fossa, standing height of lateral epicondyle of the femur ("leg length") defined as the height of the lateral epicondyle from the floor, standing greater trochanter height ("lower extremity length") defined as the height of the greater trochanter from the floor, and standing acromion height ("standing shoulder height") defined as the height of the acromion from the floor. An approximate "seated shoulder height" was calculated by subtracting lower extremity length from standing shoulder height.

Relevant dimensions for anthropomorphic test devices (ATDs) (the Hybrid III (HIII) 3yo, 6yo, 10yo, 5th percentile female (5F), 50th percentile male (50M), and 95th percentile male (95M) and the Q-Series 3yo, 6yo, and 10yo) were also obtained, where available (Humanetics, 2023). The pediatric ATDs were selected for direct anthropometric comparison to the child cohort. The adult ATDs (HIII-5F, HIII-50M, HIII-95M) were selected for comparison as they are typically used in regulatory evaluation, particularly to define the range of anthropometries for which the seat belt must fit in the vehicle, such as in FMVSS 208 (National Highway Traffic Safety Administration, 2023). For ATDs, shoulder pivot height was compared to child seated shoulder height, ATD buttock popliteal length was compared to child thigh length, and ATD knee pivot height was compared to child leg length. Anthropometric comparisons were also made between the current sample and the parametric child models from *HumanShape.org* (UMTRI, 2024) and the nationally representative National Health and Nutrition Examination Survey (NHANES) dataset (Fryar et al., 2021).

Comparisons were made between relevant vehicle geometries, booster geometries, and child anthropometries. Specifically, the child thigh lengths were compared to vehicle seat lengths and booster pan lengths, child leg lengths were compared to the vehicle seat pan height, child seated shoulder heights were compared to the vehicle shoulder belt outlet heights and booster shoulder belt guide heights, and child seated heights were compared to the vehicle roof height. Simple linear regressions compared child anthropometries in addition to investigating changes in vehicle dimensions with vehicle model year. The alpha level was set *a priori* at 0.05. Additionally, comparisons were made to current ATD anthropometries and relevant child restraint/booster recommendations and regulatory thresholds such as 145 cm (57 inches) stature and 8 or 12 years of age.

RESULTS

Summary of Children, Vehicles, and Boosters

Children included 31 females and 49 males ranging from 4–14 years of age (average 8.6 years, Appendix Figure A-1); additional child anthropometries are summarized in Table 1. Comparisons of child anthropometries for children less than and greater than 8 years of age and 145 cm can be found in Appendix A (Table A-1).

Table 1: Child Anthropometry*

Metric	All Children (n=80)	
	Mean ± SD	**[Min, Max]**
Age (yr)	8.6 ± 2.4	[4.2, 14.8]
Mass (kg)	28.7 ± 8.7	[18.3, 53.7]
Stature (cm)	130.8 ± 13.3	[107.3, 161.2]
Seated Height (cm)	67.2 ± 6.0	[55.9, 85.0]
Lower Extremity Length (cm)	66.9 ± 9.2	[50.2, 88.5]
Thigh length (cm)	35.0 ± 5.7	[22.5, 50.4]
Leg Length (cm)	38.1 ± 5.3	[25.8, 48.1]
Seated shoulder height (cm)	40.0 ± 5.2	[29.0, 53.4]
Standing shoulder height (cm)	107.0 ± 11.9	[85.0, 131.7]
BMI (kg/m^2)	16.5 ± 2.6	[12.7, 26.5]
CDC %-ile	46.6 ± 29.6	[1.0, 99.0]

**ATD anthropometry comparisons can be found in Appendix* Table A-2

Relevant ATD anthropometries are summarized and compared to child anthropometries in Appendix A (Table A-2). In general, the average child dimensions fell between those of the 6yo and 10yo ATDs. Minimum and maximum child dimensions were typically captured by the range of 3yo, 6yo, and 10yo ATDs; however, the minimum child seated shoulder height in this sample was slightly shorter than that of even the 3yo ATDs. Additionally, the minimum child thigh lengths were more in line with the 3yo ATDs compared to the 6yo ATDs. Maximum child anthropometries in this sample generally exceeded those of the 10yo ATDs, with seated height, leg length, and total weight falling between the HIII-5F and HIII-50M and seated shoulder height and thigh length falling between the HIII-50M and HIII-95M.

Child age, stature, and mass were significantly linearly related to leg length, thigh length, seated shoulder height, and seated height for this cohort (Appendix A, Table A-3), but these parameters explained different amounts of variation (R^2_{Adj} = 15.23–80.82%). Age, stature, and mass tended to explain the most variation in seated height (R^2_{Adj} = 60.62–80.82%) and leg length (R^2_{Adj} = 53.17–79.27%); however, less variation was explained for thigh length (R^2_{Adj} = 53.47–55.59%) and seated shoulder height (R^2_{Adj} = 15.23–29.10%).

N=172 unique vehicle make/model/MYs (full list included in the Appendix B, Table B-1) and n=275 individual seating positions were evaluated, with relevant vehicle geometries summarized in Table 2. Vehicle geometries are also summarized by model type (Table A-4) according to categorization from the Insurance Institute for Highway Safety (IIHS) vehicle ratings (IIHS, 2024).

N=64 booster designs were evaluated in all available booster use modes, representing n=85 unique booster use modes (full list included in the Appendix C, Table C-1), and geometries are summarized in Table 3. Booster designs were categorized as dedicated boosters (“Booster”), with subtypes including highback (“HB”), backless or low-back (“LB”), and low-profile (“Low”). Booster designs also included multi-mode child restraint systems (“Multi-CRS”). These included any boosters which also function as a rear-facing harness (RF) and/or forward-facing harness (FF) mode in addition to a booster mode (HB and/or LB). Boosters or Multi-CRS which transition from HB to LB were measured in each mode and their measurements are represented in the HB or LB mode, respectively.

Table 2: Vehicle Geometries by Row and Seating Position

Row	Seating Position	Pan Length (cm)		Pan Height (cm)		D-Ring Height (cm)		Roof Height (cm)	
		N	Mean ± SD	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD
2nd	Center	81	41.5 ± 3.8	40	61.6 ± 11.0	40	61.6 ± 11.0	40	93.0 ± 7.5
2nd	Outboard	173	45.7 ± 3.2	48	63.5 ± 4.8	48	63.5 ± 4.8	48	93.7 ± 6.3
3rd	Center	5	42.6 ± 5.3	4	78.3 ± 15.7	4	78.3 ± 15.7	4	91.9 ± 4.1
3rd	Outboard	14	44.3 ± 4.6	0	NA	0	NA	0	NA
2nd	All	254	44.3 ± 3.9	88	62.7 ± 8.2	88	62.7 ± 8.2	88	93.4 ± 6.8
3rd	All	19	43.8 ± 4.7	4	78.3 ± 15.7	4	78.3 ± 15.7	4	91.9 ± 4.1
All	Center	86	41.6 ± 3.9	44	63.1 ± 12.3	44	63.1 ± 12.3	44	92.9 ± 7.2
All	Outboard	187	45.6 ± 3.3	48	63.5 ± 4.8	48	63.5 ± 4.8	48	93.7 ± 6.3
All	All	273	44.3 ± 4.0	92	63.3 ± 9.1	92	63.3 ± 9.1	92	93.3 ± 6.7

Table 3: Booster Geometries by CRS Type and Mode

Booster Type	Mode	N	Booster Pan Length (cm)		Booster Pan Height (cm)	
			Mean ± SD	[Min, Max]	Mean ± SD	[Min, Max]
Booster-HB	HB	14	33.7 ± 3.1	[29.7, 39.0]	9.3 ± 2.4	[6.2, 13.7]
Booster-LB	LB	20	38.4 ± 2.0	[34.6, 42.7]	8.0 ± 1.2	[5.8, 9.4]
Booster-Low	Low	2	25.6 ± 6.2	[21.2, 30.0]	2.3 ± 1.1	[1.5, 3.1]
Multi-CRS	HB	39	32.8 ± 2.9	[26.7, 41.0]	11.3 ± 3.1	[5.5, 19.0]
	LB	10	37.7 ± 2.4	[34.5, 41.8]	10.7 ± 2.5	[6.7, 14.3]
All Types	HB	53	33.0 ± 3.0	[26.7, 41.0]	10.8 ± 3.0	[5.5, 19.0]
All Types	LB	30	38.1 ± 2.1	[34.5, 42.7]	8.9 ± 2.1	[5.8, 14.3]
All Types	All Modes	85	34.7 ± 3.9	[21.2, 42.7]	9.9 ± 3.1	[1.5, 19.0]

Child Thigh Length, Vehicle Seat Pan Length, and Booster Seat Pan Length

Comparing to the average child, average vehicle seat lengths exceeded thigh lengths (+9.3 cm), and only 16.4% of seating positions provided seat lengths that were less than the child thigh length mean+1SD (Figure 3). Child thigh lengths were much more compatible with booster seat pan lengths on average (boosters -0.3 cm).

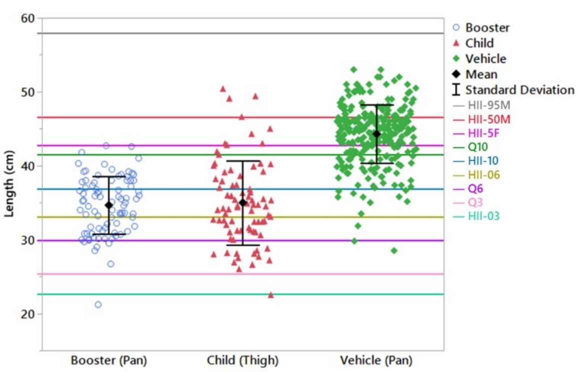

Figure 3: Comparison of Child Thigh Length to Vehicle and Booster Seat Pan Length.

Vehicle seat lengths exceeded average child thigh lengths for both center (+6.6 cm) and outboard (+10.6 cm) seating positions, as well as for both second (+9.3 cm) and third (+8.8 cm) row seating positions (Figure 4). Even when considering children at least 8yo (n=44), only 11.4% had thigh lengths greater than the mean vehicle seat length (Figure 5). For children at least 12yo (n= 8), only 37.5% had thigh length greater than the mean vehicle seat length. For children at least 145 cm (n=16), only 18.8% had thigh lengths greater than the mean vehicle seat length (Figure 6).

While a slight downward trend was observed, vehicle seat lengths (considering all rows and seating positions) have not significantly reduced with vehicle MY (Figure 7, Table A-5). When assessing the relationship between vehicle seat pan length and MY by row and seating position (Table A-6), only second row outboard seating positions have significantly decreased with MY; however, the amount of variation explained by this relationship was small (R^2_{Adj} = 1.53%). Some variation was observed in terms of seat pan length across different vehicle types (Figure A-2), with outboard minivan seating positions providing the longest pan length on average (48.3 cm) and center

SUV seating positions providing the shortest (39.2 cm).

Child thigh lengths were more comparable with average booster seat pan lengths for all multi-mode and high-back designs (-2.0 cm) and backless boosters (+3.1 cm), while low-profile designs tended to be shorter than child thigh lengths (-9.4 cm) (Figure 8). Children less than 8 years of age (31.2 cm) or shorter than 145 cm (33.7 cm) had thigh lengths more comparable to high-back (33.7 cm) and multi-mode (33.8 cm) boosters. Children at least 8 years of age (38.1 cm) or taller than 145 cm (40.3 cm) had thigh lengths more comparable to backless boosters (38.4 cm).

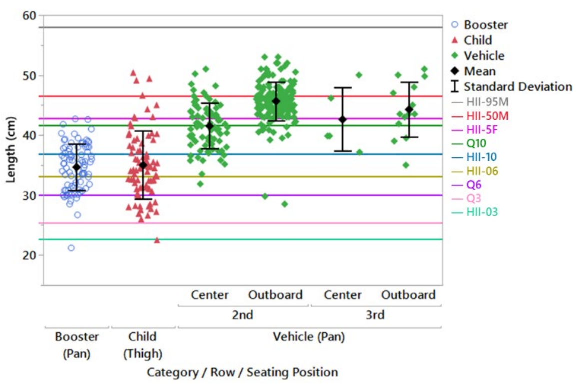

Figure 4: Comparison of Child Thigh Length to Vehicle and Booster Seat Pan Length, by Vehicle Row and Seating Position.

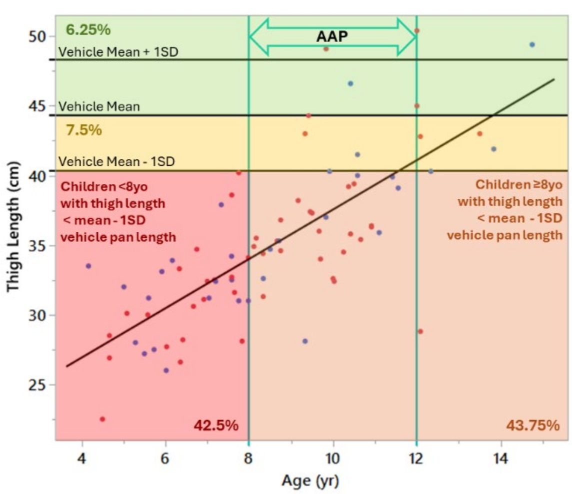

Figure 5: Child Thigh Length vs. Age, with Vehicle Seat Pan Length Mean ± SD. Fitted line represents simple linear regression, with p-value <0.05 and R^2_{Adj}=53.47%.

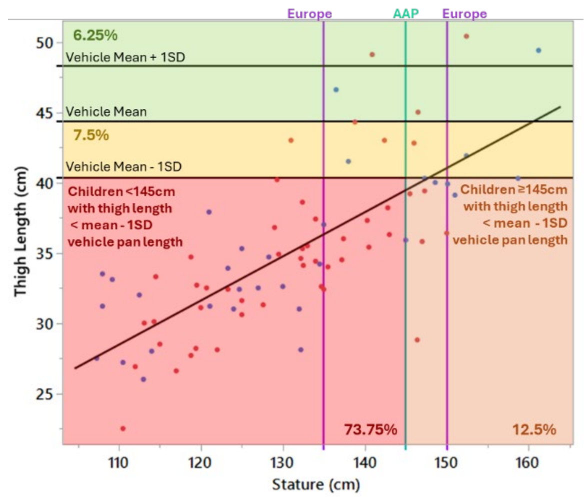

Figure 6: Child Thigh Length vs. Stature, with Vehicle Seat Pan Length Mean ± SD. Fitted line represents simple linear regression, with p-value <0.05 and R^2_{Adj} =53.54%.

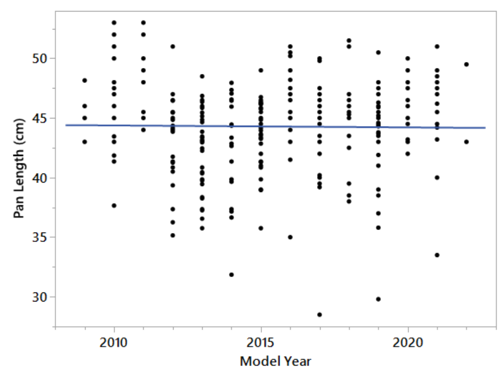

Figure 7: Vehicle Seat Pan Length vs MY. Fitted line represents a simple linear regression, with p=0.0523 and R2=-0.35%.

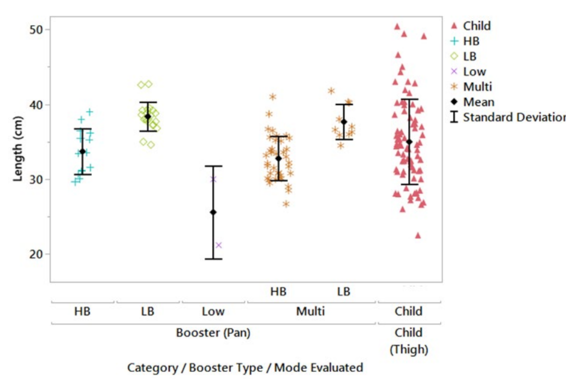

Figure 8: Comparison of Child Thigh Length to Booster Seat Pan Length by Booster Type.

Child Leg Length, Vehicle Seat Pan Height, and Booster Seat Pan Height

The average child's leg length tended to exceed vehicle seat pan height on average (+4.8 cm, Figure 9). This difference between child leg length and vehicle seat pan height was greater for third row (+8.5 cm) or center seating positions (+8.9 cm) on average (Table 2). The leg length of children younger than 8 years was comparable to the vehicle seat pan height (+0.2 cm) while children 8 years and older tended to have longer leg lengths (+8.5 cm) than the average vehicle seat pan height.

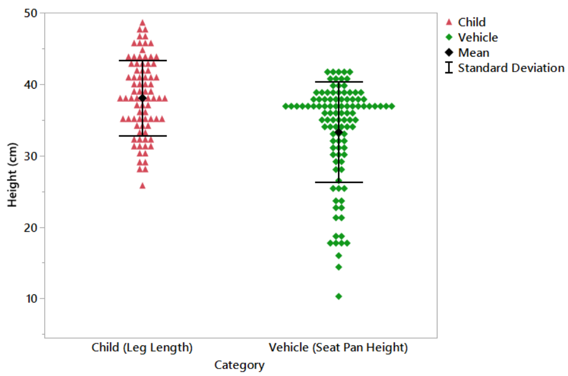

Figure 9: Comparison of Child Leg Length to Vehicle Seat Pan Height.

Booster pan heights varied by booster type (Figure 10), with multi-CRS in HB mode providing the largest pan height on average (11.3 cm) and low-profile providing the smallest (2.3 cm). Overall, the mean booster seat pan height was 9.9 ± 3.1 cm. If child leg lengths are compared to the vehicle seat pan heights plus the average booster pan height, child leg lengths tended to be less than the combined average vehicle seat and average booster pan height (-5.1 cm), suggesting that many children may no longer be able to support their lower extremities by placing their feet on the floor when seated on an average height booster.

This discrepancy was greatest for second row outboard seating positions, where the combined average vehicle seat and average booster pan height exceeded child leg lengths by 9.3 cm on average. This difference is even greater when considering only children less than 8 years of age, whose leg lengths on average were 9.7 cm shorter than the combined average vehicle seat and average booster pan height (Figure A-3). Children greater than 8 years of age had a smaller discrepancy, with their legs only 1.4 cm shorter than the combined average vehicle seat and average booster pan height.

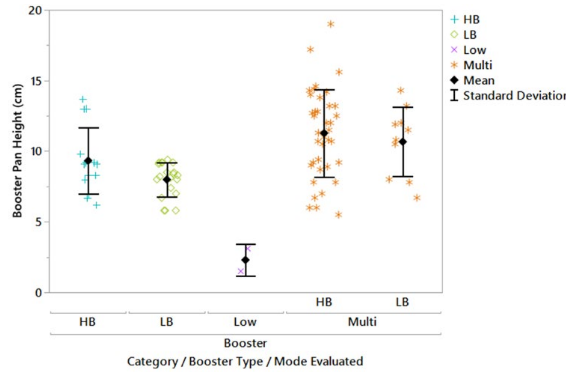

Figure 10: Booster Pan Heights by Booster Type.

Child Seated Shoulder Height and Vehicle Belt Outlet Height

Child seated shoulder heights were on average 23.3 cm shorter than the vehicle shoulder belt outlet height (Figure 11). Comparing all children, the HIII-5F's seated shoulder height (the minimum anthropometry to which shoulder belt fit is accommodated in FMVSS 208 (National Highway Traffic Safety Administration, 2023), exceeded child seated shoulder height by 4.5 cm, and only 22.5% of child seated shoulder heights meet or exceed that of the HIII-5F. Even when children were at least 8yo, their average seated shoulder height still did not reach that of the HIII-5F (-2.6 cm); however, the average of children at least 145 cm stature were more in line with the HIII-5F (-0.2 cm). Booster pan heights for both high-back (10.8 cm) and backless (8.9 cm) designs would account for this average difference in seated shoulder height to the HIII-5F. If the average child (by seated shoulder height) were seated on the average booster (pan height 9.9 cm), their seated shoulder height would exceed the HIII-5F (+ 5.4 cm) and be more in line with the HIII-50M (-1.4 cm), resulting in 87.5% of children in the current sample meeting or exceeding the seated shoulder height of the HIII-5F.

Child Seated Height and Vehicle Roof Height

Child seated heights were on average 26.1 cm shorter than the average vehicle roof height (Figure 12). Comparing to ATDs, the average child seated height fell between the HIII-10 and HIII-06. The 10yo ATDs generally represented the child mean + 1SD (average difference of 0.7 cm), and the 6yo ATDs generally represented the child mean – 1SD (average difference of -0.6 cm).

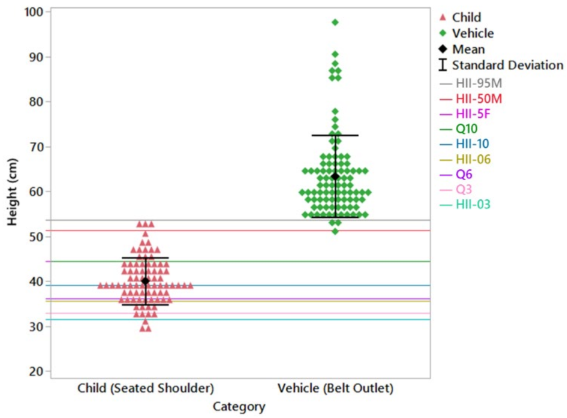

Figure 11: Comparison of Child Seated Shoulder Height to Vehicle Seatbelt Outlet Height. Horizontal lines represent ATD seated shoulder heights.

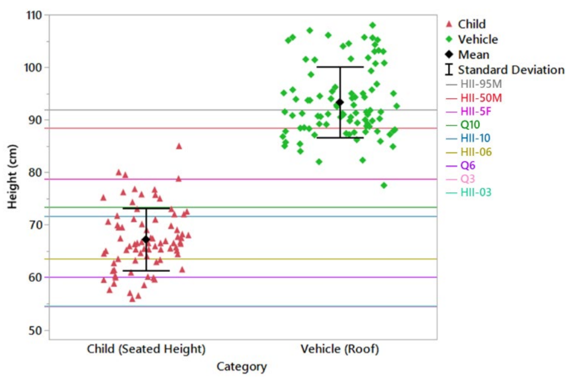

Figure 12: Comparison of Child Seated Height to Vehicle Roof Height. Horizontal lines represent ATD seated heights.

Expected Child Fit Based on Overall Anthropometry

Children were also assessed in terms of their expected fit to the average vehicle based on their overall anthropometry. Specifically, if their thigh length met or exceeded the average vehicle seat pan length (44.3 cm) **and** if their seated shoulder height met or exceeded the HIII-5F ATD seated shoulder height (44.5 cm), the child likely could be expected to have an appropriate fit of the lap and shoulder belt and have reduced possibility of slouching.

Figure 13 shows the relationship between child stature and age in addition to which children were expected to fit the average vehicle in terms of meeting or exceeding the vehicle seat length and the HIII-5F seated shoulder height. Of all 80 children evaluated, only one was expected to fit the average vehicle based on these criteria. This child was 12 years of age and had a thigh length of 45.0 cm, a seated shoulder height of 52.4 cm, a stature of 146.5 cm, and a mass of 42.0 kg. This suggests that the remaining children (n=79) may be better restrained on a CRS or booster, based on the comparison of their thigh length and seated shoulder height to the average vehicle geometry. Of these children who may be better restrained on a booster, their mass ranged from 18.3–53.7 kgs (40.4–118.4 lbs), with a mean of 28.6 ± 8.7 kg. However, four of these children had a mass greater than 45.4 kgs (100 lbs). Based on the AAP 2024 Car Safety Seat Product Listing (AAP, 2024), these children would not be able to fit the manufacturer mass requirements on 50.7% of boosters (and CRS which transition to booster mode) currently on the US market (Table A-7).

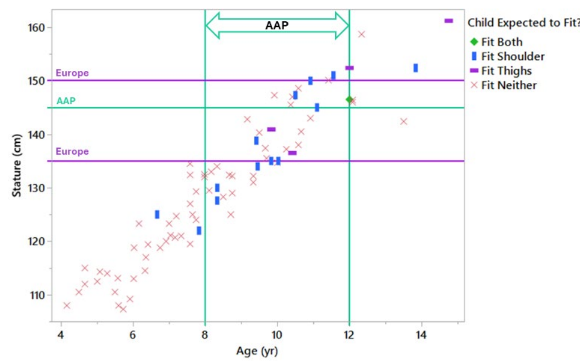

Figure 13: Expected Child Fit to Vehicle by Comparison of Child Stature vs. Age. Symbols depict if children were expected to fit both thigh length and seated shoulder height (green diamonds), only seated shoulder height (blue vertical rectangles), only by thigh length (purple horizontal rectangles), or not expected to fit (red X's). Vertical lines represent the age-based booster transition range, and horizontal lines represent the stature-based booster transition thresholds.

Comparison of Child Anthropometries to Other Samples

To contextualize the convenience sample of child anthropometry analyzed here, comparisons were made to parametric child models from *HumanShape.org* (UMTRI, 2024). The Human Shape models were developed based on 3D scans of seated child volunteers which are used to generate parametric models for children of various anthropometries and postures (Park et al., 2017). The mean child anthropometries observed in the present study (specifically, stature, BMI, and the ratio of seated height to stature) were input to *HumanShape.org* to generate a seated child model for comparison. The Human Shape model torso recline angles and torso flexion angles were set to 0° and 25°, respectively, to better represent the upright seated postures assumed by the children for the anthropometric measurements obtained in the present study. The resulting anthropometry of the Human Shape model is compared to the present study anthropometry in Table 4. The largest percentage differences were observed in leg length (-7.8%), thigh length (-6.1%), and seated shoulder height (-6.1%) where the present study observed shorter lengths for all measures.

Additional child models were generated from Human Shape and compared to relevant child anthropometry age and stature groups (i.e., <8yo, ≥8yo, <145 cm, ≥ 145 cm) which can be found in the Appendix Table A-8–Table A-11. In general, children in the present study's age and stature groups tended to have smaller leg length, thigh length, and seated shoulder height compared to corresponding Human Shape models (range of percentage difference -3.9% to -9.3%).

Additionally, comparisons of child anthropometry in the present study were made to the nationally representative National Health and Nutrition Examination Survey (NHANES) dataset (Fryar et al., 2021). The NHANES reference data from 2015–2018 for children aged 4–14yo were obtained, and averages of the 50th percentile measurements for males and females of were calculated for mass, stature, and BMI. Comparisons to the present dataset can be found in the Appendix Figure A-4–Figure A-6. Child anthropometry in the present study tended to follow the NHANES trends well in terms of median stature for ages 5–11yo, with greater deviations for 4yo's and older ages where fewer children were included in the present study. Comparisons for weight and BMI varied by child age but tended to be smaller than those observed in NHANES.

Table 4: Comparison of Child Anthropometry to Human Shape(UMTRI, 2024)

Present Study (n=80)		**Human Shape Model**		**Percent Difference**
Anthropometry	**Mean ± SD**	**Analogous Metric**	**Value**	
Age (yr)	8.6 ± 2.4	Age at testing (yr)	8.53	0.8%
Mass (kg)	28.7 ± 8.7	Mass (kg)	28.0	2.5%
Stature (cm)*	130.8 ± 13.3	Stature (cm)*	130.8	0.0%
Seated Height (cm)*	67.2 ± 6.0	Erect Sitting Height (cm)*	67.4	-0.3%
Thigh Length (cm)	35.0 ± 5.7	BPL (cm)	37.2	-6.1%
Leg Length (cm)	38.1 ± 5.3	Knee Height (cm)	41.2	-7.8%
Seated Shoulder Height (cm)	40.0 ± 5.2	Acromial Height (cm)	42.5	-6.1%
BMI (kg/m^2)*	16.5 ± 2.6	BMI (kg/m^2)*	16.27	1.4%

**Anthropometric metrics input into HumanShape.org to generate the model. Seated height was accounted for as the ratio of stature to seated height.*

DISCUSSION

Child Anthropometry

The child anthropometry data collected in this study represent a convenience sample and are not necessarily nationally representative. The children in this cohort were recruited to participate in specific research studies where participants were required to fit within the manufacturer mass and stature requirements of a selection of US boosters (4–14 years, 18.1–54.4 kg, 83.8–160.02 cm). As such, this cohort may better represent the population of potential US booster users rather than the population of all potential pediatric rear seat occupants. Additional efforts to evaluate children of larger anthropometry, children older than 12 years of age, and children representative of different populations are required. However, national US observational data from 2021 (Boyle, 2023) show a significant percentage of children between 4–12 years were restrained by the seatbelt alone (16.1% of 4-7yo's and 73.3% of 8-12yo's). This justifies the continued investigation of potential incompatibilities between child anthropometry and vehicle geometries in this age range (4–12yo). Additionally, all anthropometric measurements were directly obtained for this child cohort, and no estimations of child anthropometry based on adult relationships or older datasets were required.

Comparisons of the present child sample to nationally representative samples displayed some variation, which may influence the interpretation of these results. The child sample presented here generally tended to have smaller masses and BMI compared to NHANES when compared across age, which may influence other expected anthropometric variation as well. Additionally, when comparing the present child sample to representative models generated by Human Shape, the present study showed smaller seated shoulder height, thigh length, and leg length compared to the stature-, BMI-, and seated height-matched child model. This may be attributed in part due to differences in anthropometric measurement techniques between the volunteers and models and/or due to differences in the sample populations. However, if the child model (matched to the stature, BMI, and seated height of the average children in the present study) is compared to the vehicle seat pan lengths, similar conclusions are drawn as the child model's thigh length (37.2 cm) was still shorter than the average vehicle pan length (44.3 cm) by 7.1 cm.

The children in this study varied in terms of their age and overall anthropometry (e.g., mass, stature) in addition to specific anthropometries relevant for vehicle seat and seat belt fit (e.g., thigh length, seated shoulder height). While child age, mass, and stature were significantly linearly related to leg length, thigh length, seated shoulder height, and seated height for this cohort, they explained differing levels of variation (Appendix A, Table A-3). Age, stature, and mass explained the least amount of variation for thigh length (R^2_{Adj} = 53.47–55.59%) and seated shoulder height (R^2_{Adj} = 15.23–29.10%) which both have important implications for potential vehicle seat and seatbelt fit. While further investigations are required for a larger sample and for older and larger children, this emphasizes the importance of understanding the variation in child anthropometry, even for children of the same age or similar stature. This supports prior evaluations which have identified that age and stature alone are not adequate predictors of correct belt fit for children (Parab et al., 2022). Recent work has evaluated the effectiveness of the "5-step test" as a tool for caregivers to assess the appropriateness of seatbelt fit for children 7–12yo (Powell et al., 2024). Results indicate that the "5-step test" helped caregivers to make more accurate decisions about the appropriateness of belt fit compared to a control group (Powell et al., 2024). As such, continued emphasis on educational and outreach efforts which promote the "5-step test" may be more helpful than current recommendations which rely on age and/or stature alone as indicators for readiness of transitioning out of boosters.

Thigh Length and Vehicle Seat Cushion Length

Results from this investigation have identified significant potential incompatibility between child thigh lengths and rear vehicle seat pan lengths. This outcome supports previous investigations of older MY vehicles and nationally representative child anthropometric data (Bilston and Sagar, 2007; Huang and Reed, 2006). Previous vehicle seat cushion lengths have been reported as ranging between 40.0–49.0 cm for outboard seating positions (Bilston and Sagar, 2007) or between 42.0–51.0 cm (Huang and Reed, 2006), and the current study found a range of 28.5–54.0 cm (all rear seating positions). The mean cushion length of all seating positions in this study was 44.3 cm, which is slightly shorter than the mean cushion length of 45.3 and median cushion length of 45.5 cm previously reported (Bilston and Sagar, 2007; Huang and Reed, 2006) and may be influenced by the inclusion of third row and center seating positions. Comparing just second row outboard seating positions, the mean cushion length in this study was 45.8 cm (Table 2) which is more in line with previous studies.

In the current study, vehicle seat cushion lengths were on average 9.5 cm longer than the average child thigh length, and only 6.3% of the child cohort had thigh lengths meeting or exceeding the average vehicle seat pan length (Figure 3). Even when children met the typical thresholds for transition from booster seats (8 years of age, 12 years of age, or 145 cm stature), vehicle seat cushion lengths were too long for a large majority of children. Specifically, only 11.4% of children 8+ years, only 37.5% of children 12+ years, and only 18.8% of children 145+ cm (57+ inches) stature had thigh lengths meeting or exceeding the average vehicle seat cushion length. While a slight downward trend was observed, vehicle seat lengths have not significantly reduced with vehicle MY (MY 2009–2022, Table A-5), suggesting that improvements have not been made since the 2006 and 2007 publications highlighting this incompatibility of child thigh length and rear seat cushion lengths (Bilston and Sagar, 2007; Huang and Reed, 2006).

Additionally, outboard seating positions in minivans provided the longest seat pan lengths on average compared to other vehicle types (47.5 cm), which exceeded the average child thigh length (+12.5 cm) in addition to thigh lengths of children 8+ years (+9.4 cm) and children 145+ cm (+7.2 cm) in this cohort. This result was remarkable as minivans are typically marketed toward families and should reasonably accommodate both good CRS installations as well as compatible seat geometries for children that have outgrown boosters but still ride in the rear seat.

This incompatibility between child thigh length and vehicle seat cushion length may lead to increased instances of children assuming slouched postures by translating their pelvis forward and/or rotating it more posteriorly to achieve a more comfortable knee bend and/or support their lower extremities by placing their feet on the floor. Slouching has been observed in previous laboratory (Baker et al., 2021; Connell et al., 2024; Jones et al., 2020; Klinich et al., 1994; Reed et al., 2005) and naturalistic driving studies (Jakobsson et al., 2011; Osvalder et al., 2013) when children were seated on cushion lengths which were incompatible with their anthropometry or when attempting to alleviate other discomfort. Slouched postures prior to an evasive vehicle maneuver or crash may lead to suboptimal outcomes, such as increasing the possibility of submarining (Beck et al., 2011; Slusher et al., 2022). Results from this study emphasize the recommendation from prior studies to reduce rear seat cushion lengths to better accommodate pediatric occupant anthropometry.

Prior studies have suggested thresholds for rear seat cushion length as low as 25.5 cm (the 5th percentile BPL of rear-seat occupants 4+ years) (Huang and Reed, 2006). A candidate cushion length of 35.0 cm was also evaluated previously, and 79.0% of children 8–15 years were expected to fit based on their BPL length (Bilston and Sagar, 2007). If these candidate cushion lengths were assessed for appropriateness for the child cohort in the current study, an estimated 98.75% of children would fit the 25.5 cm cushion length, and 43.75% of children would fit the 35.0 cm cushion length.

The consequences of shorter seat cushion lengths should also be considered for other rear-seat passengers. Harnessed CRS, especially RF CRS, tend to have longer base footprints which may not be fully supported by shorter seat cushion lengths. Preliminary sled testing and computational modeling suggest that shorter seat cushion lengths result in increased y-axis rotation of RF CRS, although the magnitude of the effect was generally small (Hu, Wu, Klinich, et al., 2013; Klinich et al., 2015; Mansfield et al., 2020). Effects of short cushion lengths were less pronounced for FF harnessed CRS, boosters, and adult occupants (Klinich et al., 2015; Mansfield et al., 2020). These data suggest that shorter seat cushion lengths might not have unintended consequences for the dynamic performance of other rear seat passengers. However, further cost-benefit analyses should be conducted, especially considering the high misuse rates of harnessed CRS in the US and how installation errors might affect outcomes on shorter seat cushions.

Thigh Length and Booster Pan Length

Boosters provided seat cushion lengths much more appropriate for child anthropometry (Figure 8). On average, multi-mode and high-back design seat pan lengths were 2.0 cm less than the average child thigh length while backless boosters were longer by 3.4 cm. Children have been shown to assume slouched postures on backless boosters in short duration, laboratory evaluations (Baker et al., 2021; Jones et al., 2020) and longer (30-minute) laboratory evaluations (Connell et al., 2024), which may be influenced by the longer seat pan lengths observed for these booster types compared to boosters with backs. For the current dataset, children 8+ years of age and taller than 145 cm had thigh lengths more comparable to the backless boosters, suggesting these boosters may be more comfortable and appropriate for older and larger children. High-back and multi-mode boosters had seat pan lengths more comparable to child thigh lengths under 8 years or shorter than 145 cm, again suggesting that younger and smaller children may be more comfortably and appropriately restrained by boosters with backs. Low-profile designs tended to be shorter than child thigh lengths by 9.4 cm on average, and this, in combination with their minimal degree of boost, directly contribute to the effective seat cushion length for the child to be that of the vehicle seat. As such, low-profile designs are not helpful in addressing the issue of vehicle seat cushion lengths exceeding child anthropometry and have been also shown to contribute to slouched postures for children in short duration, laboratory evaluations (Baker et al., 2021; Jones et al., 2020) and for longer 30-minute investigations (Connell et al., 2024).

A prior study of child anthropometric fit with classroom furniture has recommended seat cushion lengths of 80–95% of the child's BPL to promote comfort and reduce slouching (Parcells et al., 1999). Longer cushion lengths may promote slouched postures while too short of cushion lengths (i.e., lack of thigh support) may also cause discomfort and contribute to variations in posture, including slouching. A more recent study of adult comfort on vehicle seats has identified that overall cushion length should be 83.46%–88.49% of BPL to promote perceived comfort; however, this study relied on estimated BPLs from participant stature (Romelfanger and Kolich, 2019). This suggests that even shorter cushion lengths may be required to provide comfortable lengths for children; however, future work is required to evaluate the percentage of thigh support that leads to decreased slouching and improvements in maintaining comfort and optimal postures, specifically for the pediatric population.

Overall, these results suggest that potential incompatibilities may also exist between child thigh lengths and some booster seat pan lengths, which may contribute to slouched postures on boosters. While the mean booster seat pan length and child thigh lengths were similar, child thigh lengths demonstrated more variation compared to booster pan lengths. 18.8% of child thigh lengths were shorter than the booster mean – 1SD pan length, and 13.4% of child thigh lengths were longer than the booster mean + 1SD pan length.

Child restraint manufacturers may wish to consider this discrepancy in relation to product design, offering varying or adjustable seat pan lengths which may help to better accommodate children of different sizes, including those at or near the minimum of their products' requirements. In addition, applying the principles of the "5-Step Test" to assess child compatibility with a particular booster design may help caregivers learn how to recognize optimal posture and belt fit. In particular, educational efforts should also focus on teaching caregivers to assess if their child can sit comfortably with their back and pelvis against the booster seatback (or vehicle seatback for a backless booster) and also if their child can comfortably bend their knees over the front edge of the booster without slouching. This would complement current caregiver education which emphasizes the importance of achieving good belt fit on boosters (i.e., shoulder belt placed mid-clavicle and lap belt placed below the ASIS).

Leg Length and Seat Cushion Height

Child leg lengths tended to exceed vehicle seat pan heights on average (Figure 9), and this difference was greater in the third row or center seating positions. This suggests that, considering leg length alone, children could likely comfortably place their feet on the vehicle floor and support their lower extremities if their thighs were able to clear the seat pan length; however, the majority of children in this sample would be more optimally restrained by a booster, due to their shorter thigh length and seated shoulder height. When the typical booster pan height is included in this comparison, child leg lengths tend to be shorter than the combined vehicle and booster seat pan height by 5.1 cm on average. This discrepancy was largest for second row, outboard seating positions at 9.3 cm and for children less than 8 years of age (9.7 cm shorter on average). Additionally, booster pan heights presented in this study were measured at the rear of the booster seat pan. Previous research has identified that booster pan angles vary, with some booster pan heights increasing toward the middle and/or the front of the pan (Baker et al., 2021). This suggests that vehicle plus booster pan height discrepancies with child leg length may be greater than those quantified here and should be investigated further.

Prior studies have observed children varying their postures to better support their lower extremities by placing their feet on the back of the vehicle seat in front of them, flexing their knees to place their feet on the front edge of the vehicle seat underneath them, crossing their legs, or assuming other postures (Baker et al., 2023; Connell et al., 2024; Osvalder et al., 2013; Reed et al., 2005). This postural variation may also introduce variability in seat belt fit and restraint interaction. During frontal crashes, children restrained in forward-facing CRS sustained lower extremity injuries due to interaction with the vehicle seatback in most cases (Jermakian et al., 2007), suggesting that understanding the implications of these varied lower extremities postures are important to potentially reduce one aspect of child injury risk. One study has investigated the influence of providing a footrest to increase child comfort in a vehicle environment; however, variation was observed in terms of the number of children that utilized the footrest during the trial, and no significant reductions in discomfort avoidance behavior scores were observed (Fong et al., 2017). Further investigations are necessary to evaluate if use of a footrest could improve comfort, belt fit, and postural variability for children in the vehicle environment without introducing adverse effects during a crash.

Seated Shoulder Height and Belt Outlet Height

Seated shoulder height is an important metric for shoulder belt fit. As children have shorter seated shoulder heights compared to adults, one of the primary roles of a booster is to increase the child's seated height, thereby providing a more similar seat belt fit for the child compared to an adult. Typically, the seatbelt is designed to accommodate a range of adult anthropometries, which is defined by the HIII-5F and HIII-95M ATDs, such as in FMVSS 208 (National Highway Traffic Safety Administration, 2023).

Without a booster, child seated shoulder heights were found to be on average 4.5 cm shorter than that of the HIII-5F ATD, and only 22.5% had seated shoulder heights meeting or exceeding the HIII-5F without a booster. Again, this suggests that a majority of children in this cohort would be more optimally restrained on a booster to help increase their seated height and improve belt fit. When considering the average booster pan height (9.9 cm), this increased children's seated shoulder heights to a level more similar to the HIII-50M, and 87.5% of children met or exceeded the HIII-5F seated shoulder height with this average increase in seated height.

However, the average pan height of the low-profile designs (2.3 cm) offers reduced increase in seated shoulder height which would result in only 32.5% of children in this sample meeting or exceeding the HIII-5F seated shoulder height. Additionally, use of a high-back or multi-mode booster also offers the additional refinement of the shoulder belt to a more optimal position for children by adjusting the position of the shoulder belt guide. A small number of low-profile boosters have been investigated in laboratory belt fit studies and tended to produce more slouched postures and more inboard shoulder belt positions compared to most other booster designs (Baker et al., 2021; Jones et al., 2020).

Seated Height and Roof Height

On average, children's seated heights were less than the average vehicle roof height, and this was also the case when considering the 9.9 cm increase provided by the average booster. The child mean + 1SD was well represented by the HIII-10 and Q10 ATDs (average difference 0.7 cm), and the child mean – 1SD was well represented by the HIII-06 and Q6 (average difference -0.6 cm). As this cohort was recruited to span the range of current US booster designs, this suggests that using both the 6yo and 10yo ATDs is necessary to represent the range of anthropometries expected for potential booster users in terms of seated height. Additionally, these data may be helpful in identifying potential fit or comfort incompatibilities for taller children considering varying roof heights or useful for defining representative boundary conditions to evaluate risk of head strike on the roof in various crash modes.

Overall Expected Fit

The overall expected fit of children in the vehicle environment was also assessed by comparing the child's thigh length to the average vehicle seat pan length **and** comparing the child's seated shoulder height to that of the HIII-5F. In the current cohort, only one child (1.25%) fit both these anthropometric criteria, suggesting that the remaining 79 children may have some difficulty in passing the "5-Step Test" and may be better restrained on a booster. Four of these remaining children exceeded 45.5 kgs (100 lbs) and would therefore not fit on 50.7% of current boosters on the US market (Table A-7). Additionally, this sample did not include many children in the older (12+) or larger anthropometric ranges, and further investigations of compatibility between child anthropometry and upper manufacturer mass and stature limits may be necessary.

Limitations

There are important limitations to consider alongside these results. Vehicle, booster, and child measurements were collected as measurements from previous studies with specific research questions, and as a result, some measurements were not obtained for all samples. Additionally, these data represent convenience and are therefore not necessarily representative of all boosters and vehicles on the market or of all expected child anthropometries. Future efforts to investigate children older than 12 years of age and of larger anthropometry are necessary in order to pinpoint better anthropometric targets for appropriate transition to vehicle seats. Additionally, all boosters, vehicles, and children represent the US market and population, and European or other markets may not be well represented by these data. Ultimately, this study compared basic anthropometries and vehicle and booster geometries, with the goal of assessing potential incompatibilities. However, no direct evaluations of posture, belt fit, seat cushion stiffness and compression, comfort, or other behavioral variations were performed and may influence potential incompatibilities between child anthropometry and vehicle geometries in ways not captured in the data presented here.

CONCLUSIONS

This study compared modern vehicle and booster geometries with relevant child anthropometries in the context of expected child posture and belt fit. Overall, important incompatibilities still exist between vehicle seat pan lengths and child thigh lengths, with vehicle seat pan lengths exceeding the thigh length of 93.75% of the children (n=80, 4–12 years of age) in this study. This was true even for children age 8 and over (only 11.4% of these children had long enough thigh lengths) or above 145 cm stature (only 18.8% of these children had long enough thigh lengths). This incompatibility between child thigh lengths and vehicle seat pan lengths have implications for comfort and likely contribute to slouched postures, especially for children who may transition out of boosters before best-practice recommendations. Vehicle seat pan lengths have not decreased since prior investigations of this incompatibility with child anthropometry (Bilston and Sagar, 2007; Huang and Reed, 2006).

Booster geometries were more compatible with child thigh lengths and assist children in achieving seated shoulder heights more in line with adult ATD anthropometries. Some backless booster pan lengths exceed younger and/or shorter child thigh lengths but were more compatible with children at least 8 years of age or 145 cm stature. This suggests that different types of boosters (e.g., high-back versus backless) may be more appropriate for certain children at different phases of growth and development, in different vehicles, and based on their specific anthropometry or behavioral factors. Applying similar principles from the "5-Step Test" to educational efforts for children on boosters may also be beneficial. Specifically, an emphasis should be made on children being able to comfortably bend their knees over the front edge of the booster seat pan while also maintaining contact between their back and pelvis to the booster (or vehicle) seatback to reduce the potential for slouched postures.

Overall, these results emphasize the continued need for shorter vehicle seat cushion lengths in the rear seat to better accommodate pediatric occupants. Additionally, these results emphasize the importance of caregiver educational efforts highlighting the importance of achieving proper belt fit and avoiding slouched postures, both for children restrained on boosters and by the lap and shoulder belt alone.

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APPENDIX A

Table A-1: Child Anthropometries by Age and Stature Group

Metric	**<8yo**		**≥8yo**		**<145 cm**		**≥145 cm**	
	N	**Mean ± SD**	**N**	**Mean ± SD**	**N**	**Mean ± SD**	**N**	**Mean ± SD**
Age (yr)	36	6.5 ± 1.1	44	10.3 ± 1.6	64	7.8 ± 1.9	16	11.6 ± 1.3
Mass (kg)	36	22.0 ± 2.4	44	34.1 ± 8.2	64	25.8 ± 6.5	16	40.3 ± 6.4
Stature (cm)	36	119.3 ± 7.6	44	140.3 ± 8.6	64	126.1 ± 10.1	16	149.7 ± 4.7
Seated Height (cm)	36	62.7 ± 3.6	44	70.9 ± 4.9	64	65.3 ± 4.5	16	74.8 ± 5.1
Lower Extremity Length (cm)	36	58.8 ± 4.9	44	73.5 ± 6.1	64	63.9 ± 7.4	16	79.0 ± 4.9
Thigh Length (cm)	36	31.2 ± 3.6	44	38.1 ± 5.1	64	33.7 ± 5.0	16	40.3 ± 5.2
Leg Length (cm)	36	33.5 ± 3.5	44	41.8 ± 3.2	64	36.5 ± 4.6	16	44.2 ± 2.7
Seated Shoulder Height (cm)	36	37.8 ± 4.6	44	41.9 ± 5.0	64	39.0 ± 4.6	16	44.3 ± 5.4
Standing Shoulder Height (cm)	36	96.6 ± 7.0	44	115.5 ± 7.5	64	102.9 ± 9.4	16	123.3 ± 4.3
BMI (kg/m^2)	36	15.5 ± 1.4	44	17.2 ± 3.1	64	16.1 ± 2.6	16	17.9 ± 2.4
CDC %-ile	36	48.3 ± 27.9	44	45.2 ± 31.2	64	45.6 ± 30.4	16	50.4 ± 26.5

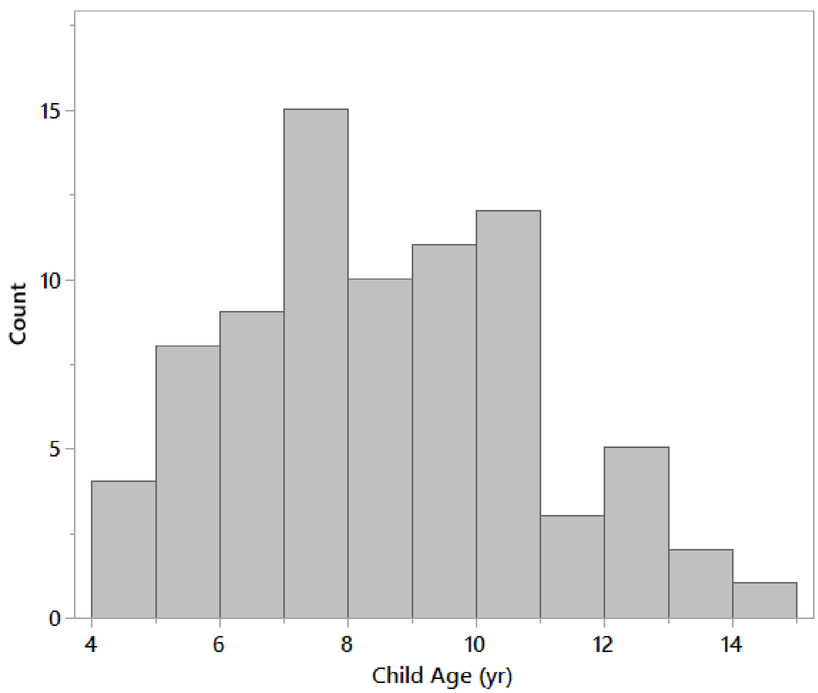

Figure A-1: Child Sample Age Distribution

Table A-2: Comparison of Child and ATD Anthropometries

Measurement	HIII 5F	HIII 50M	HIII 95M	HIII 03	HIII 06	HIII 10	Q3	Q6	Q10	Child Mean + SD
Seated Height (cm)	78.7	88.4	91.9	54.6	63.5	71.6	54.4	60.1	73.4	67.2 ± 6.0
Seated Shoulder Height (cm)	44.5	51.3	53.6	31.5	35.6	39.1	32.9	36.2	44.4	40.0 ± 5.2
Thigh Length (cm)	42.7	46.5	57.9	22.6	33.0	36.8	25.3	29.9	41.5	35.0 ± 5.7
Leg Length (cm)	40.6	49.3	53.3	22.6	27.9	34.0	*	*	40.6	38.1 ± 5.3
Mass (kg)	49.0	77.7	101.2	16.2	23.4	35.2	14.6	23.0	35.6	28.7 ± 8.7
Stature (cm)	*	*	*	95.1	114.1	130.4	98.5	114.3	145.3	130.8 ± 13.3

**Dimension not available.*

Table A-3: Simple Linear Regressions of Child Age, Mass, and Stature on Leg Length, Thigh Length, Seated Shoulder Height, and Seated Height

Ind Var	Dep Var	Mean Square	F Ratio	p-Value	R^2_{Adj}	Intercept Estimate	Ind Var Estimate
Age (yr)	Leg Length (cm)	1639.93	221.48	<.0001	73.62%	21.48	1.94
Mass (kg)	Leg Length (cm)	1192.12	90.69	<.0001	53.17%	25.29	0.45
Stature (cm)	Leg Length (cm)	1763.54	303.03	<.0001	79.27%	-8.46	0.36
Age (yr)	Thigh Length (cm)	1374.25	91.77	<.0001	53.47%	19.82	1.77
Mass (kg)	Thigh Length (cm)	1427.67	99.90	<.0001	55.59%	21.02	0.49
Stature (cm)	Thigh Length (cm)	1376.09	92.04	<.0001	53.54%	-6.09	0.31
Age (yr)	Seated Shoulder Height (cm)	547.47	26.95	<.0001	24.72%	30.46	1.12
Mass (kg)	Seated Shoulder Height (cm)	347.56	15.19	0.0002	15.23%	33.15	0.24
Stature (cm)	Seated Shoulder Height (cm)	639.54	33.42	<.0001	29.10%	12.03	0.21
Age (yr)	Seated Height (cm)	2103.43	236.14	<.0001	74.85%	48.44	2.19
Mass (kg)	Seated Height (cm)	1710.37	122.63	<.0001	60.62%	51.92	0.53
Stature (cm)	Seated Height (cm)	2268.38	333.93	<.0001	80.82%	14.46	0.40

Each row represents a separate simple linear regression.

Table A-4: Vehicle Geometries by Vehicle Type, Row, and Seating Position

Vehicle Type	Row	Seating Position	Pan Length (cm)		Pan Height (cm)		D-Ring Height (cm)		Roof Height (cm)	
			N	Mean ± SD	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD
Car	2nd Row	Center	38	42.9 ± 3.2	16	22.9 ± 7.7	22	58.6 ± 7.4	22	90.5 ± 4.4
	2nd Row	Outboard	89	46.1 ± 2.4	20	37.1 ± 2.3	24	62.3 ± 2.9	24	92.0 ± 3.7
Minicar	2nd Row	Center	4	41.2 ± 2.6	1	33.0 ± 0.0	3	65.7 ± 11.5	3	91.0 ± 4.2
	2nd Row	Outboard	13	43.2 ± 4.7	2	39.0 ± 2.5	6	61.9 ± 7.4	6	89.0 ± 2.7
Minivan	2nd Row	Center	4	43.7 ± 0.6	2	37.0 ± 3.3	1	97.6 ± 0.0	1	105.7 ± 0.0
	2nd Row	Outboard	14	48.2 ± 2.2	4	39.4 ± 2.0	3	60.5 ± 6.6	3	103.4 ± 2.2
	3rd Row	Center	2	43.0 ± 4.5	0	NA	2	85.5 ± 0.7	2	95.4 ± 0.5
	3rd Row	Outboard	5	45.3 ± 5.1	4	34.7 ± 0.7	0	NA	0	NA
Pickup	2nd Row	Center	11	41.2 ± 5.5	7	35.1 ± 4.3	4	56.6 ± 3.0	4	85.0 ± 2.4
	2nd Row	Outboard	19	44.8 ± 5.0	8	36.2 ± 4.6	4	66.7 ± 2.9	4	85.9 ± 5.9
SUV	2nd Row	Center	24	39.2 ± 3.2	14	32.5 ± 4.5	10	65.3 ± 12.9	10	101.1 ± 7.4
	2nd Row	Outboard	57	45.6 ± 3.1	17	37.8 ± 1.9	12	66.6 ± 4.8	12	99.2 ± 5.3
	3rd Row	Center	3	42.3 ± 6.8	1	22.8 ± 0.0	2	71.1 ± 23.1	2	88.4 ± 1.1
	3rd Row	Outboard	9	43.7 ± 4.5	9	28.1 ± 7.4	0	NA	0	NA

Table A-5: Simple Linear Regressions between Vehicle Geometries and MY

Ind. Var.	Dep. Var.	Mean Square	F Ratio	p-Value	R^2_{Adj}	Intercept Estimate	MY Estimate
MY	Pan Length (cm)	60.83	3.83	0.0513	0.97%	279.18	-0.12
MY	Seat Pan Height (cm)	51.93	1.05	0.3068	0.05%	-743.01	0.38
MY	D-Ring Height (cm)	0.01	0.00	0.9938	-1.10%	53.10	0.01
MY	Roof Height (cm)	97.21	2.21	0.1406	1.30%	-1338.24	0.71

Each row represents a separate simple linear regression.

Table A-6: Simple Linear Regressions between Vehicle Seat Pan Length and MY by Row and Seating Position

Seating Position	**Row**	**Ind. Var.**	**Dep. Var.**	**Mean Square**	**F Ratio**	**p-Value**	**R^2_{Adj}**	**Intercept Estimate**	**MY Estimate**
Center	2nd	Model Year	Pan Length (cm)	80.53	5.94	0.0171	5.82%	-628.27	0.33
Outboard	2nd	Model Year	Pan Length (cm)	41.81	3.94	0.0485	1.53%	273.85	-0.11
Center	3rd	Model Year	Pan Length (cm)	88.12	11.00	0.0451	71.44%	-7679.62	3.83
Outboard	3rd	Model Year	Pan Length (cm)	77.49	4.68	0.0514	22.07%	-2298.95	1.16

Each row represents a separate simple linear regression.

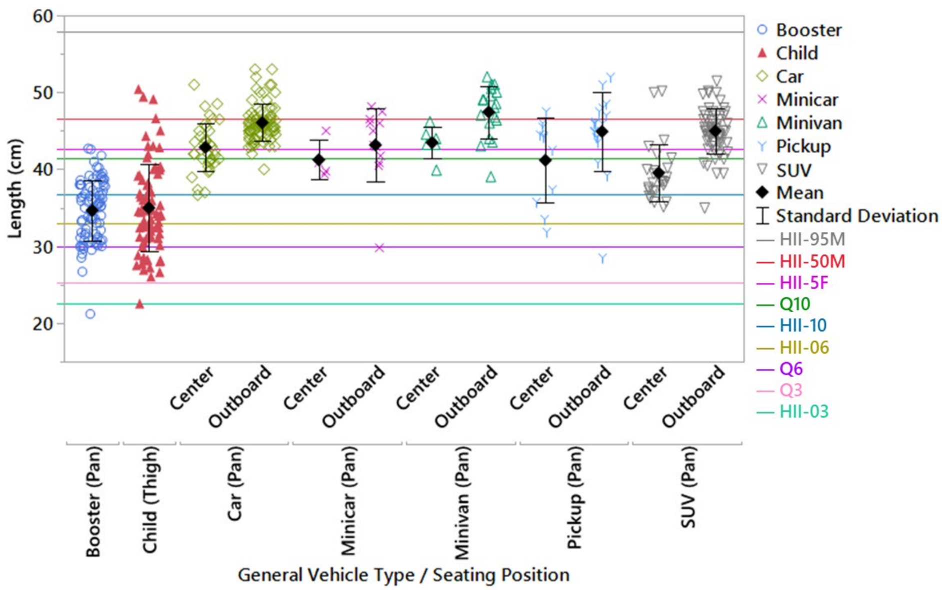

Figure A-2: Comparison of Child Thigh Length to Booster and Vehicle Seat Pan Length by Vehicle Type. Horizontal lines represent ATD thigh lengths.

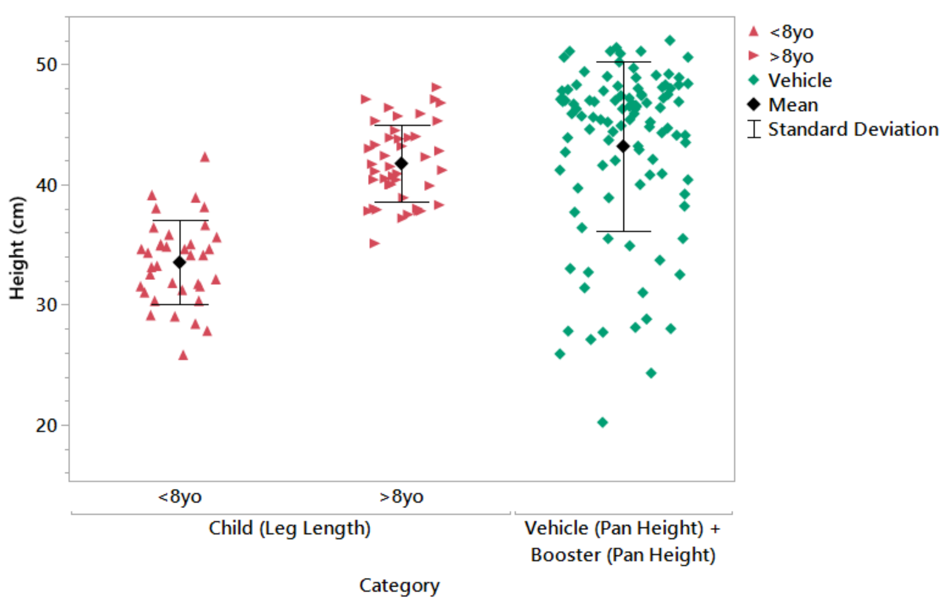

Figure A-3: Comparison of Child Leg Length to Vehicle Seat Pan Height + Average Booster Pan Height.

Table A-7: Maximum Manufacturer Allowed Child Mass from CRS/Boosters from the AAP 2024 Car Seat Product Listing (American Academy of Pediatrics, 2024)

Max Mass (lbs)	Max Mass (kg)	N	%
100	45.4	69	49.2%
110	49.9	16	11.4%
120	54.4	55	39.3%

Table A-8: Comparison of Child Anthropometry <8yo to Human Shape

Present Study <8yo (n=36)		Human Shape Model		Percent Difference
Anthropometry	**Mean ± SD**	**Analogous Metric**	**Value**	
Age (yr)	6.5 ± 1.1	Age at testing (yr)	7.22	-10.5%
Mass (kg)	22.0 ± 2.4	Mass (kg)	21.3	3.2%
Stature (cm)*	119.3 ± 7.6	Stature (cm)*	119.0	0.1%
Seated Height (cm)*	62.7 ± 3.6	Erect Sitting Height (cm)*	63.5	-1.3%
Thigh length (cm)	31.2 ± 3.6	BPL (cm)	33.2	-6.2%
Leg Length (cm)	33.5 ± 3.5	Knee Height (cm)	36.6	-8.8%
Seated shoulder height (cm)	37.8 ± 4.6	Acromial Height (cm)	39.3	-3.9%
BMI (kg/m^2)*	15.5 ± 1.4	BMI (kg/m^2)*	15.0	3.3%

**Anthropometric metrics input into HumanShape.org to generate the model. Seated height was accounted for as the ratio of stature to seated height.*

Table A-9: Comparison of Child Anthropometry ≥8yo to Human Shape

Present Study ≥8yo (n=44)		**Human Shape Model**		**Percent Difference**
Anthropometry	**Mean ± SD**	**Analogous Metric**	**Value**	
Age (yr)	10.3 ± 1.6	Age at testing (yr)	9.65	6.5%
Mass (kg)	34.1 ± 8.2	Mass (kg)	34.8	-2.0%
Stature (cm)	140.3 ± 8.6	Stature (cm)	141	-0.1%
Seated Height (cm)	70.9 ± 4.9	Erect Sitting Height (cm)	71.8	-1.3%
Thigh length (cm)	38.1 ± 5.1	BPL (cm)	40.4	-5.9%
Leg Length (cm)	41.8 ± 3.2	Knee Height (cm)	44.5	-6.3%
Seated shoulder height (cm)	41.9 ± 5.0	Acromial Height (cm)	45.8	-8.9%
BMI (kg/m^2)	17.2 ± 3.1	BMI	17.6	-2.1%

**Anthropometric metrics input into HumanShape.org to generate the model. Seated height was accounted for as the ratio of stature to seated height.*

Table A-10: Comparison of Child Anthropometry <145cm to Human Shape

Present Study <145cm (n=64)		**Human Shape Model**		**Percent Difference**
Anthropometry	**Mean ± SD**	**Analogous Metric**	**Value**	
Age (yr)	7.8 ± 1.9	Age at testing (yr)	7.97	-2.2%
Mass (kg)	25.7 ± 6.5	Mass (kg)	25.8	-1.6%
Stature (cm)	126.1 ± 10.1	Stature (cm)	126	-0.2%
Seated Height (cm)	65.3 ± 4.5	Erect Sitting Height (cm)	65	0.5%
Thigh length (cm)	33.7 ± 5.0	BPL (cm)	35.8	-6.0%
Leg Length (cm)	36.5 ± 4.6	Knee Height (cm)	39.8	-8.7%
Seated shoulder height (cm)	39.0 ± 4.6	Acromial Height (cm)	40.7	-4.3%
BMI (kg/m^2)	16.1 ± 2.6	BMI	16.1	-0.1%

**Anthropometric metrics input into HumanShape.org to generate the model. Seated height was accounted for as the ratio of stature to seated height.*

Table A-11: Comparison of Child Anthropometry ≥145 cm to Human Shape

Present Study ≥145 cm (n=44)		Human Shape Model		Percent Difference
Anthropometry	**Mean ± SD**	**Analogous Metric**	**Value**	
Age (yr)	11.6 ± 1.3	Age at testing (yr)	10.7	2.8%
Mass (kg)	40.3 ± 6.4	Mass (kg)	40.8	-1.2%
Stature (cm)	149.7 ± 4.7	Stature (cm)	149.3	0.3%
Seated Height (cm)	74.8 ± 5.1	Erect Sitting Height (cm)	75.4	-0.8%
Thigh length (cm)	40.3 ± 5.2	BPL (cm)	43.4	-7.4%
Leg Length (cm)	44.2 ± 2.7	Knee Height (cm)	47.5	-7.2%
Seated shoulder height (cm)	44.3 ± 5.4	Acromial Height (cm)	48.6	-9.3%
BMI (kg/m^2)	17.9 ± 2.4	BMI	18.4	-2.8%

**Anthropometric metrics input into HumanShape.org to generate the model. Seated height was accounted for as the ratio of stature to seated height.*

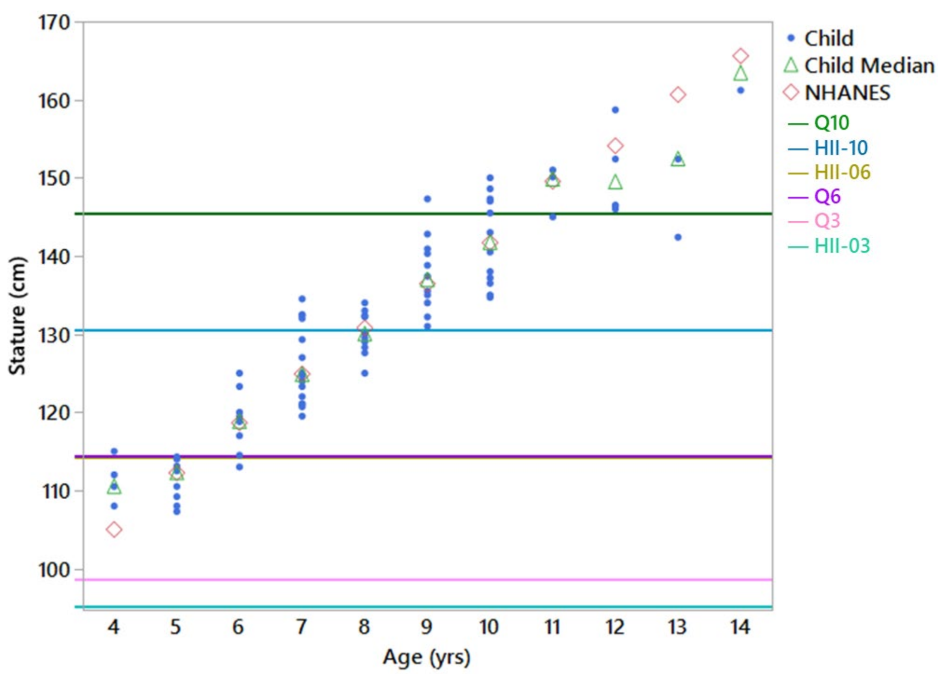

Figure A-4: Comparison of Stature to NHANES (Fryar et al., 2021) and ATDs

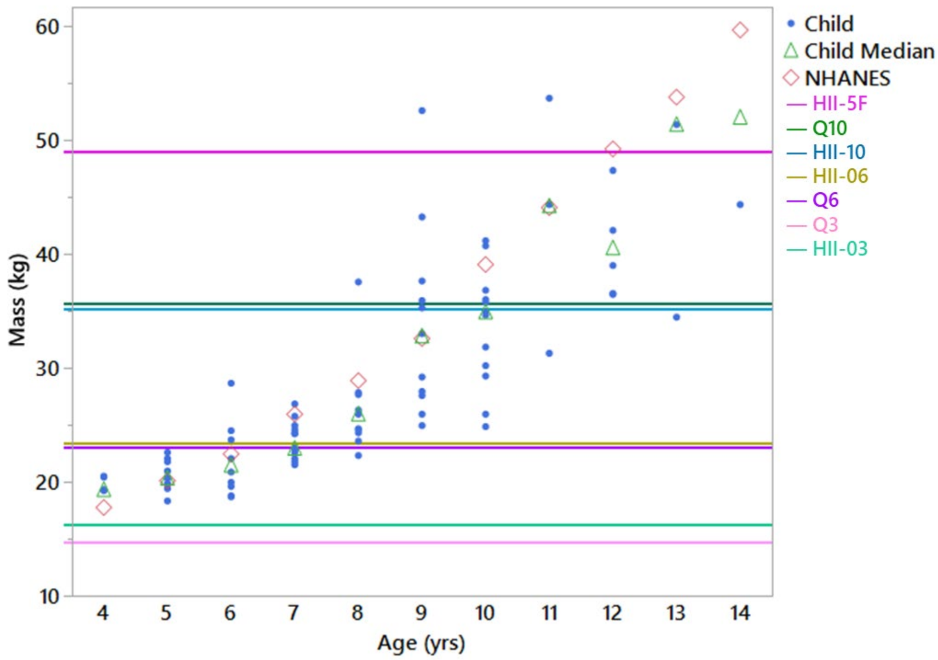

Figure A-5: Comparison of Mass to NHANES (Fryar et al., 2021) and ATDs

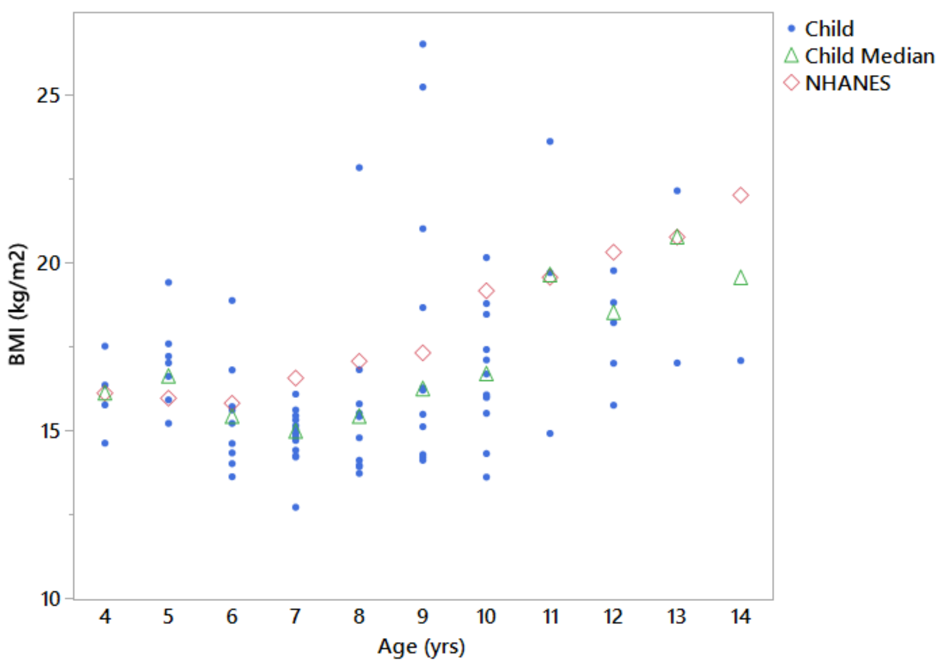

Figure A-6: Comparison of BMI to NHANES (Fryar et al., 2021)

APPENDIX B

Table B-1: Vehicles Evaluated by Make, Model, and MY

Count	Manufacturer	Model	Model Year	Number of Seating Positions Evaluated
1	Acura	RDX	2010	1
2	Audi	A4 2.0T	2009	1
3	Audi	S3 Premium Plus	2019	2
4	BMW	528xi	2016	2
5	Buick	Encore	2013	2
6	Buick	Encore Sport Touring	2017	2
7	Buick	Regal GS	2016	2
8	Buick	Verano	2015	2
9	Buick	Verano	2016	1
10	Cadillac	CTS	2010	1
11	Cadillac	CTS	2011	1
12	Cadillac	Escalade ESV Premium	2016	3
13	Chevrolet	Aveo LT	2009	1
14	Chevrolet	Camaro SS	2011	1
15	Chevrolet	Colorado LT	2021	2
16	Chevrolet	Impala	2011	1
17	Chevrolet	Malibu LS	2010	1
18	Chevrolet	Malibu LT	2020	1
19	Chevrolet	Silverado	2011	1
20	Chevrolet	Silverado 1500 Custom Trail Boss	2021	2
21	Chevrolet	Silverado 1500 LTZ71	2017	1
22	Chevrolet	Spark LS	2020	1
23	Chevrolet	Spark LT	2013	1
24	Chevrolet	Traverse	2017	3
25	Chevrolet	Traverse LTZ	2014	2
26	Chevrolet	Trax LS	2019	2
27	Chrysler	200	2015	1
28	Chrysler	200 LX	2014	2
29	Chrysler	300	2013	2
30	Chrysler	Pacifica Limited	2017	2
31	Chrysler	Pacifica Touring Plus	2017	2
32	Chrysler	Town and Country	2012	1
33	Chrysler	Town and Country	2015	2
34	Dodge	Charger SRT8	2010	1
35	Dodge	Grand Caravan SE	2010	1
36	Dodge	Journey Unlimited	2014	2
37	Dodge	Ram	2011	1
38	Dodge	Ram 1500 Express	2014	2

39	Fiat	500 Abarth	2015	1
40	Ford	Escape	2011	1
41	Ford	Explorer Sport	2013	2
42	Ford	Explorer Sport	2017	1
43	Ford	Explorer XLT	2010	1
44	Ford	F150 Crew Cab	2013	1
45	Ford	F150 FX4	2012	2
46	Ford	F150 XL	2016	2
47	Ford	F-150	2010	1
48	Ford	Fiesta	2013	1
49	Ford	Flex	2012	1
50	Ford	Focus SEL	2017	1
51	Ford	Fusion SE	2010	1
52	Ford	Fusion SE	2012	2
53	Ford	Fusion SE	2017	2
54	Ford	Fusion Titanium	2017	1
55	Ford	Mustang Ecoboost Premium	2018	1
56	Ford	Taurus	2010	1
57	Ford	Taurus SHO	2013	2
58	Genesis	G704	2021	2
59	GMC	Acadia	2012	1
60	GMC	Acadia SLE	2020	1
61	GMC	Sierra 1500	2020	2
62	GMC	Sierra 1500 SLE	2015	2
63	GMC	Terrain SLE	2019	2
64	GMC	Yukon	2019	2
65	Honda	Civic	2015	1
66	Honda	Civic EX-L	2015	2
67	Honda	CRV EX	2012	1
68	Honda	Fit	2009	1
69	Honda	Fit	2012	2
70	Honda	Fit EX	2019	2
71	Honda	Insight	2010	2
72	Honda	Odyssey	2010	1
73	Honda	Odyssey	2015	2
74	Honda	Odyssey	2021	3
75	Honda	Odyssey Elite	2020	3
76	Honda	Odyssey EX-L	2016	1
77	Honda	Pilot	2012	1
78	Honda	Pilot	2019	2
79	Honda	Pilot EX-L	2021	4

80	Honda	Ridgeline Sport	2019	2
81	Hyundai	Accent GLS	2013	2
82	Hyundai	Elantra SE	2020	1
83	Hyundai	Genesis	2010	1
84	Hyundai	Santa Fe SE	2019	2
85	Hyundai	Sonata Sport	2015	2
86	Hyundai	Veloster	2013	1
87	Hyundai	Veloster	2020	1
88	Infiniti	Q60 Red Sport 400	2018	1
89	Jeep	Compass Latitude	2018	1
90	Jeep	Grand Cherokee High Altitude	2018	1
91	Jeep	Grand Cherokee Laredo	2013	2
92	Jeep	Wrangler All New UnlimitedRubicon	2018	2
93	Kia	K900 Luxury	2015	2
94	Kia	Optima LX	2015	2
95	Kia	Rio	2019	1
96	Kia	Sedona Limited	2015	2
97	Kia	Sedona LX	2015	2
98	Kia	Soul	2010	1
99	Kia	Soul	2015	2
100	Land Rover	Discovery Sport HSE	2016	3
101	Lexus	CT 200H Premium	2012	2
102	Lexus	ES 300h Luxury	2020	2
103	Lincoln	MKS	2010	1
104	Lincoln	MKS	2013	2
105	Lincoln	MKX	2011	1
106	Lincoln	Navigator	2014	2
107	Mazda	CX-9 Grand Touring	2012	2
108	Mazda	Mazda2 Sport	2013	2
109	Mazda	Mazda2 Touring	2013	1
110	Mazda	Mazda3 iSport	2015	2
111	Mazda	Mazda 6	2010	1
112	Mazda	Mazda6 Touring	2016	2
113	Mercedes Benz	C63 AMG	2017	1
114	Mercedes-Benz	C300 Sport	2011	1
115	Mercedes-Benz	GLK 350	2013	2
116	Mercedes-Benz	S550	2014	2
117	Mercury	Milan Premier	2010	1
118	Mini	Cooper	2010	1
119	Mini	Cooper S	2009	1
120	Minicooper	Countryman All Four	2017	2

121	Mitsubishi	Galant FE	2011	1
122	Mitsubishi	Outlander GT	2017	3
123	Nissan	Altima	2011	1
124	Nissan	Altima S	2014	2
125	Nissan	Frontier S	2017	1
126	Nissan	Frontier SL	2012	2
127	Nissan	Juke S	2015	2
128	Nissan	Maxima S	2010	1
129	Nissan	Murano SV	2013	2
130	Nissan	Rogue S	2010	1
131	Nissan	Sentra SR	2019	2
132	Nissan	Titan SL	2018	2
133	Nissan	Versa S	2011	1
134	Nissan	Versa SV	2014	2
135	Pontiac	G8 GT	2009	1
136	Ram	1500 Big Horn	2021	2
137	Subaru	Ascent Limited	2019	2
138	Subaru	Forester 2.5i	2015	1
139	Subaru	Impreza WRX	2009	1
140	Subaru	Impreza WRX STI	2013	2
141	Subaru	Legacy 2.5i Premium	2014	2
142	Subaru	Outback	2016	1
143	Subaru	Outback 2.5i Premium	2013	2
144	Toyota	Camry	2012	1
145	Toyota	Camry LE	2012	2
146	Toyota	Camry LE	2018	1
147	Toyota	C-HR	2019	2
148	Toyota	Corolla	2015	2
149	Toyota	Corolla	2019	2
150	Toyota	Highlander	2012	2
151	Toyota	Highlander SLE	2017	1
152	Toyota	RAV4 XLE	2019	2
153	Toyota	Sienna Hybrid XLE	2022	2
154	Toyota	Sienna LE	2019	3
155	Toyota	Tacoma TRD Off Road	2017	1
156	Toyota	Tundra 1794 Edition	2018	2
157	Toyota	Venza L3	2013	2
158	Toyota	Yaris	2010	2
159	Toyota	Yaris	2012	1
160	Volkswagen	Atlas SE	2018	3
161	Volkswagen	Atlas SEL	2019	1

162	Volkswagen	CC Sport	2009	1
163	Volkswagen	GTI	2011	1
164	Volkswagen	Jetta S	2015	1
165	Volkswagen	Jetta SE	2012	2
166	Volkswagen	Jetta SE	2019	2
167	Volkswagen	Passat SE	2013	2
168	Volkswagen	Routan SE	2012	1
169	Volvo	S60 T6 Momentum	2020	2
170	Volvo	S90 Hybrid Plug In	2018	1
171	Volvo	XC40 T5 Inscription	2019	2
172	Volvo	XC90TC Momentum	2018	1

APPENDIX C

Table C-1: Boosters Evaluated by Manufacturer, Model, and MY

Count	Manufacturer	Model	Model Year	Modes Evaluated
1	Baby Trend	Protect Yumi	2018	HB, LB
2	Baby Trend	Hybrid No-Back Booster	2015	LB
3	Baby Trend	Hybrid LX 3 in 1 Car Seat	2015	HB, LB
4	Britax	Frontier ClickTight	2019	HB
5	Britax	Frontier ClickTight	2015	HB
6	Britax	Grow With You	2022	HB
7	Britax	One4Life	2022	HB
8	Britax	Parkway SGL XE	2015	HB, LB
9	Britax	Pinnacle ClickTight	2015	HB
10	Chicco	GoFit ClearTex	2023	LB
11	Chicco	GoFit Plus	2023	LB
12	Chicco	KidFit Zip	2015	HB, LB
13	Chicco	MyFit	2018	HB
14	Cosco	Topside	2019	LB
15	Diono	Everett NXT	2020	HB, LB
16	Diono	RadianRXT	2014	HB
17	Diono	Rainier	2014	HB
18	Diono	Solana 2	2019	LB
19	Eddie Bauer (First Adventure)	Combination Booster and Car Seat	2015	HB
20	Eddie Bauer (First Adventure)	Storage Booster	2016	LB
21	Evenflo	Amp/Big Kid Elite	2015	LB
22	Evenflo	Big Kid Elite	2015	LB
23	Evenflo	Everykid EveryFit	2021	HB, LB
24	Evenflo	EveryStage DLX	2018	HB
25	Evenflo	Evolve DLX	2016	HB, LB
26	Evenflo	Maestro	2012	HB
27	Evenflo	Maestro Sport	2019	HB
28	Evenflo	Platinum Safe Max All in One Car Seat	2016	HB
29	Evenflo	Pro Comfort Amp LX	2014	HB, LB
30	Evenflo	RightFit	2014	HB, LB
31	Evenflo	SecureKid DLX	2015	HB
32	Evenflo	Symphony	2014	HB
33	Graco	4Ever	2014	HB, LB
34	Graco	4Ever DLX	2018	HB, LB
35	Graco	4Ever DLX SnugLock	2022	HB, LB
36	Graco	Affix Backless with LATCH	2013	LB
37	Graco	Extend2Fit	2019	HB
38	Graco	Milestone All in One	2014	HB
39	Graco	Nautilus 2.0 LX	2022	HB, LB
40	Graco	Nautilus 65 DLX	2015	HB, LB
41	Graco	Nautilus SnugLock Grow	2022	HB
42	Graco	Right Guide	2019	Low
43	Graco	Slim Fit	2017	HB
44	Graco	Slim Fit 3 LX	2022	HB
45	Graco	Tranzitions 3-in-1 Harness Booster	2015	HB, LB
46	Graco	Tranzitions 3-in-1 Harness Booster	2019	HB, LB
47	Graco	Tri Ride	2020	HB
48	Graco	Turbo Booster 2.0	2023	LB
49	Graco	Turbo Booster LX	2018	HB
50	Graco	Turbo Booster LX	2022	LB

51	Graco	Turbobooster Grow	2019	HB, LB
52	Graco	Turbobooster/Highback Turbo	2015	HB, LB
53	KidsEmbrace	Deluxe Combination Booster Car Seat	2015	HB
54	Maxi Cosi	RodiFix	2020	HB
55	Mifold	Mifold	2018	Low
56	Peg Perego	Viaggio Flex 120	2020	HB
57	Recaro	Performance Booster	2015	HB
58	Recaro	Performance Sport Booster	2014	HB
59	Safety 1st	Alpha Elite 65	2014	HB
60	Safety 1st	Elite EX 100 Air+	2015	HB
61	Safety 1st	Grow and Go	2015	HB
62	Safety 1st	Grow and Go	2021	HB
63	Safety 1st	Grow and Go EX Air	2018	HB
64	Safety 1st	Turn and Go 360	2022	HB