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Assessing the Restraint Performance Of Vehicle Seats and Belt Geometry Optimized for Older Children

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16. Abstract

In a previous study, a computational model of child occupants 6 to 10 years old (YO) was validated using data from a sled test series with the 6YO and 10YO Hybrid-III ATDs. Simulations using this model were used to identify characteristics of a vehicle seat and belt geometry that would improve occupant protection for older children not using booster seats. The current report presents a series of sled tests to examine the effects for other occupants using vehicle seats optimized for 6- to 10-year-old children. Tests were conducted with a 12MO CRABI seated in a Graco SnugRide rear-facing infant restraint and a Hybrid III 50^{th} male ATD. Seat cushion length was set to 450 mm, 400 mm, and 350 mm. Lap belt conditions included one representing the mid-range of FMVSS No. 210, "Seat belt assembly anchorages," allowable seat belt anchorage conditions as well as one more forward but closer to the vehicle seat H-point. Shoulder belt conditions included the standard FMVSS No. 213 shoulder belt anchorage as well as one positioned closer to the adult male shoulder. Vehicle seats from a 2008 Dodge Town and Country were used, and some tests included modifications to make the front support structure of the seat cushion stiffer.

The tests with the midsize adult male ATD showed no negative consequences from design changes intended to improve protection for children. Kinematics were similar among all conditions tested. For the rear-facing infant restraint, none of the tests exceeded the 70° rotation angle requirement of FMVSS No. 213, although shorter cushion length and more forward belt locations produced larger rotations. The three tests with the more forward lap belt geometry slightly exceeded the 3-ms-chest clip acceleration limit of 60 g, but a review of all chest acceleration curves suggests that the vehicle seat may produce higher chest accelerations than the FMVSS No. 213 test bench. In tests with the shortest seat cushion length, the infant seat showed acceptable kinematics even though less than 80 percent of the child restraint base was initially supported on the vehicle seat.

These preliminary tests with rear vehicle seat configurations selected to optimize protection for older child occupants produced good restraint kinematics for infants in a rear-facing only child restraint and for adult mid-size males. Additional research to identify possible negative consequences for other types of child restraints should be conducted. If shorter cushion lengths are chosen as a safety countermeasure for older children, the current child restraint installation requirement to have at least 80 percent of the base contacting the vehicle seat will need to be addressed.

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Introduction

The National Highway Traffic Safety Administration (NHTSA) and the American Academy of Pediatrics now recommend that children use belt-positioning booster seats until they can properly fit in the seat belt.   However, most state legislation requires booster seat use only through ages 6 or 8. Since many parents use boosters only as long as they are legally required, many children under age 12 are using seat belts with poor fit that may not protect them optimally in a crash. In addition, many children who are legally required to use boosters do not do so. NHTSA's most recent National Survey of the Use of Booster Seats (NSUBS 2011) estimated that only 47 percent of 4- to 7-year-old children were restrained in booster seats in 2011.

Previous research at the University of Michigan Transportation Research Institute (UMTRI) has shown that children in this age range sitting on vehicle seats with typical belt configurations usually experience poor lap belt fit, with the belt positioned over the abdomen rather than on the lap (Reed, Ebert, Klinich, & Manary, 2008). Taller children experience only slightly better belt fit. Durbin et al. (2005) report that children 9 to 12 have 1.5 higher odds of injury than children from birth to 3, accounting for different recommendations of appropriate restraint and differences in rear seating frequency. These data suggest that improvements in rear vehicle seats and seat belts should be considered to improve protection for older children in crashes who are not using boosters or harness restraints.

In most current vehicles, the rear seats are not sized to accommodate children 12 and younger, who are about half of rear-seat occupants (Huang & Reed, 2006). In a survey of vehicle second-row seats, the median rear seat cushion length was found to be 455 mm, longer than the thigh length of most rear-seat occupants of all ages (Huang & Reed, 2006). Children slouch to improve comfort with a long seat cushion, which causes poor lap belt fit (Klinich, Pritz, Beebe, & Welty, 1994; Reed, Ebert, Klinich, & Manary, 2008). Shorter cushion lengths reduce slouching and improve belt fit (Reed, Ebert, Klinich, & Manary, 2008).

Several previous studies for NHTSA showed that varying belt anchorage locations affects the kinematics of the Hybrid III 10YO and 6YO anthropomorphic test devices (ATDs) (Klinich, Reed, Ritchie, Manary, Schneider, & Rupp, 2008; Klinich, Ritchie, Manary, & Reed, 2010; Klinich, Reed, Orton, Manary, & Rupp, 2011). Submarining and rollout, two adverse kinematics outcomes, were observed for some combinations of belt anchorage locations within the range observed in vehicles. These studies were performed with the FMVSS No. 213 test bench, which is longer, flatter, and softer than the most rear seats (Reed 2011).

Klinich, Reed, Orton, Manary, & Rupp (2011) evaluated the effects of seat cushion length and lap belt angle on child ATD kinematics using a real vehicle seat. Cushion length was set to a typical production length of 450 mm and shortened to 350 mm. Lap belt geometry was set to rear, mid, and forward anchorage locations that span the range of lap belt angles found in real vehicles (Reed & Ebert-Hamilton, 2013). Six tests each were performed with the standard Hybrid III 6YO and 10YO ATDs and one test was performed using a booster seat with the 6YO. In all cases, the ATDs were positioned using an UMTRI method (Klinich, Reed, Orton, Manary, & Rupp, 2011, Appendix 1) that accounts for the effects of seat cushion length on child posture. Shortening the seat cushion improved kinematic outcomes, particularly for the 10YO. Lap belt geometry had a greater effect on kinematics with the longer cushion length, with mid and forward belt geometries producing better kinematics than the rearward belt geometry. The worst kinematics for both ATDs occurred with the long cushion length and rearward lap belt geometry. The improvements in kinematics from shorter cushion length or more forward belt geometry are smaller than those provided by a booster seat. The results demonstrated potential benefits in occupant protection from shortening cushion length, particularly for children the size of the 10YO ATD, because the shorter cushion lengths result in more-rearward child positions and better belt fit.

To examine restraint parameters for children beyond the sizes of the 6- and 10-year-old ATDs, Wu et al. developed a parametric ATD model capable of representing 6- to 12YO children using MADYMO. A more realistic representation of pelvis and abdomen geometry, modified joint stiffness, and improved contact characteristics were added to a MADYMO model of the Hybrid-III 6YO ATD. The new parametric ATD model was validated against sled test results described above (Klinich, Reed, Orton, Manary, & Rupp, 2011) using a multi-objective optimization method, showing good agreement between measured and predicted ATD kinematics and seat belt forces. The parametric child model was used to identify vehicle seat characteristics and belt geometries that would provide optimal restraint for children the sizes of the 6YO and 10YO ATDs. The simulations predicted that shorter cushion lengths, a stiffer cushion, lap belt anchorages more forward and closer to the vehicle seat H-point, and shoulder belt anchorages closer to the shoulder would provide improved restraint compared to the baseline vehicle seat design tested with FMVSS No. 213 belt anchorage locations.

Improving the performance and geometry of vehicle seat belts is particularly important among older child passengers, who, despite our continuing efforts, continue to use booster seats at unacceptably low levels and are all too often riding in seat belts designed for adults, which neither fit nor protect them properly. The current test series was conducted to examine possible harm for other occupants that might occur if vehicle rear seats were designed to optimize occupant protection for older children. For this preliminary test series, tests were performed with a 12-month-old pediatric ATD in a rear-facing infant restraint, as well as a mid-sized male adult ATD.

Methods

Vehicle Seats

Six second-row captain's chairs from 2008 and later Dodge Caravans (all with the same design) were obtained from vehicle recyclers and adapted for mounting on the FMVSS No. 213 buck in place of the test bench. This particular seat was selected because its cushion length of 450 mm represents one of the shorter second row seats currently in production (approximately 10th percentile). None of the test seats showed any unusual damage or wear on visual inspection. The seats used in the current test series were also used in a prior test series described in Klinich, Ritchie, Manary, & Reed, (2010), where they also did not sustain apparent damage. The vehicle seats were positioned on the FMVSS No. 213 buck such that the fore-aft location of the H-point of the vehicle seat matched the fore-aft H-point of the standard FMVSS No. 213 bench to facilitate visual comparison between these tests and comparable tests run on the FMVSS No. 213 bench. The seat back angle was 22.5° and cushion angle was 18.5°, which matches those measured in an exemplar vehicle second-row.

The cushion length of the production vehicle seat is 450 mm, 5 mm less than the median second-row, outboard seat cushion length (Huang & Reed, 2006). The seats were disassembled and mounted such that the seat back and seat cushion were attached separately. Cushion length was adjusted by shifting the seat pan rearward relative to the seat back. Figure 1 shows the seat configured for the three cushion lengths. The blue vertical lines indicate the leading edge of the seat cushion, and allow visual comparison relative to landmarks on the buck as well as the proportion of the child restraint supported by each cushion length.

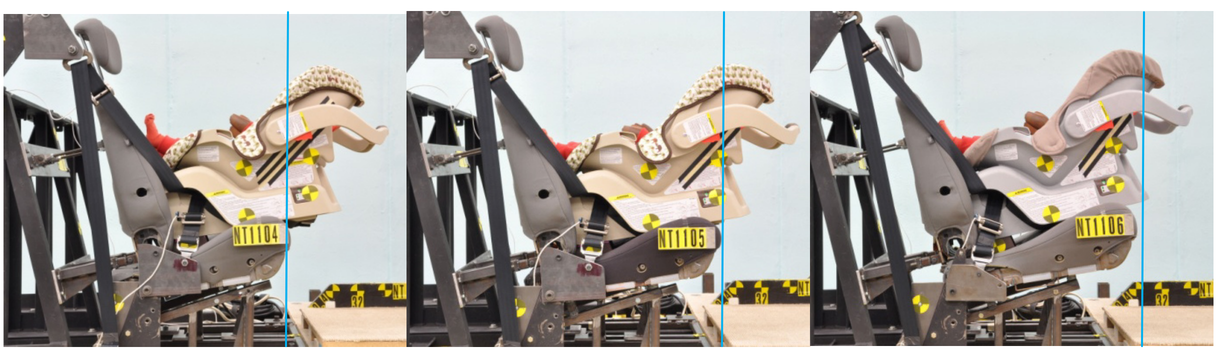


Figure 1. Side view of vehicle seat configured to cushion lengths of 350, 400, and 450 mm

Belt Geometry

Two different lap belt anchorage locations were used in this study as shown in Figure 2. The "mid" condition, which produces a lap belt angle of approximately 50° relative to the H-point of the FMVSS No. 213 buck, was used in the previous test series with these seats. The second lap belt location, optimized for the 6YO, is located 59 mm higher and 21 mm forward of the mid condition. The inboard (IB) locations are shown with open symbols, while the outboard (OB) locations are shown with filled symbols. Hardware used to achieve these lap belt locations is shown in Figure 3 and Figure 4. In the previous and current test series, a buckle stalk length of 150 mm was simulated using a heavy-duty locking clip as shown in Figure 4.

The hardware used to produce the mid and optimized 6YO shoulder belt geometry is shown in Figure 5. The mid D-ring location is the same used on the FMVSS No. 213 buck, while the optimized 6YO D-ring location was designed to be 103 mm below, 96 mm forward, and 4 mm inboard of the mid position.

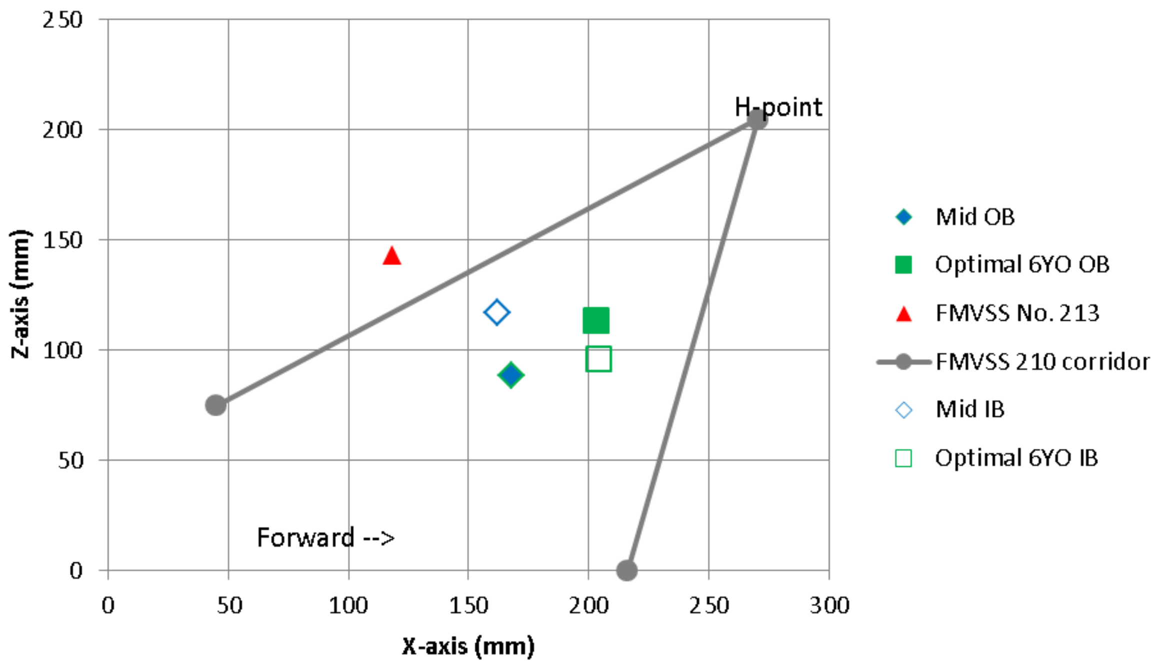


Figure 2. Lap belt geometry used in current study: Mid and optimal 6YO

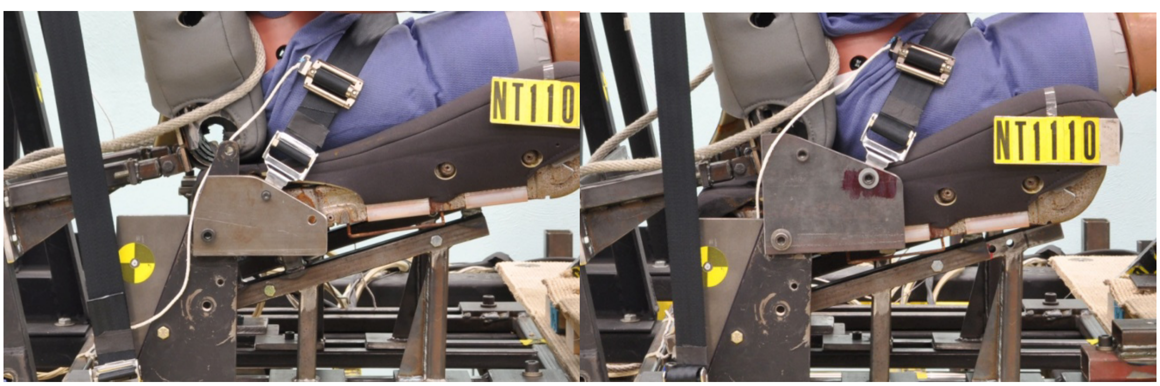


Figure 3. Mid lap belt geometry hardware (left) and optimized 6YO hardware (right)

Figure 4. Close-up of inboard anchorage hardware including simulated buckle stalk

Figure 5. Shoulder belt location for mid (left) and optimized 6YO (right) conditions

Additional Hardware

For the tests with the Hybrid III midsize male, a floor surface was constructed from plywood covered with carpet and located so the H-point to heel vertical distance was approximately 330 mm, typical of a captain's chair in a 2008 Dodge Caravan. A horizontal bar was added to simulate the interaction the ATD's legs would have with the back of the front seat as shown in Figure 6. The bar size and placement were designed to simulate the space present beneath the front-row seats of a 2008 Dodge Caravan.

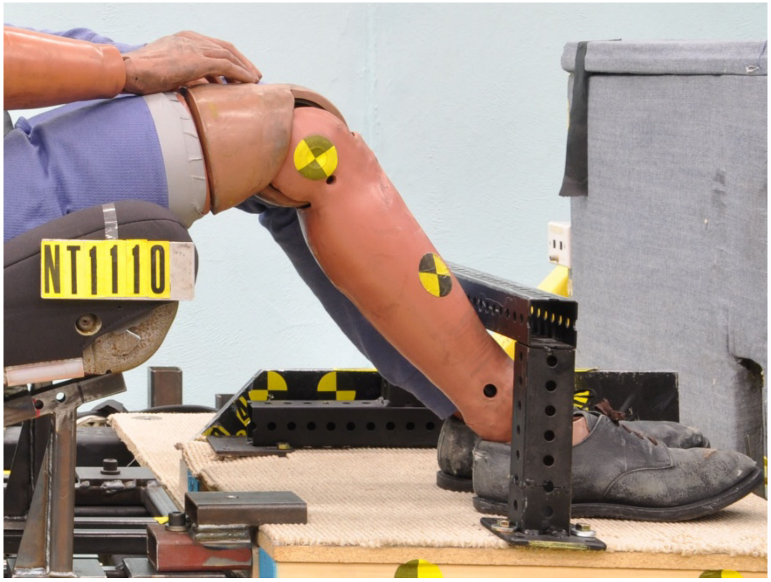


Figure 6. Hardware simulating floor and shin/vehicle seat interaction

The computational model indicated that a stiffer seat cushion has the potential to improve restraint performance for older children. In the production vehicle seat, the tests and simulations indicated that the seat cushion stiffness was more sensitive to the location of the tube underneath the foam, which is referred to as an anti-submarining bar, than the stiffness of the foam itself (Hu, Wu, Reed, Klinich, & Cao, 2013). To simulate the effect of raising the submarining bar and create a stiffer cushion, an extra aluminum plate was inserted between the cushion structure and foam as shown in Figure 7, which shows the standard cushion structure on the left and the stiffer cushion structure on the right. This hardware was intended to approximate the seat stiffening in the model, which shifted the structure of the seat cushion closer to the foam.

Figure 7. Standard seat cushion structure (left) and addition of aluminum plate to increase stiffness (right)

Installation/Seating Procedure

The infant restraint was installed using standard FMVSS No. 213 procedures that involve tightening the belt to 15 lb tension. For the midsized male, the SAE J826 machine was used to measure the H-point of the vehicle seat, and the midsized male was positioned so its H-point was within 2.54 cm of the seat H-point and the head was leveled. The belt tension was set to be 2- to 4 lb in both the lap and shoulder belt, based on measures recorded by child volunteers, as data for adult volunteers have not been collected. A FARO arm 3-D coordinate measurement system was used to document the initial position of the ATD, child restraint, vehicle seat, and belts for each test.

Test Matrix

The matrix of tests performed in this series is shown in Table 1. All tests were performed with the FMVSS No. 213 pulse. For the test series with the infant seat, the condition of 450 mm cushion length and mid belt geometry was considered the baseline. The next three test conditions added one factor at a time to arrive at conditions optimized for a 6YO occupant. Cushion length was shortened to 350 mm, the belt geometry was then adjusted to optimal position for the 6YO, and then the front of the vehicle seat was stiffened. Since these tests produced acceptable results, two more conditions were added to provide additional reference data for validating simulations. One condition used an intermediate cushion length of 400 mm with the standard seat stiffness and optimized 6YO belt geometry, while the other repeated the baseline cushion length and belt geometry but with the stiffer seat design.

For the series with the Hybrid III midsize male, the first four conditions repeated the progression used with the infant seat, although with a slight change in order. In reviewing the mostly acceptable kinematics from the first four test conditions, the shin bar used to simulate interaction between the lower extremities and the front seat back seemed to have a stronger effect on kinematics than any seat belt or cushion factors. So test NT1112 repeated test NT1110, except with the shin bar removed. Test NT1113 was performed to provide an additional test for validating simulations, using conditions of test NT1109 but with the stiffer seat cushion. Test NT1107 is missing from the numerical sequence of tests because the lap belt anchorage and shin bar failed, so results are not reported.

Table 1. Test matrix

Test ID	ATD	Cushion Length (mm)	Seat belt Geometry	Cushion Stiffness	Child Restraint/ Hardware
NT1101	CRABI 12MO	450	Mid	Standard	Snugride 30
NT1102	CRABI 12MO	350	Mid	Standard	Snugride 30
NT1103	CRABI 12MO	350	Optimal 6YO	Standard	Snugride 30
NT1104	CRABI 12MO	350	Optimal 6YO	Stiffer	Snugride 30
NT1105	CRABI 12MO	400	Optimal 6YO	Standard	Snugride 30
NT1106	CRABI 12MO	450	Mid	Stiffer	Snugride 30
NT1108	H350	350	Mid	Standard	Shin bar
NT1109	H350	450	Mid	Standard	Shin bar
NT1110	H350	350	Optimal 6YO	Standard	Shin bar
NT1111	H350	350	Optimal 6YO	Stiffer	Shin bar
NT1112	H350	350	Optimal 6YO	Standard	No shin bar
NT1113	H350	450	Mid	Stiffer	Shin bar

Kinematic Assessments

Each ATD was instrumented with triaxial accelerometers in the head, thorax, and pelvis. Six-axis load cells were installed in the upper neck and lumbar spine. Anterior-superior iliac spine (ASIS) load cells were also mounted in each pelvis. Angular rate sensors were mounted in the spine box and pelvis of the mid-sized male ATD. For the tests with the infant restraint, the maximum rotation angle was digitized from video using reference tape placed on the restraint prior to the test. For the tests with the mid-sized male ATD, head and knee excursions were calculated using the same procedures prescribed by FMVSS No. 213. The angular rate sensor in the spine box was integrated to calculate the thorax change in angle of the mid-sized male ATD. The difference between knee and head excursions was also calculated. Previous work using pediatric ATDs found that these measures were useful in assessing kinematics. Good kinematics are characterized by the torso moving forward past vertical and smaller values of knee-head excursion. Submarining was characterized by torso angles indicating that the torso does not rotate forward of vertical and in pediatric ATDs, knee-head excursions of 200 mm and greater. While these trends with torso angle would also be expected to apply to adult ATDs, the differences in size between adult and pediatric ATDs may require different thresholds of knee-head excursion to characterize submarining.

Results

Rear-facing Infant Seat Tests

Test measures from the six tests using the rear-facing infant restraint are summarized in Table 2 and graphs of these values for each test condition are shown in Figure 8 through Figure 11. Values in bold exceed threshold values specified in FMVSS No. 213. Table 3 shows the frames of initial and peak rotation. The red angled lines show the differences in initial orientation and final rotation.

Table 2. Summary of test conditions and results for tests with rear-facing infant restraint

Test ID	Cushion Length (mm)	Seat belt Geometry	Cushion Stiffness	HIC (36)	3-ms-Chest g	CRS Rotation Angle
NT1101	450	Mid	Standard	739	58	55
NT1102	350	Mid	Standard	609	53	64
NT1103	350	Optimal 6YO	Standard	608	**61**	66
NT1104	350	Optimal 6YO	Stiffer	614	**62**	66
NT1105	400	Optimal 6YO	Standard	717	**62**	60
NT1106	450	Mid	Stiffer	739	59	53

Table 3. Initial and peak frames for tests with rear-facing infant restraint

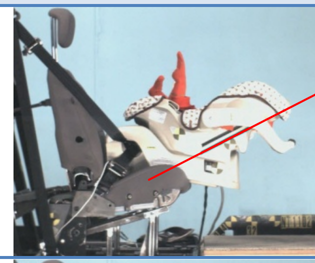
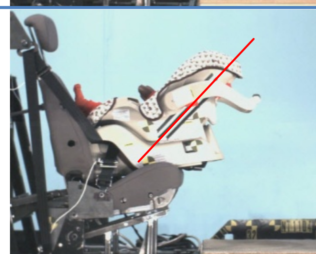
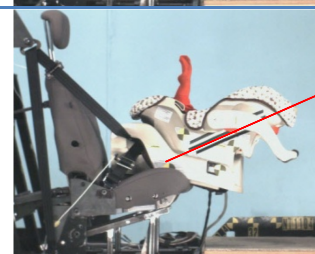
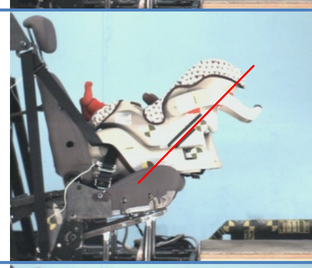
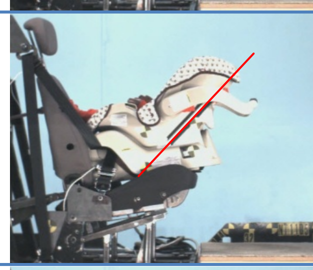
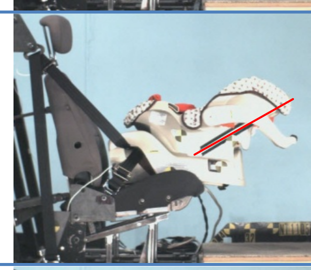
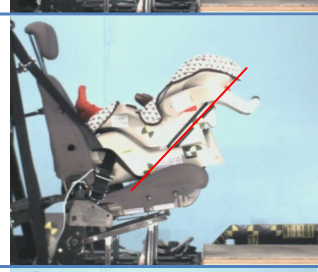
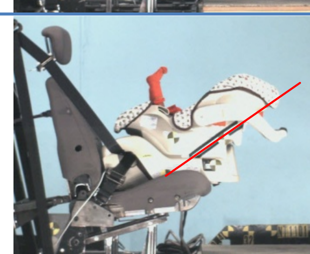
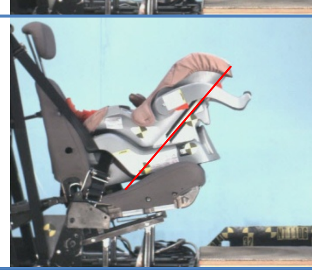
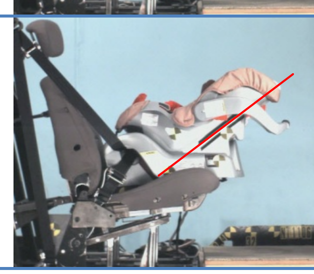
Test ID: cushion length (mm), belt geometry, stiffness	Initial rotation	Peak rotation
NT1102: **350** **Mid** **Standard**		
NT1104: **350** **Optimal 6YO** **Stiffer**		
NT1103: **350** **Optimal 6YO** **Standard**		
NT1105: **400** **Optimal 6YO** **Standard**		
NT1101: **450** **Mid** **Standard**		
NT1106: **450** **Mid** **Stiffer**		

Figure 8 shows the 36-ms HIC values for each condition. Although all tests had 36-ms HIC values well below the limit of 1000, HIC increased with cushion length but was not affected by cushion stiffness or belt geometry. The head of the infant ATD was extended past the front edge of the cushion (though within the child restraint) in the tests where the 350 mm cushion length was used. When the child restraint reached peak rotation, the cushion did not provide as much reactive force beneath the head as in the tests with the longer cushion, resulting in lower head accelerations and HIC values.

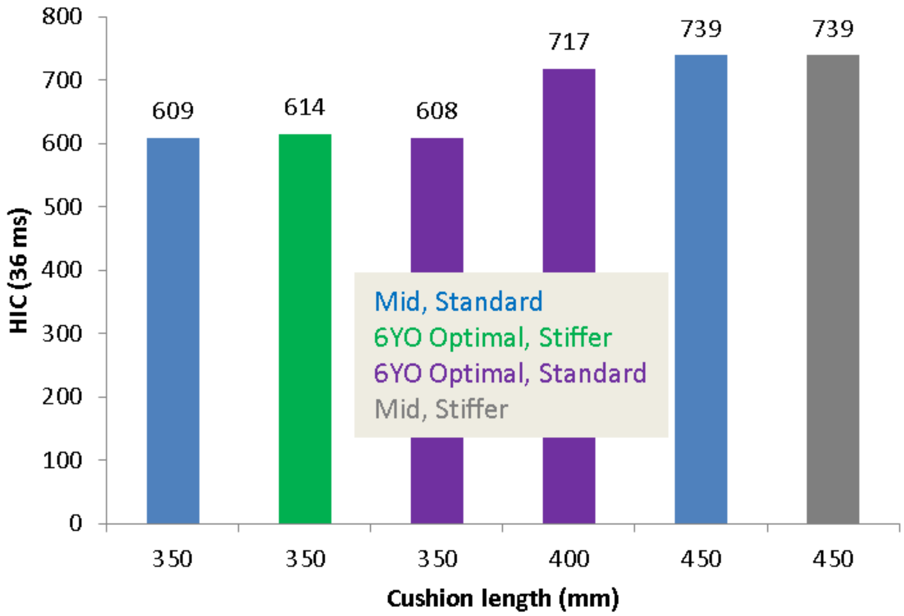


Figure 8. HIC (36 ms) values for test conditions using the rear-facing infant restraint

The values of 3-ms- chest clip acceleration for each test condition are shown in Figure 9. The three conditions using the 6YO optimal belt condition slightly exceeded the limit of 60 g. (Experience with testing rear-facing infant restraints indicates that this measure is generally repeatable within 3 g or so, so all of the tests would be considered similar except for the test measuring 53 g). Figure 10 shows the plots of resultant chest acceleration vs. time. The three tests with passing values achieve their peak earlier than the three tests that do not. The belt geometry optimized for the 6YO that is slightly more forward of the mid geometry allows chest loading to continue longer. With the same belt geometry, cushion length had minimal effect on chest acceleration. Stiffer cushion increased chest acceleration slightly.

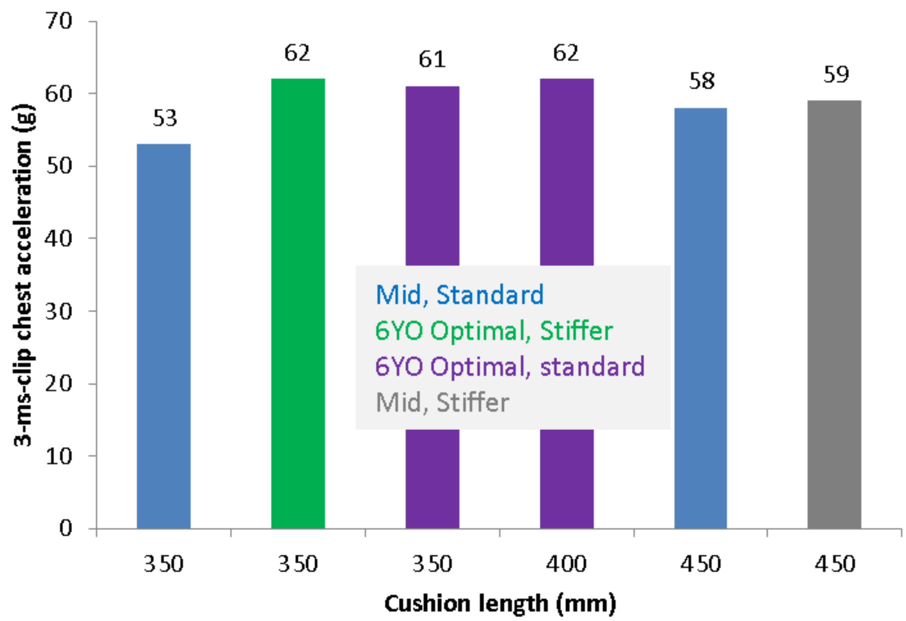


Figure 9. 3-ms- chest clip acceleration for each test condition.

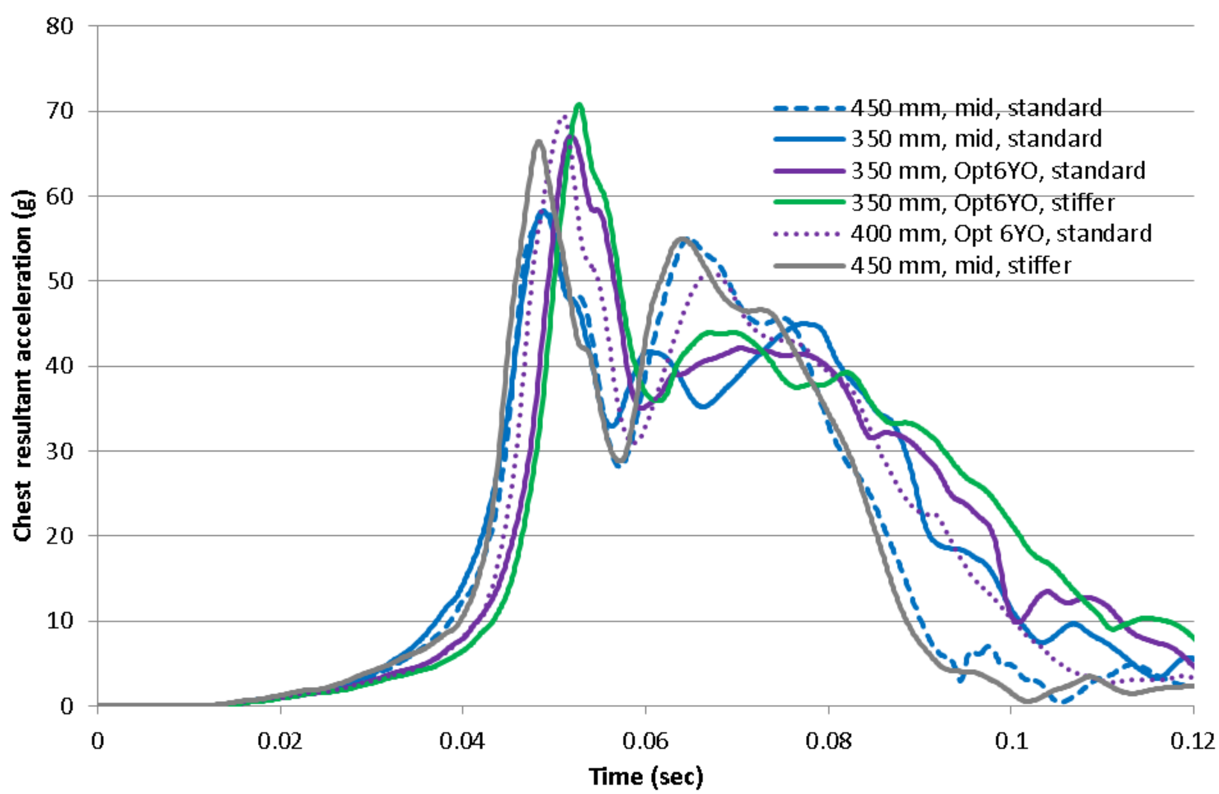


Figure 10. Resultant chest acceleration versus time for each test condition.

The values of maximum child restraint rotation are shown for each test condition in Figure 11. No tests exceeded the criteria of 70°. Rotation angle increased with shorter cushion lengths. Stiffness and belt geometry did not have a substantial effect.

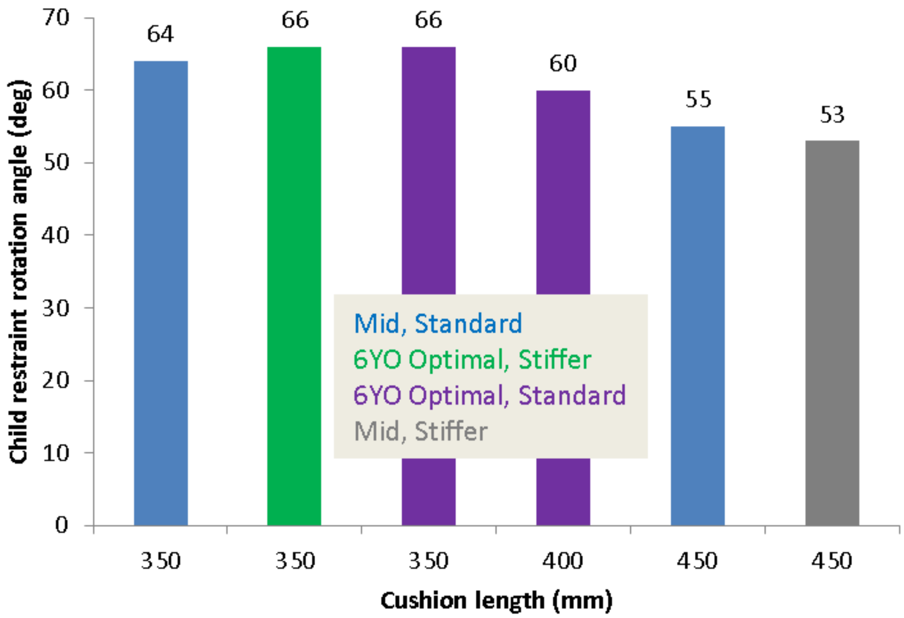


Figure 11. Maximum child restraint rotation angle for each test condition.

Mid-sized Male ATD Tests

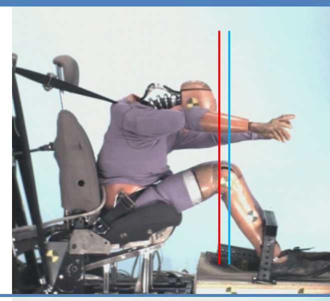
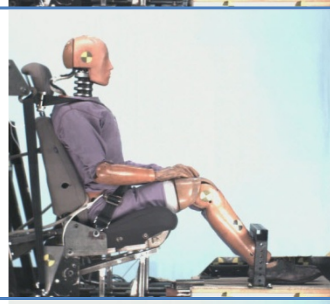
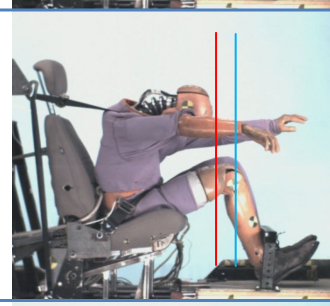
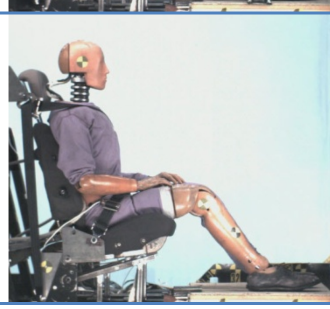
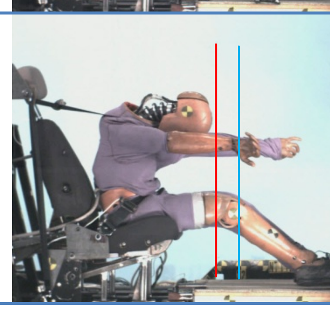
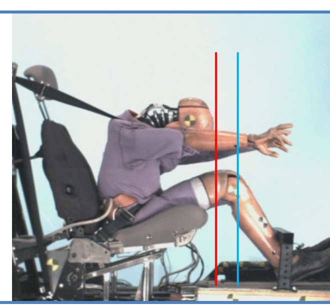
Table 4 summarizes the tests conditions and results for tests performed with the mid-sized male ATD, while Table 5 illustrates the initial and peak positions for each test. The red vertical lines indicate initial knee position and the blue vertical lines indicate the peak knee excursion.

Table 4. Summary of test conditions and results for tests with mid-sized male ATD

Test ID	Cushion Length (mm)	Belt Geometry	Seat Stiffness	HIC (36)	3-ms-Chest g	Change in torso angle (deg)	Head Excursion	Knee Excursion	Head-knee Excursion
NT1108	350	Mid	Standard	566	44	-29	708	821	113
NT1110	350	Optimal 6YO	Standard	513	43	-29	698	823	125
NT1111	350	Optimal 6YO	Stiffer	661	48	-25	679	852	173
NT1112#	350	Optimal 6YO	Standard	617	44	-24	682	901	219
NT1109	450	Mid	Standard	527	45	-28	*	*	*
NT1113	450	Mid	Stiffer	754	45	-27	687	856	169

* Right-side video failure # No shin bar

Table 5. Initial and peak positions for tests with mid-sized male ATD

Test ID: cushion length (mm), belt geometry, stiffness	Initial	Peak rotation
NT1108: 350 Mid Standard		
NT1110: 350 Optimal 6YO Stiffer		
NT1111: 350 Optimal 6YO Standard		
NT1112: 350 Optimal 6YO Standard No Shin bar		
NT1109: 450, Mid Standard		
NT1113: 450 Mid Stiffer		

Red: peak head excursion Blue: peak knee excursion

Overall, results were generally similar among the six test conditions. All tests exhibited kinematics and measured values that would be considered acceptable, with the torso rotating past vertical in a similar manner in each test. The 3-ms chest clip value varied from 43 to 48 g across all tests, while the change in torso rotation varied from 24 to 29 degrees forward. As shown in Figure 12, the difference among test conditions in peak head excursion between the smallest and largest values was only 26 mm and did not seem to vary with any particular test parameters. For the knee excursion shown in Figure 13, the test without the shin bar had the highest value, but the other four conditions measured varied 35 mm between the highest and lowest values. The knee-head excursion shown in Figure 14 also shows the largest values in the test without the shin bar, but no other consistent trends with belt geometry or seat length. The HIC values (shown in Figure 15) vary the most out of the evaluated outputs, but do not seem to be associated with any particular change in test condition.

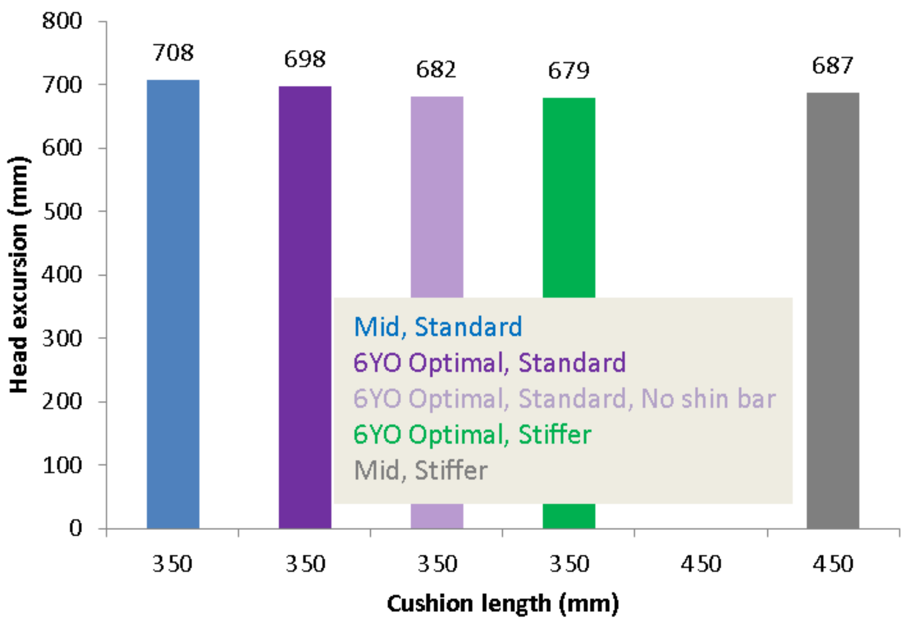


Figure 12. Peak head excursion for each test condition

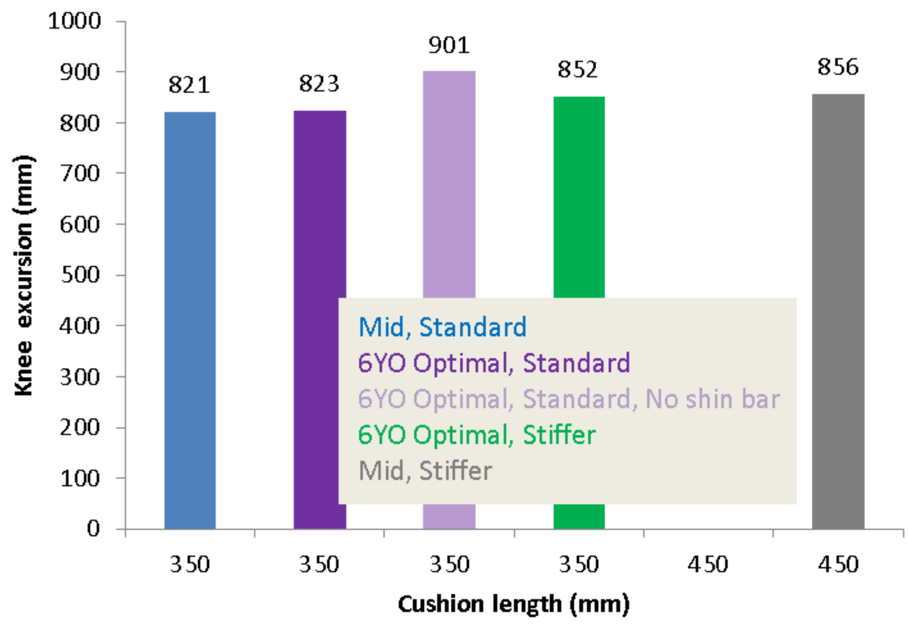


Figure 13. Peak knee excursion for each test condition

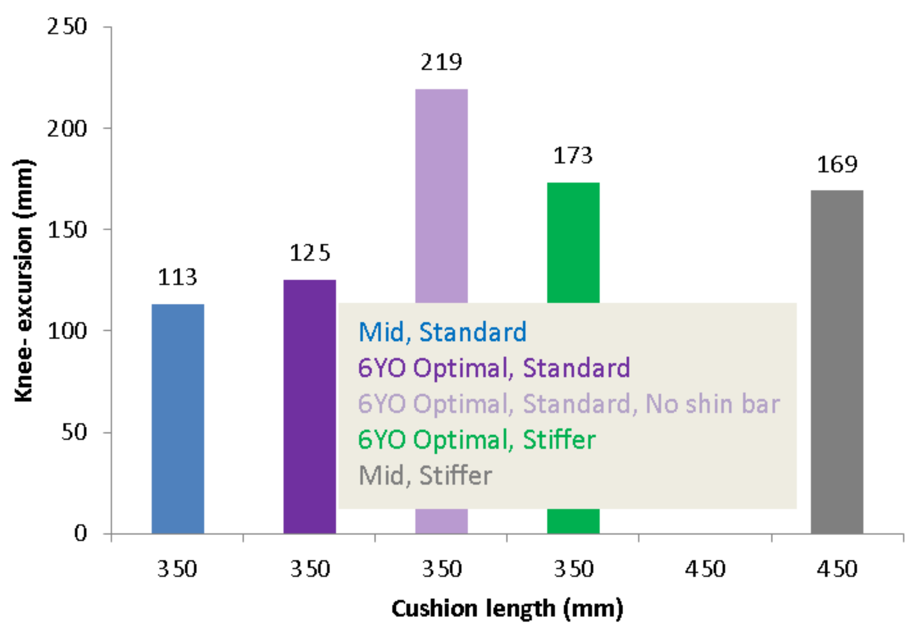


Figure 14. Peak knee-head excursion for each test condition

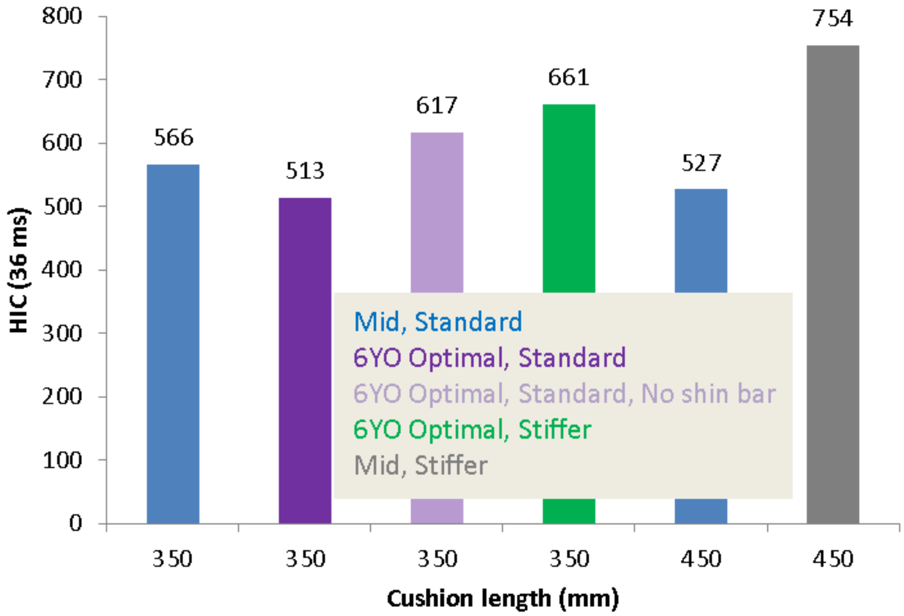


Figure 15. HIC (36 ms) values for each test condition

Discussion

This test series was performed to identify possible negative consequences for infants in rear-facing child restraints and midsized adult male occupants using a vehicle rear seat cushion length and belt geometry optimized for 6YO children. Test conditions included shortening the cushion length from 450 mm to 400 or 350 mm, and adding a member to the front structure to make it stiffer. The shoulder belt anchorage was moved closer to the ATD's shoulder, and the lap belt anchorage moved to provide an angle near 55°and moved closer to the H-point of the seat. The results of these preliminary tests did not reveal any important decrements in restraint performance for these occupant categories.

The rear-facing infant restraint, secured with the three-point seat belt, did not exceed the allowable peak rotation angle of 70° under any test condition. The angle increased from values of 53-54° with the 450 mm cushion length to 64-66 with the 350° cushion length. The three test conditions using the belt geometry optimized for the 6YO exceeded the allowable 3-ms-chest clip acceleration by 1-2 g. Analysis of the kinematics showed that the belt anchorages located more forward allowed movement that placed the ATD's chest over the stiffest part of the front of the seat when the belts were maximally loaded. However, two of the other test conditions barely passed the chest acceleration criteria with values of 58-59 g. Experience in our laboratory with testing infant restraints indicates that the 3-ms-chest clip measurement is repeatable within about 3 g, and typical child restraints produce values between 50 and 55 g on the FMVSS No. 213 bench. However, rear-facing restraints tested on vehicle seats often have 3-ms chest clip values near the threshold value due to most vehicle seats bottoming out sooner than the FMVSS No. 213 bench (Glass 2002). Because field data do not show that acceleration-induced chest injuries among rear-facing infants is an important problem (Arbogast, Locey, Zonfrillo, & Maltese, 2010; Melvin, Weber, & Lux, 1980), we do not believe that the current results provide cause for concern.

All of the tests using the mid-sized male ATD showed similar kinematics and injury measures, all of which would be considered acceptable. A floor and shin bar was constructed for use with the FMVSS No. 213 buck structure to approximate a realistic interaction with the floor and the back of the front seat. The interaction between the shin bar and the ATD's legs seemed to have more effect on kinematics than any changes to the vehicle seat cushion or belt geometry. The design of the shin bar created a large rearward force on the ATD's shins and femurs. The ATD feet engaged with the floor and the legs contacted the structure, creating a large bending moment on the leg. Although this improved kinematics, this type of loading could be a source of injury for an occupant. In real vehicles, there would be additional interaction between the knees and front seat back that was not simulated. Future tests to simulate a realistic rear seating environment should include a more realistic representation of the interaction with the front seat.

In the tests with the 350 mm seat cushion length, less than 70 percent of the child restraint base was in contact with the seat cushion. Most child restraint manufacturers require in their users' manuals that at least 80 percent of the base is in contact with the seat cushion. However, the child restraint performed acceptably in these test conditions while not meeting this common installation requirement. If shorter cushion lengths are recommended as a safety countermeasure for older children, the 80 percent contact requirement will need to be addressed.

This research effort did not address the issue of comfort for rear seat adult occupants. Because rear seat cushion lengths are generally longer than needed to accommodate most of the occupants who sit in the rear seat (Huang & Reed 2006), vehicle manufacturers seem to have a perception that longer seats are needed to provide adequate comfort for adults. We have been unsuccessful in finding published literature on studies performed that document any association between comfort and seat cushion length. It is possible that vehicle manufacturers have proprietary information regarding this association, or that it is a traditional practice that has not been tested with volunteers.

This study has several limitations. Only one vehicle seat model was used, and it was a captain's chair rather than a bench seat. Results may not apply to other vehicle seat models. In addition, although the seats did not have visible damage either before or after testing, they were acquired from used vehicles and likely had different amounts of use. The stiffness of every seat cushion tested was not quantified before or after testing.

In addition, the methods used to simulate a stiffer seat cushion may not be realistic. The modeling used to develop the optimal 6YO rear seat conditions indicated that seat stiffness was more sensitive to the position of the anti-submarining bar than the stiffness of the foam. Thus the testing approximated shifting the bar by inserting a plate between the bar and seat foam. While it may have been informative to also test other foam stiffness, the project budget and scope did not allow for manufacture of seats with different stiffnesses of foam. Since vehicle manufacturers likely vary how they design the seat structure and foam to control both safety and comfort, results developed from this study may not necessarily apply to all vehicle seats.

These results suggest that vehicle seats with cushion lengths and belt geometry designed for older children do not seem to pose a problem for infants in a rear-facing child restraint normally positioned midsize men in a frontal impact. Additional testing and modeling are needed to explore potential negative outcomes with other models of child restraints. It may also be valuable to test additional vehicle seat models.

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