Considerations for Optimizing Occupant Protection to Children in Side Impact Crashes

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Abstract - This paper reports on the findings of side impact sled testing conducted to better understand the mechanisms by which children in child safety seats (CSSs) are injured during side impact crashes and to assess ways to mitigate those injury mechanisms. The sled tests employed the same model CSSs involved in two investigated crashes as well as two other CSSs incorporating different side wing designs. The CSS models involved in the investigated crashes and the sled testing included both rear-facing and forward-facing configurations. It is well understood that, in a side impact crash involving a child in a CSS, the side wing is a primary restraining component and the side wings should be lined with energy absorbing padding to further optimize the child's crash protection. The results of our sled tests indicate that the effectiveness of the side wing is not only affected by the depth, angle, height, and padding of the wing as reported by other researchers, but also by the distance between the wing and the head. To optimize crash ride down and minimize the relative velocity of the head when it contacts the side wing, the side wing must be in close proximity to the head. The testing also confirmed what previous researchers have found, namely that CSS designs secured by webbing rather than rigid ISOFIX anchorages experience significant rotation and lateral displacement, thus placing the child occupant at greater risk of head impact with the interior of the vehicle.

BACKGROUND

Side impact motor vehicle crashes account for a disproportionately high percentage of child injuries and fatalities. While less frequent than frontal crashes, side crashes result in approximately as many injuries and fatalities per year [1-6]. In spite of these facts, the National Highway Traffic Safety Administration (NHTSA) and child safety seat manufacturers in the U.S. have been slow to consider the performance of child safety seats (CSSs) in side impact conditions in the design of CSSs. Although the Federal Motor Vehicle Safety Standard (FMVSS) 213 - Child Restraint Systems incorporated frontal test performance requirements in 1981, even today, the safety standard does not require testing of CSSs in any type of simulated side impact conditions.

One reason cited for this lack of emphasis on side impact protection has been the lack of biofidelic child dummies for side impact testing [7]. However, for decades researchers have successfully conducted side impact testing to study the performance of child safety seats and have reported useful findings from these tests [8-42]. When NHTSA incorporated frontal crash sled testing into FMVSS 213 in 1981, the available child crash dummies were far from biofidelic. Nonetheless, the compliance test requirements resulted in improved CSS performance in frontal crashes.

Another cited reason is the relative lack of understanding of how children are injured in side crashes; yet, numerous studies have been conducted and papers published that discuss the injuries to children in side impacts and the mechanisms for those injuries [43-83]. Consistently, these studies have found that the most frequently injured body region was the head and the mechanism for the injury was head impact. Again, when NHTSA incorporated frontal crash sled testing into FMVSS 213, little was known of the threshold of injury for children. Adult Injury Assessment Requirement Values (IARV) for Head Injury Criteria (HIC) and chest acceleration were therefore adopted for child restraint tests. More importantly, since head impact had been identified as the leading mechanism for serous injury in frontal crashes, a head excursion limit was adopted.

The required compliance testing with these less-than-perfect crash test dummies and IARVs resulted in significant improvement in the performance of child safety seats in frontal crashes in the U.S. The frontal crash head excursion requirement, considered the performance standard for child safety seats, has been revised and updated, as the benefit and public acceptance of top tethers became apparent from their use in Australia and Canada. Since head impact is also the leading mechanism of serious injury in side impacts, clearly important performance factors for a child safety seat in a side impact are its ability to limit head excursion, minimize head acceleration, and contain/shield the head. As these are some of the very factors considered in required frontal crash tests, it is reasonable to conclude that these factors can be appropriately incorporated and evaluated in side impact test requirements.

Previous research conducted on protecting children in side impact crashes has identified that minimizing head excursion needs to be a top priority to effectively reduce the potential for, and severity of, head impacts with the vehicle's interior [84-88]. In side impact crashes, the child is restrained by the CSS restraint harness and side wings [89-97]. Deep, tall side wings have been found to be critical for minimizing lateral head excursion [98]. Side wings limit lateral head excursion by acting as a head containment barrier, maintaining the head within the confines of the side wings. However, there is a limit as to the effect of side wings on child head and torso kinematics. Most side crashes have some frontal crash force component since the vehicle struck in the side typically is traveling forward at the time of impact and experiences a deceleration of its forward velocity. As the frontal component of the crash increases, there is a greater potential for the child's head to move forward of the side wing's front edge. Note, however, that, as this occurs, the kinematics of the child and the performance of the CSS become more like that seen in frontal crashes.

The potential for the head to slip beyond the side wing is also increased if the CSS is allowed to yaw toward the impacted side. This will decrease the effective profile presented to the head and the angle of the side wing relative to the head and will promote forward deflection of the head off the side wing. With rear-facing CSSs, a greater forward crash component will tend to move the child's head forward and load against the CSS's seat back, decreasing the potential for the head to slip out of the side wing's confines.

School buses are designed to provide occupant crash protection during frontal crashes through compartmentalization. The school bus seats incorporate high seat backs with padding and are positioned forward-facing and close together so that during a frontal crash the occupant loads into the seat back forward of their occupant position and rides the crash down against the padded seat back. Similarly, the side wings of a CSS act to compartmentalize the child's head and body. The authors, therefore, hypothesized that the proximity of the side wing to the child's head prior to a crash and side wing geometry would not only affect the side wing's ability to contain the head, but also affect the acceleration of the head by altering the CSS.

The side wings not only act to limit the child's head excursion, but they act as a barrier between the vehicle's interior and the child's body. During a side crash, both forward and rear-facing CSSs, when secured by seat belts or LATCH (Lower Anchors and Tether for CHildren) belts, tend to roll and yaw toward the impacted side of the vehicle. A CSS located on the near side relative to the impact and in the center occupant positions can impact or be impacted by the interior side of the vehicle. Therefore, it is important that the side wings incorporate energy absorbing (EA) material to minimize the accelerations applied to the CSS and child from this impact. Such padding has been recommended by researchers for many years and many CSSs currently incorporate some type of EA material in the side wing [99-101].

Current child safety seats incorporate side wings with various geometries. This study investigated two side impact crashes and determined the mechanism of injuries sustained by children restrained in CSSs during the crash. It also included testing of several CSSs, including the models used during the investigated crashes, in simulated side crashes to determine their effectiveness in containing the head and minimizing head acceleration.

Field Investigations

Field Case 1 – rear-facing child safety seat

Case 1 involved a 2001 PT Cruiser being driven on an icy, two lane road when the driver lost control and the vehicle slid across the center line into the oncoming lane of traffic. The right side of the PT Cruiser was then impacted by a full-size sport utility vehicle. As a result of the impact, the PT Cruiser experienced a crash pulse of 10-13 mph delta-V (16-21 km/h) and a principle direction of force (PDOF) of 76-90 degrees. The maximum permanent intrusion into the right rear occupant space at the window sill level, just aft of the mid door, was approximately 8.4 inches (213 mm) (Figure 1). The total intrusion, including elastic deformation, was likely approximately 10 inches at the window sill [102]. An 11 month old child was secured in a rear-facing CSS located in the rear center occupant position of the PT Cruiser at the time of the crash. (Figure 2) During the crash the child sustained the following injuries:

- Acute subdural hematoma over the left hemisphere with a significant midline shift that extended beyond the sides of the hematoma with the suggestion of significant brain swelling
- Fractured left clavicle
- Abrasion over right eye

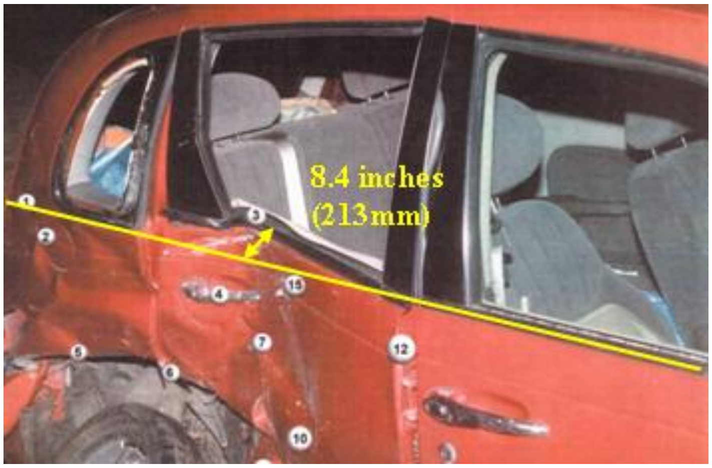


Figure 1. Intrusion into PT Cruiser in Case 1 crash

Figure 2. 12 month CRABI child dummy installed
in an exemplar CSS installed in an exemplar PT Cruiser

Field Case 2 – forward-facing child safety seat

Case 2 involved a 1993 Saturn SL2 impacted on the right side by a compact pick-up truck. As a result of the impact, the Saturn experienced a crash pulse of 15-21 mph delta-V (24-34 km/h) and a PDOF of 45 degrees. The maximum intrusion into the right occupant compartment was approximately 10-12 inches (254-305 mm) at the window sill (Figure 3). A 2 year, 1 month old child was secured in a forward-facing CSS located in the center rear occupant position of the Saturn at the time of the crash (Figure 4). During the crash, the child sustained the following injuries:

- Depressed and comminuted right parietal skull fracture - extending down through right occipital bone extending into the posterior aspect of the foramen of Monro with underlying hemorrhagic contusion and associated subdural and epidural hematoma
- Parenchymal contusion within the right parietal lobe
- Subarachnoid hemorrhage
- Midline shift of approximately 6 mm from right to left
- Transverse fracture through the right temporal bone with disruption of the ossicular chain
- Moderate bleeding from the right ear
- Thrombosis of right transverse sinus
- Large hematoma
- Edema in periportal triads (swelling of liver tissue)
- Cleft at tip of spleen
- Edema/fluid between splenic vessels and pancreas, extending to area of mesentery

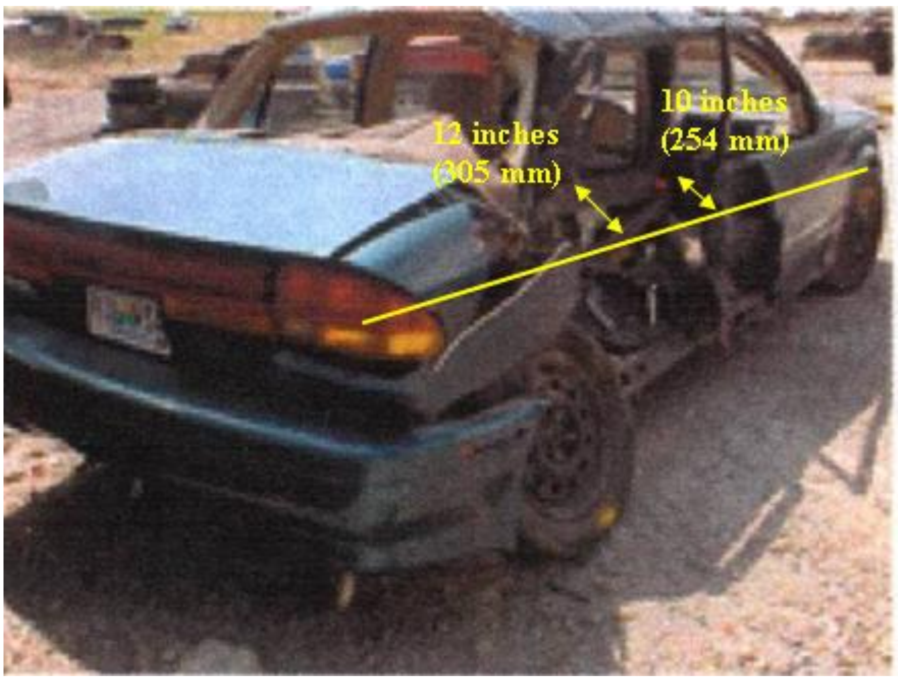


Figure 3. Intrusion to Saturn SL2 in Case 2

Figure 4. Surrogate child secured in an exemplar CSS in the rear center of an exemplar Saturn SL2

APPROACH

To better understand the children's kinematics and mechanisms of injury during the crashes investigated and to determine if modifications to the child safety seats could eliminate the injury mechanisms, two series of sled tests were conducted. Each test series had the test CSS installed in the center rear occupant position of an exemplar vehicle. One series utilized rear-facing child safety seats; the other utilized forward-facing child safety seats.

Rear-Facing Child Safety Seat Test Series

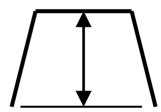
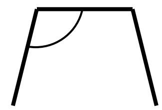
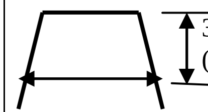
A horizontal sled test facility was used to simulate a side impact crash condition. The passenger compartment portion of a Chrysler PT Cruiser was mounted to the sled, oriented to simulate a 90 degree PDOF right side impact. With a rear-facing CSS, a 90 degree PDOF challenges the side wings' ability to contain the occupants head more than side impacts with some frontal component. The aft portion of the right rear door was repositioned 10 inches (254 mm) inboard to simulate intrusion into the right rear occupant compartment. The tested rear-facing child safety seats, each with different side wing configurations, are shown in Figures 5, 6, and 7 and listed in Table 1 with their general wing geometry. CSS A was the same model CSS as that was involved in Field Case 1.

Figure 5. Rear-facing CSS A

Figure 6. Rear-facing CSS B

Figure 7. Rear-facing CSS C

Table 1. Side wing geometry for rear-facing child safety seat test series

Child Safety Seat	Wing Depth(1) inches (mm) 	Wing Angle(2) (degrees) 	Wing Width(3) inches (mm)  3¼ (82 mm)
CSS A	5⅛ (130)	130	16¼ (413)
CSS B	6 (152)	100	6¼ (159)
CSS C	7⅝ (194)	105	12¾ (324)
CSS C w/ modified side wings	7⅝ (194)	105	6¾ (171)

(1) – Wing depth measured at a level 15½ inches (394 mm) up from seat bight [12mo seated shoulder height + 1/2 (seated height - shoulder height)]

(2) – Wing angle measured at a level 15½ inches (394 mm) from seat bight, when wing curved the tangent at 3¼ inches (82 mm) forward of the seat back was used [3¼ inches (82 mm): ½ head depth of average 12 month child]

(3) – Wing width measured at a level 15½ inches (394 mm) from bight and 3¼ inches (82 mm) forward of seat back

Table 2 shows the test matrix for the rear-facing child safety seat test series. Except as noted, each CSS was installed in the rear center occupant position, in accordance with the manufacturer's instructions, using the lower anchorages of the LATCH system. A 12-month-old CRABI child dummy was secured in accordance with the manufacturer's instructions in all tests. Two crash pulses were used. For tests 1.1, 1.2 and 1.3, the crash pulse had a peak acceleration of approximately 26 g and a duration of 75 msec, which produced a delta-V of 20 mph (32 km/h). For tests 1.4 to 1.10, the peak acceleration was approximately 24 g and the duration was 125 msec. This produced a delta-V of 24 mph (39 km/h). The testing was captured by three onboard high-speed video cameras, two positioned overhead, viewing the center and right rear occupant space, and a third outside the right rear door viewing into the right rear window.

Table 2. Test matrix for rear-facing child safety seat test series

Test Number	Child Safety Seat	Seat belt / harness installation	Sled acceleration pulse
1.1	CSS A	Per manufacturer's instructions	Delta-V = 20 mph (32 km/hr)
1.2	CSS B	Per manufacturer's instructions	Delta-V = 20 mph (32 km/hr)
1.3	CSS C	Per manufacturer's instructions	Delta-V = 20 mph (32 km/hr)
1.4	CSS A	2¼ inches (57 mm) of slack in seat belt)	Delta-V = 24 mph (39 km/hr)
1.5	CSS B	Per manufacturer's instructions	Delta-V = 24 mph (39 km/hr)
1.6	CSS C	Per manufacturer's instructions	Delta-V = 24 mph (39 km/hr)
1.7	CSS B	Per manufacturer's instructions & w/Australian type tether	Delta-V = 24 mph (39 km/hr)
1.8	CSS A	Per manufacturer's instructions	Delta-V = 24 mph (39 km/hr)
1.9	CSS A	With unlocked harness	Delta-V = 24 mph (39 km/hr)
1.10	CSS C w/modified side wings	Per manufacturer's instructions	Delta-V = 24 mph (39 km/hr)

Forward-facing Child Safety Seat Test Series

A horizontal accelerator sled test facility was used to simulate a side impact crash condition. The passenger compartment portion of a 1993 Saturn SL2 was mounted to the sled oriented to simulate a 45 degree PDOF right side impact. A 45 degree PDOF has a frontal component equal to the lateral component. This significant frontal component challenges the side wing to contain the head. The aft portion of the right rear door was repositioned 10-12 inches (254-305 mm) inboard to simulate intrusion into the right rear occupant compartment. The simulated crash pulse used in all of the testing in this series had a delta-V of 18-21 mph (29-34 km/h) and peak acceleration of 16.5-17 g. The testing was captured by three onboard high-speed video cameras: one positioned overhead, viewing the center and right rear occupant space; a second positioned behind and above the rear occupant space, viewing the center and right rear occupant space; and a third outside the right rear door viewing into the right rear window. All child safety seat test units were secured forward-facing in the rear center occupant position using the vehicle's lap belt. Prior to each test, a Hybrid III three year old child test dummy was secured in the CSS in accordance with the manufacturer's instructions. The child dummy's head was instrumented with a tri-axial head accelerometer. The tests were conducted with three different child safety seats as shown Figures 8, 9, and 10 and as listed Table 3. Tether use and adjustment of the lap belt was varied as noted in Table 4.

Figure 8. Forward-facing CSS A

Figure 9. Forward-facing CSS B

Figure 10. Forward-facing CSS C

Table 3. Side wing geometry for forward-facing child safety seat test series

Child Safety Seat	**Wing Depth(1) inches (mm)**	**Wing Angle(2) (degrees)**	**Wing Width(3) inches (mm)** 3¼ (82 mm)
CSS D	3 (76)	135	14¼ (362)
CSS E	6 (152)	100	6¼ (159)
CSS F	7⅝ (194)	105	12¾ (324)

(1) – Wing depth measured at a level 15½ inches (394 mm) up from seat bight [12mo seated shoulder height + 1/2 (seated height - shoulder height)]

(2) – Wing angle measured at a level 15½ inches (394 mm) from seat bight, when wing curved the tangent at 3¼ inches (82 mm) forward of the seat back was used [3¼ inches (82 mm): ½ head depth of average 12 month child]

(3) – Wing width measured at a level 15½ inches (394 mm) from bight and 3¼ inches (82 mm) forward of seat back

Table 4. Test Matrix for forward-facing child safety seat test series

Test Number	Child Safety Seat	Tethered (Y/N)	Lap belt Adjustment
2.1	CSS D	N	Snug
2.2	CSS D	N	2 inches of slack from snug
2.3	CSS D	Y	Snug
2.4	CSS D	N	2 inches of slack from snug
2.5	CSS D	Y	2 inches of slack from snug
2.6	CSS E	Y	2 inches of slack from snug
2.7	CSS F	Y	2 inches of slack from snug

TEST RESULTS

Rear-facing Child Safety Seat Test Series

During all of the rear-facing CSS tests, the top of the rear-facing CSS rotated toward and impacted the right rear door. In none of the first three sled tests, conducted at the lower delta-V, did the infant dummy's head contact the right rear door. In test 1.1 using the CSS with smaller and shallower angled wings (CSS A), the dummy's head came closest to contacting the right door (Figure 11). The head was well contained within the side wings of CSS B (Figure 12) and CSS C (Figure 13) due to the large size of the side wing and the near perpendicular angle of the wing relative to the CSS seat back. The close proximity of the side wings to the dummy's head in CSS B also appeared to help maintain the head within the wings.

Time 0 Maximum head excursion

Figure 11. Maximum head excursion w/CSS A during Test 1.1

Time 0 Maximum head excursion

Figure 12. Maximum head excursion w/CSS B during Test 1.2

Time 0 Maximum head excursion

Figure 13. Maximum head excursion w/CSS C during Test 1.3

While head injury tolerance for infants is not well defined, especially for side impacts, NHTSA has estimated through geometric and material property scaling that a HIC_{15} value of 390 with a 12 month child dummy indicates a 31 percent probability of skull fracture when an impact is applied to the frontal bone. No head injury values have been proposed for impacts to the side of the head. Nonetheless, HIC is a valuable tool for comparing relative head protection performance between different CSS designs.

During test 1.8, conducted with the higher delta-V, CSS A did not contain the dummy's head and the head impacted the right rear door (Figure 14), resulting in a HIC_{15} of 668. CSS B more effectively contained the head within the side wing until the child dummy began to rebound and its head brushed the intruded door. (Figure 15) The larger, close-fitting side wing reduced the head velocity and severity of impact with the right rear door, resulting in a HIC_{15} of only 138. The reduction in HIC with CSS B indicates a substantial reduction in the risk of injury.

CSS C maintained the head within the side wings (Figure 16). Nonetheless, a HIC_{15} value of 757 was recorded. The authors postulated that, due to the large distance between the head and side wing, the head developed a significant velocity relative to the wing prior to head impact. To assess this theory, the side wings of CSS C were modified in the head region by adding 3 inches (76 mm) of padding to the internal surface of each wing (Figure 17) and the test repeated as test 1.10. During this test, the head was well contained within the side wing (Figure 18) and the HIC_{15} was reduced to 462, a 39% reduction. It was noted after the test that the padding was not compressed, indicating that the HIC reduction was primarily from the improved crash ride down and not from energy absorption by the padding. Incorporation of more easily compressed energy absorbing padding would undoubtedly further decrease the HIC value.

Time 0 Maximum head excursion

Figure 14. Maximum head excursion w/CSS A during Test 1.8

Time 0 Head to door contact during rebound

Figure 15. Maximum head excursion w/CSS B during Test 1.5

Time 0 Maximum head excursion

Figure 16. Maximum head excursion w/CSS C during Test 1.6

Figure 17. CSS C with 3 inches (76 mm) of EA padding added to the side wings

Time 0 Maximum head excursion

Figure 18. Maximum head excursion with CSS C incorporating modified side wings during Test 1.10

CSS A was also tested with the securing LATCH strap loosened 2¼ inches (57 mm), test 1.4, and with an unlocked harness adjuster (Test 1.9). As expected, both of these factors resulted in higher HIC_{15}, 883 and 791 respectively.

CSS B was also tested with a tether attached to the head end of the CSS and behind the rear center occupant position. No significant observable difference in head excursion was noted with the tether versus the non-tethered condition during these simulated side impact tests.

Forward-facing Child Safety Seat Test Series

CSS D incorporated the smallest side wings in this test series. The dummy's head was not contained by the side wing in any of the tests conducted with CSS D, and the head impacted the right rear door's window sill every time (Figure 19 for a representative test view). When untethered, as in tests 2.1 and 2.2, the head impact resulted in a HIC_{36} of 244 and 237 respectively. When tethered, as in tests 2.3 and 2.5, the severity of the head impact with the door's window sill (Figure 20) was reduced, resulting in HIC_{36} of 115 and 109 respectively during these 45° tests.

Time: 0 Maximum head excursion

Figure 19. Maximum head excursion with untethered CSS A during Test 2.1

Time 0 Maximum head excursion

Figure 20. Maximum head excursion with tethered CSS A during Test 2.3

During Test 2.6 with the tethered CSS E, the dummy's head "brushed" the right side wing as it moved forward and slightly outside of the wing. Due to less child safety seat rotation compared to the CSS D, no head impact with the door window sill occurred; however, the head did contact a relatively flexible vertical window frame member (Figure 21). The resulting HIC_{36} was 114.

Time 0 Maximum head excursion

Figure 21. Maximum head excursion with tethered CSS B during Test 2.6

Similar to CSS E, during Test 2.7 conducted with the tethered CSS F, the head brushed the right side wing, but was not contained within wing. Due to less rotation compared to CSS D, the head did not contact the door window sill. However, during rebound the head did brush the same vertical window frame member contacted during the test with CSS E (Figure 22), the resulting HIC_{36} was 121.

Time 0 Maximum head excursion

Figure 22. Maximum head excursion with tethered CSS C during Test 2.7

DISCUSSION AND FINDINGS

Rear-facing Child Safety Seat Test Series

The tests conducted with CSS A demonstrated that the mechanism of the head and face injuries sustained by the child in Case 1 was impact with the right rear door window sill. Testing also demonstrated that CSSs with deep side wings, as used in Test 1.10, would have eliminated the mechanism for the severe head injury sustained by the child in Case 1.

The results from the rear-facing child safety seat test series confirm the findings of previous researchers that large side wings are critical to protect children in side impact crashes [103-106]. The results, however, also indicate that the side wing, to be most effective, must also be near 90 degrees to the CSS seat back to prevent the head from glancing off and sliding past the wing. Previous researchers studying the performance of forward-facing belt-positioning-booster seats found that a slight angle (7 degrees) of the side wing beyond 90 degrees had little affect on head containment [107]. In the subject test series, the large angle (40 degrees) beyond 90 degrees of the wings of CSS A resulted in poor head containment. Testing conducted by NHTSA found similar results [108]**.** The wings must also be close-fitting to the head. This minimizes the development of a relative velocity between the head and the side wing before contact with the wing and helps to ensure that the head is contained within the wing by engaging the wing early in the crash before the head experiences significant forward excursion relative to the side wing. Kapoor et al., and Huot et al., [109-110] also noted reduced head acceleration from close fitted padded wings when they conducted side impact testing with the child seat positioned immediately adjacent to the impacted door (near side relative to the impact).

The high degree of yaw and roll rotation allowed the child safety seats to impact the intruded vehicle side structure. As noted by other researchers, a rigid anchoring of the child safety seat with sufficient strength significantly reduces this rotation, reduces dummy head excursion, and reduces the associated head injury risk [111-112].

Lining the outside surface of the side wings in the head region with energy absorbing padding would also reduce the peak accelerations created when that region of the CSS impacts the side interior of the vehicle and would help protect adjacent occupants should they impact the CSS. Other researchers have conducted testing with energy absorbing padding on the outside surface of the side wing and found it to reduce the head acceleration of the CSS occupant when the CSS impacted the interior side of the vehicle [113]**.**

Another technology that may reduce the injury risk from head impact with the vehicle's interior is side impact airbags. These airbags have been incorporated into many vehicles as "inflatable curtains." Unfortunately, most of these curtains do not extend down to the window sill. Further research is needed to study the performance of child safety seats during side impacts in vehicles equipped with side airbags and inflatable curtains. Children represent a large percentage of rear seat occupants, therefore rear seat side airbag and/or inflatable curtain systems should be designed to be effective in protecting children in child safety seats as well as larger children in adult seat belts.

The tests showed that had the tested CSS been positioned in the left rear occupant position, there would have been sufficient clearance to avoid child safety seat and head impact with the intruded vehicle interior. As reported by NHTSA, the pre-test clearance between the side window and a center positioned child dummy's head ranged between 12 inches (305 mm) and 22 inches (559 mm) in 20 Side Impact New Car Assessment Program (SNCAP) tests [114]. The SNCAP crash testing results show intrusion into the rear occupant space at the window sill ranging from 2.7 inches (69 mm) to 10.3 inches (262 mm), with an average of 7.4 inches (188 mm). As in the two cases reported in this paper, with this degree of intrusion, there is sufficient head clearance for a child in a rear-facing CSS at the far side occupant position to avoid impact with the opposite side interior, even with large lateral rotation of the rear-facing CSSs observed during the sled testing. Nonetheless, it is still desirable to limit rotation of CSS on the far side to avoid contact with other possible occupants and CSSs in the rear occupant space.

The tests also showed that, had the child safety seats been positioned in the right rear occupant position, the occupant position on the impacted side, during a crash similar to the crash simulated in the testing, the CSS would be impacted by intruding structure. This intrusion would prevent significant rotation of the CSS toward the impact and would accelerate the CSS inboard. Under these circumstances, rotation toward the impact is not a significant issue, but containment of the head within the side wings and energy absorbing material to minimize the peak acceleration of the CSS and to minimize the severity of the head impact with the side wing are the critical design challenges. Additional research is needed to optimize rear-facing CSSs performance in near-side crashes.

Forward-facing Child Safety Seat Test Series

The tests conducted with CSS D demonstrate the mechanism for the head and face injuries sustained by the child in Field Case 2 was impact with the right rear door window sill.

The testing of forward-facing child safety seats at a 45 degree PDOF revealed that even the large, close fitting side wings alone had little affect on kinematics, in part due to the significant frontal component of the crash. Two other factors also reduced the effectiveness of the side wings under these conditions. First, the CSSs yawed and rolled toward the impact, causing the side wing to move away from the head and presented a smaller profile to the head, and second, the side wings flexed as the head loaded the wing, increasing the angle of the wing and thus allowing the head to more readily escape the side wing (Figure 23). These factors resulted in the head escaping the side wings in all of the tests. The forward head excursion was significantly reduced when a top tether was used in these tests, even when slack was introduced into the securing seat belt. The tethered CSS E and CSS F were more effective in limiting forward and downward head excursion than the tethered CSS D. This is likely due to the differences in how the tethers anchor and route on the child safety seats, as wells as the rigidity of the child seats themselves. The CSS E and CSS F tethers are attached directly to the top of their seat back, while the tether in CSS F is attached lower down and routes up the front of the seat back (Figure 24) and over the top (Figure 25). This routing allows the tether to slide laterally at the top of the seat back (Figure 26) and the tether loads against the flexible plastic seat back. The seat backs of CSS E and F appear to be more rigid than CSS D. Testing of CSS E and F indicate that they would have eliminated the mechanism for the severe head injuries suffered by the child in Field Case 2.

Time 0 Maximum wing displacement

Figure 23. Maximum wing displacement due to CSS yaw and roll and flexion of the side wing during Test 2.7

Figure 24. CSS A Low tether attachment

Figure 25. CSS A Tether routing over the top of the CSS seat back

Figure 26. CSS A Tether slid laterally across the top of CSS1

As with the rear-facing CSSs, had the forward-facing CSS been positioned in the left rear occupant position, the position away from the impact (far side), no head contact with the vehicle interior would have occurred due to the greater head clearance. Nonetheless, as with the rear-facing CSSs, it is still desirable to limit rotation of the CSS on the far side to avoid contact with other possible occupants and CSSs in the rear occupant space.

Had the forward-facing CSSs been positioned in the right rear, the side near the impact, the roll and yaw of the CSSs would have been prevented by the intruding vehicle structure and the CSS would have been accelerated inboard. Under this scenario, the influencing design factors would be side wing geometry, energy absorbing material, and vehicle side airbags and/or air curtains in the rear occupant compartment.

FUTURE RESEARCH, DEVELOPMENT AND TESTING

As discussed above, the crash environment experienced by a child in a child safety seat during a side impact crash vary depending upon the severity and PDOF of the crash pulse, the degree of vehicle crush intrusion into the occupant space, occupant compartment size, the location of the CSS relative to the crash, i.e. near side, far side or center occupant position, whether the CSS is forward or rear-facing, and size of the child. All of these factors present technical challenges to the design of a CSS if the intended purpose of the seat is to protect the child during such impact conditions.

Testing and analysis of CSSs in simulated side impact conditions can provide a strong technical basis for evaluating the performance and effectiveness of CSS design. When conducting tests of CSSs positioned in the center rear or far side relative to the impact in a side impact crash, the authors found that structure intrusion can be accurately simulated using representative static structures placed at the position of maximum intrusion. The authors studied the timing of vehicle structure intrusion as seen in FMVSS 214 compliance side impact tests and/or Side New Car Assessment Program (SNCAP) tests for multiple vehicles. The authors then analyzed the timing of head excursion of child dummies restrained in CSSs during side impact sled tests. The analysis revealed that the dynamic motion of the vehicle structure intrusion in comparable FMVSS 214 and SNCAP side impact tests is over before a child restrained in a CSS and seated in the center rear or far side position moves sufficiently to impact the intrusion.

For a child in the center rear or far side occupant positions, limiting head excursion can potentially eliminate head impact with the vehicle interior. Therefore, limitation of lateral head excursion should be a primary objective of child safety seats and the primary parameter for assessing the performance of CSS in side impact crashes. Consequently, minimization of CSS rotation and translation and containment of the head within the CSS should be the primary objectives.

In side impact crashes with the child safety seat positioned on the near side or adjacent to the impact, the child safety seat is often struck by intruding structure. Therefore, while testing with static vehicle structure can provide some insight as to the performance of CSS positioned on the near side, to assess its performance under conditions including significant intrusion, the test requires the simulation of dynamic intrusion. Several such test methods have been developed. These tests use a horizontal accelerator facility that either impacts a vehicle seat, with child safety seats installed, into a simulated door or impacts a door into a vehicle seat with child safety seats installed [115-118]. In 1992, the New South Wales (NWS) Road and Transit Authority (RTA) partnered with consumer advocate groups in Australia to create the Child Restraint Evaluation Program (CREP). As part of the CREP program, 90 degree and 45 degree side impact sled tests were conducted with a door structure in place. This testing assessed the CSS's ability to retain the child's head within the CSS [119]. As a result of the success of the CREP program, the side impact testing methodology was adopted into the Australian standard for child safety seats. Currently, Australia requires two different side impact simulated crash sled tests to be conducted as part of the compliance requirements for child safety seats. One test is conducted with a child safety seat installed in the center of a freestanding bench seat. The other is conducted with the child safety seat positioned on a bench seat immediately adjacent to a simulated door [120, 121]. The European Economic Commission (EEC) conducts 90 degree, 30 mph moving barrier side impact testing with an 18 month child dummy secured in forward-facing and rear-facing CSS located in the near side rear occupant position. The Australian experience, EEC testing, the testing by other researchers, as well as the results reported in this paper demonstrate the efficacy of using sled testing with simulated static vehicle structure to assess the performance of CSSs in side impact crashes. To date, the United States government has not required any type of side impact testing; it is time that it does.

CONCLUSIONS/RECOMMENDATIONS

1. As found by other researchers, simulated side impact crash testing can be conducted on a horizontal accelerator with intrusion statically represented to study CSS performance. Representation of intrusion statically in sled testing is sufficient for assessing the performance of CSS located on the far side and center occupant positions when the intrusion is as severe as a side NCAP crash test.

2. The Hybrid-III 3-year-old child dummy, while not developed for side impact testing, is a useful tool for evaluating the performance of child safety seats in side impact. Until more biofidelic child dummies are developed for side impact, it and similar child dummies, such as the CRABI family of child dummies and the Hybrid-III 6-year-old child dummy, should be used to evaluate the design and performance of child safety seats in side impacts.

3. Side impact compliance testing of child safety seats should be implemented with the test capabilities currently available. Improvements in the compliance testing can be made as more biofidelic child dummies, more accurate IARVs, and improved test methodologies are developed. The use of a fixed door positioned to simulate the more severe SNCAP level of intrusion should be used to assess the performance of CSSs positioned on the far side and center seat positions. A dynamic intrusion test should be adopted for child safety seats on the near side representing the more severe level of intrusion observed in SNCAP testing. Until a dynamic test is available, a static intrusion sled test should be adopted for the near side occupant as well, similar to that adopted by Australia, New Zealand and the EEC

4. For optimal protection in side impacts the CSS should:
   - Be designed to minimize yaw and roll rotation toward the impact. Prior research indicates that rigid anchorages are most effective in limiting CSS yaw and roll.
   - Incorporate large, close fitting side wings, nearly perpendicular to the CSS seat back.
   - Incorporate side wings lined on the inner surface with energy absorbing padding with a force deflection characteristic optimized to minimize head acceleration.
   - Incorporate a tether at the top of the seat back that cannot move relative to the top of the seat back. The CSS structure should not flex significantly due to tether loading.
   - Incorporate energy absorbing padding on the outer surface of the side wing to reduce the peak acceleration generated by impacting the vehicle structure and to protect other occupants in the rear seat area from impact with the CSS.
   - The use of pretensioners and inflatables should be considered for child safety seats to:
     - Remove slack from and tighten the CSS harness to reduce head excursion and improve crash ride down
     - Create a snug fit between the head and the side wing to maximize crash ride down and head retention within the wings.

5. Work should continue to develop more biofidelic child dummies for side impact testing.

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