Protection of children in forward-facing child restraint systems during oblique side impact sled tests: Intrusion and tether effects

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ABSTRACT

Objective: Testing was conducted to quantify the kinematics, potential for head impact, and influence on head injury metrics for a center-seated Q3s in a forward-facing child restraint system (FFCRS) in oblique impacts. The influences of a tether and intruded door on these measures were explored.

Methods: Nine lateral oblique sled tests were conducted on a convertible forward-facing child restraint seat (FFCRS). The FFCRSs were secured to a bench seat from a popular production small SUV at the center seating position utilizing the lower anchor and tether for children (LATCH). The vehicle seat was fixed on the sled carriage at 60° and 80° from full frontal (30° and 10° forward rotation from pure lateral) providing an oblique lateral acceleration to the Q3s and FFCRS. A structure simulating an intruded door was mounted to the near (left) side of vehicle seat. The sled input acceleration was the proposed FMVSS 213 lateral pulses scaled to a 35 km/h delta-V. Tests were conducted with and without the tether attached to the FFCRS.

Results: Results indicate the influence of the tether on kinematics and injury measures in oblique side impact crashes for a center- or far-side-seated child occupant. All tests without a tether resulted in head contact with the simulated door, and 2 tests at the less oblique angle (80°) with a tether also resulted in head contact. No head-to-door contact was observed in 2 tests utilizing a tether. High-speed video analysis showed that the head moved beyond the CRS head side wings and made contact with the simulated intruded door. Head injury criterion (HIC) 15 median values were 589 without the tether vs. 332 with the tether attached. Tests utilizing a tether had less lateral head excursion than tests without a tether (median 400 vs. 442 mm).

Conclusion: These tests demonstrate the important role of the tether in controlling head excursion for center- or far-side-seated child occupants in oblique side impact crashes and limiting the head injury potential with an intruded door. The tether may not influence the kinematics of a near-side-seated occupant as strongly where the vehicle door or side structure interacts with the CRS and influences its motion. The results indicate that there may be an opportunity to improve child head kinematics and head protection in oblique side impacts through different CRS attachment methods and/or alternative vehicle side structure protection or padding.

Introduction

Advances in child occupant protection have placed recent emphasis on mitigating fatalities and injuries to children in child restraint systems (CRS) in side impact or oblique crashes (Arbogast et al. 2010; NHTSA 2014b). Crashes of this direction are the second most common but the direction with the highest injury and fatality rate after rollovers (Maltese et al. 2007; NHTSA 2014b; Sherwood et al. 2003). Previous studies have specified that oblique side impact crashes are more common than pure lateral and that the combination of lateral and longitudinal components contributes to injury causation (Arbogast et al. 2005; Maltese et al. 2007; McCray et al. 2007; Sherwood et al. 2003).

Recent regulatory advances worldwide have begun to focus on developing test procedures to evaluate child restraint safety in side impacts; however, most of this work to date has concentrated on near-side child occupants (Brown et al. 1997; NHTSA 2014b; Sullivan and Louden 2009; Sullivan et al. 2011). Data suggest that for children ages 1 to 3 fatally injured while restrained in CRS in side impact crashes, 17% were positioned in the rear center position, and 21% were positioned in a rear far-side position (Starnes and Eigen 2002). This risk to non-near-side occupants extends to serious injuries as well (Arbogast et al. 2010; Brown et al. 2002; Huntley 2002; McCray et al. 2007; Orzechowski et al. 2003; Sherwood et al. 2003; Sullivan and Louden 2009). The injury causation scenario of these injuries has been reported as head contact with the interior vehicle components such as the front seat back, their own or a neighboring CRS, intruding components, and other occupants (Arbogast et al. 2010; Brown et al. 2002; Huntley 2002; McCray et al. 2007; Orzechowski et al. 2003; Sherwood et al. 2003; Sullivan and Louden 2009).
2010; Brown et al. 2002; Charlton et al. 2007; McCray et al. 2007; Sherwood et al. 2003; Sullivan and Louden 2009). The study by Sherwood et al. (2003) suggested that intrusion was a factor in many of the injuries and deaths.

One response to increased attention to the elevated risk in side impacts to those restrained in CRS has been the introduction of large side structures or side wings designed to limit lateral head excursion and provide a padded structure between the child’s head and upper body with any lateral intrusion of vehicle components. In our previous work (Hauschild et al. 2015), we evaluated the effect of these side wing structures on controlling head excursion in oblique sled tests of forward-facing child restraint seats (FFCRS) positioned far side to the crash. In that study, the findings indicated that the side wings were ineffective because the anthropomorphic test device (ATD) head rolled out of the CRS late in the event, reaching magnitudes of lateral excursion that would put the child’s head at risk for impact into the intruding door.

More important, the previous tests highlighted the tether’s importance in controlling lateral head excursion. Two vehicle seats were used in the test series: one with an integrated head restraint that required the tether to be routed up and over the head restraint and one with an adjustable head restraint in which the tether could be routed underneath the head restraint. In the tests with the integrated head restraint, the tether slipped off the head restraint introducing slack in the tether, resulting in a significant increase in lateral head excursion of approximately 80 mm. In contrast, in the tests with the adjustable head restraint, where the tether remained taut throughout the test, the lateral head excursion was lower.

To date, the role of tethers in child occupant protection has primarily focused on protection in frontal crashes (Kapoor et al. 2011; Legault et al. 1997; Lumley 1997; Maltese et al. 2014; NHTSA 2014c). Only a few studies have examined the effect of tethers in side impact crashes (Brown et al. 1997; Hauschild et al. 2015; Klinich et al. 2005). Klinich et al. (2005) found that various tether anchor locations and the lower anchor and tether for children (LATCH) anchors reduced head excursions from about 25 to 100 mm compared to the no-tether condition. Brown et al. (1997) examined differences in CRS attachment methods that included attachment via rigid lower attachment plus a tether, vehicle belt and tether, and a flexible lower anchor with and without a tether. The study indicated that the ATD in FFCRS performed better in the tether restrained CRS and the untethered CRS allowed the ATD head to have significant impact with a simulated door. The role of the tether in side impact is particularly important for those positioned in the center or far side to the impact. In near-side impact crashes the child occupant may not realize the greatest benefit from the tether due to the interaction of the CRS and the intruding vehicle side structure.

In contrast, a far-side- or center-seated child occupant in a CRS may yaw and roll in the impact direction due to the lateral and longitudinal force components (Ghati et al. 2009; Henary et al. 2007). The CRS motion is controlled only by the belt webbing secured with the lower anchors and tether attachment to the vehicle seat. The tether may be particularly important to the center-seated occupant because excursion in a side impact or oblique crash has the potential to result in impact with an intruding side structure or deforming front seat back.

Based on these findings, the role of the tether in improving protection of CRS in side impact deserves further exploration. In this study, we quantified the influence of a tether on the kinematics and head injury metrics for a center-seated Q3s in an FFCRS in oblique side impacts. In order to better assess the potential for head impact, we simulated intrusion by including a door structure on the testing buck.

Methods

A series of 9 sled tests was conducted with an FFCRS on a production bench seat from a common recent model year (2013–2014) small sport utility vehicle. The seat was equipped with LATCH anchors and an adjustable head restraint in the center rear seat position. The vehicle seat frame and LATCH anchors were reinforced for use in multiple tests. The vehicle seat was attached to a fixture that could be rotated to any angle and simulated intrusion from the left side.

The simulated door was composed of 3 flat aluminum sections bolted to load cells, upper door, middle door, and lower door/armrest and 2 pieces of foam, one for the door panel and the other for the armrest. The door and armrest foams selected were similar to those used during other side impact testing (Hauschild et al. 2013; Sullivan et al. 2011). The door panel foam was Dow Ethafoam 220 (2.2 lb/ft³ density) and the armrest was Armacell Oletex (4.0 lb/ft³ density).

The simulated door was positioned to mimic static intrusion levels in side impact new car assessment program (SINCAP) tests. Specifically, crush data measured at the mid rear door level were extracted from SINCAP tests of 2012–2015 model year small-sized sport utility vehicles (range 163 to 296 mm, average = 220 mm, SD = 40 mm). Other research of Economic Commission for Europe (ECE) side impact tests found similar intrusion levels of 180 to 310 mm in all vehicles between 1990 and 2004 model years and recommended 250 mm for the ISO CRS side impact testing (Johannsen et al. 2007). A study by Tamborra et al. (2005) found peak crush averages for NHTSA NCAP and Insurance Institute for Highway Safety side impact tests to be 303 and 387 mm at mid-door and 281 and 290 mm at the window sill and noted increased crush toward the rear of the side structure. The simulated door panel in this research was placed at 508 mm and the simulated armrest was placed 445 mm left of the center line of the center seating position LATCH anchors (Figure 1) and was based on previous research, small sport utility vehicle interior dimensions, and fixture limitations. Door and armrest height was based on the same vehicle as the seat fixture, with the top of the door foam at 508 mm and the top of the armrest foam at 235 mm above the lower seat cushion measured at the seat bight. Craft paper was placed over the foam to identify contact locations. Foam was replaced when there was an impact.

The FFCRS was secured via LATCH flexible webbing lower anchors per the FMVSS 213 (NHTSA 2014a) procedures where applicable and the CRS manufacturer’s instructions. Tests were conducted with and without the top tether. A new FFCRS was secured on the bench seat for each test. When the tether was utilized it was routed over the seat back and under the vehicle head restraint. The vehicle head restraint was turned rearward to eliminate interference with the FFCRS (Bing et al. 2015; Sherwood, Abdelilah, and Crandall 2007). If the head restraint can
be secured in the reversed position, reversal of the head restraint is a recommended practice when it interferes with CRS installation (Safe Kids Worldwide 2008).

Restraint webbing loads were collected on the far-side LATCH belt and tether. The LATCH anchor webbing was pretensioned to a range of 279 to 304 N, measured on the far side, and the tether was pretensioned 64 to 73 N. The pretension value was chosen based on the tightness of the CRS on the vehicle seat per the manufacturer’s instructions for securing the CRS. The CRS was placed on the seat fixture and the webbing tightened so that there was less than 1 inch of side to side movement as instructed by the CRS manufacturer’s instructions as well as the National Child Passenger Safety Certification program. The force was then measured on the far-side LATCH webbing and tether webbing and used for the target values for the other tests.

The Q3s ATD was secured to the FFCRS using the available CRS 5-point webbing per the FMVSS 213 (NHTSA 2014a) procedures and the manufacturer’s instructions. The ATD was instrumented with head accelerometers, head angular rate transducers, upper neck 6-axis load cell, lateral chest displacement InfraRed - Telescoping Rod for Assessment of Chest Compression (IR-TRACC), shoulder displacement transducer, thoracic accelerometers, pelvis accelerometers, and a pubic symphysis load cell. Data were processed per SAE J211 (Society of Automotive Engineers 2014) recommended practice and head injury values (HIC15 and brain injury criterion [BrIC]) were calculated. Because no child critical values are established for BrIC, the adult ATD critical values were used for the calculations \( \omega_x = 66.3 \text{ rad/s}, \omega_y = 56.5 \text{ rad/s}, \text{and } \omega_z = 42.8 \text{ rad/s}; \) Takhounts et al. 2013).

The sled acceleration was the proposed FMVSS 213 (NHTSA 2014b) side impact pulse scaled up to a target 35 km/h delta-V with a 60 ms pulse width (Figure A1, see online supplement). The delta-V was chosen to correspond to side NCAP test data from which the crush information was obtained. Other testing has previously used this crash severity (Ghati et al. 2009; Hauschild et al. 2013).

Tests were conducted at oblique lateral angles of 80° and 60° from pure frontal (10° and 30° from pure lateral; 80°/10° and 60°/30°). A total of 9 tests were conducted, 5 at the 60°/30° angle and 4 at the 80°/10° angle; at least 2 tests were conducted in each configuration. A third test was conducted at the 60°/30° angle without a tether due to observation of differences between the first 2 tests. Posttest for test 204 the chest clip appeared to be positioned differently. The test angles were based on previous test series and available field studies (Arbogast et al. 2005; Hauschild et al. 2015; Maltese et al. 2007; McCray et al. 2007; Sherwood et al. 2003; Sullivan et al. 2011). A test matrix is shown in Table 1.

Head kinematic data were collected using a VICOM 3-dimensional motion camera system (TS40, VICOM, Denver, CO) at 1,000 frames per second. Retroreflective markers were placed on the ATD, FFCRS, and vehicle seat fixture in a noncollinear pattern. A 3-dimensional coordinate measuring machine (FARO Technologies, Lake Mary, FL) was used to measure the markers, ATD, FFCRS, and vehicle seat fixture. The coordinate measuring machine data and VICOM data were combined to create a local coordinate system for each item of interest and calculate the ATD head center of gravity (CG) displacements relative to the vehicle seat fixture. Head CG locations were offset to their starting positions for each test.

Median values and interquartile ranges (IQR) were calculated for all collected data. A Wilcoxon rank-sum test was performed to assess the differences in kinematics, reaction loads, and injury metrics with tether use. The analysis was done on STATA/IC 13.1 for Mac revision 19 Dec 2014 (StataCorp, College Station, TX).

### Results

#### Overall ATD and CRS kinematics

Sled change in velocity ranged from 34.6 to 34.9 km/h and an average acceleration range of 17.4 to 17.8 g. Peak acceleration ranged from 23.0 to 23.8 g. Target pulse width was 60 ms (Table 1; Figure A1, online supplement).
The CRS and ATD kinematics are displayed in images from the high-speed video, which are included in Figures A4 and A5 (see online supplement).

During the first approximately 40 ms the FFCRS translated sideways along the vehicle seat. Next it began to yaw and roll over toward the intruded door. For the 80°/10° tests, the CRS armrest made contact with the intruded door armrest at 56 ms and if tested without a tether, the CRS torso side wing contacted the intruded door armrest. For the 60°/30° tests, similar kinematics occurred but slightly later. Qualitative analysis of the CRS motion indicated less tipping or rolling sideways with tether use.

In all tests, after moving laterally, the ATD shoulder moves up and out of the CRS shell while the head rolls out and away from the CRS head side wings in all tests. The head reaches maximum lateral displacement coincided with head contact to the simulated door in the 80°/10° tests regardless of tether use. Maximum forward displacement in the 80°/10° tests occurred late during the rebound event. Head maximum vertical downward displacement occurred after maximum lateral displacements in all tests. In some tests, the head was trapped between the CRS shell and head side wing postimpact rebound. There was no head contact with the simulated door armrest.

**Head**

The tether influenced both head excursion and HIC15 (Tables 2 and 3). The lateral (Y) head CG displacement and HIC were significantly higher in tests without the tether (P = .05 and P = .05, respectively). In contrast, longitudinal (X) and vertical (Z) head CG displacement demonstrated no difference with tether use (P = .62 and P = .33). The BrIC (Table 3, Table A1, see online supplement) values did not differ with tether use (P = .46).

During all nontether tests, the ATD head made contact directly with the simulated door or with a portion of the CRS and door. Two of 4 tests with a tether demonstrated head contact with the simulated door during the 80°/10° tests, but HIC values were low (319 and 312).

**Upper neck**

Peak neck tension forces ranged from 1.9 to 3.0 kN and did not vary with tether use (P = .81) (Table 3, Table A2, see online supplement). The upper neck lateral bending moments (X) varied with tether use (P = .01), whereas the upper neck flexion moments (Y) did not differ (P = .27). There was a low correlation between neck tension and lateral excursion values (r² = 0.4) but there was a stronger correlation of the longitudinal head excursions and neck tension values (r² = 0.7).

**Thorax and abdomen**

Lateral shoulder deflections, lateral chest deflections, pelvis resultant acceleration, and pubic symphysis force are reported in Table A3 (see online supplement). The lateral shoulder deflection, lateral thoracic deflection, and pelvis resultant accelerations varied with tether use (P = .02, .04, and .03; Table 3). Other thoracic kinematic measures including thoracic resultant acceleration, T1 lateral acceleration, and pubic symphysis loads did not demonstrate significant differences with tether use (Table 3).

**Belt webbing loads**

The median force of the lower LATCH belt webbing was 3.6 kN (IQR = 0.2) with the tether and 4.1 kN (IQR = 0.1) without the tether (P = .01; Table A4, see online supplement). The median tether belt force was 1.1 kN when utilized.

**Discussion**

The tests described herein extend a line of previous work examining the kinematics and injury potential for children restrained center or far side in FFCRS in oblique crashes. These test results evaluated the role of the tether in controlling kinematics and specifically head excursion and neck kinetics and indicated its importance during a side impact crash.

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**Table 2.** HIC15, head resultant accelerations, and X, Y, Z excursions organized by tether configuration.

| Test Angle | Tether Use | HIC15 | T1 | T2 | Head Resultant Time | Y Lateral Excursion Time | X Longitud. Excursion Time | Z Vertical Excursion Time | Head Impact |
|------------|------------|-------|----|----|---------------------|-------------------------|--------------------------|--------------------------|-------------|
| 60/30      | Yes        | 345   | 67 | 82 | 60.8                | 75                      | −376                     |                          | N           |
| 60/30      | Yes        | 402   | 66 | 81 | 66.2                | 75                      | −382                     |                          | N           |
| 60/30      | Yes        | 319   | 67 | 82 | 58.6                | 70                      | −418                     |                          | N           |
| 60/30      | Yes        | 312   | 72 | 87 | 61.3                | 82                      | −431                     |                          | Y           |
| 60/30      | No         | 589   | 79 | 93 | 82.4                | 88                      | −442                     |                          | Y           |
| 60/30      | No         | 322   | 76 | 91 | 57.8                | 89                      | −426                     |                          | Y           |
| 60/30      | No         | 562   | 78 | 93 | 81.4                | 87                      | −430                     |                          | Y           |
| 60/30      | No         | 1015  | 71 | 86 | 115.8               | 81                      | −445                     |                          | Y           |
| 60/30      | No         | 1022  | 71 | 86 | 113.5               | 81                      | −448                     |                          | Y           |

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**Table 3.** Injury and kinematic metrics and significance organized by tether use.

| Metric                     | With Tether | Without Tether | p-value |
|----------------------------|-------------|----------------|---------|
| HIC15                      | Median      | IQR            | Median  | IQR  |         |
| Head Resultant Acceleration| 5           | 3.8            | 5.8     | 4.5  | 43      | 0.05    |
| Lateral Head Excursion     | 61.1        | 4.1            | 82.4    | 32.1 | 14      | 0.14    |
| Longitudinal Head Excursion| −400       | 46             | −442    | 15   | 0.05    |
| Vertical Head Excursion    | 137         | 55             | 180     | 85   | 0.62    |
| BrIC                       | 1.32        | 0.15           | 1.37    | 0.07 | 0.46    |
| Upper Neck Tension         | 2.4         | 769            | 2.6     | 513  | 0.81    |
| Upper Neck Moment X        | 30.4        | 13.1           | 18.6    | 4.7  | 0.01    |
| Upper Neck Moment Y        | −19.1       | 3.7            | −16.7   | 1    | 0.27    |
| T1 Lateral Acceleration    | 52.8        | 4.5            | 49.5    | 23.7 | 0.81    |
| Thoracic Resultant Acceleration| 54.9      | 5.4            | 50.3    | 17.8 | 0.62    |
| Chest Lateral Deflection   | 3           | 3              | 7       | 3    | 0.04    |
| Shoulder Lateral Deflection| 9           | 1.5            | 11      | 1    | 0.02    |
| Pelvis Resultant Acceleration| 48.4      | 4.3            | 54.2    | 1    | 0.03    |
| Pubic Symphysis Force      | 149         | 121            | 62      | 155  | 0.46    |
In our previous study (Hauschild et al. 2015), the ATD head moved forward and laterally and extended beyond the FFCRS side wings in oblique lateral impacts. The observation in that study of the head motion indicated potential injurious head impacts due to the excursion distance (lateral displacement range = 372 to 485 mm) and impact potential with an intruding vehicle side structure. In the current study, similar head motion was observed where the ATD head moved out of the CRS head side wings. During 7 of the 9 tests the ATD head impacted either the simulated door or the CRS. The head contacted the simulated door approximately halfway between the top of the door and the top of the simulated armrest. A modeling study by Hu et al. (2014) found that small occupants in side impacts may impact the vehicle door or side structure and that the area below the window sill could have counter measures designed in that location to protect small occupants better. Although that study examined near-side occupants, the center-seated ATD in this study had head contact near the same area of the door. NHTSA (2014b) also commented that children may benefit if the vehicle provided protection below the beltline.

The lateral excursions and injury metrics enforce the tether importance in side impact crashes to limit potential injurious head contact. In all tests without the tether and in all tests at 80°/10°, the ATD head made contact with the simulated door. The 2 tests with a tether where contact occurred were lower force impacts resulting in HIC15 values of 319 and 312. Maximum excursions of test configurations are displayed in Figures 2 and 3 from the high-speed video frames. Lateral excursions in this testing with the tether had a median value of 400 and 442 mm without the tether. Klinich et al. (2005) also found higher excursions in side impact tests when the tether was not utilized.

During tests without a tether, the HIC15 values exceeded recommended values when there was contact with the simulated door. In all tests where the tether was utilized the HIC15 values were below the recommended 570 value and there was less variance across the tests. Brown et al. (1997) found in near-side child occupant testing with and without a tether, including a simulated door, that the head injury values were also influenced by tether use. In the current study, 4 of the 5 tests without the tether exceeded the EuroNCAP child head resultant acceleration maximum recommended value (<80 g with contact and <72 g without contact) (Euro NCAP 2014). The head resultant acceleration values ranged from 58 to 116 without the tether and ranged 56 to 66 with the tether.

Though there are no currently accepted child ATD BrIC values, measures were calculated herein for exploration. The numbers presented here should only be used as a comparison between these sets of tests and may not correspond to other studies until more research has been conducted. Median BrIC values for the Q3s ATD were 1.32 with the tether and 1.37 without the tether and could not distinguish between scenarios of contact and no contact. The most dominant angular velocities (X and Y) occur prior to head impacts and maximum excursion (Table A1). Further research is needed to understand the injury implications of these elevated rotational head motions that precede contact.
In addition to elevated head injury metrics, neck injury metrics were above existing thresholds. No difference in neck tension values was noted with tether use, and all tests exceeded the EuroNCAP limit for 4 stars (1.7 kN for frontal) (EuroNCAP 2014). Neck tension was slightly correlated ($r^2 = 0.7$) with longitudinal head excursion, indicating that a focus on head protection can also have benefits to the neck.

These results appear to indicate that neck tension could be better controlled by limiting the excursions past the confines of the CRS. Testing done by Ghati et al. (2009) on a center-seated Hybrid III 3-year-old ATD in 36 km/h lateral side impacts showed that the head came out of the CRS, leading to large neck tension forces. Oblique angle full-scale crash testing at 56 km/h has also shown high neck tension forces in a Hybrid III 3-year-old ATD; neck tension was nearly 90% of the injury assessment reference values (Mertz et al. 2003) for both near-side and far-side placed occupants (Hauschild et al. 2016). In those crash tests the head also moved beyond the CRS shell. During oblique lateral crashes, the forward component of the crash encourages the ATD head to move beyond the CRS and place the neck into tension. No universally accepted neck injury criteria exist for side impact child dummies. These high tension values may indicate a need to evaluate current injury assessment reference values for side impact child dummies. As with other dummy neck injury criteria, it may be appropriate to develop neck injury predictors that would incorporate the neck tension and moments. One computational model study by Sherwood, Marshall, and Crandall (2007) suggests that neck tension injury costs for a 12-month-old in a rear-facing CRS are the largest component of the model cost function and changes to neck tension would be the most beneficial. In addition, the attachment of the CRS appears to influence neck metrics. One computational study of near-side impacts found a reduction in neck injury parameters through the use of a rigid ISOFIX compared to flexible LATCH with an approximate 50% reduction of resultant upper neck forces (Kapoor et al. 2011). Future work should explore the effect of rigid anchors on head kinematics and neck tension in the type of oblique testing conducted in this study.

Limited field studies exist to which to compare these results. One study by McCray et al. (2007) examined Crash Injury Research and Engineering Network (CIREN) data from 14 case studies of children in FFCRS involved in side impact crashes and found that the head was the most injured region followed by the neck. In reviewing the details of those cases, one center-seated child occupant in an FFCRS had head injuries and lower extremity injuries due to impact with a deformed front seat back, and another was reported to have had contact with the intruded door. Far-side child occupants were reported to have head, spine, and upper extremity injuries. One far-side case study included a lateral extension injury of the cervical spine caused in part by greater lateral movement of the CRS due to improper routing of the vehicle belt through the CRS.

The results of this testing demonstrate the important influence of the CRS tether for forward-facing children in far-side or center seating positions involved in oblique side impacts. In all tests without a tether the lateral head excursions and head injury values were higher as evidenced by contact with the intruded door. When the tether was used, the head injury values were reduced and impact was less common or less forceful.

The head kinematics in these oblique impacts resulted in the head moving out of the CRS confines. Neck tension values were high for all tests. Keeping the occupant head within the confines of the CRS may help reduce both neck and head injury values. This may be achieved through consideration of alternative CRS attachment methods that better control the CRS kinematics. Improved protection may also be needed on the vehicle interior such as additional padding or supplemental restraints such as side curtain airbags that extend further down to the areas of impact noted in this study.

Further research needs to be done to examine the potential neck and brain injury of child occupants in side impact events regardless of seating position and explore aspects of CRS design including methods of attachment that control kinematics and mitigate injury.

**Limitations**

The study is limited to the parameters examined in this series and should be taken into consideration when comparing to other data sets. Different inputs, such as sled pulse or intrusion level, and factors such as the specific CRS and vehicle seat fixture may produce differing results. The CRS used is a popular style and only represents the model tested. Other models and types of seats may have unique characteristics that could produce different results. The CRSs were only tested on one production model vehicle seat fixture. Previous testing has shown that items such as the vehicle head restraint may influence the CRS motion. The seat chosen had a center LATCH and it was from a popular small SUV.

Lastly, the CRSs were attached using the flexible LATCH webbing system. Other attachment methods such as vehicle belts, rigid LATCH, and ISOFIX may produce different results as has been demonstrated by other research (Charlton et al. 2004; Ghati et al. 2009; Kapoor et al. 2011; Klinich et al. 2005).

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