Field Investigation of Child Restraints in Side Impact Crashes

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ABSTRACT

Objective: Various test procedures have been suggested for assessing the protection afforded by child restraints (CRS) in lateral collisions. Analyses of real world crashes can be used to identify relevant characteristics of the child, restraint, collision, and injury mechanisms that should be incorporated into the design of the test procedures as well as in the design of related ATD's and injury metrics. The objective of this work is to use in-depth crash investigations of children restrained in CRS in side impacts to elucidate specific sources and mechanisms of injuries and explore the role of crash severity variables such as magnitude and location of intrusion and specific impact angle.

Methods: Real world crashes involving children restrained in forward facing CRS in side impacts were analyzed from Partners for Child Passenger Safety, an on-going child specific crash surveillance system in which insurance claims are used to identify cases. In-depth crash investigations using standardized protocols were used to calculate the crash severity and determine the mechanisms and sources of the injuries sustained.

Results: Cases of 32 children restrained in CRS in 30 side impact crashes were examined. Twenty-five percent sustained AIS 2+ injuries. The most common injuries sustained by children restrained in CRS in side impact crashes were to the face, head, and lower extremity. Characteristics of the crashes that appeared related to injury were intrusion that entered the child's occupant space or caused an interior part of the vehicle to enter the child's occupant space, forward component of the crash, and the rotation of the CRS, restrained by a seat belt, towards the side of the impact.

Conclusions: The ability to assess the injury potential in a laboratory setting for the body regions of common injury, the head, face, and lower extremity, must be explored. Characteristics of a regulatory-based test procedure to assess injury risk should include a frontal component to the crash and intrusion into the occupant's seating position. Design enhancements of the CRS should address rotation during lateral impacts. These results provide guidance to current efforts to design and regulate these restraints for the safety of child passengers in side impacts

KEY WORDS: child restraints, side impact, intrusion

INTRODUCTION

Substantial emphasis has been placed in Europe and the US on understanding the need for and defining characteristics of an effective regulatory test procedure for child restraints (CRS) in side impact crashes. In Europe, research and development led by the International Standards Organization (ISO) Working Group 1 and supported by efforts of the Transport Research Lab (TRL) in the United Kingdom and the Technical University of Berlin (TUB) resulted in a proposed CRS test procedure characterized by a lateral sled test with a simulated intruding door (Johannsen et al. 2003; National Highway Traffic Safety Administration 2003). The EuroNCAP (European New Car Assessment Program) conducts tests in which a vehicle is impacted by a moving deformable barrier at 90°. An 18-month-old or 3-year-old anthropomorphic test device (ATD) seated in a CRS in the rear seat is evaluated and rated for head containment and head acceleration [EuroNCAP, 2004]. Australian efforts in New South Wales have focused on a sled test evaluation protocol in which the ATD is evaluated in a tethered CRS in a 20 mph 90° test configuration. Head excursion relative to a fixed door structure determines a particular CRS's ranking [National Highway Traffic Safety Administration, 2003a; Paine, Griffiths et al., 2003].

In the US, the Transportation Recall and Accountability Act (TREAD) issued in 2000 called on the National Highway Traffic Safety Administration (NHTSA) to "simulate an array of accident conditions, such as side impact crashes…" as part of a more comprehensive program for evaluating the protection of children in CRS (Fitzgerald 2001). In response to TREAD, NHTSA issued an Advanced Notice of Proposed Rulemaking (ANPRM) in June 2002, stating that substantial questions regarding the protection of children in CRS in side impact crashes remain and that a regulation at this time would be premature. NHTSA's questions included: what are the injury mechanisms in side impact crashes; what crash characteristics lead to serious injury; what should be the characteristics of a regulatory procedure; and what anthropometric test device (ATD) (and associated injury criteria) should be used in this procedure? (National Highway Traffic Safety Administration 2003) In June 2003, NHTSA chose not to propose a rule addressing protection of children in side impact crashes, stating that existing analyses failed to provide enough data to answer these questions (National Highway Traffic Safety Administration 2003).

Analyses of real world crashes can be used to identify relevant characteristics of the child, restraint, collision, and injury mechanisms that should be incorporated into the design of the test procedures as well as in the design of related ATD's and injury metrics. Our previous work identified an elevated injury risk for children in forward facing CRS in struck-side crashes (8.9 injured children per 1000 crashes) than for children seated on the non-struck side of the crash (2.1 injured children per 1000 crashes) and identified the most common injuries sustained in struck side impact crashes as those to the face, head, and lower extremity (Arbogast et al. 2004). This finding was supported by work by Starnes and Eigen that found for children zero to 8 years of age, 61% of side impact fatalities involved struck-side children while only 20% involved far-seated children (Starnes and Eigan, 2002).

These analyses, based on data from large surveillance systems are critical for identifying the risk of injury; however they cannot be used to determine injury sources and mechanisms as the depth of medical and crash details is limited. Sherwood et al (Sherwood et al. 2003) reviewed detailed reports from the US Fatal Analysis Reporting System (FARS) of 92 children in child restraints who sustained fatal injuries. Forty percent of these cases were side impacts and almost half of those were deemed unsurvivable. Of the 14 determined to be non-catastrophic side impacts, factors related to the fatal injury were head contact with external object, intrusion, a forward component of the crash, child restraint misuse, and loading by adjacent adult occupants. These data, because they were based on FARS, were limited in their medical details and information about injury mechanisms and sources.

The analyses contained herein build upon these previous studies and use in-depth crash investigations of children restrained in CRS in side impacts to elucidate specific sources and mechanisms of injuries and explore the role of crash severity variables such as magnitude and location of intrusion and specific impact angle.

METHODS

Data collected from December 1, 1998 to November 30, 2002 as part of Partners for Child Passenger Safety (PCPS) form the basis of this study. Detailed descriptions of the study population and methods involved in data collection and analysis have been previously published (Durbin et al. 2001). PCPS consists of a large scale, population based, child-specific crash surveillance system. Insurance claims from State Farm Insurance Co. (Bloomington, IL) function as the source of subjects, with telephone survey and on-site crash investigations serving as the primary sources of data. The telephone interviews provide data for a surveillance system used to describe characteristics of the population including risk factors for injury while the crash investigations provide detailed mechanisms of injury.

Crashes qualifying for inclusion in the surveillance system were those involving at least one child occupant < 15 years of age riding in a model year 1990 or newer State Farm-insured vehicle. Qualifying crashes were limited to those that occurred in fifteen states and the District of Columbia, representing three large regions of the United States (East: NY, NJ, PA, DE, MD, VA, WV, NC, DC; Midwest: OH, MI, IN, IL; West: CA, NV, AZ). On a daily basis, data from qualifying and consenting claims were transferred electronically from all involved State Farm field offices to researchers at The Children's Hospital of Philadelphia and University of Pennsylvania. Data in this initial transfer included contact information for the insured, the ages and genders of all child occupants, and a coded variable describing the medical treatment received by all child occupants.

In order to gain more detailed information about the kinematics of the child and the mechanisms of the injury, a series of cases were chosen for in-depth crash investigation, based on manual review of claims files to identify children in CRS with moderate to severe injuries in side impact collisions. Cases were screened via telephone with the policyholder to confirm the restraint status and medical details of the case. Contact information from selected cases was then forwarded to a crash investigation firm and a in-depth on-site crash investigation was conducted using custom child-specific data collection forms.

Crash investigation teams were dispatched to the crash scenes within 24 hours of notification to measure and document the crash environment, damage to the vehicles involved, and occupant contact points according to a standardized protocol. The on-scene investigations were supplemented by information from witnesses, crash victims, physicians, hospital medical records, police reports, and emergency medical service personnel. From this information, reports were generated that included estimates of the vehicle dynamics and occupant kinematics during the crash and detailed descriptions of the injuries sustained in the crash by body region, type of injury, and severity of injury. Delta v, (the instantaneous change in velocity) an accepted measure of crash severity, was calculated using WinSmash and the crush measurements of the vehicles involved. The Institutional Review Boards of both The Children's Hospital of Philadelphia and The University of Pennsylvania School of Medicine approved the conduct of this project.

A retrospective review of 650 crash investigations completed to date identified thirty two children (in 30 crashes) that met the selection criteria for this specific study – an occupant, 12 to 47 months of age riding in a forward facing CRS in a crash with a principal direction of force (PDOF) of 30-150° or 210-330°. For side impact collisions, the estimation of crash severity by a calculation of delta V has many limitations (Foret-Bruno 1980; Strother 1990; Frampton et al. 1998), and therefore crush was chosen as a suitable proxy. In order to compare crush over a variety of vehicle sizes, the width of the vehicle was defined into 8 zones. The first 7 were equi-distant across the impact half of the occupant compartment and the eighth zone represented the other half of the vehicle as shown in Figure 1. The maximum intrusion was coded according to the highest zone to which the measured value corresponds. For this study, no or minor intrusion was defined as zones 0-2, moderate intrusion as zones 3-4, and severe intrusion as zones 5-8 (Arbogast et al. 2001). Misuse was defined according the National Safe Kids Campaign (National Safe Kids, 2005). Descriptive statistics were calculated for all cases, while illustrative cases were selected to highlight interesting injury mechanisms and crash characteristics that lead to injury.

RESULTS

Cases of 32 children restrained in CRS in 30 side impact crashes were examined using in-depth investigation to identify the injury mechanisms and crash characteristics that lead to injuries. Twenty-five percent (n=8) of children in these cases sustained AIS2+ injuries: 5 with AIS 2 injuries, 1 with AIS 3, and 2 with AIS 6. The body region distribution of the AIS2+ injuries is shown in Figure 2.

The distributions of child age, seat position, vehicle type, crash partner, and crush zone for the overall study sample and those with AIS2+ injuries are shown in Figures 3-7. Children of all ages sustained injuries (Figure 3). Of note, of the seven children in the rear outboard position involved in non-struck side crashes not one sustained AIS2+ injuries (Figure 4). The number of injured children seated in the center rear, a seat position traditionally thought to be the safest, was surprising. Four of five injured children in the center rear were in crashes with higher weight crash partners: 2 with large vans and 2 with large passenger cars. There were no substantial differences between the overall and injured study sample with respect to case vehicle type (Figure 5) and crash partner (Figure 6). Figure 7 demonstrates that injuries occurred to children in crashes experiencing all levels of maximum crush.

Details of each case of an AIS2+ injured child are discussed in detail below.

Case 1

The case vehicle (1996 Dodge Intrepid) was traveling west approaching an intersection. Vehicle 2 (1998 GMC Safari van) was traveling south and did not yield to the oncoming traffic. The frontal plane of vehicle 2 impacted the case vehicle on its right side. A 2-year-old male was seated in the center rear seat and was restrained by a CRS with a 5-point harness. The harness straps were threaded through the middle slots of the CRS seatback, a misuse for this CRS.

PDOF: 60º

Delta v: total – 34 kph, longitudinal – 17 kph, lateral – 29 kph

Max crush: 50 cm

Intrusion at child's location: 36 cm

Child's ISS: 22

AIS 2+ injuries:

- Brain hemorrhage - right frontal lobe (AIS = 3)
- Comminuted left distal tibia fracture and left distal fibula fracture (AIS = 2)
- Fracture of superior medial wall of the right orbit (AIS = 2)

AIS 1 injuries:

- Right superior facial lacerations above eyelid (AIS =1)

Proposed Injury Mechanism:

- The longitudinal component of the force caused the right front seat to be pushed into the case occupant's seating space.
- The CRS which was thought to be attached loosely rotated towards the right during the crash.

- The misuse of the harness straps, which effectively increased the length of the harness restraining the child, allowed for increased head excursion, which caused the child's head/face to impact the intruding right rear door structure as evidenced by contact points (deformation and damage) to the interior door surface along the belt line. There was no evidence that the child was ejected from the harness.
- The left lower extremity fracture (contralateral to the side of impact) was likely due to the leg whipping around and contacting the intruding right front seat.

MAIS other occupants:

Driver – AIS 1 contusions and abrasions to forehead, nose and hip

Case 2

The case vehicle (1997 Chrysler Town and Country) was traveling east and entered the intersection. The front end of vehicle 2 (1993 Ford Explorer) was traveling north and impacted the right side of case vehicle. The case vehicle then crossed over the curb and the rear bumper impacted a tree. A 3-year-old male was seated in the second row right side and was restrained by a CRS with a T-shield harness.

PDOF: 71º

Delta v: total – 37kph, longitudinal – 12 kph, lateral – 35 kph

Max crush: 109 cm

Intrusion at child's location: 117 cm

Child's ISS: 75

AIS 2+ injuries:

- Fatal atlanto-occipital distraction (AIS=6); was dead on scene

AIS 1 injuries:

- Other injuries unknown. (The information on the fatal injury was obtained from a death certificate not a full medical record).

Proposed Injury Mechanism:

- The substantial side interior intrusion loaded the seat back of the vehicle seat the child was seated on and thus the seat back of the CRS resulting in a rotation of the child seat towards the side of impact.

- This loading allowed the torso to be pushed away from the head due to the intruding structure causing large tension loads to build in the neck. This was likely accompanied by neck flexion either in the sagittal or coronal plane and potential head contact with the right side interior surface of the vehicle along the belt line.

MAIS other occupants:

Driver – AIS 6 – fatal chest trauma

Right front adult – AIS 6 - fatal chest, brain, and neck injuries

Second row left 9-year-old child - AIS 1 contusions to right shoulder and right jaw

Third row, position unknown 6-year-old child – AIS 1 abrasions to right hip and knee

Case 3

The case vehicle (1991 Ford Tempo) was traveling west and was attempting to turn left at an intersection. Vehicle 2 (1982 Lincoln Town Car) was traveling eastbound approaching the intersection in an attempt to continue straight through the intersection. The frontal plane of vehicle 2 hit the right side plane of the case vehicle. It was sleeting and the roadway was icy at the time of crash. A 16-month-old male was seated in the center rear restrained in a CRS with a 5-point harness.

PDOF: 85º

Delta v: total – 27 kph, longitudinal – 2 kph, lateral – 27 kph

Max crush: 34 cm

Intrusion at child's location: 12 cm

Child's ISS: 5

AIS 2+ injuries:

- Concussion (AIS=2); diagnosed by continued vomiting. There was no evidence of head contact with vehicle interior structures.

AIS 1 injuries:

- Minor contusions to the right face, head, and shoulder likely due to contact with the side of the CRS

Proposed Injury Mechanism:

- The engagement of the sill indicated a more serious crash than the maximum crush value implied.
- The concussion was likely attributed to head acceleration exacerbated by increased head excursion caused by loose harness straps that were not correctly routed for forward facing.

MAIS other occupants:

Driver – none

Case 4

The case vehicle (1990 Chevrolet Lumina) proceeded into the intersection with the intention of continuing straight, in a northeasterly direction. Vehicle 2 (1997 Ford Probe) was proceeding in a southeasterly direction and did not stop at the red light. As the two vehicles converged, the frontal plane of vehicle 2 impacted the left side plane of case vehicle. A 3-year-old male was seated in the left rear seat position and restrained by a CRS with a 5-point harness. This CRS was a combination seat that can be converted to a booster seat as the child becomes older. These seats are characterized by slimmer side profiles than traditional convertible seats.

PDOF: 290º

Delta v: total – 14 kph, longitudinal – 5 kph, lateral – 13 kph

Max crush: 22 cm

Intrusion at child's location: 6 cm

Child's ISS: 5

AIS 2+ injuries:

- Concussion (AIS=2)

AIS 1 injuries:

- Minor contusions to the bridge of the nose, left forearm, left hip, and left thigh

Proposed Injury Mechanism:

- The facial contusions were likely due to contact with the left interior door surface. The concussion was likely attributed to either head to head contact with the center rear occupant upon rebound or initial impact with the left interior door surface along the belt line.

MAIS other occupants:

Driver – none

Center rear 6-year-old child – AIS 1 contusions

Right rear 12-year-old child – AIS 1contusions to right shoulder

Case 5

The case vehicle (1993 Dodge Intrepid) was traveling southbound and departed the right side of the roadway. The driver initiated a counterclockwise rotation in an attempt to reenter the roadway and completely crossed over into the northbound travel lane. The right side of the case vehicle was struck by the frontal plane of vehicle 2 (1994 Pontiac Bonneville). A 3-year-old female was seated in the center rear and restrained by a CRS with a 5-point harness.

PDOF: 60º

Delta v: total – 60 kph, longitudinal – 30 kph, lateral – 52 kph

Max crush: 102 cm

Intrusion at child's location: 47 cm

Child's ISS: 5

AIS 2+ injuries:

- Spiral fracture of the left tibia at the mid shaft (AIS=2)

AIS 1 injuries:

- Minor abrasions to the lower lip and right and left thigh

Proposed Injury Mechanism:

- The longitudinal component of the force caused the right front seat to be pushed into the case occupant's seating space.
- The left lower extremity fracture (contralateral to the side of impact) was likely due to contact with the intruding right front seat (compare to case 1). The leg was possibly pinned between the right front seat back and rear seat bottom.
- In contrast to case 1, another child in the right rear seating positing (restrained in a CRS) prevented the rotation of the case occupant's CRS towards the side of impact perhaps preventing the head/facial injuries seen in case 1.

MAIS other occupants:

Driver – AIS 1 facial laceration and shoulder contusions

Right rear 20-month-old child – AIS 1 lip laceration, right cheek laceration

Case 6

The case vehicle (1996 Dodge Neon) was traveling west and was approaching the intersection. Vehicle 2 (1986 Mazda RX7) was traveling south on a curvy road, lost control, and entered the intersection. The rear quarter panel of vehicle 2 impacted the right side of the case vehicle. A 14-month-old female was seated in the center rear and restrained in a CRS with a 5-point harness.

PDOF: 30º

Delta v: total – 29 kph, longitudinal – 25 kph, lateral – 15 kph

Max crush: 37 cm

Intrusion at child's location: 28 cm

Child's ISS: 75

AIS 2+ injuries:

- Complete fatal occipital distraction and transection of the spinal cord at C1-C2 (AIS =6)
- Multiple subarachnoid hemorrhages with diffuse cerebral edema and left subdural hemorrhage (AIS=3)
- Right mandibular fracture (AIS=2)
- Right lower incisors fractured and dislodged (AIS=2)

AIS 1 injuries:

- Tongue avulsion at the C2 level
- Contusions to the lower extremity, upper extremity, mouth, forehead and right cheek

Proposed Injury Mechanism:

- The longitudinal component of the force caused the right front seat to be pushed into the case occupant's seating space.
- The CRS recently installed by a child seat fitting station likely had less rotation towards the side of impact as compared to case 1.

- Admitted looseness of the harness straps allowed them to slip off the child's shoulders and contributed to increased head excursion. This was evidenced by bruising on the upper arms. This possibly caused the child's head/face to impact the intruding right front seat back possibly causing the mandibular fracture. There was no physical evidence however of head contact on the seat back.
- When the harness straps engaged (causing bruising on the child's upper arms and upper thighs), the neck experienced large tension loads and the head rapidly decelerated likely causing the fatal head and neck injuries.

MAIS other occupants:

Driver – AIS 1 minor back pain

Case 7

The case vehicle (1997 Ford Taurus) was travelling north approaching an intersection. Vehicle 2 (1987 Chevrolet Chevette) was travelling west and stopped at the intersection. Vehicle 3 (1985 GMC Vanderra Van) was travelling south approaching the intersection. As the case vehicle passed through the intersection, vehicle 2 entered the intersection and struck the right side of the case vehicle. The case vehicle was redirected to the left and crossed the center line into the on-coming travel lane and struck the frontal plane of the vehicle 3 in an offset head on impact configuration. A 19-month-old male was seated in the center rear restrained by a CRS with a 5-point harness.

PDOF: 85º

Delta v: total – 12 kph, longitudinal – 1 kph, lateral – 12 kph

Max crush: 24 cm

Intrusion at child's location: 0 cm

Child's ISS: 5

AIS 2+ injuries:

- Non-displaced fracture to shaft of right tibia below knee near growth plate (AIS=2)

AIS 1 injuries:

- Contusion to right temporal area of head, crotch area, right and left neck due to contact with the child safety seat and its interior components

- Laceration to the upper gums

Proposed Injury Mechanism:

- The secondary frontal impact caused the right front seat to be pushed into the case occupant's seating space.
- The leg fracture was likely caused from direct contact with the intruding right front seat back.

MAIS other occupants:

Driver – AIS 2 right pelvic fracture

Right front adult – AIS 2 hand fracture

Case 8

The case vehicle (1997 Ford Taurus) was proceeding in a southwestern direction approaching a sharp left curve. Vehicle 2 (1995 Dodge Dakota) was travelling in the opposite lane. Vehicle 2 did not negotiate the sharp turn and began to skid. The front left corner of vehicle 2 impacted the left side plane of the case vehicle. A 10 month old female was seated in the left rear seat position restrained in a CRS with a 5-point harness.

PDOF: 310º

Delta v: total – 23 kph, longitudinal – 15 kph, lateral – 17 kph

Max crush: 32 cm

Intrusion at child's location: 45 cm

Child's ISS: 4

AIS 2+ injuries:

- 10 cm laceration along the left hairline

AIS 1 injuries:

- Contusions to the left ear, left and right inner thigh
- Small puncture wound above and medial to the left eye
- 8 cm laceration behind her left ear

Proposed Injury Mechanism:

- Direct contact with the left door surface along the belt line

- Several misuses of the CRS likely led to increased excursion: no locking clip, loose harness, harness in wrong routing slot.

MAIS other occupants:

Driver – AIS 1 lacerations to upper arm

Right front adult – AIS 1 lacerations to upper arm

DISCUSSION

This review of in-depth cases of children restrained in CRS in side impact crashes revealed detailed information on the mechanisms of several serious injuries and characteristics of the crashes in which those injuries occurred. Although our previous work indicated that injuries to children in forward facing CRS in side impact crashes are rare (Arbogast et al. 2004), these cases provide guidance for enhancements to current regulatory procedures and provide direction for providing increased protection for children in this restraint system. Of note, all of the children were restrained in CRS that were attached by the vehicle seat belt rather than a LATCH or ISOFIX system, which has been suggested to reduce the risk of rotation (Lowne et al. 1997). None of the restraints were using a tether strap as well. As such, these observations may not be applicable to the newer form of attachment.

Specifically, the results suggest that further reductions in serious injuries to children in CRS in side impact crashes might be achieved by reducing head, face, and extremity injury risks. This injury pattern points to the importance of developing appropriate tolerance for head injury for children in side impact crashes and development of measurement capability for the lower extremity in pediatric side impact ATD's. All facial injuries sustained in this case series were a result of contact and will likely be mitigated by efforts to control head excursion and acceleration.

Three specific characteristics of these crashes provide guidance for how this reduction may be achieved: control of intrusion, protection during the forward component of the crash, and restriction of CRS rotation towards the impact side. Each of these characteristics is discussed in detail below.

The cases highlighted the importance of intrusion as a necessary contributing component for injury similar to that shown for fatal crashes by Sherwood et al (Sherwood et al. 2003). Most of the injuries appeared to be a result of direct contact – leg fractures, facial fractures, facial lacerations, brain contusions. Two distinct types of intrusion were noted: direct intrusion of the lateral door structure often impacting struck-side occupants (i.e. Case 8) and indirect intrusion of other vehicle interior parts (i.e. the front seat back in Cases 1, 5 and 7) into the occupant space of the child. This indirect intrusion appeared to be the mechanism by which children seated in the center rear seat position were injured. Often this took the form of an impact at the right front door that pushed the right front seat into the child's occupant space. This scenario was a common cause of the lower extremity injuries seen in these children. The dynamic nature of the relative movement of the child forward toward the struck side of the vehicle and the rearward motion of the front seat structure is challenging to recreate experimentally. Ongoing efforts by vehicle manufacturers to minimize intrusion into the occupant space for adult passengers should also translate to benefits for child passengers.

The overall magnitude of the intrusion does not appear to be the best predictor of injury; understanding the specifics of the location of intrusion and its effect on the child's occupant space is more predictive. This is evident in Figure 7 where even crashes of maximum crush in zone 2 (cases 3, 4, 7) had children who sustained AIS2+ injuries. It is important to note that in these three cases, however, the children sustained isolated injuries (two cases with concussions and one with a leg fracture) rather than that complex multisystem pattern of injuries seen in the other cases of greater crush. This is evidenced by the increasing values of ISS with increasing values of crush.

Another characteristic of these crashes was that although they were side impacts, several had a substantial forward velocity component (Cases 1, 5, and 7). This encouraged forward excursion of the occupant rather than direct lateral movement. In this kinematic pattern, the CRS side structure (i.e. side wings) plays less of a role than intended and intrusion of front seat structures was more important. The data suggested that the child rolls out and around the child restraint during the crash rather than direct lateral loading of the side structure of the CRS. This finding was also seen in Sherwood et al (Sherwood et al. 2003). It will be challenging to create designs that provide sufficient side wings to catch the occupant while also creating a user friendly restraint addresses the child's need to see out and around.

This kinematic pattern also has implications for the proposed test procedures highlighting the value of an impact scenario that mimics a frontal component to the crash. The frontal crash component can be achieved via sled test through an angled impact or by using a full-scale crash test with a crabbed barrier. In addition, the procedure should assess the potential for impact with intruding front seat structures and consideration should be given to further research into seat properties and mountings and their effect on injury risk to occupants seated behind them in this type of oblique loading.

Injury likelihood was exacerbated by the tendency of the CRS to rotate and slide towards the side of the crash. By rotating towards the side of impact, the child's head/neck complex was likely loaded in more of a frontal mode with nothing restricting its movement than in a pure coronal direction cradled by the CRS side structure as in a purely 90 degree lateral impact. This characteristic was exemplified in the contrast between case 1 and case 5. In case 5, another child was present in the right rear seating position (restrained in a CRS) possibly preventing the rotation of the center rear occupant's CRS towards the right side of impact. This effect on kinematics perhaps prevented the head/facial injuries see in case 1 where no such adjacent occupant was present to influence the rotation. The dynamic nature of the movement of the child in the CRS in relation to the intrusion represents a challenging occupant safety problem to solve. Thee addition of a top tether and lower dedicated attachment will likely directly mitigate this problem, however attention should be paid to the specific design of that lower attachment. Several designs currently exist (i.e. rigid, flexible continuous loop, and flexible separate loop) and their effect on CRS rotation in side impact should be evaluated.

It is important to recognize that 5 of 8 of the injured children were in crashes where the crash partners was a vehicle of larger mass or ride height. The importance of crash partner was also highlighted in our previous analyses on a broader representative sample (Arbogast et al. 2004). Efforts to account for this type of loading in countermeasure development have been led by the Insurance Institute for Highway

Safety's development of a raised, contoured side impact barrier and Transport Canada's extensive set of vehicle-to-vehicle side impact crashes with a mid-size SUV as the bullet vehicle (Arbelaez et al. 2002). Our results suggest protection of children in CRS in this mode of loading is of importance and worth further study.

The review of these cases highlighted the role of misuse as a contributing factor to the injury. In 4 of the 8 cases, misuse of the child restraint likely contributed to the injuries sustained. Most commonly, looseness of the harness or the harness in the wrong routing slots for forward facing led to increased head excursion and head acceleration and resulting head or facial injuries (i.e. Cases 1, 3, 6, and 8). Although the development of the LATCH and ISOFIX system was directed to reduce the misuse of installing the child restraint, to date no specific design change has been proposed to reduce the incidence of the loose harness straps. Future design efforts should consider how to address this error which in this sample of cases appeared to contribute to the injury.

Several limitations in the interpretation of our results must be considered. The study sample is a convenience sample of a population of children occupying model year 1990 and newer vehicles insured in 15 states and the District of Columbia. Thus to the extent that older or uninsured vehicles differ substantially from newer insured vehicles with regard to the protection afforded users of CRS, results of this study may not be generalized to occupants of these vehicles. Lastly, these cases were analyzed to provide detailed information about the types of injuries sustained and their mechanisms and should not be viewed as a population based estimate of the risk of injury.

CONCLUSIONS

The review of cases of injured children restrained in CRS in side impact crashes provide guidance to current efforts on the part of various regulatory bodies and CRS manufacturers to design and regulate these restraints for the safety of child passengers in side impacts. First, these results revealed the significance of the forward velocity of these side impact crashes, which encouraged forward excursion of the occupant rather than direct lateral movement. Second, intrusion appeared to a contributing factor to injury; either direct intrusion of the lateral door structure or indirect intrusion of other vehicle interior parts into the occupant space of the child. Third, the child seat often appeared to experience rotation towards the side of impact emphasizing the lack of pure lateral loading on the occupant. The most common body regions of AIS2+ injury were the head, face, and lower extremity. This injury pattern points to the importance of developing appropriate tolerance for head injury for children and development of measurement capability for the lower extremity in pediatric side impact ATD's. The data suggest characteristics of appropriate test procedures that would mimic real world loading conditions associated with serious injury. These include: a crabbed or angled impact to simulate a frontal component and a dynamic assessment of the potential for interaction with intruding structures. Design efforts such as LATCH/ISOFIX to control rotation towards the side of impact and self adjusting harnesses to mitigate misuse need to be assessed.

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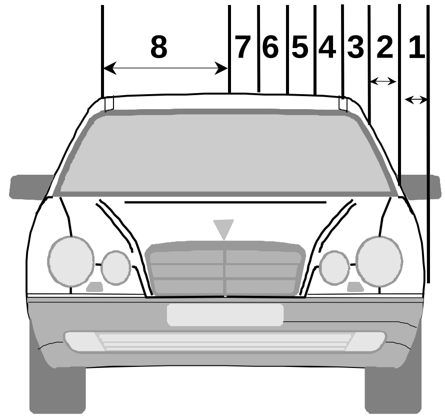

Figure 1: Defined crush zones in the side impact crashes

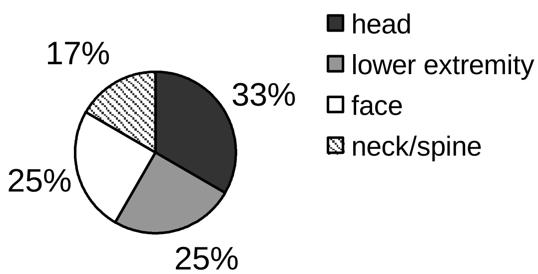

Figure 2: Body region distribution of AIS 2+ injuries in children 12 to 47 months old restrained in CRS in side impact crashes (n=8)

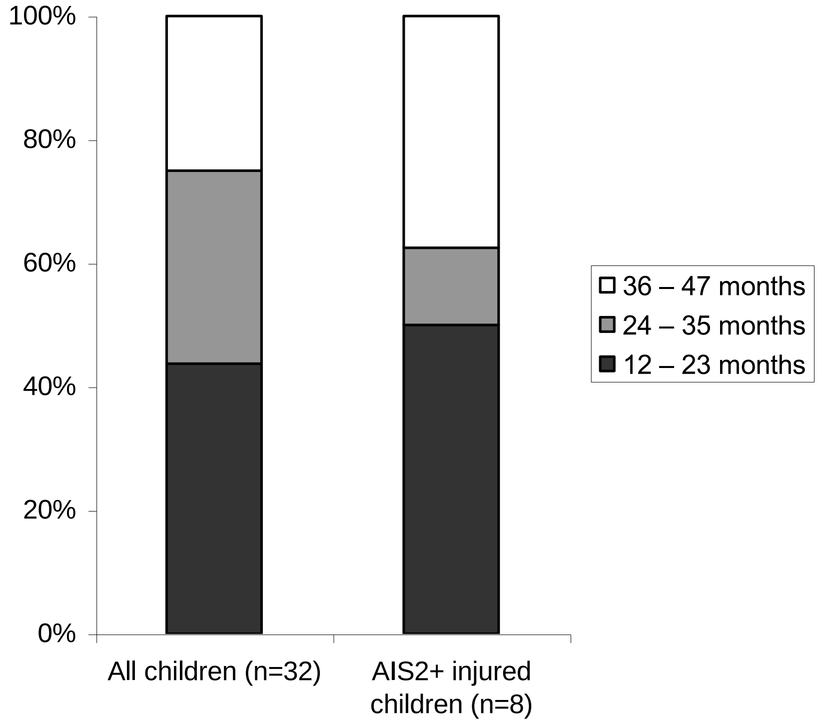

Figure 3: Distribution of age in the overall and injured study sample

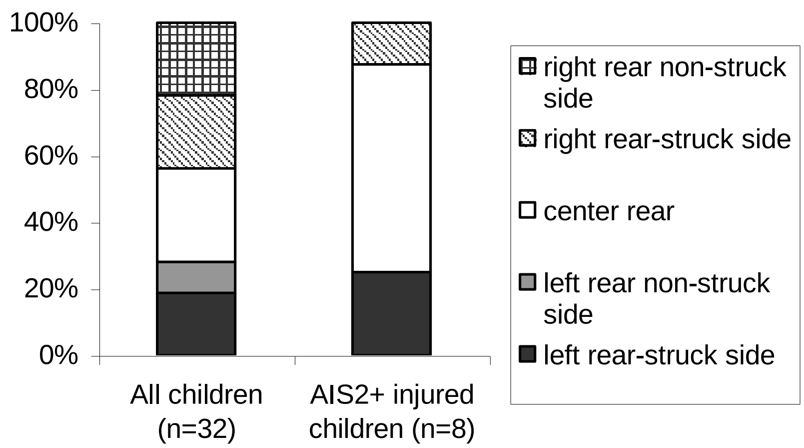

Figure 4: Distribution of seat position in the overall and injured study sample

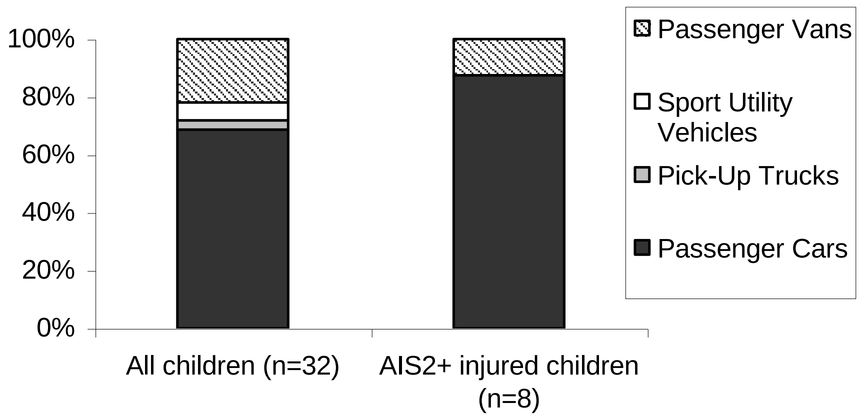

Figure 5: Distribution of case vehicle type in the overall and injured study sample

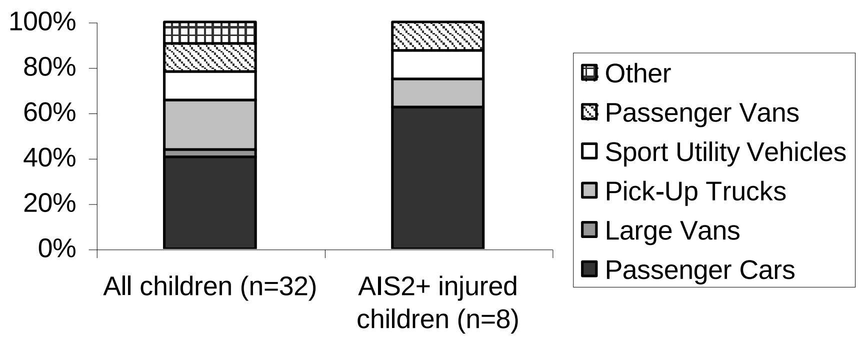

Figure 6: Distribution of crash partner in the overall and injured study sample

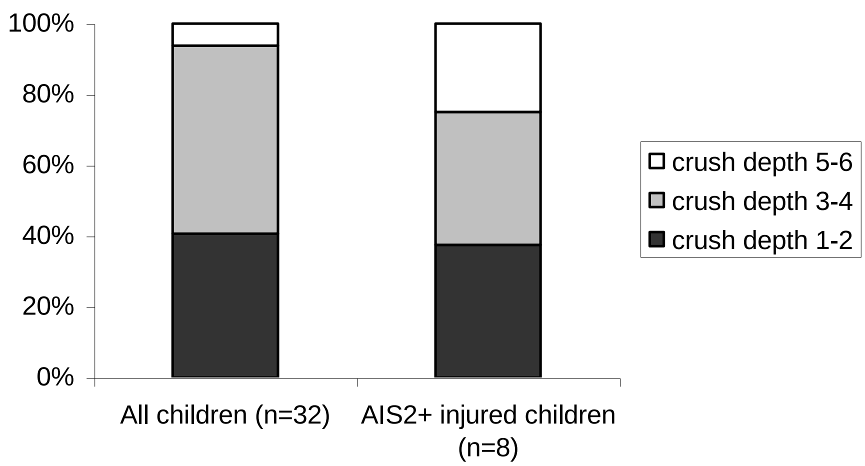

Figure 7: Distribution of crush zone in the overall and injured study sample

Figure 8: Vehicle damage for case 1.

Figure 9: Vehicle damage for case 2.

Figure 10: Vehicle damage for case 3.

Figure 11: Vehicle damage for case 4.

Figure 12: Vehicle damage for case 5.

Figure 13: Vehicle damage for case 6.

Figure 14: Vehicle damage for case 7.

Figure 15: Vehicle damage for case 8.