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Characteristics of crashes involving injured children in side impacts

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The objective of this study was to define the crash characteristics of near-side impact crashes in which children seated in the rear rows are injured. The crash characteristics included the direction of force, heading angle, horizontal impact location, vertical impact location, extent of deformation and intrusion at the child occupant's seating position. Cases from in-depth crash investigation databases of the NASS-CDS (National Automotive Sampling System-Crashworthiness Data System), CIREN (Crash Injury Research and Engineering Network) and Chalmers University of Technology were reviewed. The principal direction of force was most frequently between 60° and 75°. The heading angle of the bullet vehicle was most commonly between 61° and 90°. The bullet vehicle hit the passenger compartment of the target vehicle, particularly the rear door. Often, one or both of the adjacent pillars to the rear door were involved, most commonly the B pillar. In 11 of 16 crashes, the car sill was not engaged. Most commonly, the deformation extent was into Zone 3 or more – about 40 cm – and the intrusion at the child's seating position was in the range 20–30 cm. This review of the crashes revealed differences between the current side impact test procedures and the actual side impact crashes in which children were injured.

Keywords: side impact; child; injury; structure; crash test; restraint system

1. Introduction

Traffic-related trauma is the most common cause of fatality and severe injury to children in developed countries. Most of the traffic-related trauma to children occurs when they are passengers in vehicles in frontal or side impacts. The side impacts result in more fatalities than frontal crashes [13] despite the fact that side impacts only account for approximately one quarter of all crashes, while about half of the crashes are frontal [16]. Research by the National Highway Traffic Safety Administration (NHTSA) indicates that 42% of the fatalities sustained by rear-seated children less than nine years of age are to those in side impacts. These facts point to the importance of improving the protection of rear-seated children in side impacts. Furthermore, children as small as three-year-olds may be restrained directly by the vehicle's safety belts, although in combination with a belt positioning booster. Most 13-year-olds have reached the size of a small adult and thus use the vehicle safety belt as their restraint. Thus, this range of sizes corresponds to the smallest occupants protected mainly by the vehicles' safety systems.

Side impact injury risk and injury pattern for child occupants has been described in several studies [1, 2, 4, 7, 10–12, 15, 16]. These studies highlight the head as the most frequently injured body region among children up to 15 years of age. Further, the injury rate has been shown to vary by seating position. Injury severity is traditionally defined according to the Abbreviated Injury Scale (AIS) outlined by the Association for the Advancement of Automotive Medicine [5], and ranges from 0 to 6. For example, 0 indicates no injury, 2 is major injury, 3 is severe injury and 6 is untreatable. MAIS is the maximum AIS sustained by the occupant. The AIS2+ injury risk is significantly higher in near-side impacts than in central or far-side impacts [Arbogast *et al.*, 2004; 7, 16]. The principal mechanism of injury was contact with the vehicle interior, mainly associated with intrusion into the occupant compartment at the child's position and/or lateral translation of the child's body [7]. Maltese *et al.* (2007) showed that near-side, rear-seated children often had head impacts with the upper rear quarter of the door, including the window sill (upper part of the door trim), or with structures on the bullet vehicle (crash partner).

While these previous studies described well the injury risk and injury patterns, they failed to provide crash characteristics with enough detail to create test protocols for sled tests, barrier-to-vehicle tests and vehicle-to-vehicle tests – the next step in developing countermeasures. Our study fills that gap by more comprehensively describing the crash characteristics so that laboratory or computational crash tests can be designed in a way that mimics real-world crash events. Specifically, the objective of this study is to

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Table 1. The case inclusion criteria for the NASS-CDS study.

Variable	Criteria
Case year	1997–2007
Child age	3–13 years
Restraint	Appropriate restraint: 3- to 4-year-olds in harness child restraint OR 3- to 10-year-olds in booster seat and three-point safety belt OR 8- to 13-year-olds in three-point safety belt only
Child seat position	Rear seat, near side
PDOF	30°–150° or 210°–330°
Bullet vehicle type	Vehicles only, fixed objects not included
Case vehicle	Passenger vehicles including two- to five-door sedan or hatchback, minivan, station wagon or compact utility

describe the crash characteristics of near-side impact crashes in which children seated in the rear rows are injured.

2. Methods

The focus of the present study was crashes involving restrained children between 3 and 13 years of age who were occupants in passenger vehicles in rear-seat positions in a near-side impact. The impacts included both oblique and perpendicular impacts with an impact angle of 30°–150° or 210°–330°. Since this study focused on describing the crash characteristics that led to injury-producing crashes, rather than the injury mechanisms of the occupants, we chose to include only children who were appropriately restrained, defined as three- to four-year-olds in harness child restraints, 3- to 10-year-olds in booster seats and three-point safety belts or 8- to 13-year-olds in three-point safety belts. Cases were identified from the NASS-CDS (National Automotive Sampling System-Crashworthiness Data System) database, a population-based sample of tow-away crashes in the US. Crashes occurring between 1997 and 2007 were included (Table 1). The data in the NASS-CDS database are both unweighted and weighted, but only the weighted data were used in the analysis.

The crash direction of force (DOF, direction defined by clock hours, 1 to 12), principal direction of force (PDOF, direction defined by degrees [°], 0° to 360°), heading angle, horizontal impact location and extent of deformation were described for the whole sample and two subsamples: MAIS2+ or fatal injuries (MAIS2+), and MAIS3+ or fatal injuries (MAIS3+). The MAIS2+ sample comprises all children with at least one injury of level AIS2 or greater, while the MAIS3+ sample comprises the children with at least one AIS3+ injury. The definitions for PDOF, deformation extent and horizontal impact location are shown in Figure 1. The DOF and PDOF describe the same direction of force but differently. The heading angle is the angle between the two impacting vehicles at the time of impact, where 90 means that the bullet vehicle is oriented perpendicular to the target vehicle. Both DOF and PDOF were presented in this study because PDOF is not always calculated in crash databases. All variables are defined according to the SAE J224/1 (1980) standard.

Finally, based upon the NASS-CDS study, a more detailed examination of cases was conducted in order to more precisely describe the horizontal impact location, vertical impact location and intrusion at the child occupant's seating position. These data are not coded NASS-CDS variables and required individual case review.

To improve the side impact protection for adults, the Federal Motor Vehicle Safety Standard (FMVSS) 214, 'Side Impact Protection' was amended in 1990 and was phased into new passenger cars during model years (MYs) from 1994 until 1997 [8]. The improvements to cars following this amendment may have improved the safety for children as well, and were considered in the detailed case review by specifically studying MY97 and newer vehicles. In addition, the cases in the detailed study were selected based on the most common crash and occupant

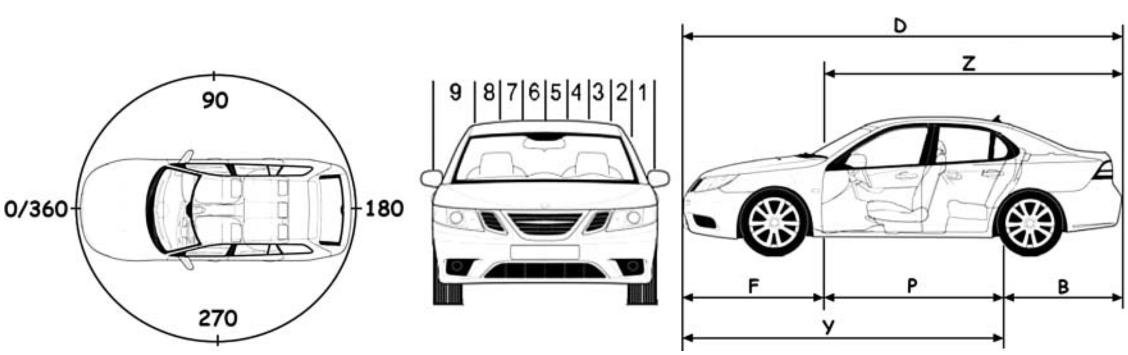

Figure 1. Definition of PDOF in degrees (°), deformation extent (deformation on left side shown, definition mirrored for deformations on the right side) and horizontal impact location according to the SAE J224/1 standard (1980).

Table 2. Additional case inclusion criteria for the detailed study.

Variable	Criteria
Vehicle model year	1997 or later
Case year	NASS-CDS: 1997–2008, CIREN: 1997–2008, Chalmers: 2004–2006
Injury severity	MAIS2+ and fatal
PDOF	30°–90° and 270°–330°
Deformation extent	2, 3, 4 or 5
Horizontal impact location	D, P, Y or Z

characteristics determined from the NASS-CDS review above. These additional selection criteria are listed in Table 2. The cases in the detailed study were drawn from the NASS-CDS database, the Crash Injury Research and Engineering Network (CIREN) database and the Chalmers University of Technology (hereafter Chalmers) accident database. The CIREN database obtains its data from patients admitted to a network of Level-1 trauma centres in the US, who are subsequently selected for a detailed crash investigation. The Chalmers database contains vehicle and injury data from 67 crashes involving children admitted to hospitals in the western region of Sweden between 2004 and 2006. The detailed impact location was determined by analysing the case documentation, including the photographs. The intrusion at the child's seating position was determined by the documented intrusion measurements at the case occupant position. Cases with more than one significant crash event were excluded.

3. Results

3.1. NASS-CDS study

3.1.1. Sample characteristics

The sample characteristics are presented in Table 3. In total, 75,473 children (weighted) met the sampling criteria for the NASS-CDS study. Forty per cent of the children

Table 3. Sample characteristics based on an NASS-CDS sample of 3- to 13-year-old children, sitting in the rear seat in right- or left-side impacts with PDOF 30°–150° or 210°–330°.

	All	MAIS2+ Fatal	MAIS3+ Fatal
N			
Unweighted	157	23	16
Weighted	75,473	3164	865
Gender			
Female	40% (30,268)	60% (1884)	64% (555)
Male	59% (44,603)	40% (1280)	36% (310)
Unknown	1% (601)	0	0
Age (years)			
3–5	16% (11,737)	7% (235)	27% (235)
6–8	10% (7810)	5% (150)	15% (133)
9–11	39% (29,436)	83% (2611)	43% (374)
12–13	35% (26,490)	5% (169)	14% (123)
Restraint			
Harness child restraint (3- to 4-year-olds)	8% (5913)	1% (23)	3% (23)
Booster seat (with or without back) with lap and shoulder belt (3- to 10-year-olds)	13% (9946)	7% (212)	25% (212)
Lap and shoulder belt only (8- to 13-year-olds)	79% (59,613)	92% (2929)	73% (630)
Target vehicle type			
Two-/three-door sedan/hardtop/coupe/ hatchback	4% (3097)	3% (96)	11% (96)
Four-/five-door sedan/hardtop/hatchback/station wagon/utility station wagon	53% (40,339)	17% (543)	58% (502)
Compact pickup/utility/minivan	40% (30,456)	39% (1234)	31% (267)
Large pickup/utility/other van	2% (1581)	41% (1291)	0
Target vehicle MY			
Before 1992	14% (10,544)	7% (233)	24% (208)
1993–96	28% (21,378)	38% (1214)	36% (315)
1997–2002	47% (35,823)	49% (1561)	29% (249)
2003–07	10% (7727)	5% (156)	11% (93)
Bullet vehicle type			
Two-/three-door sedan/hardtop/coupe/hatchback	20% (15,255)	4% (134)	15% (134)
Four-/five-door sedan/hardtop/hatchback/station wagon/utility station wagon	30% (22,738)	79% (2504)	36% (314)
Compact pickup/utility/minivan	29% (21,550)	9% (291)	34% (291)
Large pickup/utility/other van	18% (13,891)	4% (141)	16% (141)
Truck	2% (1685)	3% (94)	3% (30)
Unknown	1% (402)	0	0

Note: The children were sitting on the struck side and were appropriately restrained. Cases from 1997 to 2007.

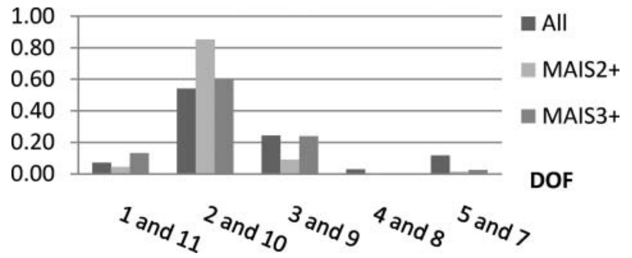

Figure 2. The distribution of DOFs in near-side impact crashes with appropriately restrained, rear-seated children of ages 3–13 years. The abscissa shows categories of DOFs.

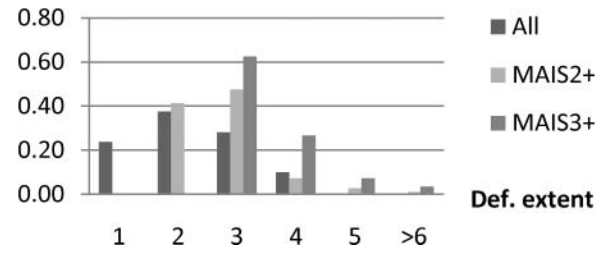

Figure 4. The distribution of deformation extent in near-side impact crashes with appropriately restrained, rear-seated children of ages 3–13 years.

were female, and 74% of the children were between 9 and 13 years of age, out of which 3164 children had an MAIS2+ or fatal injury, and 865 children had an MAIS3+ or fatal injury.

The distribution of target vehicle types in the overall sample shows that 53% of the children were riding in a four-door passenger car. Another 40% sat in a compact pickup, a utility vehicle or a minivan. This distribution differed from the bullet vehicle type distribution, which had a greater proportion of two-door passenger cars, large pickups, large utility vehicles or large vans. Fifty-eight per cent of all target vehicles were MY97 or newer in the overall sample, while only 40% of the MAIS3+ sample were vehicles of the current age.

3.1.2. *DOF and PDOF*

The distributions of impact DOF and PDOF are illustrated in Figures 2 and 3. The impact DOF was 2 or 10 o'clock in 54% of all crashes, in 85% of the MAIS2+ crashes and in 60% of the MAIS3+ crashes (Figure 2). The '30° to 60°' and '300° to 330°' crashes accounted for 14% of all crashes, and 35% and 27% of the crashes resulted in MAIS2+ or MAIS3+ injuries, respectively (Figure 3). The '60° to 90°' and '270° to 300°' crashes accounted for 75% of all crashes, and 63% and 70% of the crashes resulted in MAIS2+ or MAIS3+ injuries, respectively (Figure 3).

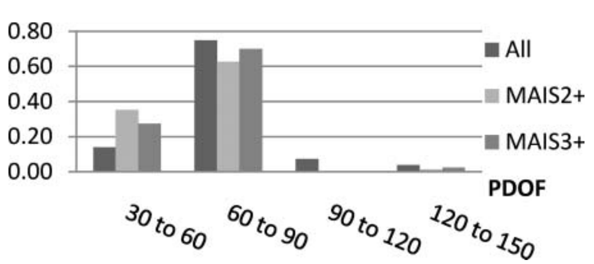

Figure 3. The distribution of PDOFs (degrees [°]) in near-side impact crashes with appropriately restrained, rear-seated children of ages 3–13 years. The '30 to 60' interval includes the impacts with PDOF between 300° and 330°, '60 to 90' includes PDOFs between 270° and 300°, etc.

3.1.3. *Deformation extent*

Sixty-two per cent of the crashes in the sample are of Extent 1 or 2 (Figure 4), while all of the MAIS3+ injuries occurred in crashes of Extent 3 or greater. Eighty-nine per cent of the MAIS2+ injuries occurred in crashes of Extent 2 or 3.

3.1.4. *Heading angle*

The heading angle was between 61° and 90° in 61% of all crashes in the sample, while 19% of the MAIS2+ and 78% MAIS3+ injury crashes were of those heading angles (Figure 5). Crashes with the heading angle between 31° and 90° accounted for 67% of the crashes resulting in MAIS2+ injuries and 87% of the crashes resulting in MAIS3+ injuries. Specifically, 69% of the MAIS3+ injuries occurred in crashes with a heading angle of 61°–90°.

3.1.5. *Horizontal impact location*

The distribution of horizontal impact locations is shown in Figure 6. F, Y and Z impacts were more frequent than P and B impacts among all crashes. D impacts were rare. Among the crashes that result in MAIS2+ injuries, the P impact – to the occupant compartment between the A and C pillars – was the most frequent, followed by F and Z. The passenger compartment was involved in 73% of the crashes resulting in MAIS2+ injuries. Z impacts – from the A pillar rearwards – were most frequent among the crashes resulting

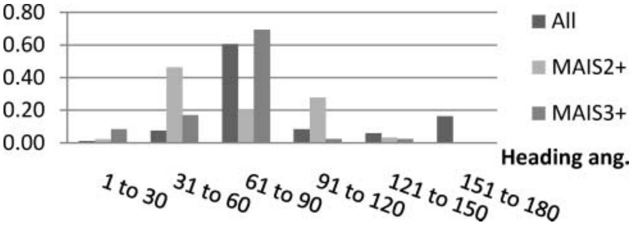

Figure 5. The distribution of heading angles in near-side impact crashes with appropriately restrained, rear-seated children of ages 3–13 years.

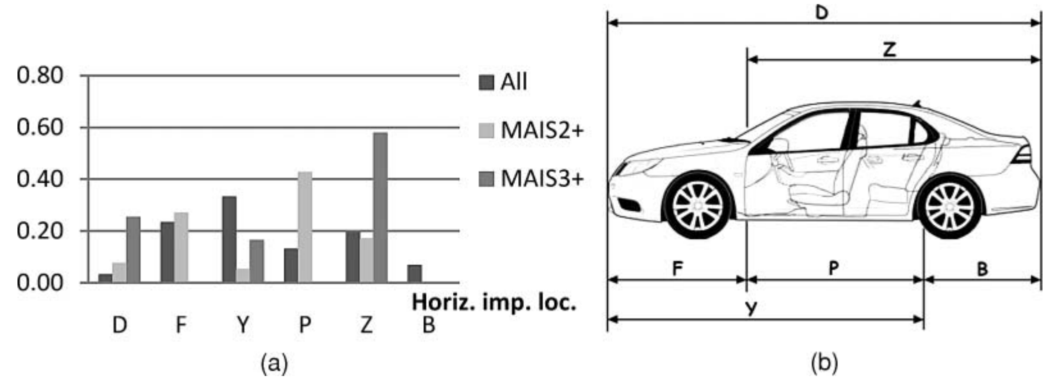

Figure 6. (a) The distribution of horizontal impact location in near-side impact crashes with appropriately restrained, rear-seated children of ages 3–13 years. (b) Definitions of the horizontal impact locations.

in MAIS3+ injuries, while no MAIS3+ injuries occurred in F, P or B impacts.

3.2. *Detailed case study*

There were 16 cases in total that matched the case selection criteria for the detailed study (Tables 1 and 2). The case data regarding target and bullet vehicle type, collision deformation classification (CDC) code, heading angle, child age, restraint type, injuries, horizontal and vertical impact location, and intrusion at occupant's seating location are presented in Table 4.

3.2.1. *Detailed horizontal impact location*

The detailed study described a more detailed horizontal location of the impact than was described in the coded data of the NASS-CDS analysis (Table 4). The rear door (adjacent to the child) was impacted in all of the 16 selected cases except one. In the one case without deformation in the proximity of the child, the maximum injury was an AIS2 injury to the lower extremity.

The front door was impacted in 10 cases. The B pillar was impacted in 11 of the cases, and the C pillar in nine cases. The bullet vehicle overlapped two pillars in 11 cases: A and B pillars in six cases, and B and C pillars in five cases; however, only slight overlap with the C pillar occurred in two of those five cases. A, B and C pillars were overlapped in one case, but in this case, there was only a minor overlap with the C pillar.

3.2.2. *Detailed vertical impact location*

The roof rail was impacted in five of the 16 cases. The window sill (the part of the rear door just below the glass) was struck in 10 cases. The area between the window sill and the sill was impacted in all of the selected cases, while the sill was impacted in only five of the selected cases. The details are presented in Table 4.

3.2.3. *Intrusion at the occupant's position*

In Table 4, the maximum intrusion of the door adjacent to the child is specified. The intrusions range from 0 to 62 cm. The median intrusion was 26 cm. In seven of the 16 cases, the intrusion was between 21 and 29 cm, and two cases had an intrusion that was greater than 43 cm. One case did not have an impact or intrusion at the position of the child. Apart from this case, the smallest intrusion was 9 cm.

4. Discussion

This study reviewed the crash circumstances for appropriately restrained children in near-side impacts. While previous work focused on understanding the mechanisms of injury for these occupants, this study was the first to focus on defining the nature of the crashes with a goal towards enhancement of test procedures in this impact direction.

Fifty-eight per cent of the target vehicles in the sample were MY97 or newer. All of these vehicles fulfilled the FMVSS 214 1990 amendment requirements. This update of the standard may be the cause of the relatively smaller share of MY97 or newer vehicles in the MAIS2+ and the MAIS3+ subsamples, which were 54% and 40%, respectively. Further, 57% of the target vehicles were passenger-type vehicles. This figure corresponded to the share of passenger-type vehicles in other studies, which have varied between 50% and 85% [Arbogast *et al.*, 2004, 11, 15]. The share of passenger vehicles in the MAIS2+ and MAIS3+ samples were 20% and 69%, respectively. The dip in the share of passenger vehicles' MAIS2+ sample mainly was an effect of one case, a large van, which had a weight factor of 1291. This case affected the distributions in the MAIS2+ sample throughout the study.

Of note, there were relatively few children younger than nine years in the sample. This is because only appropriately restrained children were included. Ample evidence exists that child restraints, including booster seats, are incredibly effective restraint systems and thus children in these

Table 4. Data from the cases that matched the case selection criteria in the detailed study.

No.	Target vehicle	Bullet vehicle	CDC	PDOF (°)	Age (year)	Restraint	Injury	Horizontal impact location	Vertical impact location	Max door intrusion (cm)
1	Mid-size MY98	Large pickup MY97	02RZAW3	50	3	Five-point harness child restraint, belt attached	Head (3)	Rear third of rear door, C, rear fender and rear wheel	From above the window sill and down to above the sill	9
2	Mid-size four-door sedan MY97	Large four-door sedan MY97	63RYEW5	80	3	Low-back booster and three-point belt	Thorax (4) Pelvis (2)Pelvis (2) Head (2)	A, front door, B, rear door, slight/indirect C	Below window sill, down to just above the sill, but indirect/late damage to sill.	62
3	Mid-size four-door sedan MY99	Large pickup MY00	02RYEW3	60	4	Low-back booster and three-point belt	Head (5)Head (5)Head (3)Head (3)Neck (2)	A, front door, B, front half of rear door	Window sill down to sill. Slight direct sill involvement, sill also pulled up by A- and B-pillar deformation	23
4	Small four-door sedan MY00	Bus	03RZAW3	80	5	Shield booster and three-point belt	Head (4) Head (2)	Rear half of rear door, C, front half of rear fender	From above the window sill and down to above the sill, sill not involved.	13
5	Mid-size four-door sedan MY02	Small SUV MY93	02RZAW3	60	5	High-back booster and three-point belt	Head (4) Thorax (4) Head (3) Head (3) Abdomen (2)	Just behind B, rear door, C, rear fender, rear wheel	Roof rail (at C), window sill, door, just above the sill.	27
6	Small four-door sedan MY00	Mid-size luxury MY89	02RPEW3	60	5	High-back booster and three-point belt	Head (3)	Front door, B, rear door	From below the window sill and down to above the sill.	29
7	Four-door SUV MY03	Minivan	02RZED2	50	7	Three-point belt	Pelvis (2)	Front door, B, rear door, C, rear fender	From mid-between window sill and bottom of door down to and including the rear door sill and the rear wheel. Deformation to the sill in a small area on the front door (impact with a breakaway pole).	10
8	Mid-size four-door sedan MY03	Tractor	03RPAW4	Not spec.	8	Low-back booster and three-point belt	Face (2)	Slight A involvement, front door, B, rear door	Top of B down to mid-between window sill and sill. The sill was pulled up by the B-pillar deformation, but was not directly involved.	25

9	Small four-door station wagon MY00	Sports coupe MY78	10LZAW3	50	8	Kitchen cushion and three-point belt	Head (4)Head (3)Head (3)Head (3)Face (2)	Just behind B, rear door, C, rear wheel	From above the window sill and down to above the sill.	23
10	Compact two-door coupe MY97	Large MY98	10LZEW3	50	9	Three-point belt	Lower extremity (3) Abdomen (2) Upper extremity (2)	Rear of front door, B, rear side in front of C (two-door)	Below the window sill and above the sill.	40
11	Mid-size four-door sedan MY98	Truck MY90	03RYAW4	90	9	Three-point belt	Head (4) Head (3) Abdomen (2) Pelvis (2) Thorax (2) Abdomen (2)	A, front door, B, rear door, partially C	Roof rail down to and including the front door sill.	43
12	Small SUV MY05	Medium truck MY78	03RPAW3	80	10	Three-point belt	Lower extremity (2) Lower extremity (2)	A, front door, B, rear door	The window sill down to above the sill. Sill not included.	21
13	Large van MY99	Mid-size four-door sedan MY99	10LPEW2	70	10	Three-point belt	Lower extremity (2)	A, front door, B	The lower part of the front-door skin and the sill were impacted.	0
14	Mid-size four-door sedan MY00	Compact pickup MY00	02RPAW4	50	11	Three-point belt	Head (3) Lower extremity (2)	B, rear door, C	Window sill down to above the sill, no sill involvement.	38
15	Small four-door sedan MY03	Compact SUV MY00	03RZEW4	80	11	Three-point belt	Abdomen (5) Thorax (4) Abdomen (4) Pelvis (3) Pelvis (2)	Rear door just behind B, C, rear wheel, rear fender	Impact above the window sill down to just above the sill, indirect deformation of the sill at C.	29
16	Mid-size four-door sedan MY99	Large four-door sedan MY95	01RDEW5	30	12	Three-point belt	Abdomen (5) Abdomen (4) Abdomen (2) Abdomen (2) Lower extremity (2) Pelvis (2)	Just behind A, front door, B, rear door, C	Top of B-pillar down to the sill. The front door sill was involved; the rear door sill was not involved.	57

Note: The data include vehicle data, CDC, age of child, injury data and specific data regarding horizontal and vertical location. The AIS level of each injury is shown within parentheses after the injury description in the ‘Injury’ column. A, B and C in the horizontal impact location column refer to the A, B and C pillar, respectively. The maximum door intrusion was measured at the child’s seating position.

restraints appear less frequently in the injured subsamples of this analysis. Specifically, in the sample only 1% were restrained in harness seats and 7% in boosters and safety belts were present in the MAIS2+ dataset, while the remainder were restrained by the vehicle safety belt only. The results of this study therefore mainly reflect the situation for safety belt-restrained 9- to 13-year-olds.

There were in total 16 cases that met the inclusion criteria of the detailed study. The injury distribution in the detailed study was consistent with the findings of Maltese *et al.* (2007). Their study showed that the head is the most frequently injured body region among 3- to 15-year-olds in near-side impacts. Among the 16 cases of this study, there were 10 children with head or face injuries. The authors also highlighted that the head injuries often were associated with intrusion and head impact with the upper half of the door trim. All of the cases in the present study with head or face injury had door panel intrusion and probable head impact with the upper part of the door trim or the bullet vehicle hood. It should be noted that both this and Maltese's study are partially based on the CIREN database.

Among the studied crashes that resulted in AIS2+ injuries, the bullet vehicle generally hit the target vehicle on the rear door (or the side in the two-door case) and on one of the two adjacent pillars. In most of the cases, it hit the B pillar. It was less common that the bullet vehicle overlapped both of the adjacent pillars. The bullet vehicle structure did not overlap with the target vehicle sill. There seemed to be two reasons for the lack of overlap: either the bullet vehicle was taller, with a bumper/crash structure that was higher than the target vehicle's sill, or the bullet vehicle elevated from the ground just before the impact with the target due to some unevenness of the road (traffic islands, etc.). The sill is an important crash structure in side impacts. If it is not engaged, there is less resistance to deformation of the vehicle and intrusion into the occupant compartment.

The maximum resulting intrusion at the child's seating position in the studied crashes varied between no intrusion and extreme intrusion of 57 and 62 cm in two of the cases. However, nearly half of the cases had an intrusion between 21 and 29 cm. Nearly two thirds of all crashes had a deformation extent of 1 or 2, but there were no MAIS3+ injuries among them. The vast majority of the crashes resulting in MAIS2+ or MAIS3+ injuries were of Extent 2–3 in the NASS-CDS, but among the cases in the detailed study, there was only one Extent 2 crash. The case with the 1292 weight factor was Extent 2, which explains the difference between the NASS-CDS samples and the current case samples. Therefore, crashes that cause MAIS2+ injuries to children are most commonly of Extent 3 or more, and the intrusion at the child's seating position is in the range 20–30 cm.

The resulting force on the cars in the studied crashes was presented by PDOF and DOF. By combining the two, it can be concluded that the most common DOF acting on the cars was between 60° and 75° to either the left or the right side of the longitudinal axis of the car; the DOF category '2 o'clock' corresponds to the range 45°–75°, which only partly overlaps the PDOF category '60° to 90°'. Thus, the upper limit of the combined range is dictated by the PDOF category, i.e. 60°, while the lower limit is dictated by the DOF category, i.e. 75°. The results are well in line with those in the studies by Langwieder *et al.* (1996), Arbogast *et al.* (2005), Maltese *et al.* (2007) and Scullion *et al.* (2008).

It is of interest to compare the results of this study with the FMVSS 214 barrier to car test procedure. The FMVSS 214 barrier is designed to geometrically simulate a passenger car. The barrier has angled wheels that correspond to a PDOF of 63°. Its heading angle is 90°. It does not specifically specify the overlap with the rear door in either the horizontal or the vertical direction. A test procedure to evaluate the injury risk for rear-seated children in near-side impacts would be similar to the FMVSS 214 test procedure in some respects, but different in others. The barrier velocity and heading angle correspond well. The position of the barrier bumper, on the other hand, results in an overlap with the sill for most of today's cars. The low frequency of side impacts with sill overlap and MAIS3+ injuries in vehicles of MY97 and later may be an effect of this feature of the FMVSS 214 test. However, the FMVSS 214 has not managed to mitigate the injuries when the sill is not involved. Therefore, a relevant test method should include an impact without sill involvement. Furthermore, the test method should also prescribe a barrier lineup that does not overlap both the B and the C pillar, but rather impacts only the B pillar and part of the rear door. The FMVSS 214 often results in an overlap with at least the lower part of the C pillar (wheel house), besides the A and B pillars. The latest final rule of the FMVSS 214 was published in 2007 and will be phased in from 2010 to 2014. This update affects the rear-seat position in that the SID-HIII (Side Impact Dummy, Hybrid III) will be replaced by the SID-IIs (Side Impact Dummy, Second Generation, Small), which is more sensitive to intrusion by adding rib deflection measurements. This may lead to cars that are more resistant to intrusion. However, barrier speed, angle and impact location remain unchanged.

The IIHS (Institute for Higway Safety) truck-to-car consumer test has an intent to make the barrier hit the vehicle in between the A and C pillars, and the barrier has a ground clearance that results in a smaller overlap with the sill than in the FMVSS 214 test. However, the velocity of the IIHS barrier is perpendicular to the car's longitudinal axis. To resemble the findings of this study, the IIHS barrier should have slightly greater ground clearance and a velocity which has the same angle as that of the FMVSS 214 barrier.

The study was to a large extent based on US data and thus the results of this study may not be applicable worldwide. US cars are developed according to the US standards and regulations. These standards and regulations differ from the ECE (UN) Regulations and EU Directives. From a rear-seat occupant side impact protection point of view, the US cars of MY97 and later meet stricter requirements. The ECE (UN) Regulations and EU Directives do not measure injury criteria for rear-seat occupants, while the FMVSS does. This study has identified areas for improvement in the testing of vehicles that fulfil the toughest requirements.

Also, the vehicle fleet in the US differs from that of other consumer areas, for example, by having a smaller proportion of small or mini vehicles. This study's sample comprised a range of small- to mid-size passenger cars and SUV (sport utility vehicle). Intrusion at the occupant's seating position was a common contributing factor for injury causation, and this study highlighted the characteristics that lead to that intrusion. These characteristics are the impact DOF and the impact location relative to generic structures such as sill and pillars. These characteristics can be assumed to be applicable independent of the vehicle size or design.

The findings of this study should also have implications for tests of child restraints. Still, the ECE R44.04 and FMVSS 213 regulations do not include side impact in the test method, but they will, within a few years. The child restraint tests that already include the side impact, i.e. some consumer tests and AS/NZS 1754, do not consider the forward component of the side impact. As a consequence, there is no incentive for mitigation of the injury mechanisms due to the forward component. For example, Henary *et al.* (2007) showed that rear-facing restraints are five times more efficient than forward-facing restraints in side impacts. They attributed this difference to the difference in occupant's kinematics. Due to the frontal component in the side impacts, the children in forward-facing restraints move forward and out of the side supports of the child restraints. In the rear-facing restraints, the children move further into the restraint's shell. These kinematics will become more evident in a side impact test with a forward component.

5. Conclusion

Review of characteristics of near-side impact crashes involving appropriately restrained child occupants revealed some areas of improvement for side impact testing procedures. The bullet vehicle hit the passenger compartment of the target vehicle. Particularly, the rear door was damaged, with an intrusion between 21 and 29 cm. Either of the adjacent pillars of the rear door were involved, most commonly the B pillar. The car sill, which is an important structure in side impacts, was not engaged. The PDOF was most frequently between 60° and 75° to either the right or the left side of the longitudinal axis. The deformation extent, measured anywhere on the side of the car, was into Zone 3 or more – about 40 cm or greater. Finally, the heading angle of the bullet vehicle was most commonly between 61° and 90°. These conclusions were based on crashes that resulted in AIS2+ or fatal injuries.

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