

Injury Risk Investigation of the Small, Rear-seat Occupant in Side Impact

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ABSTRACT

For children seated next to the struck side, real-world crash outcome was determined for the rear-seat of passenger vehicles over the entire range of side impact crash severities. The method was first to calculate the actual risk for an occupant based on field data. The data sources were non-rollover, tow-away crashes from the 1997 - 2009 National Automotive Sampling System. By limiting the struck passenger vehicle to model year 1985 or newer, field data were identified for a total of 588 children. In all crashes, the child was seated in the rear-seat area on the struck side of the passenger vehicle. A matrix of MADYMO model simulations calculated the response of child dummies over the entire range of the field data. Age dependent, moderate to serious ($AIS \geq 2$) injury risk curves were derived and evaluated for children in side impact. Risks to the children were calculated by combining the derived child risk curves with the MADYMO model simulations. The evaluations were conducted from the point of view of an aggregate approximation of $AIS \geq 2$ injury rates across the crash severity range for the entire child group of all ages. The results were that the simulations and biomechanical injury risks reasonably matched the actual NASS-CDS-based trauma risks. For all children, the accumulated injury risk approximation was 10.66% and the field-based approximation was 10.73%. This field-based methodology focuses occupant safety design toward a more far-reaching system approach where the entire range of side-impact crash severities and occupant variability are considered.

CITATION: Morgan, R., Scullion, P., Nix, L., Kan, C. et al., "Injury Risk Investigation of the Small, Rear-seat Occupant in Side Impact," *SAE Int. J. Passeng. Cars - Mech. Syst.* 5(1):2012, doi:10.4271/2012-01-0092.

INTRODUCTION

In side impact, the Harm to struck-side occupants is roughly 2.5 times that to non-struck-side occupants. (Scullion, 2008b; Starnes, 2002; Gabler, 2005) As a result of this distinction, many safety studies begin by investigating the crash environment on the struck side in a side-impacted vehicle.

The head and the face are the primarily-injured body region in side impacts for children. Using data from Partners for Child Passenger Safety (PCPS), Arbogast et al. (2005) conducted investigations of 32 children seated in forward-

facing child restraints in side impacts. The study found that one-fourth of the children had $AIS \geq 2$ injuries, with the most common injuries to the head, face, and lower extremity. McCray et al. (2007) also investigated the injury to children in side impacts. Head injuries accounted for a total of 59, or 57%, of the total 104 injuries sustained by 28 children ages 1 to 3, according to National Automotive Sampling System/Crashworthiness Data System (NASS-CDS) data for 1995, 1996, and 1998-2004. Maltese et al. (2007) confirmed that the head is the most injured body region for 24 cases involving children aged 4 to 15 who were restrained using the vehicle belts in the rear, struck-side position in a side impact.

These cases were drawn from both the Crash Injury Research Engineering Network (CIREN) database and PCPS. Finally, [Scullion et al. \(2009\)](#) assessed the primarily involved physical component for the head and face of nearside child occupants seated directly adjacent to the struck side of a vehicle in a side impact collision. Based on 699 individual child occupants reported in NASS-CDS between the years 1993-2007, they confirmed that the head/face was the most-injured body region for children 1 - 12 years old.

In side impact, the major Harm to children occurs at a principal direction of force (PDOF) of 30 degrees (1 O'clock or 11 O'clock) to 60 degrees (2 O'clock or 10 O'clock) ([Scullion, 2008a](#), [2008b](#); [Sullivan, 2009](#)).

In lateral crashes on the struck side of the vehicle, direct contact of the child's head and face with the side interior surface of the vehicle accounts for the greatest percentage of Harm ([Scullion, 2009](#); [Bohman, 2009](#); [Scullion, 2008a](#); [Sullivan, 2009](#)).

Previous studies suggest that 3-point safety belt systems give only a small increment of increased safety for the occupant on the struck-side in side impact. ([Kahane, 2000](#)) In 2009, *Consumer Reports* noted that many passenger vehicles have curtain air bags and that torso air bags are beginning to appear in the rear seat area. By simulation, this study will investigate the impact loading to children (especially the head and face) on the struck side of the vehicle. Following [Korner \(1989\)](#) and [Laituri \(2005\)](#), and based on real-world crash data (NASS-CDS in the US), the investigators determined injury risk for 3, 6, and 10-year-old children over the key crash severities for side impact.

REAL WORLD CRASH DATA ANALYSIS

The following section provides an overview of the real-world crash data analysis of rear-seat nearside child occupant protection in side impact collisions. A nearside occupant was defined as an occupant seated adjacent to the struck side of the vehicle in a side-impact collision.

NASS-CDS CRASH DATA ANALYSIS - OVERVIEW

[Table 1](#) shows the overall distribution of occupant involvement by impact type for both child occupants aged 1-12 years old, as well as older occupants aged 13 years old, or older. From this table it can be identified that in approximately 1 in 20 of those involved in a side impact collision whereby the child occupant was seated directly adjacent to the struck side of the vehicle (Nearside).

Table 1. NASS-CDS 1995-2009 - Occupant frequency distribution by crash type and occupant age (weighted data).

	CHILD (1-12)	OLDER (13+)
Side Impact - Nearside	6%	94%
Side Impact - Farside	10%	90%
Frontal Impact	8%	92%
Rear Impact	10%	90%
Unknown / Other	10%	90%
All	8%	92%

Table 2. NASS-CDS 1995-2009 - Occupant moderate-to-fatal risk by crash type and occupant age (weighted data).

	CHILD (1-12)	OLDER (13+)
Side Impact - Nearside	5%	9%
Side Impact - Farside	2%	6%
Frontal Impact	2%	8%
Rear Impact	1%	3%
Unknown / Other	1%	2%
All	2%	7%

In [Table 2](#) the risk of a child occupant sustaining a moderate to fatal injury in a side impact collision was approximately 5 percent. For the child 1- 12 years old, 5% risk for near-side occupant is higher than the child risk in any other crash mode.

METHODOLOGY - REAR-ROW CHILD OCCUPANT INJURY RISK IN SIDE IMPACT COLLISIONS

To further understand nearside rear-row child occupant injuries in side impact collisions, the following selection criteria were applied to NASS-CDS data in order to identify specific cases of interest:

- NASS-CDS Data years 1995-2009
- Passenger cars and Light Trucks and Vans
- General Area of Damage (GAD) to left or right side of the occupant vehicle
- Occupant seated in rear-row of the vehicle and adjacent to the struck side
- Occupants aged 1-12 years old
- Occupants were not fully ejected from the vehicle

To avoid confounding injuries as the result of multiple impacts, only vehicles with either (1) no secondary damage, or (2) vehicles whereby the extent of damage for the

Table 3. Summary of NHTSA recommended child restraint usage based on age, height, and weight.

	Age (years)	Weight (lb)	Height (cm)
Toddler	Age ≥ 1	20 $\leq$ Weight < 40	
Booster	1 $\leq$ Age < 8	40 $\leq$ Weight	Height < 145
Belted	2 $\leq$ Age < 8	40 $\leq$ Weight	Height ≥ 145
	8 $\leq$ Age ≤ 12	OR	

secondary impact did not exceed an extent of damage beyond zone 2 (front or side) were considered for the analysis. This was to improve the confidence that the injuries being addressed are more closely associated with the primary collision, and not the result of more complex injury mechanisms brought about by a multiple event crash.

Occupant Appropriate Restraints

The analysis herein was performed on a child (1) in a side crash of a passenger vehicle and (2) seated on the side adjacent to the crash. The child was analyzed along with his/her restraint as used. This term, as used, means that a child occupant may or may not have been in a proper restraint. Those seeking a good statistical analysis of only children in a proper restraint system and in a crash might read the Starnes and Eigen report. (Starnes, 2002)

In this study, child occupants were divided into three groups by age and size. Occasionally, the preparation of the data was confounded by the situation of a young child of large mass. Using the real-world crash data, child occupants were sorted into three groups based on the child's age and the child's weight. These child occupants were categorized into one of three Occupant Appropriate Restraint (OAR) sub-classifications; toddler, booster, or belted. These classifications were defined using the National Highway Traffic Safety Administration (NHTSA) recommended appropriate restraint system, circa September 2010. The occupant classification criteria are summarized in Table 3. (As recommendations for child restraint change over time, a parent seeking a proper restraint for their child should follow current recommendations by the American Academy of Pediatrics and the NHTSA.) In cases whereby either the child height or weight was unknown, this value was assigned based on the average height or weight for a given child of similar age. This was determined using anthropometric data obtained from the US Center for Disease Control (CDC - Growth Charts).

To further understand the near-side child occupant injury risk, vehicles were initially classified based on the impact severity, delta-V (ΔV) in km/h, and interior intrusion based on the post-crash damage.

Impact Severity

For this study, the rear-seat occupant seating position has been approximated to include the area between the center of the wheelbase (close to b-pillar), and the rear of the wheelbase (close to c-pillar). When considering a direct impact, the damage should be found to have overlapped the occupant seating position.



Figure 1. Direct damage does not overlap proximal to occupant seat position.



Figure 2. Direct Impact - Direct damage overlaps proximal to occupant seat position.

Interior Intrusion

In NASS-CDS, up to 10 interior intrusion measurements are provided relative to occupied seating positions in each of the involved vehicles (where vehicle inspection conducted). For this study, the focus was specifically on intrusion of nearside interior components to the rear-seat nearside occupant seating position. These interior components were defined as being the vehicle pillars, side panel (forward of a pillar), door panel (side), side panel (rear of b-pillar), and the roof side-rail. The magnitudes of these intrusions were grouped into four distinct ranges (Table 4).

Table 4. Side Interior Intrusion ranges.

Intrusion Group	Magnitude of Intrusion Side Interior
Intrusion 1	0 - 2 cm
Intrusion 2	3 - 14 cm
Intrusion 3	15 - 45 cm
Intrusion 4	46 + cm

Table 5. Real-world weighting factors - OAR group.

OAR Group	W_{OAR}
Toddler	0.3146
Booster	0.3061
Belted	0.3793

Table 6. Real-world weighting factors - impact severity.

Impact Severity	W_{impact}
Direct	0.6224
Indirect	0.3776

Non-Weighted Analysis

The authors believe that it was necessary to exercise caution when using the ratio inflation factor to establish a national representation. As explained in NASS Analytical User's Manual the NASS observations are a probability sample. As previously mentioned, approximately 5,000 crashes are sampled each year and multiplied by a weighting factor commonly known as the ratio inflation factor. This provides a nationwide estimate as to the frequency of similar crashes occurring within the entire USA. In this study, due to the small number of cases for each of the given crash conditions (i.e. when considering the various combinations of intrusion, ΔV , and impact severity), there was an increased likelihood that these number cases were not sufficient in number, when weighted, to reasonably represent the overall crash population of police-reported tow-away crashes. As a result, the authors carried out this study using the NASS-CDS database sample without employing the ratio inflation factor. This paper is mostly an engineering study based on the non-weighted data, and is not necessarily representative of the overall crash population within the United States. Only [Table 1](#) and [Table 2](#) were based on weighted data.

ANALYSIS OF NASS-CDS DATA - DEVELOPMENT OF FIELD MODEL SIMULATIONS

Based on the NASS-CDS case selection criteria, occupant classification, and impact characterization (intrusion, ΔV , impact severity) there were a total of 588 cases available for

analysis. The NASS-CDS data were used to derive real-world weighting factors (not to be confused with the NASS-CDS ratio inflation factor) that could be used to weight the injury risk data. Based on the data, weighting factors were calculated based on (1) OAR group, (2) Impact Severity, (3) Estimated ΔV (km/h), and (4) Estimated Intrusion. The following sub-sections (0-0) provide the initial weighting factors calculated for use in this study.

Occupant Appropriate Restraints

The majority of child occupants in the study sample were qualified to be restrained in an adult safety belt system based on their combination of occupant age, height and weight (38%). Toddler and booster type occupants each comprised 31% of the study sample of NASS-CDS data. The following real-world weighting factors were determined for each OAR group ([Table 5](#)).

Impact Severity

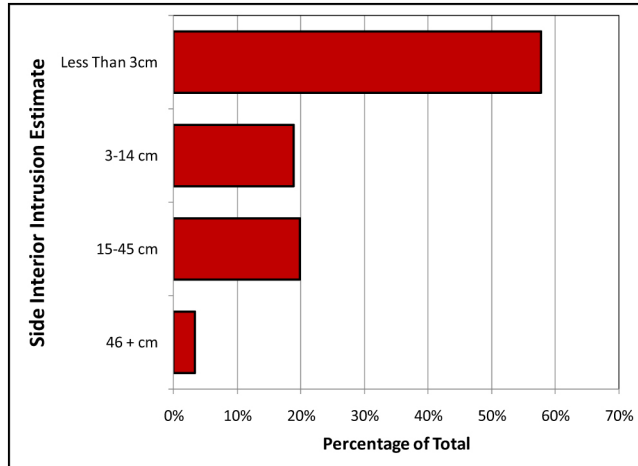
Approximately two-thirds of the child occupants were exposed to a *Direct* Impact where the damage was observed to have overlapped the rear occupant seating position ([Figure 2](#)). Based on these data the following real-world weighting factors were assigned for each impact severity group ([Table 6](#)).

Intrusion Estimate

More than half of the side impact crashes were observed to have less than 3 centimeters of intrusion of the side interior door into the occupant seating position (see [Figure 3](#)). Almost two-fifths of impacts were either 3-14 cm, or 15-45 cm.

Table 7. Real-world weighting factors - intrusion estimate.

Intrusion	$W_{\text{intrusion}}$
Intrusion Level 1: 0-2 cm	0.5765
Intrusion Level 2: 3-14 cm	0.1888
Intrusion Level 3: 15-45 cm	0.2007
Intrusion Level 4: 46+ cm	0.0340

**Figure 3. Distribution of intrusion into occupant region of the child on the struck side.**

Based on these data the following real-world weighting factors were determined for each intrusion range (see [Table 7](#)).

ACCUMULATED INJURY RISK

Laituri et al. (2003) used these real-world weighting factors to develop a weighted injury risk for each of the given combinations of crash events.

Occupant injury risk assessment based on crash conditions

A matrix was developed to consider the possible permutations of impact scenario. As previously mentioned, there were 588 child occupant cases that matched the NASS-CDS selection criteria. It was necessary to define the simulation matrix to ensure that each of the impact scenarios within the matrix could be assessed in terms of the AccIR. The input parameters for the simulation of the *Direct* Impact were defined to exclude consideration for the ΔV estimate. For the purposes of simulation, the magnitude of interior intrusion was considered to be the primary indicator of crash severity trauma in *Direct* impacts. As previously mentioned in the introduction, in lateral crashes on the struck side of the vehicle, direct contact of the child's head and face with the side interior surface of the vehicle accounts for the greatest percentage of Harm ([Scullion, 2009](#); [Bohman, 2009](#); [Scullion, 2008a](#); [Sullivan, 2009](#)). For the *Direct* impact there were a total of 12 impact scenarios:

1 (Impact Severity) x 4 (Intrusion Levels) x 3 (OAR Groups)...
= 12 Impact Scenarios

The occupant injury risk assessment for *Direct* impacts is expressed mathematically in [Equation 1](#).

$$AccIR(s) = \sum_{i=1}^{n=1 \text{ Severity}} \sum_{j=1}^{n=4 \text{ Intrusion}} \dots \sum_{l=1}^{n=3 \text{ OAR groups}} W_i(s) * \max[R_{ijkl}^{AIS2+}(s)]$$

Equation 1: Equation for Accumulated Injury Risk Metric - Direct Impact

The input parameters to be considered for the *Indirect* Impact were also defined. In only 3% of *Indirect* impacts there was AIS 2+F injury sustained by the child occupant involved. As a result both the ΔV estimate and Intrusion levels were not considered when calculating the AccIR. For the *Indirect* impact there were a total of 3 simulations:

1 (Impact Severity) x 3 (OAR Groups) = 3 Impact Scenarios

In total, 15 impact scenarios were identified. Comparisons of field model and MADYMO simulations will be used to assess the occupant injury risk in both the presence and absence of a countermeasure designed to improve rear-row nearside child occupant safety, for each of these impact scenarios. The revised occupant injury risk assessment for *Indirect* impacts is expressed mathematically in [Equation 2](#).

$$AccIR(s) = \sum_{i=1}^{n=1 \text{ Severity}} \dots \sum_{l=1}^{n=3 \text{ OAR groups}} W_i(s) * \max[R_{ijkl}^{AIS2+}(s)]$$

Equation 2: Equation for Accumulated Injury Risk Metric - Indirect Impact

The data in [Table 8](#) shows the distribution of injuries for each of the 15 crash scenarios to be simulated by sled test in MADYMO. It should be noted that in *Indirect* crashes, across