Small Rear Occupant Side Impact Investigation

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Objective

- The **objective** – to predict the efficacy in the real-world of a modified car design over the entire range of near-side crashes where injuries occur to children.

- With knowledge of the real-world crash severity distribution, the overall effectiveness of alternative design approaches can be estimated by child dummy responses correlated with real-world injury.
Method

• Followed method of Korner, J., “A Method for Evaluating Occupant Protection by Correlating Accident Data with Laboratory Test Data,” SAE Paper No. 890747, and

Data: NASS-CDS Case Selection Criteria

- NASS-CDS 1993-2009
- General Area of Damage to the left or right side of the vehicle
- Vehicle model year 1985+
- Passenger cars and light truck vehicles
- Occupants aged 1-12 years old
- Occupants seated on *near-side* of the rear-row
- . . . not fully ejected from the vehicle
- . . . no vehicles involved in a rollover or fire
NASS-CDS: Crash Involvement for Children Compared to Adult

Children account for approximately *1 in 20* of *ALL near-side occupants* in near-side lateral crashes.

<table>
<thead>
<tr>
<th>Impact Type</th>
<th>Child (1-12)</th>
<th>Adult (13+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side Impact - Nearsie</td>
<td>6%</td>
<td>94%</td>
</tr>
<tr>
<td>Side Impact - Farside</td>
<td>10%</td>
<td>90%</td>
</tr>
<tr>
<td>Frontal Impact</td>
<td>8%</td>
<td>92%</td>
</tr>
<tr>
<td>Rear Impact</td>
<td>10%</td>
<td>90%</td>
</tr>
<tr>
<td>Unknown / Other</td>
<td>10%</td>
<td>90%</td>
</tr>
<tr>
<td><strong>All</strong></td>
<td><strong>8%</strong></td>
<td><strong>92%</strong></td>
</tr>
</tbody>
</table>
NASS-CDS: Injury Risk for Children Highest for Near-Side Crash

Near-side child occupants have a higher risk of MAIS 2+Fatality injury compared to children in other crash modes.

<table>
<thead>
<tr>
<th></th>
<th>Child (1-12)</th>
<th>Adult (13+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side Impact - Nearside</td>
<td>5%</td>
<td>9%</td>
</tr>
<tr>
<td>Side Impact - Farside</td>
<td>2%</td>
<td>6%</td>
</tr>
<tr>
<td>Frontal Impact</td>
<td>2%</td>
<td>8%</td>
</tr>
<tr>
<td>Rear Impact</td>
<td>1%</td>
<td>3%</td>
</tr>
<tr>
<td>Unknown / Other</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td><strong>All</strong></td>
<td><strong>2%</strong></td>
<td><strong>7%</strong></td>
</tr>
</tbody>
</table>
NASS-CDS Cases with Near-Side Children

• Based on these case selection criteria there were 588 child occupants that qualified for inclusion in this analysis.

• To assess the child occupant injury rates each of the crashes was then assigned an impact severity, age distribution, and range of near-side interior intrusion.
Real-World Crash Data
Frequencies at Rear Seat

- Occupant Age Categorization (3 groups)
- Impact Severity (2 groups, Direct Crash and Indirect Crash)
- Intrusion for Direct Crash (4 groups)
- Delta-V for Indirect Crash
Theoretical Risk Assessment Procedure

A field model was constructed to evaluate real-world crash injury risk for children.

<table>
<thead>
<tr>
<th></th>
<th>TODDLER</th>
<th></th>
<th>BOOSTER</th>
<th></th>
<th>BELTED</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ALL</td>
<td>MAIS 2+F</td>
<td>ALL</td>
<td>MAIS 2+F</td>
<td>ALL</td>
<td>MAIS 2+F</td>
</tr>
<tr>
<td>Indirect</td>
<td>*</td>
<td>71</td>
<td>2</td>
<td>66</td>
<td>2</td>
<td>85</td>
</tr>
<tr>
<td>Direct</td>
<td>Less Than 3cm</td>
<td>43</td>
<td>5</td>
<td>33</td>
<td>1</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>3-14 cm</td>
<td>31</td>
<td>2</td>
<td>33</td>
<td>3</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>15-45 cm</td>
<td>36</td>
<td>11</td>
<td>40</td>
<td>12</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>46 + cm</td>
<td>4</td>
<td>1</td>
<td>8</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>185</td>
<td>21</td>
<td>180</td>
<td>25</td>
<td>223</td>
</tr>
</tbody>
</table>

- **Occupant Age** [3 groups]
- **Impact Severity** [2 Groups, Direct and Indirect]
- **Intrusion** [Direct – 4 groups] [Indirect – intrusion not used]
Impact Severity
Divide into Direct And Indirect Crash

‘INDIRECT’ Impact
Direct damage does not overlap proximal to the rear occupant seating position

‘DIRECT’ Impact
Direct damage overlaps proximal to the rear occupant seating position
Direct Impact and Intrusion
Four Levels of Side Interior Intrusion

Based on NASS-CDS crash investigation measurements of *side interior intrusion* (e.g., side door panel, vehicle pillars, etc.):

- **Level 1** Less than 3-cm
- **Level 2** 3-cm to 14-cm
- **Level 3** 15-cm to 45-cm
- **Level 4** 46-cm or greater

**Indirect Impact** *not based on intrusion.*
Accumulated Injury Risk Metric (AccIR)

Direct Impact

\[ \text{AccIR} = \sum_{i=1}^{\text{n=4 Intrusions}} \sum_{j=1}^{\text{n=1 Severity}} \sum_{k=1}^{\text{n=3 AgeGroups}} W_{ijk} \left[ P^{AIS\ 2+} \right]_{ijk} \]

Indirect Impact

\[ + \sum_{j=1}^{\text{n=1 Severity}} \sum_{k=1}^{\text{n=3 AgeGroups}} W_{jk} \left[ P^{AIS\ 2+} \right]_{jk} \]

\[ W_{ijk} = W_{\text{Intrusions}} W_{\text{severity}} W_{\text{age}} \]

\[ W_{jk} = W_{\text{severity}} W_{\text{age}} \]

\[ \left[ P^{AIS\ 2+} \right]_{ijk} = \text{Probability of an AIS 2+ Injury to near-side rear-row child occupant} \]
# Real-World Weighting Factors (for AccIR)

<table>
<thead>
<tr>
<th>Direct</th>
<th>Indirect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Impact Severity</strong></td>
<td><strong>Impact Severity</strong></td>
</tr>
<tr>
<td>$W_{impsev\ (Dir)} = 0.62$</td>
<td>$W_{impsev\ (Ind)} = 0.38$</td>
</tr>
<tr>
<td><strong>Intrusion</strong></td>
<td><strong>Intrusion</strong></td>
</tr>
<tr>
<td>$W_{Intrusion\ (Level\ 1)} = 0.58$</td>
<td>$W_{Intrusion\ (Level\ 1)}$</td>
</tr>
<tr>
<td>$W_{Intrusion\ (Level\ 2)} = 0.19$</td>
<td>$W_{Intrusion\ (Level\ 2)}$</td>
</tr>
<tr>
<td>$W_{Intrusion\ (Level\ 3)} = 0.20$</td>
<td>$W_{Intrusion\ (Level\ 3)}$</td>
</tr>
<tr>
<td>$W_{Intrusion\ (Level\ 4)} = 0.03$</td>
<td>$W_{Intrusion\ (Level\ 4)}$</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td><strong>Age</strong></td>
</tr>
<tr>
<td>$W_{age\ (Toddr)} = 0.32$</td>
<td>$W_{age\ (Toddr)} = 0.31$</td>
</tr>
<tr>
<td>$W_{age\ (Boost)} = 0.30$</td>
<td>$W_{age\ (Boost)} = 0.30$</td>
</tr>
<tr>
<td>$W_{age\ (Beltd)} = 0.38$</td>
<td>$W_{age\ (Beltd)} = 0.39$</td>
</tr>
<tr>
<td><strong>DeltaV</strong></td>
<td><strong>DeltaV</strong></td>
</tr>
<tr>
<td>$W_{deltav\ (Low)} = 0.58$</td>
<td>$W_{deltav\ (Low)}$</td>
</tr>
<tr>
<td>$W_{deltav\ (Med)} = 0.39$</td>
<td>$W_{deltav\ (Med)}$</td>
</tr>
<tr>
<td>$W_{deltav\ (High)} = 0.04$</td>
<td>$W_{deltav\ (High)}$</td>
</tr>
</tbody>
</table>
Theoretical Risk Assessment Procedure

Direct Impact

(1) Impact Severity
  x (4) Intrusion
  x (3) Occupant Size

12 Impact Scenarios

Indirect Impact

(1) Impact Severity
  x (3) Occupant Size

3 Impact Scenarios

15 Impact Scenarios used for calculation of AccIR
Accumulated Injury Risk Metric (AccIR)

\[
\text{AccIR} = \sum_{i=1}^{n=4} \sum_{j=1}^{n=1} \sum_{k=1}^{n=3} W_{ijk} \left[ P_{\text{AIS 2+}} \right]_{ijk} \\
\]

**Direct Impact**

**Indirect Impact**

\[
W_{ijk} = W_{\text{Intrusions}} W_{\text{Severity}} W_{\text{Age}} \\
W_{jk} = W_{\text{Severity}} W_{\text{Age}} \\
\left[ P_{\text{AIS 2+}} \right]_{ijk} = \text{Probability of an AIS 2+ Injury to near-side rear-row child occupant}
\]

**Real World Weighting Factors**
## Calculating AccIR

### Intrusion Est
<table>
<thead>
<tr>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>57.8%</td>
<td>18.9%</td>
<td>19.9%</td>
<td>3.4%</td>
</tr>
</tbody>
</table>

### Impact Severity

<table>
<thead>
<tr>
<th>Indirect</th>
<th>Direct</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.8%</td>
<td>62.2%</td>
</tr>
</tbody>
</table>

### Age

<table>
<thead>
<tr>
<th>Toddler</th>
<th>Booster</th>
<th>Belted</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.5%</td>
<td>30.6%</td>
<td>37.9%</td>
</tr>
</tbody>
</table>

### MAIS 2+F Injury Risk

<table>
<thead>
<tr>
<th>MAIS 2+F Injury Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toddler</td>
</tr>
<tr>
<td>2.8%</td>
</tr>
</tbody>
</table>

### Event Injury Risk

<table>
<thead>
<tr>
<th>Event Injury Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.6%</td>
</tr>
</tbody>
</table>

### Involvement Risk (IR)

<table>
<thead>
<tr>
<th>Involvement Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8%</td>
</tr>
</tbody>
</table>

**Non-weighted**
Scaling Techniques in Biomechanics

- Risks to the children were calculated by combining biomechanical risk curves for the child with the model simulations.
- NHTSA proposed head injury curves expanded from the Prasad/Mertz AIS ≥ 4 brain injury curves. The curves went from AIS = 1 through to fatal head injury.
- The equation (male adult) for AIS ≥ 2 is \( \text{Prob} = [1 + \exp((2.49 + 200/\text{HIC}) - 0.00483 \text{HIC})]^{-1} \)
Adult curves proposed by NHTSA expanded from Prasad/Mertz AIS ≥ 4 brain injury curves (AIS 1 – Fatal)
Scaling Techniques in Biomechanics

- Scaling ratios (\(\lambda\)) are used based on fundamental properties.
- \(\lambda = \lambda_{\text{child}} / \lambda_{\text{adult}}\)
- Following Melvin (SAE Paper No. 950872, Feb – Mar 1995), when scaling data from adults to children, differences in moduli of elasticity should be considered.
Scaling Techniques in Biomechanics

- Length $\lambda_{\text{length}} = \frac{L_{\text{child}}}{L_{\text{adult}}}$
- Modulus of elasticity $\lambda_{E} = \frac{E_{\text{child}}}{E_{\text{adult}}}$
- Time $\lambda_{T} = \lambda_{\text{length}} / (\lambda_{E})^{1/2}$
- Acceleration $\lambda_{A} = \lambda_{E} / \lambda_{\text{length}}$
- HIC $\lambda_{HIC} = \frac{(\lambda_{E})^{2}}{(\lambda_{\text{length}})^{1.5}}$
## Scaling Techniques in Biomechanics

<table>
<thead>
<tr>
<th></th>
<th>10 Year Old</th>
<th>6 Year Old</th>
<th>3 Year Old</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{\text{length}}$</td>
<td>0.931</td>
<td>0.914</td>
<td>0.876</td>
</tr>
<tr>
<td>$\lambda_{\text{bone E}}$</td>
<td>0.854</td>
<td>0.667</td>
<td>0.475</td>
</tr>
<tr>
<td>$\lambda_{\text{HIC}}$</td>
<td>0.812</td>
<td>0.509</td>
<td>0.275</td>
</tr>
</tbody>
</table>

Values for $\lambda_{\text{length}}$ and $\lambda_{\text{bone E}}$ taken from Mertz, Irwin, and Prasad, Stapp 2003.
Scaling Techniques in Biomechanics

Using $\lambda_{\text{HIC}} = \frac{\text{HIC}_{\text{child}}}{\text{HIC}_{\text{adult}}}$, the equations for AIS $\geq 2$ (head injury) are:

$$P_{\text{adult}} = \left[1 + \exp((2.49 + \frac{200}{\text{HIC}}) - 0.00483 \times \text{HIC})\right]^{-1}$$

$$P_{10YO} = \left[1 + \exp((2.49 + \frac{162}{\text{HIC}}) - 0.00595 \times \text{HIC})\right]^{-1}$$

$$P_{6YO} = \left[1 + \exp((2.49 + \frac{102}{\text{HIC}}) - 0.00949 \times \text{HIC})\right]^{-1}$$

$$P_{3YO} = \left[1 + \exp((2.49 + \frac{55}{\text{HIC}}) - 0.01756 \times \text{HIC})\right]^{-1}$$
Compact vehicle used in MADYMO simulations of side impact

Started with a finite element model of a compact vehicle, Kia Forte.

Validated FEM structural response against actual NCAP data

Incorporated FEM interior into MADYMO sled model for simulations with child occupant
Human Facet child model used in MADYMO side impact simulations

- Used the 3-year-old, 6-year-old, and 10-year-old human child model.
- The MADYMO human facet model has a flexible spine → models each vertebral segment with individual rigid bodies.
MADYMO Human Facet Model of Child

1.5yo  3yo  6yo  10yo
Simulating the 5 Impact Severities for Side Impact

5 levels of crash severity based on real world classification

<table>
<thead>
<tr>
<th>Intrusion Level</th>
<th>Delta- V</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>15.7 km/hr</td>
<td>Indirect Crash</td>
</tr>
<tr>
<td>0-2 cm</td>
<td>17.5 km/hr</td>
<td>Direct Crash 1</td>
</tr>
<tr>
<td>3 – 14 cm</td>
<td>19.0 km/hr</td>
<td>Direct Crash 2</td>
</tr>
<tr>
<td>15 – 45 cm</td>
<td>25.8 km/hr</td>
<td>Direct Crash 3</td>
</tr>
<tr>
<td>&gt; 45 cm</td>
<td>45.0 km/hr</td>
<td>Direct Crash 4</td>
</tr>
</tbody>
</table>
6YO Simulations

Direct 1

Direct 3
# 6YO Injury Risk (AIS ≥ 2) Simulation Results

<table>
<thead>
<tr>
<th>Impact Severity</th>
<th>Head</th>
<th>Pelvis</th>
<th>Highest Risk, R(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HIC 36</td>
<td>Risk, R(%)</td>
<td>Peak G's</td>
</tr>
<tr>
<td>Indirect (No Intrusion)</td>
<td>61</td>
<td>2.7%</td>
<td>19</td>
</tr>
<tr>
<td>Direct 1 (&lt;3 cm Intrusion)</td>
<td>63</td>
<td>2.9%</td>
<td>18</td>
</tr>
<tr>
<td>Direct 2 (3-14 cm Intrusion)</td>
<td>135</td>
<td>12.3%</td>
<td>29</td>
</tr>
<tr>
<td>Direct 3 (15-45 cm Intrusion)</td>
<td>216</td>
<td>28.7%</td>
<td>35</td>
</tr>
<tr>
<td>Direct 4 (&gt;45 cm Intrusion)</td>
<td>509</td>
<td>89.5%</td>
<td>111</td>
</tr>
</tbody>
</table>

Impact Severity:
- **Head**
- **Pelvis**

Highest Risk, R(%):
- **HIC 36 Risk, R(%)**
- **Peak G's Risk, R(%)**
- **Highest Risk, R(%)**
### 6YO Real-World v. Simulation

<table>
<thead>
<tr>
<th>Impact Severity</th>
<th>Involvement Rate (%)</th>
<th>Event Injury Risk, R(%)</th>
<th>Involvement Risk, IR(%)</th>
<th>Accumulated Injury Risk, AccIR(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Real-World</td>
<td>Simulation</td>
<td>Real-World</td>
<td>Simulation</td>
</tr>
<tr>
<td>Indirect (No Intrusion)</td>
<td>11.6</td>
<td>3.0</td>
<td>2.7</td>
<td>0.35</td>
</tr>
<tr>
<td>Direct 1 (&lt;3 cm Intrusion)</td>
<td>11.0</td>
<td>3.0</td>
<td>2.9</td>
<td>0.33</td>
</tr>
<tr>
<td>Direct 2 (3-14 cm Intrusion)</td>
<td>3.6</td>
<td>9.1</td>
<td>12.3</td>
<td>0.33</td>
</tr>
<tr>
<td>Direct 3 (15-45 cm Intrusion)</td>
<td>3.8</td>
<td>30.0</td>
<td>28.7</td>
<td>1.14</td>
</tr>
<tr>
<td>Direct 4 (&gt;45 cm Intrusion)</td>
<td>0.6</td>
<td>87.5</td>
<td>89.5</td>
<td>0.57</td>
</tr>
</tbody>
</table>
6YO Event Risk - Crash Severity

Probability of AIS2+ Injury
6-Year-Old

Risk, R(%) vs. Involvement Rate (%)

Crash Severity
- Indirect (No Intrusion)
- Direct 1 (<3 cm Intrusion)
- Direct 2 (3-14 cm Intrusion)
- Direct 3 (15-45 cm Intrusion)
- Direct 4 (>45 cm Intrusion)

- Real-World
- Simulation
- Involvement Rate

Probability values for different crash severities and involvement rates.
6YO Injury Involvement Risk
Product of the event risk and involvement rate

![Graph showing involvement risk for 6-year-old children in different crash severities (Indirect (No Intrusion), Direct 1 (<3 cm Intrusion), Direct 2 (3-14 cm Intrusion), Direct 3 (15-45 cm Intrusion), Direct 4 (>45 cm Intrusion)). The graph compares real-world and simulation data, as well as involvement rate.](Image)
6YO Accumulated Injury Risk
The summation of the involvement injury risks

Accumulated Injury Risk
6-Year-Old

Crash Severity
Real-World  Simulation

Accumulated Weighted Injury Risk, AccIR(%)
Discussion

• NASS-CDS has crash data on a total of 588 children.

• The side impact crash severity was divided into a direct impact into the rear-seat occupant compartment and an indirect impact without any intrusion into the occupant’s compartment.

• Simulations for the 6-year-old children suggest reasonable levels of correlation with real-world risk assessment for each crash severity levels.
Discussion (continued)

• On-going simulations continue with the 3-year-old human facet model and the 10-year-old human facet model.

• To predict the effect of a countermeasure, the model simulations will be redone for the child human facet models with the introduction of the countermeasure.
Acknowledgements

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Thank you for your Attention...