Does Unbelted Safety Requirement Affect Protection for Belted Occupants?

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Background & Objective

• Background:
  – Seatbelt can reduce fatality risk by more than 50%
  – Seat belt use rate in the US is about 86%
  – Seatbelt interlock $\rightarrow$ ~100% seatbelt use rate
  – NHTSA belted and unbelted requirements

• Objective:
  – To compare the performance of restraint systems optimized for belted only occupants with those optimized for both belted and unbelted occupants through computational design optimizations
Technical Schematic

Baseline Model Selection
- Select two baseline FE models for restraint optimization
  - Mid-size Sedan
    - Validated against tests
  - Mid-size SUV
    - Validated against tests

Parametric FE Simulations
- Conduct parametric simulations within a design space
  - Unbelted DOE
    - 50th and 5th ATDs
    - Driver and passenger
    - 6N simulations in each condition sample by ULHS
    - Statistical analysis
  - Belted DOE
    - 50th and 5th ATDs
    - Driver and passenger
    - 6N simulations in each condition sampled by ULHS
    - Statistical analysis

RSM Models
- RSM-Unbelted
  - RBF surrogate models
  - Error evaluation of the surrogate models
- RSM-Belted
  - RBF surrogate models
  - Error evaluation of the surrogate models

Design Optimization
- Conduct optimizations for restraint systems with and without unbelted requirements based on RSM models
  - Belted only
    - Objective: 50th and 5th ATD Pjoint in NCAP
    - Constraint: ODB
  - Belted & Unbelted
    - Objective: 50th and 5th ATD Pjoint in NCAP
    - Constraint: ODB and unbelted requirements

Field Performance Evaluation
- Weighted injury estimation based on injury risk ratios between two optimal designs

Field Data Analysis
- Typical crash conditions for simulations
- Current injury counts
- Weighting functions for performance evaluation

FE Simulations
- FE vehicle models to generate crash pulses
- Simulations in typical crash conditions
- Injury risk ratios between two designs

Do results with optimal designs match FE simulations?
No
Yes
Baseline Model Selection

- Mid-size Sedan
- Mid-size SUV
Vehicle Baseline Model Correlations

- Sedan Driver – 50\textsuperscript{th} Male
- SUV Driver – 5\textsuperscript{th} Female
Objectives & Constraints

## Belted Occupants

<table>
<thead>
<tr>
<th>Test</th>
<th>Driver</th>
<th>Passenger</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 mph Rigid Barrier*</td>
<td>50th male</td>
<td>50th male</td>
</tr>
<tr>
<td>35 mph Rigid Barrier*</td>
<td>5th female</td>
<td>5th female</td>
</tr>
</tbody>
</table>

*Has to meet occupant safety regulatory requirements

## Unbelted Occupants

<table>
<thead>
<tr>
<th>Test</th>
<th>Angle in degrees</th>
<th>Driver</th>
<th>Passenger</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 mph Rigid Barrier</td>
<td>0</td>
<td>5th female</td>
<td>5th female</td>
</tr>
<tr>
<td>25 mph Rigid Barrier</td>
<td>0 (-30 to 30)*</td>
<td>50th male</td>
<td>50th male</td>
</tr>
</tbody>
</table>

* Zero-degree was the main condition for restraint optimization, but -30 and 30 degree crash conditions were checked after restraint optimization to make sure that they meet regulatory requirements.
Objectives
NCAP Injury Assessment

- Belted

<table>
<thead>
<tr>
<th></th>
<th>HIII 50M dummy</th>
<th>HIII 5F dummy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Head</strong> (HIC15)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{\text{head}}(\text{AIS3}+) = \Phi \left( \frac{\ln(\text{HIC15}) - 7.45231}{0.73998} \right) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Where ( \Phi = \text{cumulative normal distribution} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Neck</strong> (N( _{ij} ) and tension / compression in kN)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{\text{Ni}}(\text{AIS3}+) = \frac{1}{1 + e^{3.2269-1.9688N_{ij}}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{T}(\text{AIS3}+) = \frac{1}{1 + e^{10.9745-2.375T}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{C}(\text{AIS3}+) = \frac{1}{1 + e^{10.9745-2.375C}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{\text{neck}} = \text{Max}(P_{\text{Ni}}, P_{T}, P_{C}) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{\text{Ni}}(\text{AIS3}+) = \frac{1}{1 + e^{3.2269-1.9688N_{ij}}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{T}(\text{AIS3}+) = \frac{1}{1 + e^{10.9745-3.770T}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{C}(\text{AIS3}+) = \frac{1}{1 + e^{10.9745-3.770C}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{\text{neck}} = \text{Max}(P_{\text{Ni}}, P_{T}, P_{C}) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Chest</strong> (deflection in mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{\text{ch}}(\text{AIS3}+) = \frac{1}{1 + e^{10.5456-1.568*D^{0.4612}}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{\text{ch}}(\text{AIS3}+) = \frac{1}{1 + e^{10.5456-1.7212*D^{0.4612}}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Femur</strong> (force in kN)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{\text{femur}}(\text{AIS2}+) = \frac{1}{1 + e^{5.7955-0.5196F}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{\text{femur}}(\text{AIS2}+) = \frac{1}{1 + e^{5.7949-0.7619F}} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ P_{\text{joint}} = 1 - (1 - P_{\text{head}}) \times (1 - P_{\text{neck}}) \times (1 - P_{\text{chest}}) \times (1 - P_{\text{femur}}) \]
Constraints
FMVSS208 Injury Assessment

- Unbelted

<table>
<thead>
<tr>
<th>Body Region</th>
<th>Parameter</th>
<th>50M dummy</th>
<th>5F dummy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>HIC-15</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>Neck</td>
<td>Nij</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Neck axial tension (kN)</td>
<td>4.17</td>
<td>2.62</td>
</tr>
<tr>
<td></td>
<td>Neck compression (kN)</td>
<td>4.0</td>
<td>2.52</td>
</tr>
<tr>
<td>Chest</td>
<td>Chest acceleration (3ms, g)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Sternum deflection (mm)</td>
<td>63</td>
<td>52</td>
</tr>
<tr>
<td>Leg</td>
<td>Femur axial force (kN)</td>
<td>10</td>
<td>6.805</td>
</tr>
</tbody>
</table>
# Design Parameters

<table>
<thead>
<tr>
<th>LS-DYNA parameter</th>
<th>Description</th>
<th>Baseline</th>
<th>Lower bound</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCINCH</td>
<td>Cinching plate inactive/active</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>DAPTTTB</td>
<td>Anchor pretensioner no/yes</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>DSBLev1 (N)</td>
<td></td>
<td>2850</td>
<td>2000</td>
<td>4000</td>
</tr>
<tr>
<td>DSBLev2 (N)</td>
<td></td>
<td>2850</td>
<td>2000</td>
<td>4000</td>
</tr>
<tr>
<td>DSBPay1 (mm)</td>
<td></td>
<td>150</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>DVentD (mm)</td>
<td>Static vent diameters (two holes)</td>
<td>35</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>DVentDD (mm)</td>
<td>Dynamic vent diameter (one hole)</td>
<td>0</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>DVentDT (ms)</td>
<td>Dynamic vent time</td>
<td>30</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>DtethA (mm)</td>
<td>Lower tether length</td>
<td>260</td>
<td>100</td>
<td>300</td>
</tr>
<tr>
<td>DtethC (mm)</td>
<td>Upper tether length</td>
<td>290</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>DMassR</td>
<td>Inflator flow factor</td>
<td>1</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>CBL (N)</td>
<td>Steering column load</td>
<td>3000</td>
<td>2000</td>
<td>4000</td>
</tr>
</tbody>
</table>

<table>
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<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>PAPTTTB</td>
<td>Anchor pretensioner no/yes</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>PSBLev1 (N)</td>
<td></td>
<td>2850</td>
<td>2000</td>
<td>4000</td>
</tr>
<tr>
<td>PSBLev2 (N)</td>
<td></td>
<td>2850</td>
<td>2000</td>
<td>4000</td>
</tr>
<tr>
<td>PSBPay1 (mm)</td>
<td></td>
<td>150</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>PVentD (mm)</td>
<td>Static vent diameters (two holes)</td>
<td>60</td>
<td>30</td>
<td>90</td>
</tr>
<tr>
<td>PVentDD (mm)</td>
<td>Dynamic vent diameter (one hole)</td>
<td>0</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>PVentDT (ms)</td>
<td>Dynamic vent time</td>
<td>50</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>PtethA (mm)</td>
<td>Upper tether length</td>
<td>460</td>
<td>360</td>
<td>560</td>
</tr>
<tr>
<td>PMassR</td>
<td>Inflator flow factor</td>
<td>1</td>
<td>0.8</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Optimization Procedure

1. DOE runs (ULHS)
   - 72 runs for belted occupants in each condition
   - 42 runs for unbelted occupants in each condition
2. RSM (Radial Basis Function)
3. Virtual optimization (NSGA-II)
4. Optimal solution check with Ls-Dyna runs
   - If not satisfied, rerun items 2-4
   - If satisfied, done
Sedan Optimum

- Driver
- Passenger

Results from Ls-dyna runs
SUV Optimum

- Driver

Orange dots indicate violations of unbelted requirements

Results from Ls-dyna runs
Design Optimization Summary

- Optimizations significantly reduced $P_{\text{joint}}$ values for both 5\textsuperscript{th} and 50\textsuperscript{th} ATDs in NCAP crash conditions from the baseline model.
- Unbelted requirements do not affect the optimal designs in 3 out of 4 vehicle/side conditions, except for the SUV passenger side.
- Knee bolster design parameters were not included in the optimization, because the knee-to-bolster contacts are small for belted occupants.
Final Optimal Designs - Sedan

- Knee bolsters were removed for the “Belted-only” optimal designs

Driver

Passenger

Cost reduction: $2.92
Mass reduction: 1.27 kg
Final Optimal Designs - SUV

• Knee bolsters were removed for the “Belted-only” optimal designs

Driver

Passenger

Blue parts removed

Reduce gage from 1.5mm to 1.0mm

Cost reduction: $3.04
Mass reduction: 1.37 kg
Field Performance - Simulation Matrix

- 11 crash scenarios (Venza full barrier, ODB, pole, frontal and offset crash to Yaris, Taurus, Explorer, and Silverado)
- 5 impact speeds for each crash scenarios (15, 20, 25, 30, 35mph)
- 2 vehicles (sedan vs. SUV)
- 2 ATDs (5th vs. 50th)
- 2 sides (driver vs. passenger)
- 2 designs (belted only vs. belted&unbelted)
- 2 belt conditions (belted vs. unbelted)

1760 runs in total
Field Performance Example

35mph Full Frontal Venza-Explorer Belted Case

Vehicle crash simulation

Prescribed motion to the occupant compartment

- SUV model
- sedan model

5th female passenger

5th female driver

50th male driver
Simulation Results: Phead

- Belted, WUB
- Unbelted, WUB
- Belted, WOUB
- Unbelted, WOUB

delta V (km/hr)

Phead
Regression Curves for Simulated Phead

**Phead, sedan**
- Dashed: unbelted
- Solid: belted
- Thin: with unbelted requirement
- Thick: without unbelted requirement
- Dark: full frontal
- Light: offset frontal
- Small Sedan
- Large Sedan
- Pickup
- SUV
- Barrier
- Pole

**Phead, SUV**
- Dashed: unbelted
- Solid: belted
- Thin: with unbelted requirement
- Thick: without unbelted requirement
- Dark: full frontal
- Light: offset frontal
- Small Sedan
- Large Sedan
- Pickup
- SUV
- Barrier
- Pole
Estimating Baseline Injury Risk

- Generate injury risk models for each body region as a function of \( \ln(\text{delta V}) \), belt use, crash partner, crash type
- Use occupants in 2002-2012 CDS as the standard population
- \( P = \frac{1}{1 + \exp[-(\text{intercept} + \ln(\text{dV}) \times (A + B_n \times \text{crash type} + C_n \times \text{crash partner} + D_n \times \text{belt use}) + E_n \times \text{(crash partner)} + F_n \times \text{(crash type)} + G_n \times \text{(crash partner)} \times \text{(crash type)} + \text{belt use} \times (H_n + J_n \times \text{crash type} + K_n \times \text{crash partner})]}} \)
Head Injury Risk Model

- Dashed: unbelted
- Solid: belted
- Thin: with knee bolster
- Thick: without knee bolster
- Dark: full frontal
- Light: offset frontal
- Small Sedan
- Large Sedan
- Pickup
- SUV
- Barrier
- Pole

Delta V (km/hr) vs. Phead

- BFFFB
- BFFLS
- BFFPU
- BFFSUVA
- BFFSS
- BNCPT
- BLOFB
- BLOLS
- BLOPU
- BLOSS
- BLOPU*
- BLOSS*
- BFFFB*
- BFFLS*
- BFFSUVA*
- BFFSS*
- BNCPT*
- BLOFB*
- BLOLS*
- UFFFB
- UFFLS
- UFFPU
- UFFSUVA
- UFFSS
- UNCPT
- ULOFB
- ULOLS
- ULOPU
- ULOSS
- ULOSUVA
- ULOSS*
Estimated Total Injury Percentage to The Current Injury Counts

Combining head/face, neck/C-spine, chest, and KTH injuries

Based on the FE-mode-predicted injury risk differences between WOUB and WUB

<table>
<thead>
<tr>
<th>Belted</th>
<th>Unbelted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.87</td>
</tr>
<tr>
<td>0.81</td>
<td>0.98</td>
</tr>
<tr>
<td>0.86</td>
<td>0.81</td>
</tr>
</tbody>
</table>

With current injury risks under different belt usage rates

Without unbelted requirements under different belt usage rates
Estimated Total Injury Percentage to The Current Injury Counts

Combining head/face, neck/C-spine, chest, and KTH injuries

Based on the FE-mode-predicted injury risk ratios between WOUB and WUB

With current injury risks under different belt usage rates

Without unbelted requirements under different belt usage rates

<table>
<thead>
<tr>
<th>Belted</th>
<th>Unbelted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>.87</td>
</tr>
<tr>
<td>.81</td>
<td>1.03</td>
</tr>
<tr>
<td>.81</td>
<td>.71</td>
</tr>
</tbody>
</table>
Summary

• Optimizations significantly reduced Pjoint values for both 5th and 50th ATDs in NCAP crash conditions from the baseline model.

• Unbelted requirements do not affect the optimal designs in 3 out of 4 vehicle/side conditions, except for the SUV passenger side.

• Removing the unbelted requirements will likely reduce the total injury risks for belted occupants in the field, but may increase the injury risks for unbelted occupants.
Limitations

• The crash pulses and vehicle kinematics used in the field performance evaluations are from a vehicle (Venza) that is different to and generally stiffer than the baseline sedan and SUV models.

• Different methods for calculating injury risk ratios will resulted in different trends in results for field performance evaluation. Further analysis is necessary.

• The design parameter ranges are relatively narrow, and further design changes focusing on belted occupants are needed.
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Thanks!

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