Difference in dummy responses in matched side impact tests of vehicles with and without side airbags

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ABSTRACT

Objective: Insurance Institute for Highway Safety (IIHS) high-hooded side impacts were analyzed for matched vehicle tests with and without side airbags. The comparison provides a measure of the effectiveness of side airbags in reducing biomechanical responses for near-side occupants struck by trucks, SUVs, and vans at 50 km/h.

Method: The IIHS moving deformable barrier (MDB) uses a high-hooded barrier face. It weighs 1,500 kg and impacts the driver side perpendicular to the vehicle at 50 km/h. SID 1s dummies are placed in the driver and left second-row seats. They represent fifth percentile female occupants.

IIHS tests were reviewed for matches with one test with a side airbag and another without it in 2003–2007 model year (MY) vehicles. Four side airbag systems were evaluated: (1) curtain and torso side airbags, (2) head and torso side airbag, (3) curtain side airbag, and (4) torso side airbag.

There were 24 matched IIHS vehicle tests: 13 with and without a curtain and torso side airbags, 4 with and without a head and torso side airbag, 5 with and without a side curtain airbag, and 2 with and without a torso airbag. The head, chest, and pelvis responses were compared for each match and the average difference was determined across all matches for a type of side airbag.

Results: The average reduction in head injury criterion (HIC) was 68 ± 16% (P < .001) with curtain and torso side airbags compared to the HIC without side airbags. The average HIC was 296 with curtain and torso side airbags and 1,199 without them. The viscous response (VC) was reduced 54 ± 19% (P < .005) with curtain and torso side airbags. The combined acetabulum and ilium force (7 ± 15%) and pelvic acceleration (−2 ± 17%) were essentially similar in the matched tests.

The head and torso side airbag reduced HIC by 42 ± 30% (P < .1) and VC by 32 ± 26% compared to vehicles without a side airbag. The average HIC was 397 with the side head and torso airbag compared to 729 without it. The curtain airbag and torso airbag only showed lower head responses but essentially no difference in the chest and pelvis responses.

Conclusion: The curtain and torso side airbags effectively reduced biomechanical responses for the head and chest in 50 km/h side impacts with a high-hooded deformable barrier. The reductions in the IIHS tests are directionally the same as estimated fatality reductions in field crashes reported by NHTSA for side airbags.

Introduction

Background on side impacts

Accident data from the 1950s and 1960s showed that vehicle crashes and fatalities were on the rise (Campbell 1965; Johnson 1965; Bondet al. 1967). Crash safety became a national issue. Field accident analyses identified door opening as a cause for ejection and serious injury (Garrett 1961; Lister and Nielson 1969; States and States 1968). Crash tests showed that door deformation and latch failure occurred in severe crashes and led to occupant compartment intrusion and occupant ejection particularly in side impacts (Severy et al. 1962). A need for strengthening and stiffening the door and reducing intrusion was identified in Europe (Cesari et al. 1978; Danner 1977).

Fisher Body Division of General Motors introduced side guard door beams in General Motors vehicles in 1969 to increase the possibility of side swipes being redirected rather than penetrating the door (Hedeen and Campbell 1969). At the same time, vehicle manufacturers were developing concepts to improve latch and hinge strength and to reduce door intrusion. The inclusion of a horizontal beam inside the door (door beam) and adding reinforcements became a design direction that reduced side-structure intrusion in crash tests without changing the vehicle external appearance (Fine and Dinda 1975).

In 1970, NHTSA issued FMVSS 214. The standard included a static strength requirement for vehicle doors. All passenger cars had to achieve minimum strength requirements by January 1, 1973 (see Kahane [2015] for changes to FMVSS 214). As a result,
door beams and improved structures were installed in all makes and models of cars sold in the United States. Jones (1977), Chi (1980), and Kahane (1982) evaluated the safety benefit associated with door beams. Kahane (1982) estimated that FMVSS 214 saved about 480 lives per year in single-vehicle side crashes and significantly reduced serious injuries in single- and multivehicle side impacts. He also reported little or no effect on fatalities in vehicle-to-vehicle side impacts.

FMVSS 214 was amended in 1990 and included a dynamic test simulating a right-angle vehicle-to-vehicle crash. The test requirements were phased into new passenger cars during the 1994–1997 model year (MY). The test consisted of a crabbled moving deformable barrier (MDB) striking the side of a vehicle at 48 km/h (30 mph). FMVSS 214 had front and rear near-side SID dummies. There were thorax and pelvis response requirements. There was no head requirement and side airbags were not required.

Blaisdell et al. (1994) summarized the history of door latch requirements and addressed the background for greater latch and door strength. New designs for energy-absorbing door panels and components were also introduced, such as foam blocks and airbags (Lorenzo et al. 1996).

Field data showed that further limiting vehicle intrusion and adding interior padding on the door would result in a lower real-world risk of injury and fatality in side impacts (Kahane 1999). Augenstein et al. (2000) investigated side impact crashes and found that near-side occupants had the highest risk for serious injury because of their proximity to intrusion. Many studies have shown that intrusion of the occupant compartment is associated with more severe crashes, occupant injury, and death (Blum et al. 2008; Coimbra et al. 2008; Conroy et al. 2008; Stefanopoulos et al. 2003; Strother et al. 1984; Viano and Parenteau 2010).

Viano et al. (1990) showed that the height of the front of trucks was a factor in near-side impact injury, because the higher fronts deformed the side door of passenger cars above the sill. The speed and extent of intrusion were generally greater with trucks, SUVs, and vans impacting the side of passenger vehicles. These were factors in injury, particularly to older occupants, who were more prone to turning in front of oncoming vehicles (Ridella and Viano 1996; Sunnevang et al. 2015). Similar concerns were voiced by the Insurance Institute for Highway Safety (IIHS 2004).

The IIHS identified the need for a field-relevant barrier typifying a truck, SUV, and van. The FMVSS 214 barrier was developed in the early 1980s and was representative of a passenger car. SUVs and pickups became more prevalent in the late 1990s. The risk for head injury from impacts with high-hooded vehicles could not be assessed with the FMVSS 214 barrier, which was below the head of the seated dummy. As a result, the IIHS began its side test program in 2003 with a barrier designed to represent the front end of a typical SUV and pickup.

**Side airbags and curtains**

Current U.S. regulations do not require side airbags. However, in 2003, most manufacturers entered into a voluntary agreement to improve occupant protection in side impacts with SUVs and pickups, which resulted in standardization of side airbags for head protection in light vehicles by the 2010 MY (IIHS 2006). The agreement was that side-impact head protection should be provided in all cars, SUVs, and pickups by the 2010 MY. Since 2014, most manufacturers provide side airbags and curtains to meet FMVSS 214 and FMVSS 226.

Figure 1 shows the distribution of side airbags based on the MY of the vehicles tested by the IIHS (www.iihs.org/iihs/ratings/safety-features). Table A1 (see online supplement) provides the IIHS data. The percentage with side airbags was 32.2% in 2000, 74.2% in 2005, and 91.5% in 2010; 47.5% of 2005 MY vehicles provided head and torso protection.

Figure 1 shows the percentage of vehicles equipped with side airbags by type and vehicle MY based on vehicles involved in fatal crashes in the Fatality Analysis Reporting System (FARS; Kahane 2014). Table A2 (see online supplement) provides the FARS data. The percentage of side airbag availability was greater in the IIHS sample than in FARS. Only 15% of vehicles were equipped with side airbags in 2000 FARS crashes. There were 28% in 2005 and 95% of vehicles in FARS in 2010. From 2000 to 2011 there was a steady increase in the number of vehicles with side curtains and torso airbags. By 2011, 85.8% of those MY vehicles had side curtains and torso airbags.

The safety benefits of side airbags have been evaluated. Mellander et al. (1989) were one of the first to assess side airbag effectiveness. They used laboratory tests with and without side airbags and estimated a reduction of 40% in serious to fatal injuries. However, McGwin et al. (2003) found similar injury risks in field data with front seat occupants of vehicles with and without side airbags. The risk ratio was 0.96 (95% confidence interval [CI], 0.79–1.15). The risk ratio was 0.90 (95% CI,
0.76–1.08) when adjusting for confounding factors such as age, gender, and seat belt use.

IIHS (2003) estimated a 45% reduction in deaths for car drivers struck on the near side with side airbag head protection and 11% without a side airbag. Braver and Kyrychenko (2004) reported an injury risk reduction in cars equipped with head/torso airbags (0.55 risk ratio; 95% CI, 0.43, 0.71) and with torso-only airbags (0.89 risk ratio; 95% CI, 0.79, 1.01) relative to cars without side airbags using FARS and General Estimates System data.

IIHS (2006) and McCartt and Kyrychenko (2007) found that side airbags with head protection reduced the risk of near-side driver fatality by 37 and 52% in SUV drivers. Kahane (2007) reported that torso plus head airbags reduced fatality risk for nearside occupants by an estimated 24%. Scarboro et al. (2007) noted that side airbags provided better protection in lateral crashes than in oblique crashes, partly because of the higher severity of the oblique crashes. Sunnevang et al. (2009) reported that side airbags were effective in reducing injury for 10- to 59-year-old occupants in crashes with delta V up to 40 km/h (25 mph). Airbag effectiveness varied with crash severity and direction of force.

IIHS has carried out a series of crash tests with and without side airbags. They reported some of their test results within the same model run. For example, they tested the 1997 BMW 528 with a torso airbag and 1998 BMW 528 with a head protection system and torso airbag in a 20 mph side impact into a 10-in.-round rigid pole. The head injury criterion (HIC) was more than 7 times higher without the head protection system than with (i.e., HIC 4,720 and 620, respectively). In 1999, IIHS compared the 29 km/h (18 mph) side-into-pole crash test results involving a 1998 Lincoln Town Car without side airbags and a 1999 Lincoln Town Car with a head and thorax side airbag. The HIC was 5390 without the side airbag and 376 with it.

In this study, the IIHS high-hooded side impact tests were analyzed for matched vehicles tested with and without side airbags. The comparison provides a measure of the effectiveness of side airbags for near-side occupants struck by trucks, SUVs, and vans at 50 km/h (31.1 mph).

Methodology

IIHS side impact with a high-hooded moving deformable barrier

The IIHS MDB uses a deformable aluminum barrier face on a standard FMVSS 214 side impact cart (IIHS 2014). The cart wheels are aligned with the longitudinal axis of the cart (0°) to allow a perpendicular impact. The front aluminum mounting plate is raised 100 mm higher off the ground and is 200 mm taller than a standard FMVSS 214 barrier. The IIHS deformable barrier has a top surface 300 mm higher off the ground than the FMVSS 214 barrier.

Figure A2 (see online supplement) shows the IIHS high-hooded MDB and test setup. The MDB test weight is 1,500 ± 5 kg (3,300 ± 11 lb.) with the deformable face, test instrumentation, camera, and camera mount. The side impact test consists of a stationary vehicle struck by the IIHS MDB at an impact velocity of 50 km/h (31.1 mph). It strikes the vehicle on the driver side at a 90° angle. The longitudinal impact point of the barrier on the side of the test vehicle is dependent on the vehicle wheelbase. The test weight of the struck vehicle includes instrumentation, 3 cameras, and 2 SID IIs dummies. It is about 150–225 kg (330–495 lb.) heavier than the curb weight of the vehicle.

Two SID IIs are used to represent fifth percentile female occupants. One is seated on the driver seat and other on the left second-row seat. The injury responses are assessed for the head/neck, torso, and pelvis/leg, and the vehicles are rated on their ability to protect occupant's head and resist occupant compartment intrusion.

IIHS has conducted 157 side impact tests with the SID IIs dummy in 2003–2007 MY vehicles evaluated in this study. Table A3 (see online supplement) lists the tests with 2003–2007 MY vehicles. Newer vehicles have been tested but were beyond to scope of this evaluation.

Side airbag groups with matched vehicle tests

The following airbag groups were analyzed:

- Curtain and torso side airbag with matched vehicles tested with and without a curtain and torso airbag.
- Head/torso airbag with matched vehicles tested with and without a head and torso combination airbag.
- Curtain airbag with matched vehicles tested with and without a curtain airbag.
- Torso airbag with matched vehicles tested with and without a torso airbag.

Biomechanical responses

The peak responses analyzed in this study included the following:

- Head: HIC15, head acceleration, 3 ms head acceleration.
- Mid-thorax: 3 ms acceleration, deflection, deflection rate, and viscous criteria.
- Pelvis: peak acceleration and combined acetabulum and ilium force.

Injury assessment reference values

Each biomechanical response was assessed with respect to the percentage of injury assessment reference values (IARVs). The HIC, mid-thorax 3 ms acceleration, deflection, deflection rate, viscous criteria, and pelvis force IARVs were available in the IIHS test reports. The peak head acceleration IARV was obtained from Mertz et al. (2003). The average and ±1 SD are reported.

Side airbag effectiveness

Airbag effectiveness was assessed by first determining the relative difference in each biomechanical response for each matched vehicle test with and without airbag. The effectiveness was determined by dividing by the response without a side airbag. This gave a percentage reduction in biomechanical response with the side airbag in the vehicle. The average and standard deviation of the matched tests were determined by airbag groups.

Statistical analysis

The significance of differences between the means for biomechanical responses in the matched comparisons was determined
Table 1. Average reduction in responses for matched tests with compared to without side airbags.

| Side airbag              | n  | Head | 3 ms | Mid thorax | Pelvis |
|-------------------------|----|------|------|------------|--------|
|                         |    | HIC<sub>15</sub> | Acceleration (g) | Deflection (mm) | Acceleration (g) |
| Curtain and torso       | 13 | Average | 67.7% | 58.8% | 47.8% | 17.9% | 42.1% | 53.8% | 2.1% | 6.9% | 31.3% |
|                         |    | SD    | .16% | .19% | .15% | .20% | .17% | .16% | .19% | .16% | .14% | .25%–37.1% |
| Head/torso              | 4  | Average | 41.8% | 45.2% | 29.7% | 12.1% | 24.4% | 31.8% | 9.8% | 12.5% | 24.8% |
|                         |    | SD    | .30% | .31% | .25% | .21% | .27% | .25% | .8% | .29% | 17.7%–31.2% |
| Curtain                 | 5  | Average | 41.3% | 41.9% | 27.9% | 1.2% | 2.2% | 1.2% | 1.8% | 4.8% | 16.4% |
|                         |    | SD    | .12% | .23% | .19% | .13% | .18% | .26% | .18% | .36% | 3.0%–28.0% |
| Torso                   | 2  | Average | 41.9% | 22.4% | 20.9% | 19.2% | 3.2% | 1.8% | 16.3% | 1.1% | 7.8% |
|                         |    | SD    | .4%  | .5%  | .4%  | .51% | .36% | .87% | .36% | .76% | 0.4%–14.7% |
| Total matches           | 24 |       |      |          |        |      |      |      |      |      |

<sup>a</sup> Based on IIHS high-hooded side impact crash tests and Kahane (2015).

using the t-test for paired samples in Excel. The P value is added when the difference is significant.

**Results**

There were 24 matched IIHS vehicle tests: 13 with and without side curtain and torso airbag, 4 with head and torso airbag, 5 with and without side curtain airbag, and 2 with and without a torso airbag. Table A4 (see online supplement) lists the matched vehicle tests available for this study. It also shows peak biomechanical responses for the each matched pair of tests. There were 3 tests with the 2004–2005 Chevrolet Malibu: one without inflatable side protection (IIHS test # CES0404), one with a curtain airbag (IIHS test # CES0403), and one with a curtain and torso airbag (IIHS test # CES0509). The tests were used in 3 airbag group comparisons.

Table 1 shows the average reduction in biomechanical responses for the matched tests with and without side airbags. The largest reductions in responses were with side curtains and torso airbags. The last column in Table 1 lists the fatality reduction effectiveness from NHTSA analysis of FARS (Kahane 2015). For example, Kahane (2014) found a 36.6% (25.0–37.1%) reduction in fatality risk with side curtains and torso airbags.

**Side curtain and torso airbag**

Figure 2 shows the average reduction in biomechanical response for the matched tests with side curtain/torso airbags compared to without. The reduction in HIC averaged 68 ± 16% with a side curtain and torso airbag compared to the response without the side airbags. The difference was statistically significant (t = 4.40, P < .001, df = 12). The average HIC was 296 with curtains and torso airbags and it was 1,199 without side airbags. The largest HIC response was in the 2004 Honda Accord without airbags at 2,548. There was also a reduction in mid-thorax viscous response (VC) of 54 ± 19%, which was statistically significant (t = 3.98, P < .005, df = 12). The combined acetabulum and ilium forces (7 ± 15%) and pelvic acceleration (−2 ± 17%) were essentially similar in the matched tests.

**Head/torso airbag**

Figure A3 (see online supplement) shows the results for the head and torso airbag effectiveness. It was most effective in reducing head acceleration, at 45 ± 31% (P < .1), followed by HIC at 42 ± 30% (P < .1) and VC at 32 ± 26% compared to no side airbag. The average HIC was 397 with the side head and torso airbag compared to 729 without it. The average chest deflection was above IARV with and without the side head and torso airbag. VC was above the IARV without the airbag. All other responses were below the IARV’s.

**Curtain airbag only**

Figure A4 (see online supplement) shows curtain airbag only effectiveness. It was effective in reducing HIC and head acceleration. The reduction was 41 ± 13% for HIC (P < .05) and 42 ± 24% for peak head acceleration (P < .1). The average HIC without the curtain airbag was 27% higher than the IARVs at 988. The thorax and pelvis responses were similar, irrespective of the curtain airbag availability in the test vehicle.


Torso airbag only

Figure A5 (see online supplement) shows the reduction in dummy responses with the addition of a side torso airbag. For both test series, the vehicles (Chevrolet Malibu and Nissan Quest) were equipped with a side torso airbag. The side torso airbag reduced HIC and head acceleration but increased the chest deflection and pelvic acceleration. The effectiveness was 42 ± 4% for HIC and 22 ± 5% for peak head acceleration. It was −19 ± 51% for chest deflection and −16 ± 4% for pelvic acceleration. The responses were below IARVs, except for chest deflection with the side torso airbag.

Discussion

Side airbags were first introduced in 1996 as optional safety equipment. Selected laboratory tests showed improvements in dummy responses (IIHS 1997; Mellander et al. 1989). However, crash test ratings were not always improved with the torso airbag or a head/torso airbags, reducing the incentive for side airbag introduction. The field data was also unclear. In 2003, McGwen et al. found similar injury risks, irrespective of side airbags, whereas IIHS reported a 45% reduction. As a result, side airbags were not common in 2003. IIHS (2003) carried out a survey and reported that 14% of drivers would lease or buy a car with side airbags.

The pole side impact test became part of FMVSS 201 starting with 1998 MY as an optional requirement. This led to the introduction of side airbags with head protection. However, the side pole impact test only became mandatory in 2007 as part of FMVSS 214, with an initial phase-in of 20% with 2010 MY vehicles and 100% with 2013 MY (see Kahane [2015] for references to the standards). The introduction of side curtains with head protection was driven, in part, by the IIHS high-hooded side impact barrier test. The taller barrier design and use of a fifth percentile female dummy were factors in extending the coverage of the curtain down to the beltline at the lower edge of the side windows. This provided greater coverage for occupants of shorter stature.

This study is one of the first to report on the IIHS matched tests with and without side airbags. The analysis showed that curtain and torso side airbags were most effective in reducing head and torso biomechanical responses for the SIDIs. The effectiveness varied from 59 ± 19% for peak head acceleration (P < .001) to 68 ± 17% for HIC15 (P < .001). The reduction with the side airbags was slightly lower for the chest responses, ranging from 18 ± 20% for chest deflection (P < .005) to 54 ± 20% for VC (P < .005). Even with relatively large standard deviations, the differences were significant because of the matched statistical comparison.

Head and torso combination airbag were the second most effective system in reducing biomechanical responses. The reductions were 30–45% for head responses and 12–32% for the chest. There was not a consistent reduction in pelvic responses with the side airbags. This is understandable, because the airbags are directed at inflating in the area of the head and chest. In these tests, adding a torso airbag to curtain-equipped vehicles reduced head responses but increased chest responses.

The results obtained in this study are consistent with the fatality reduction estimated by Kahane (2015). These estimates are based on fatal field crashes in FARS. Table 1 shows that the curtain and torso airbag was most effective with a reduction of 31.3% (25.0–37.1%), followed by head and torso combination airbags at 24.8% (17.7–31.2%), curtain only at 16.4% (3.0–28.0%), and torso only side airbag at 7.8% (0.4–14.7%).

D’Elia et al. (2012, 2013), from Monash University, matched police reports of 2001–2009 driver-side crashes in Victoria, Australia, with insurance injury claims. They reported a 51% reduction in the odds of death and injury to all body regions and 53% reduction in death and injury risk to the head, neck, and face in vehicles equipped with head and torso airbags. These results are higher than the ones reported in this study and in the one by Kahane (2014, 2015).

Brumbelow et al. (2015) reported that future updates to the IIHS impact test may lower the number of injuries. In that study, field analysis suggested that, compared to the current IIHS test protocol, further improvements could include moving the MDB further forward, increasing impact severity, and implementing more restrictive injury criteria.

Limitations

The matched tests reported here are from a single impact configuration used by IIHS. The range of real-world side impact crashes is considerable and the results shown here are not universally applicable to all side impacts. For example, NHTSA (2008) tested 6 vehicles that received “good” IIHS ratings and conformed to the voluntary agreement for side head protection. Table A5 (see online supplement) shows that 4 of the 6 vehicles did not meet the criteria for the oblique pole test with the SIDIs test dummy. NHTSA stated that 2 vehicles needed improved head protection and 4 vehicles needed better pelvic protection.

Various factors can influence the effectiveness of side airbags, including impact speed, geometry of the striking vehicle or object, occupant age, size, and seating position (Sunnevang et al. 2009; Teoh and Lund 2011). These factors were not assessed in this study and merit additional work. In addition, there were a limited number of vehicles and only one seating position and dummy were evaluated.

By IIHS introducing the high-hood barrier test, manufacturers were motivated to modify vehicle structures and side airbag performance to reduce biomechanical responses in the test. The results found in this study may be expected.

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