Injury risks and crashworthiness benefits for females and males: Which differences are physiological?

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CONTENTS

ABSTRACT

Objective

Previous research has found elevated injury risk for females relative to males in passenger vehicle crashes but has not accounted for ways the crashes themselves differ between these populations. Vehicle curb weight, ride height, safety rating, airbag deployment, and crash configuration all influence injury outcome and often are not well-represented by delta-V alone. This study evaluated the effect of occupant sex on injury risk in front and side crashes while limiting or controlling for non-physiological crash differences. Additionally, the effects of crashworthiness improvements were compared for females and males.

Methods

We analyzed National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) cases from 1998–2015 involving a belted driver in a front crash or a front-row near-side occupant in a side crash. Logistic regression was used to estimate the risk of certain injury outcomes for females relative to males as well as the change in risk due to improved crashworthiness. Sex-based differences in occupant age, mass, and stature; crash test rating; delta-V; crash configuration; and vehicle-to-vehicle compatibility were considered either through case selection or the inclusion of additional regression covariates.

Results

Before controlling for crash and vehicle differences, female drivers in front crashes had higher estimated overall and body-region-specific risks of a Maximum Abbreviated Injury Scale (MAIS) ≥ 2 injury and a MAIS ≥ 3 injury, as consistent with previous findings. After accounting for such differences, all female injury odds ratios were reduced. Females remained at higher risk of MAIS ≥ 2 injury (odds ratio [OR], 2.23; 95% confidence interval [CI], 1.42–3.51), especially extremity injury, but had similar odds for MAIS ≥ 3 non-extremity injury (OR, 0.98; 95% CI, 0.56–1.7). While controlling for crash differences in side impacts, female injury odds tended to be lower than male injury odds for MAIS ≥ 2 and higher for MAIS ≥ 3 outcomes, but none of the estimates were significant at the $p = 0.05$ level. Estimated benefits of improved crashworthiness were similar or greater for females than for males for most injury outcomes.

Conclusions

Female-specific crashworthiness improvements may be required to provide additional protection against Abbreviated Injury Scale (AIS) 2 extremity injury. Much of the remaining discrepancy in sex-based injury risk can be attributed differences between vehicles and crashes, not to physiological differences. Addressing these differences will require other types of countermeasures.

Keywords

Injury risk; crash analysis; crashworthiness; consumer ratings; sex-based differences.

INTRODUCTION

Fatal crash rates are higher for males than females regardless of how they are measured—per capita, per miles travelled, or per licensed driver—(Insurance Institute for Highway Safety [IIHS] 2019; Mayhew 2003) but the gaps are narrowing as more females are licensed and spend more time driving (Mayhew 2003). Still, females accounted for fewer than 30% of crash deaths in 2018 in the United States (IIHS, 2019). For crashes of all severities, females have lower rates of crashes per licensed driver but higher rates per miles travelled (Bose et al. 2011; Ferguson and Braitman 2007; Li et al. 1998; Massie et al. 1995; Massie et al. 1997).

Males are involved in more crashes involving risk-taking behaviors such as speeding and impairment (IIHS 2019; Romano et al. 2008) and tend to be involved in more severe crashes overall (Li et al. 1998), but after adjusting for crash severity and other factors, studies show females are at increased risk of fatal injury compared with males. In double-pair comparison studies, young females have an increased fatality risk of 20 to 28% compared with young males in similar crashes, although the discrepancy decreases with age and is eliminated or reversed by middle age (Abrams and Bass 2020; Evans 2001; Kahane 2013). Using a different method, Evans and Gerrish (2001) found unbelted young females have an increased fatality risk of 22% compared with unbelted males, a similar magnitude as found using the double-pair method. When considering serious injuries, multivariate logistic regression studies using National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) data found that females have 47 to 73% higher odds of serious injury on the Abbreviated Injury Scale (AIS $\geq$ 3) than males after accounting for other occupant, vehicle, and crash factors (Bose et al. 2011; Forman et al. 2019). Kahane (2013) also found a larger relative risk to females compared with males for serious injuries (37%) than fatal injuries (17%) using a double-pair comparison method.

Crashworthiness improvements in newer vehicles have reduced the risk of death and injury (Farmer and Lund 2006; Kullgren et al. 2020), and there is evidence that females may have benefited more from crashworthiness improvements than males (Kahane 2013; Kullgren et al. 2020). Serious and fatal injury risk is reduced 29 and 40% for males and females, respectively, when comparing vehicle models introduced in 1980–1989 with those introduced in 2010–2019, and the effect is even larger when considering fatal injuries alone (50% for males, 89% for females) (Kullgren et al. 2020). Another study showed that the increased relative risk of fatal injury for females has been cut in half between model years 1980–1989 and 2000–2011 (Kahane 2013).

Studies of the differential risk between females and males have attempted to control for crash severity by studying relative risk in the same vehicle and/or crash (Abrams and Bass 2020; Evans 2001; Kahane 2013; Kullgren et al. 2020); by adjusting for vehicle type, airbag deployment, or delta-V (Bose et al. 2011; Forman et al. 2019); or by adjusting for vehicle mass differences (Kullgren et al. 2020). However, these studies included all crash types and have limitations in their crash severity adjustments. One potential source of confounding is the different distributions of crash types, vehicle types, and vehicle safety performance between females and males (Table A1 in the Appendix). Figure 1 shows the distribution of vehicle types by occupant sex for the front and side crashes included in the current study. Proportionally, males were more likely to be occupants of pickups than females, with females more likely to be car occupants. Even within vehicle types, males tended to be in heavier vehicles than females. In theory, controlling for delta-V captures some effects of curb weight differences. However, delta-V does not capture any increased risk that may be associated with vehicle height incompatibility, and delta-V itself can be underestimated in NASS-CDS when there is underride (Brumbelow 2019). In addition, delta-V does not capture any vehicle acceleration differences resulting from vehicle size. Studies based on relative risk to occupants in the same crash and/or vehicle have controlled for some vehicle and crash factors but have not always accounted for differences in seat position, impact location relative to the occupant, or risk differences in the front-striking and side-struck vehicle. None have controlled for occupant stature or body mass differences between males and females, or the possibility that the types of crashes they are involved in differ in systematic ways related to injury risk.

The objective of this study was to evaluate the effect of occupant sex on injury risk in front and side crashes while limiting or controlling for the influence of vehicle and crash differences between females and males. Isolating the risk differences that truly are due to physiological factors is an important step in identifying areas for improvement in front and side crash test programs.

METHODS

Front and side crash data were obtained from NASS-CDS. NASS-CDS was a sample-weighted survey of police-reported crashes in the U.S. conducted from 1979–2015. For the current study, calendar years 1998–2015 were included, and vehicle model years were restricted to those less than 10 years old in each calendar year. All occupants were ages 16 years or older, and females pregnant beyond the first trimester were not included. Cases with subsequent rollovers or significant secondary impacts (EXTENT2 > 2) were excluded, as were those with "trajectory-only" delta-Vs calculated without crush measurements. Front crash analyses were performed using belted drivers in vehicles with a primary front impact (GAD1 = F). Side crashes were defined as those with a primary side impact (GAD1 = L or R) with damage overlapping the passenger compartment (SHL1 = D, P, Y, or Z) from the front of another vehicle or an object. Belted front-row struck-side occupants were included unless they were seated adjacent to an unbelted occupant.

Logistic Regression

Logistic regression was used to estimate the effect of occupant sex on the risks of overall and body-region-specific injury at AIS ≥ 2 and AIS ≥ 3 levels while controlling for other factors. Fatally injured occupants with maximum AIS levels that were less than 3 or unknown were considered injured for overall injury risk analyses but excluded from analyses of risk to specific body regions. Covariates included in all models were occupant age, occupant height, occupant mass, delta-V, and the presence of a good rating in the corresponding IIHS test (moderate overlap frontal or side impact). Resultant delta-V was used in front-crash models, with both longitudinal and lateral delta-V included in side-crash models.

Additional controls were used to account for the possibility that the different vehicle and crash distributions between females and males could affect the estimated injury odds ratios for sex. For front crashes, a categorical variable was introduced to represent the type of front crash. There were four levels, with the first three representing two-vehicle crashes: front-to-front, front-to-side, front-to-rear, and front-to-object. In addition, logistic regression models were constructed for the subset of front crashes in which the subject vehicle's front airbag deployed and which were considered "compatible." Compatible crashes included all single-vehicle crashes plus front-to-rear crashes involving two cars, front-to-side crashes in which the side-struck vehicle was a car, and front-to-front crashes in which the curb weight difference between the vehicles was less than 454 kg (1,000 lb). Compatible crashes also had no coded under- or override in NASS-CDS. There were too few side-impact cases available to define a subset of compatible crashes, so in addition to the covariates listed in the previous paragraph, the regression models estimating side-impact injury risk controlled for partner type (car, SUV/minivan, pickup, or object) and the interaction between partner type and the sill height of the subject vehicle. Vehicle sill height measurements are not included in the compiled NASS-CDS datasets but are available in the online viewer for 2004 and later cases. They were downloaded using the "rvest" package in the R programming language (Wickham 2019). For older cases and those with missing sill heights, NASS-CDS measurements for other vehicles of the same make, model, and approximate model year (±4), when available, were averaged to provide the measurement for the case vehicle.

In addition to injury odds ratios for sex, front- and side-crash injury odds were estimated for occupants of vehicles rated good in the IIHS moderate overlap frontal or side impact tests, relative to vehicles without a good rating. Good-rating injury odds ratios were calculated for all occupants as well as for females and males separately. The interaction terms between sex and rating also were evaluated to determine whether the effect of a good rating was significantly different for females and males. For front crashes, this analysis was restricted to compatible crashes, as defined in the previous paragraph, with front airbag deployments.

All regression models were calculated using the "survey" package (Lumley 2019b) in R to account for sampling weights. As described by Brumbelow (2019), sampling weights were adjusted downward for cases that were mis-stratified or where a driver was hospitalized without a police-reported incapacitating injury. Such cases accounted for 6% of those in the overall sample.

Multiple Imputation

Cases with missing data for occupant height, occupant mass, and subject vehicle sill height were multiply imputed to enable inclusion in the analyses. In addition, occupant height outside the range of 125–250 cm, occupant mass greater than 250 kg, or any combination of height and mass that resulted in a Body Mass Index (BMI) outside the range of 14–70 kg/m^2 were assumed to be erroneous and treated as missing. Altogether, 9.8% of cases were missing occupant mass and 10.3% were missing occupant height, while 14.8% of the side impact cases were missing sill height. The "mice" (van Buuren and Groothuis-Oudshoorn 2011) and "mitools" (Lumley 2019a) packages in R were used to perform the multiple imputation with each regression model based on 20 separate imputations of the missing data.

RESULTS

Female injury odds ratios for front and side crashes are shown in Table 1. In all front crashes meeting our inclusion requirements, female drivers had significantly higher odds of sustaining an AIS ≥ 2 (odds ratio [OR], 3.11; $p < 0.001$) or AIS ≥ 3 (OR, 1.92,; $p = 0.006$) injury. Most of the injury odds ratios for specific body regions also were significant at the $p = 0.05$ level.

When restricting to compatible front crashes in which the subject vehicle's front airbag deployed, all injury odds ratios for females were reduced. While the estimated difference in overall maximum AIS (MAIS) ≥ 2 injury risk between females and males remained statistically significant at the $p = 0.05$ level, this was not true for MAIS ≥ 2 non-extremity injuries or for any of the evaluated MAIS ≥ 3 injury outcomes. Relative to males, MAIS ≥ 3 injury odds for females remained elevated for lower extremity injuries (OR, 1.72; $p = 0.11$) but lower for pelvis injuries (OR, 0.52; $p = 0.33$), and similar for non-extremity (OR, 0.98; $p = 0.94$), head (OR, 0.90; $p = 0.83$), and thorax (OR, 1.10; $p = 0.8$) injuries.

In side impacts, none of the sex-based injury odds ratios were significant at the $p = 0.05$ level. The estimated MAIS ≥ 2 injury odds were lower for females overall, as well as for upper and lower extremity injuries separately. This trend was reversed for MAIS ≥ 3 injuries, with higher odds of overall and body-region-specific injury for females, except for injuries to the thorax. Detailed results of the logistic regression models are given in the Appendix (Tables A2–A4).

A good rating in the IIHS moderate overlap frontal test was estimated to reduce the risk of every type of studied injury for all drivers, with the exception of MAIS ≥ 2 upper extremity and MAIS ≥ 3 thorax injuries (Table 2). The risk reductions for the lower extremities (both MAIS levels) and head (MAIS ≥ 3) were significant at the $p = 0.05$ level. Modeling the interaction between sex and crash test rating indicated that a good rating produced greater benefits for females than for males in every category except MAIS ≥ 3 lower extremity injuries. None of the interaction terms were significant at the $p = 0.05$ level, with the difference in the effect of a good rating for overall MAIS ≥ 3 injury producing the greatest statistical significance ($p = 0.08$). A good rating was associated with a MAIS ≥ 3 injury risk reduction of 46% for females ($p = 0.02$) but an increase of 6% for males ($p = 0.83$). All good-rating odds ratios were below 1.0 for females, while less than half were below 1.0 for males.

A good rating in the IIHS side impact test was estimated to reduce the risk of every type of studied injury for all occupants, with the exception of MAIS ≥ 3 lower extremity injury (Table 3). MAIS ≥ 2 injury risk reductions for all body regions, upper extremities, and non-extremities were significant at the $p = 0.05$ level, as were overall, non-extremity, and thorax MAIS ≥ 3 reductions. The estimated effect of a good rating was similar for females and males as measured by most MAIS ≥ 2 injury reductions. In terms of MAIS ≥ 3 injury reductions, the benefit of a good rating was greater for females in every category studied except pelvis injuries, which were not sustained by any male occupants of good-rated vehicles. The lowest p value for any of the sex and rating interaction terms was 0.32.

DISCUSSION

The sex with higher estimated injury odds differs according to crash mode, body region, and injury severity. While female drivers had higher estimated injury odds in all front crashes, after restricting to crashes with front airbag deployments and placing some limits on vehicle incompatibility, all differences were reduced, and some were eliminated. Much of the elevated injury risk for females reported in previous research (Bose et al. 2011; Forman et al. 2019) appears to be due to crash severity differences that are not captured with delta-V in NASS-CDS. After controlling for some of these differences, the current study found that the odds of serious (AIS ≥ 3) non-extremity injury were essentially equal for males and females (female OR: 0.98). Significant differences did remain for moderate severity injuries (AIS ≥ 2), especially to the extremities. As male drivers tended to be in heavier vehicles, even within the controls of this study, it is unknown how much of the remaining differences in injury odds may still be due to non-physiological factors.

The reduced number of side impact crashes in NASS-CDS results in less definitive conclusions for these crashes than for front crashes. Despite this, the lack of consistency in female injury odds ratios between side and front crashes suggests that either the different injury mechanisms in these crash types affect males and females differently, or that other uncontrolled differences in factors such as seat position, posture, or crash configuration still may be influencing the results. Whereas female drivers in front crashes tended to have higher odds of AIS ≥ 2 injury but similar or lower odds of AIS ≥ 3 injury than males, the trend was reversed for occupants in side crashes. Previous research has shown differences in the magnitude of increased fatality risk for females due to impact type, with higher relative female fatality risk in near-side impacts than in front crashes (Kahane 2013). This injury risk discrepancy by impact type requires further study.

The current study included front and side crashes involving vehicle model years from 1989–2016. Manufacturers made many crashworthiness improvements to their vehicles over this time in response to federal safety standards, consumer information testing, and their own research findings. These improvements, as measured in this study by just one test in each crash mode, tended to benefit females at levels equal to or greater than the benefits for males. The MAIS ≥ 2 and MAIS ≥ 3 non-extremity injury odds reductions associated with good IIHS test ratings were similar or greater for females than males in both crash modes. This is consistent with previous research in which serious and fatal injury risk has decreased more for females than males when comparing newer and older model year vehicles (Kahane 2013; Kullgren et al. 2020) and provides evidence that current testing programs have promoted countermeasures that are effective at reducing the risk to both sexes, perhaps to females more. Seat belts and modern front and side airbags have been shown to be equally effective at reducing fatal injuries for males and females (Braver et al. 2010; Kahane 2015; McCartt and Kyrychenko 2007), suggesting that some of the differential benefit to females may be due to non-restraint crashworthiness improvements such as stronger structures and improved energy management.

U.S. regulatory and consumer information test programs use crash test dummies representing the midsize male or small female. IIHS frontal and side crash tests have incorporated metrics for structural integrity and intrusion as part of their ratings program, because one dummy in one seating position does not fully represent the range of size, posture, and physiological characteristics of occupants who get injured in crashes. Research that examined the effect of the individual components of IIHS's side test ratings on real-world injury risk found that B-pillar intrusion had the strongest association with real-world death rates (Teoh and Arbelaez 2019). In front crashes, decreased toepan intrusion reduces lower extremity risk (Austin 2012; Crandall et al. 1996). In the current study, vehicles with good IIHS test ratings, which maintain structural integrity with minimal intrusion, were associated with decreased risk for lower extremity injury for both sexes.

The vulnerability of females to extremity injuries, particularly lower extremity injuries, requires further understanding. Other researchers comparing relative injury risk by body region also reported that the increased risk of lower extremity injury for females is higher than the relative risk of injury to other body regions (Kahane 2013; Forman et al. 2019). This higher risk may be due to factors such as physiological differences (Forman et al. 2019), stature (Crandall et al. 1996; Dischinger 1995), or footwear (Crandall et al. 1996). Biomechanical studies on injury tolerance have historically included limited female-specific data (Viano et al. 1989), but inclusion of female subjects is more common in recent studies (Forman et al. 2015) and should be prioritized as new biomechanical data are collected. This study confirms that a primary difference in injury risk is due to extremity injuries, highlighting the need for research focused on female-specific injury risk curves, particularly for lower extremity injuries. Despite this potential bias in the underlying data, front crashworthiness improvements have reduced the risk of lower extremity injury for both sexes more than the risk of injury to other body regions.

This study focused on front and side crashes only and controlled for several additional crash severity factors beyond those used in other studies, to best approximate the difference in injury risk between males and females due to physiological factors. Covariates beyond traditional severity metrics included more specific restrictions on crash partner and configuration, vehicle weight and height differences, and airbag deployment, but additional confounding factors that are non-physiological may remain, such as seat position, posture or other crash factors. This study sought to compare injury risk in comparable crashes to identify areas for improvements in crash test programs, but there is evidence of increased risk to females due to sex-based differences in crash exposure. These differences are equally important in addressing the sex-based discrepancy in injury risk but were not the focus of this study. Despite these limitations, this study provides evidence of the effects of crashworthiness improvements for both females and males, and points to priority areas for additional research.

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FIGURES AND TABLES

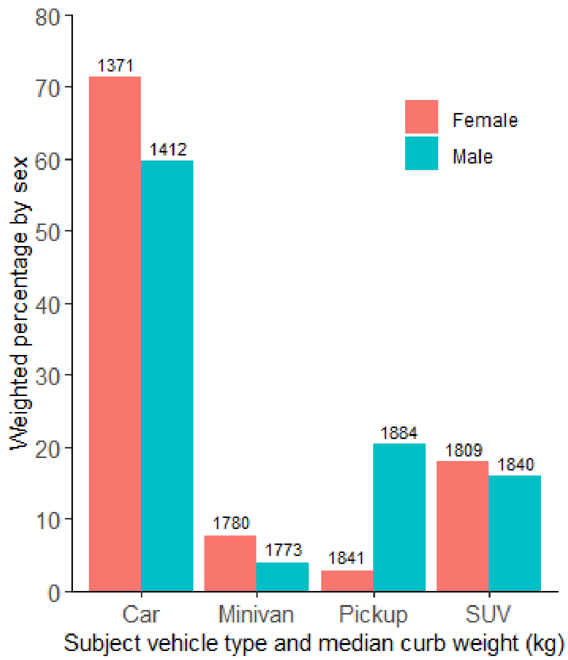

Figure 1. Distribution of vehicle types by sex and median curb weight within each category.

Table 1. Female injury odds ratios and 95% confidence intervals for front and side crashes

	Body region	Front: all crashes (n = 10,068)	Front: compatible + airbag deployment (n = 4,995)	Side: all crashes (n = 2,534)
MAIS ≥ 2	All	**3.11 (1.62, 6.00)**	**2.23 (1.42, 3.51)**	0.92 (0.49, 1.74)
	Upper extremity	**2.35 (1.42, 3.88)**	**1.95 (1.07, 3.55)**	0.63 (0.21, 1.90)
	Lower extremity	**4.38 (1.54, 12.4)**	**2.72 (1.57, 4.71)**	0.80 (0.34, 1.91)
	Non-extremity	**1.70 (1.07, 2.71)**	1.31 (0.84, 2.04)	1.08 (0.56, 2.07)
MAIS ≥ 3	All	**1.92 (1.21, 3.06)**	1.45 (0.81, 2.56)	1.55 (0.82, 2.94)
	Lower extremity	1.74 (0.98, 3.08)	1.72 (0.88, 3.34)	1.43 (0.45, 4.56)
	Non-extremity	**1.71 (1.04, 2.80)**	0.98 (0.56, 1.70)	1.40 (0.74, 2.65)
	Head	1.39 (0.56, 3.45)	0.90 (0.34, 2.39)	1.22 (0.55, 2.71)
	Thorax	1.60 (0.84, 3.03)	1.10 (0.54, 2.23)	0.98 (0.52, 1.85)
	Pelvis	1.39 (0.34, 5.67)	0.52 (0.14, 1.94)	1.47 (0.63, 3.44)

Note. MAIS = Maximum Abbreviated Injury Scale.
Bolded results are significant at $p \leq 0.05$.

Table 2. IIHS moderate overlap good-rating injury odds ratios and 95% confidence intervals for front crashes

	Body region	All drivers	Female drivers	Male drivers	Sex*rating *p* value
MAIS ≥ 2	All	0.72 (0.48, 1.07)	0.68 (0.38, 1.19)	0.79 (0.50, 1.26)	0.67
	Upper extremity	1.02 (0.55, 1.90)	0.94 (0.39, 2.29)	1.14 (0.51, 2.54)	0.75
	Lower extremity	**0.40 (0.24, 0.66)**	**0.37 (0.19, 0.72)**	**0.46 (0.24, 0.88)**	0.66
	Non-extremity	0.91 (0.59, 1.40)	0.83 (0.43, 1.60)	1.02 (0.64, 1.62)	0.59
MAIS ≥ 3	All	0.73 (0.50, 1.08)	**0.54 (0.32, 0.90)**	1.06 (0.60, 1.88)	0.08
	Lower extremity	**0.52 (0.32, 0.85)**	0.56 (0.29, 1.07)	0.47 (0.21, 1.04)	0.74
	Non-extremity	0.87 (0.55, 1.36)	0.71 (0.37, 1.36)	1.05 (0.56, 1.96)	0.39
	Head	**0.42 (0.18, 0.95)**	0.28 (0.06, 1.37)	0.59 (0.23, 1.50)	0.45
	Thorax	1.26 (0.76, 2.09)	0.98 (0.43, 2.22)	1.53 (0.79, 2.96)	0.42
	Pelvis	0.48 (0.13, 1.69)	0.14 (0.01, 1.38)	1.08 (0.28, 4.20)	0.12

Note. MAIS = Maximum Abbreviated Injury Scale.
Bolded results are significant at p ≤ 0.05.

Table 3. IIHS side impact good-rating injury odds ratios and 95% confidence intervals for side crashes

	Body region	All occupants	Female occupants	Male occupants	Sex*rating *p* value
MAIS ≥ 2	All	**0.20 (0.10, 0.42)**	**0.25 (0.09, 0.68)**	**0.15 (0.05, 0.47)**	0.53
	Upper extremity	**0.06 (0.02, 0.16)**	**0.12 (0.02, 0.59)**	**0.04 (0.01, 0.16)**	0.36
	Lower extremity	0.39 (0.09, 1.71)	0.22 (0.02, 2.24)	0.71 (0.13, 4.03)	0.42
	Non-extremity	**0.23 (0.10, 0.52)**	**0.23 (0.08, 0.65)**	**0.23 (0.06, 0.81)**	0.97
MAIS ≥ 3	All	**0.24 (0.08, 0.71)**	**0.17 (0.03, 0.83)**	0.38 (0.10, 1.47)	0.42
	Lower extremity	1.07 (0.19, 5.89)	0.72 (0.08, 6.61)	1.92 (0.21, 18.0)	0.53
	Non-extremity	**0.30 (0.10, 0.84)**	0.22 (0.05, 1.00)	0.43 (0.12, 1.63)	0.49
	Head	0.22 (0.02, 2.20)	0.18 (0.004, 8.82)	0.29 (0.07, 1.23)	0.82
	Thorax	**0.27 (0.08, 0.97)**	0.11 (0.01, 1.84)	0.52 (0.13, 2.02)	0.32
	Pelvis	0.08 (0.01, 1.29)	0.09 (0.01, 1.79)	**	**

Note. MAIS = Maximum Abbreviated Injury Scale.
Bolded results are significant at p ≤ 0.05.
** No males in good-rated vehicles sustained AIS ≥ 3 pelvis injuries.

APPENDIX

Table A1. Survey-weighted mean and proportion estimates (with standard errors) for select variables considered in regression model specification

Front crashes	Female drivers	Male drivers
Curb weight difference: mean (subject–partner; kg)	−90 (14)	−47 (19)
Pickup subject vehicle: proportion	0.023 (0.0029)	0.17 (0.011)
Good-rated subject vehicle: proportion	0.36 (0.014)	0.32 (0.017)
Front airbag deployment: proportion	0.57 (0.017)	0.53 (0.018)
Single-vehicle crash: proportion	0.089 (0.0072)	0.12 (0.012)
Side crashes	Female occupants	Male occupants
Curb weight difference: mean (subject–partner; kg)	−70 (29)	+96 (100)
Sill height: mean (cm)	28 (0.52)	31 (1.8)
Pickup subject vehicle: proportion	0.038 (0.013)	0.29 (0.098)
Good-rated subject vehicle: proportion	0.21 (0.066)	0.11 (0.022)
Single-vehicle crash: proportion	0.046 (0.014)	0.031 (0.0076)

Note. Mean curb weight differences exclude single-vehicle crashes. Mean sill height excludes cases with unknown information; a greater proportion of male occupants and pickups had unknown sill heights.

Table A2. Parameter estimates for regression models predicting specified driver injury in all front crashes.

Outcome	Model result	Intercept	Resultant dV (km/h)	Age (yrs)	Mass (kg)	Height (cm)	Sex: female	Type: front-to-rear	Type: front-to-front	Type: front-to-side	Rating: good
MAIS ≥ 2	Estimate	−6.151	0.080	0.026	0.017	−0.007	1.136	−0.011	0.256	−0.477	−0.662
	SE	1.640	0.014	0.008	0.005	0.010	0.335	0.714	0.210	0.259	0.282
	p value		< 0.001	0.001	< 0.001	0.44	0.001	0.99	0.22	0.07	0.02
MAIS ≥ 2 upper extremity	Estimate	−9.892	0.076	0.018	0.016	0.009	0.855	−1.160	0.434	−0.027	−0.065
	SE	1.891	0.006	0.006	0.006	0.012	0.256	0.483	0.328	0.328	0.250
	p value		< 0.001	0.00s2	0.01	0.45	0.001	0.02	0.19	0.94	0.79
MAIS ≥ 2 lower extremity	Estimate	−6.201	0.075	0.030	0.024	−0.017	1.477	0.676	0.427	−0.875	−1.326
	SE	2.306	0.018	0.013	0.007	0.013	0.533	0.835	0.321	0.407	0.434
	p value		< 0.001	0.02	< 0.001	0.20	0.01	0.42	0.18	0.03	0.002
MAIS ≥ 2 non-extremity	Estimate	−7.796	0.081	0.024	−0.003	0.007	0.532	−1.224	0.118	−0.351	−0.149
	SE	2.591	0.005	0.005	0.006	0.015	0.237	0.443	0.210	0.253	0.173
	p value		< 0.001	< 0.001	0.54	0.63	0.03	0.01	0.58	0.17	0.39
MAIS ≥ 3	Estimate	−10.896	0.112	0.034	0.011	0.004	0.654	−1.527	0.574	−0.460	−0.160
	SE	2.339	0.005	0.004	0.005	0.013	0.237	0.428	0.201	0.237	0.162
	p value		< 0.001	< 0.001	0.02	0.78	0.01	< 0.001	0.004	0.05	0.33
MAIS ≥ 3 lower extremity	Estimate	−10.748	0.102	0.025	0.015	−0.001	0.553	-0.994	0.720	−0.319	−0.423
	SE	2.552	0.006	0.006	0.006	0.015	0.292	0.626	0.267	0.315	0.224
	p value		< 0.001	< 0.001	0.01	0.96	0.06	0.11	0.01	0.31	0.06
MAIS ≥ 3 non-extremity	Estimate	−12.222	0.108	0.045	0.008	0.008	0.536	−1.772	0.398	−1.072	−0.022
	SE	2.410	0.006	0.006	0.006	0.014	0.252	0.439	0.238	0.279	0.193
	p value		< 0.001	< 0.001	0.18	0.57	0.03	< 0.001	0.10	< 0.001	0.91
MAIS ≥ 3 head	Estimate	−8.822	0.081	0.034	0.004	−0.009	0.329	−2.397	0.487	−0.889	−0.189
	SE	4.200	0.008	0.008	0.011	0.025	0.465	1.047	0.369	0.461	0.362
	p value		< 0.001	< 0.001	0.70	0.71	0.48	0.02	0.19	0.05	0.60
MAIS ≥ 3 thorax	Estimate	−14.824	0.099	0.050	0.012	0.018	0.470	−2.126	0.294	−1.240	0.297
	SE	2.812	0.006	0.006	0.007	0.015	0.326	0.616	0.262	0.368	0.230
	p value		< 0.001	< 0.001	0.11	0.24	0.15	0.001	0.26	0.001	0.20
MAIS ≥ 3 pelvis	Estimate	−6.094	0.086	0.023	0.029	−0.039	0.328	−4.066	0.858	−1.207	−0.438
	SE	5.733	0.011	0.011	0.013	0.034	0.718	1.138	0.585	0.693	0.555
	p value		< 0.001	0.03	0.03	0.25	0.65	< 0.001	0.14	0.08	0.43

Note. dV = delta-V; MAIS = Maximum Abbreviated Injury Scale; SE = standard error.
Categorical variable reference levels: male sex, front-to-object crash type, non-good rating or unrated.

Table A3. Parameter estimates for regression models predicting specified driver injury in compatible front crashes with deployed airbags.

Outcome	Model result	Intercept	Resultant dV (km/h)	Age (yrs)	Mass (kg)	Height (cm)	Sex: female	Type: front-to-rear	Type: front-to-front	Type: front-to-side	Rating: good
MAIS ≥ 2	Estimate	−6.748	0.085	0.016	0.017	−0.001	0.801	−2.001	0.196	−0.383	−0.334
	SE	2.045	0.008	0.005	0.006	0.012	0.232	0.470	0.242	0.227	0.205
	p value		< 0.001	0.003	0.01	0.93	0.001	< 0.001	0.42	0.09	0.10
MAIS ≥ 2 upper extremity	Estimate	−8.509	0.064	0.014	0.014	0.007	0.666	−1.905	0.341	−0.049	0.018
	SE	2.362	0.009	0.007	0.009	0.015	0.306	0.552	0.354	0.347	0.318
	p value		< 0.001	0.04	0.09	0.64	0.03	0.001	0.34	0.89	0.96
MAIS ≥ 2 lower extremity	Estimate	−8.276	0.098	0.009	0.026	−0.004	1.000	−2.980	0.530	−0.268	−0.915
	SE	2.540	0.008	0.008	0.009	0.016	0.281	0.890	0.348	0.319	0.252
	p value		< 0.001	0.23	0.003	0.81	< 0.001	0.001	0.13	0.40	< 0.001
MAIS ≥ 2 non-extremity	Estimate	−7.459	0.074	0.029	−0.005	0.007	0.269	−1.541	−0.053	−0.725	−0.097
	SE	2.286	0.008	0.005	0.007	0.012	0.226	0.599	0.249	0.290	0.223
	p value		< 0.001	< 0.001	0.48	0.56	0.23	0.01	0.83	0.01	0.66
MAIS ≥ 3	Estimate	−9.504	0.111	0.039	0.012	−0.004	0.368	−2.268	0.452	−0.138	−0.309
	SE	2.941	0.006	0.005	0.006	0.016	0.293	0.728	0.215	0.269	0.198
	p value		< 0.001	< 0.001	0.06	0.81	0.21	0.002	0.04	0.61	0.12
MAIS ≥ 3 lower extremity	Estimate	−10.422	0.104	0.028	0.018	−0.004	0.543	−2.552	0.627	−0.052	−0.658
	SE	3.132	0.008	0.006	0.007	0.017	0.339	0.751	0.298	0.361	0.254
	p value		< 0.001	< 0.001	0.01	0.83	0.11	0.001	0.04	0.89	0.01
MAIS ≥ 3 non-extremity	Estimate	−10.309	0.107	0.053	0.006	−0.002	−0.022	−2.155	0.196	−0.692	−0.144
	SE	2.667	0.007	0.005	0.007	0.016	0.282	0.890	0.242	0.304	0.230
	p value		< 0.001	< 0.001	0.45	0.92	0.94	0.02	0.42	0.02	0.53
MAIS ≥ 3 head	Estimate	−8.277	0.077	0.041	0.001	−0.009	−0.109	−0.967	0.214	−0.673	−0.874
	SE	4.820	0.011	0.008	0.010	0.027	0.499	1.103	0.401	0.543	0.418
	p value		< 0.001	< 0.001	0.89	0.74	0.83	0.38	0.60	0.22	0.04
MAIS ≥ 3 thorax	Estimate	−15.585	0.092	0.056	0.002	0.029	0.092	−3.698	0.057	−0.877	0.233
	SE	3.137	0.009	0.006	0.009	0.017	0.362	1.057	0.270	0.386	0.256
	p value		< 0.001	< 0.001	0.83	0.09	0.80	< 0.001	0.83	0.02	0.36
MAIS ≥ 3 pelvis	Estimate	1.250	0.084	0.035	0.040	−0.087	−0.644	−15.419	0.804	−0.812	−0.742
	SE	5.308	0.013	0.011	0.013	0.034	0.666	0.936	0.605	0.759	0.645
	p value		< 0.001	0.002	0.002	0.01	0.33	< 0.001	0.18	0.29	0.25

Note. dV = delta-V; MAIS = Maximum Abbreviated Injury Scale; SE = standard error.
Categorical variable reference levels: male sex, front-to-object crash type, non-good rating or unrated.

Table A4. Parameter estimates for regression models predicting specified near-side front-row occupant injury in side crashes.

Outcome	Model result	Intercept	Lat. dV (km/h)	Long. dV (km/h)	Age (yrs)	Mass (kg)	Height (cm)	Sex: female	Sill ht. (cm)	Crash partner: Minivan/ SUV	Crash partner: Pickup	Crash partner: Object	Sill height * partner: Minivan / SUV	Sill height * partner: Pickup	Sill height * partner: Object	Rating: good
MAIS ≥ 2	Estimate	−8.410	0.106	−0.067	0.017	0.008	0.023	−0.083	−0.061	−0.954	0.179	−2.262	0.034	0.024	0.101	−1.604
	SE	4.718	0.023	0.017	0.008	0.008	0.029	0.325	0.035	1.329	2.287	1.944	0.046	0.072	0.064	0.371
	p value		< 0.001	< 0.001	0.03	0.35	0.42	0.80	0.09	0.47	0.94	0.25	0.45	0.74	0.12	< 0.001
MAIS ≥ 2 upper extremity	Estimate	−16.627	0.065	−0.038	0.012	−0.003	0.078	−0.467	−0.089	−1.568	2.114	−1.670	0.074	−0.011	0.072	−2.802
	SE	8.807	0.028	0.019	0.014	0.012	0.050	0.564	0.037	1.713	2.453	1.966	0.053	0.073	0.060	0.499
	p value		0.02	0.05	0.41	0.83	0.12	0.41	0.02	0.36	0.39	0.40	0.17	0.88	0.23	< 0.001
MAIS ≥ 2 lower extremity	Estimate	−4.856	0.082	−0.058	0.017	0.017	−0.010	−0.221	−0.093	−1.409	−4.146	−1.700	0.088	0.152	0.123	−0.939
	SE	5.429	0.011	0.021	0.011	0.009	0.027	0.444	0.035	1.494	2.338	1.723	0.046	0.081	0.057	0.754
	p value		< 0.001	0.01	0.13	0.07	0.71	0.62	0.01	0.35	0.08	0.32	0.06	0.06	0.03	0.21
MAIS ≥ 2 non-extremity	Estimate	−5.092	0.124	−0.085	0.026	0.005	−0.005	0.073	−0.046	−0.778	−1.735	−2.818	0.018	0.067	0.116	−1.467
	SE	2.899	0.013	0.017	0.006	0.008	0.016	0.334	0.043	1.533	2.093	1.944	0.054	0.074	0.063	0.409
	p value		< 0.001	< 0.001	< 0.001	0.52	0.77	0.83	0.28	0.61	0.41	0.15	0.74	0.37	0.07	< 0.001
MAIS ≥ 3	Estimate	−10.592	0.141	−0.090	0.035	0.006	0.021	0.437	−0.093	−1.240	−0.311	−3.608	0.060	0.034	0.170	−1.443
	SE	3.568	0.016	0.020	0.005	0.008	0.018	0.327	0.034	1.492	1.710	1.886	0.051	0.062	0.060	0.564
	p value		< 0.001	< 0.001	< 0.001	0.49	0.26	0.18	0.01	0.41	0.86	0.06	0.24	0.58	0.01	0.01
MAIS ≥ 3 lower extremity	Estimate	−9.146	0.098	−0.028	0.021	−0.007	0.019	0.355	−0.106	−4.616	−1.516	−1.744	0.179	0.067	0.141	0.065
	SE	4.855	0.014	0.028	0.009	0.015	0.028	0.593	0.039	1.659	1.797	1.783	0.053	0.062	0.061	0.871
	p value		< 0.001	0.31	0.02	0.66	0.50	0.55	0.01	0.01	0.40	0.33	0.001	0.28	0.02	0.94
MAIS ≥ 3 non-extremity	Estimate	−10.316	0.138	−0.076	0.037	0.007	0.018	0.336	−0.087	−0.793	0.039	−3.713	0.047	0.027	0.166	−1.218
	SE	3.572	0.015	0.020	0.005	0.008	0.018	0.325	0.035	1.505	1.731	1.899	0.052	0.063	0.061	0.534
	p value		< 0.001	< 0.001	< 0.001	0.36	0.34	0.30	0.01	0.60	0.98	0.05	0.36	0.67	0.01	0.02
MAIS ≥ 3 head	Estimate	−14.022	0.110	−0.041	0.035	−0.006	0.033	0.197	−0.037	−0.599	3.797	−1.186	0.061	−0.086	0.114	−1.520
	SE	4.604	0.012	0.025	0.008	0.011	0.026	0.409	0.036	1.681	1.877	1.983	0.055	0.067	0.068	1.178
	p value		< 0.001	0.10	< 0.001	0.59	0.21	0.63	0.29	0.72	0.04	0.55	0.28	0.20	0.09	0.20
MAIS ≥ 3 thorax	Estimate	−10.080	0.121	−0.072	0.039	0.007	0.013	−0.020	−0.062	−0.180	0.218	−3.328	0.028	0.018	0.150	−1.305
	SE	3.345	0.013	0.022	0.006	0.009	0.018	0.325	0.027	1.363	1.832	1.710	0.045	0.066	0.055	0.651
	p value		< 0.001	0.001	< 0.001	0.44	0.48	0.95	0.02	0.90	0.91	0.05	0.54	0.79	0.01	0.05
MAIS ≥ 3 pelvis	Estimate	0.306	0.092	−0.067	0.018	0.016	−0.034	0.385	−0.146	−4.591	−2.775	−3.913	0.166	0.096	0.137	−2.523
	SE	4.530	0.012	0.025	0.009	0.012	0.022	0.434	0.060	2.195	1.968	2.900	0.076	0.072	0.107	1.419
	p value		< 0.001	0.01	0.04	0.19	0.12	0.38	0.02	0.04	0.16	0.18	0.03	0.18	0.20	0.08

Note. dV = delta-V; MAIS = Maximum Abbreviated Injury Scale; SE = standard error.
Categorical variable reference levels: male sex, front-to-object crash type, non-good rating or unrated.