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Comparing the Effects of Age, BMI and Gender on Severe Injury (AIS 3+) in Motor-Vehicle Crashes

Patrick M. Carter[1,2], **Carol A.C. Flannagan**[1,3], **Matthew P. Reed**[1,3], **Rebecca M. Cunningham**[1,2,4], and **Jonathan D. Rupp**[1,2,3,5]

[1]University of Michigan Injury Center, Ann Arbor, Michigan.

[2]University of Michigan Department of Emergency Medicine, Ann Arbor, Michigan.

[3]University of Michigan Transportation Research Institute, Ann Arbor, Michigan.

[4]Department of Health Behavior and Health Education, University of Michigan School of Public Health, Ann Arbor, Michigan.

[5]University of Michigan Department of Biomedical Engineering, Ann Arbor, Michigan.

Abstract

Background—The effects of age, body mass index (BMI) and gender on motor vehicle crash (MVC) injuries are not well understood and current prevention efforts do not effectively address variability in occupant characteristics.

Objectives—1) Characterize the effects of age, BMI and gender on serious-to-fatal MVC injury 2) Identify the crash modes and body regions where the effects of occupant characteristics onthe numbers of occupants with injuryis largest, and thereby aid in prioritizing the need forhuman surrogates that the represent different types of occupant characteristics and adaptive restraint systems that consider these characteristics.

Methods—Multivariate logistic regression was used to model the effects of occupant characteristics (age, BMI, gender), vehicle and crash characteristics on serious-to-fatal injuries (AIS 3+) by body region and crash mode using the 2000-2010 National Automotive Sampling System (NASS-CDS) dataset. Logistic regression models were applied to weighted crash data to estimate the change in the number of annual injured occupants with AIS 3+ injury that would occur if occupant characteristics were limited to their 5th percentiles (age ≤ 17 years old, BMI ≤ 19 kg/m^2) or male gender.

Results—Limiting age was associated with a decrease inthe total number of occupants with head [8,396, 95% CI 6,871-9,070] and thorax injuries [17,961, 95% CI 15,960 – 18,859] across all

Corresponding Author: Patrick M. Carter MD, Department of Emergency Medicine, University of Michigan, 24 Frank Lloyd Wright Drive – Suite H 3200, Ann Arbor, Michigan, 48105. Phone: 781-820-1881, cartpatr@med.umich.edu.

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crash modes, decreased occupants with spine [3,843, 95% CI 3,065 – 4,242] and upper extremity [3,578, 95% CI 1,402 – 4,439] injuries in frontal and rollover crashes and decreased abdominal [1,368, 95% CI 1,062 – 1,417] and lower extremity [4,584, 95% CI 4,012 – 4,995] injuries in frontal impacts. The age effect was modulated by gender with older females morelikely to have thorax and upper extremity injuries than older males. Limiting BMI was associated with 2,069 [95% CI 1,107 – 2,775] fewer thorax injuries in nearside crashes, and 5,304 [95% CI 4,279 – 5,688] fewer lower extremity injuries in frontal crashes. Setting gender to male resulted in fewer occupants with head injuries in farside crashes [1,999, 95% CI 844 – 2,685] and fewer thorax [5,618, 95% CI 4,212 – 6,272], upper [3,804, 95% CI 1,781 – 4,803] and lower extremity [2,791, 95% CI 2,216 – 3,256] injuries in frontal crashes. Results indicate that age provides the greater relative contribution to injury when compared to gender and BMI, especially for thorax and head injuries.

Conclusions—Restraint systems that account for the differential injury risks associated with age, BMI and gender could have a meaningful effect on injury in motor-vehicle crashes. Computational models of humans that represent older, high BMI, and female occupants are needed for use in simulations of particular types of crashes to develop these restraint systems.

Keywords

Motor Vehicle Crash; Age; Gender; Body Mass Index; Unintentional Injury

1. Introduction

In 2010, motor vehicle crashes (MVC) were responsible forover 32,000 fatalities and 2.2 million injuries, with crash occupant injuries accounting for 15% of all non-fatal emergency department injuries treated annually. (CDC 2010, CDC 2011, NHTSA 2012) The annual economic cost of MVC related injury is substantial, estimated at $230 billion. (Blincoe, Seay et al. 2000) Crash related injury patterns and severity results from the complex interaction of many biomechanical factors, including seatbelt use, crash severity (measured using deltaV, the reconstructed change in velocity of the center of gravity of the vehicle determined based on measurement of post crash vehicle damage), airbag deployment and collision type (frontal, side impact, rollover).(Arbabi, Wahl et al. 2003, Zhu, Layde et al. 2006) Public health and automotive safety experts attempt to address these various factors through improvements in roadway engineering, driver behavior modification and improved automotive design.

Occupant factors, including age, body habitus and size, injury tolerance and mechanical response of affected body regions, arean important component of the complex interactions that determine injury severity.(Bedard, Guyatt et al. 2002, Bose, Segui-Gomez et al. 2011) Elderly drivers have higher fatality rates per vehicle miles driven than all other age groups except young drivers and have a significantly increased risk of injury that rises steeply after age 50. (Augenstein, Perdeck et al. 2003, Austin and Faigin 2003, Newgard 2008, Insurance Institute on Highway Safety 2010, Ridella, Rupp et al. 2012) Obesity also increases the risk of death and serious injury, although males and females may be affected differently. (Choban, Weireter et al. 1991, Boulanger, Milzman et al. 1992, Mock, Grossman et al. 2002, Arbabi, Wahl et al. 2003, Neville, Brown et al. 2004, Zhu, Layde et al. 2006, Ryb and

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Dischinger 2008, Viano, Parenteau et al. 2008, Sivak, Schoettle et al. 2010, Jehle, Gemme et al. 2012, Rupp, Flannagan et al. 2013) Some studies find an increased risk only for male obese drivers,(Zhu, Kim et al. 2010, Ma, Laud et al. 2011) while others find an increased risk for both obese male and female drivers, although greater for obese males. (Viano, Parenteau et al. 2008) On average, male drivers experience more severe crashes than female drivers (Insurance Institute on Highway Safety 2010), but prior research has also shown that in crashes of equal severity, women are more likely than men to be injured or killed. (Evans 2001, Evans 2001, Evans and Gerrish 2001, Bedard, Guyatt et al. 2002) This prior research examining occupant factors is limited, however, by a focus on specific body regions and challenges combining datasets for direct comparison of occupant factors. Thus, the relative influence of age, weight and dimensions of the occupant on the likelihood of injury or death in motor vehicle crashes is incompletely understood. (Mock, Grossman et al. 2002)

Current motor-vehiclesafety systems (vehicle structures, seatbelt, airbags and other passive safety devices) are designed and tested with crash dummies representing a mid-sized male (stature=175cm, BMI = 24.3 kg/m^3) and small female (stature = 151 cm, BMI = 21 kg/m^3) (Zhu 2006; Bose 2011). Demographic trends continue to emphasize the increasing disparity in body dimensions between the current driving population and these standards for occupant safety testing, with an increasing proportion of the population that is elderly and obese. (United Nations 2011, Ogden, Carroll et al. 2012) Previous studies have suggested that vehicle design and testing without adequate consideration of the relative effects of occupant factors may contribute to higher fatality rates and serious injury among populations that deviate from the standard test models.(Zhu, Layde et al. 2006, Bose, Segui-Gomez et al. 2011) However, before devoting substantial resources to developing crash test dummies and other human surrogates, such as computational models that can be used to assess the ability to vehicle safety systems to protect a wider range of occupant types, a detailed quantification of the effects of occupant characteristics on injury is needed.

As indicated above, previous efforts have focused on characterizing the effects of age, gender, and BMI on the risk of injury while controlling for other factors that affect the probability of injury given that a crash has occurred. However, such approaches do not consider the exposures to crashes of young and old, men and women, and high- and low-BMI occupants.For example, older occupants may be at greater risk in crashes, but they may be less likely than younger occupants to be exposed to crashes, reducing the number of injuries that could be prevented by improving protection for older occupants. Two prior studies have explored the effect of occupant characteristics on the number of injured occupants. Kent *et al.*(2009) used information on the distribution of occupants involved in crashes by age and the risk of injury as a function of age normalized to the risk of a twenty year old to characterize the effects of age on the number of occupants killed and injured in crashes. Rupp *et al.*(2013) modeled the risk of serious-to-fatal injury to different body regions in frontal, nearside, farside, and rollover crashes as functions of significant predictors of injury and then applied these models to a probability sample of occupants in crashes, adjusting the BMI distribution in this sample to estimate the effect of BMI in terms of the numbers of occupants with injury to different body regions in different crash modes.

In the current study, we expand upon the methods used by Rupp et al. (2013), with the objective of determining the relative effects of age, gender, and BMI on the numbers of occupants with serious-to-fatal injuryto different body regions in MVCs. These estimates describe the magnitude of the individual and combined effects of age, gender, and BMI and there by aid in prioritizing the development of tools to assess vehicle safety performance for different occupant types as well as countermeasures to better protect these occupants.

2. Methods and Procedures

2.1 Data Source and Dataset Development

2.1.1. NASS-CDS Dataset—The effects of occupant characteristics (age, gender and BMI) on the risk of serious-to-fatal injury were estimated using data from the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS), a nationwide stratified probability sample of crashes collected by National Highway Traffic Safety Administration (NHTSA). NASS-CDS samples approximately 5,000 police reported tow-away crashesin the United States annually. Data collectionoccurs at 24 primary sampling units distributed across the country and selected to collect cases from rural, urban, or suburban strata. Trained investigators collect data on the crash scene, the damaged vehicle(s), as well as obtaining medical information on occupant injuries. Weighted NASS-CDS data are commonly used to generate national estimates of factors relating to vehicle crash performance and occupant injury.

Injury in NASS-CDS is documented using the Abbreviated Injury Scale,(Association for the Advancement of Automotive Medicine 1998) which is a coding system that defines the injured body region and anatomic structure and substructure within a body region. The Abbreviated Injury Scale (AIS) ranks the severity of each injury on a 1 to 6 scale based on mortality and multiple other factors related to outcome. AIS 3+, which is used for this analysis, is considered serious-to-fatal injury. A typical AIS 3 injury would include a displaced femur fracture, or open humerus fracture (AIS = 6: Maximal injury, usually fatal).

2.1.2. Inclusion and Exclusion Criteria—NASS-CDS data from 2000-2010 wereusedbecause the dataset contains more current representations of the distributions of key predictor variables than NASS data from previous years. The dataset was limited to include:

- Vehicle model year ≥ 2000,
- Known vehicle types
- Three-point belted or unbelted occupants
- Occupants in front outboard seating positions
- Non-pregnant adults or 1st trimester pregnant adults (≥ 16 years old)
- Occupants with known height, weight and age

Occupants of heavy trucks, buses or motorcycles and any occupants less than 16 years of age were excluded from the dataset. Occupants were also removed if belt use was unknown or if they had missing height or weight information.

2.2 Variables and Analytical Techniques

2.2.1. Models of the Effects of Occupant Characteristics on Injury Risk—The effects of occupant, vehicle and crash characteristics on injuries with an AIS score of 3 or higher (serious-to-fatal injuries) by body region and crash mode were modeled using multivariate logistic regression analysis. These regression models have been previously reported by Ridella et al. (2012) who characterized the effects of occupant age on injury risk while adjusting for other significant predictors of serious to fatal injury such as crash severity, seat belt use, BMI, gender, vehicle type, and interactions among these variables.

Logistic regression is a general linear model shown in Equations 1 and 2. The linear component, $\hat{y}$, is also called the logit, or log odds of the outcome (in this case, injury). Fit is determined using a maximum likelihood approach, which find the set of parameters that maximize the joint probability of the data, given the model.

$$\hat{p}=1/\left(1+exp\left(-\left(\hat{y}\right)\right)\right) \quad (1)$$

where $\hat{p}$ is the predicted probability of injury, $\hat{y}$ is the linear predictor, given in Equation 2.

$$\hat{y}=\hat{c}_0+\sum_{i=1}^{r}\hat{c}_i x_i \quad (2)$$

where x_i are the values of the predictors, and $\hat{c}_i$ are the estimated coefficients

Separate models were developed for the head, spine, thorax, abdomen, upper extremities (UX) and lower extremities (LX) for frontal, nearside, farside and rollover crashes. Models were developed using a reverse stepwise approach in which all predictors were initially included in a model for a particular body region and crash mode. The least significant predictor was removed from the model until all remaining predictors were significant ($\alpha <$ 0.05). Predictors utilized inthe final models are summarized in Table 1.

Age, BMI, crash severity, and height were treatedas continuous variables. All other variables were treated as categorical, using the categories shown in Table 1. The models are reproduced in the accompanying appendices (Appendix Tables A2, A3, A4, A5) for reference. Crash severity was defined for this analysis using deltaV, which is the change in the velocity of the occupant's vehicle estimated with standard crash reconstruction methods. Body regions were identified using the AIS code. All analyses used weighted data and survey methods to account for the sample design in estimating variance (i.e., PROC SURVEYLOGISTIC in SAS). Interactions between age and gender, BMI and vehicle type, and BMI and gender were tested in the development of all models since these interactions have been previously demonstrated or postulated in the literature.(Rupp, Flannagan et al. 2013) Of note, a regression model was not generated for a body region and crash mode combination if the NASS-CDS sample contained an insufficient number of injuries (less than 100AIS 3+ injuries in the unweighted dataset).

2.2.2. Characterizing the Occupant Characteristic Effect on Occupants with Injury—The logistic regression models describe the effects of occupant characteristics (Age, BMI, and Gender) and other covariates on serious-to-fatal injury risk, but provide limited insight into the potential effects of occupant characteristics on the numbers of injured occupants because they do not consider differences in exposure associated with age, gender, and BMI. To estimate the effect of occupant characteristics on numbers of injured occupants, the crash, vehicle and occupant information associated with each occupant in a NASS-CDS 2007-2008 dataset was entered intoto the logistic regression models to predict a risk for each occupant. The risk for each occupant was then multiplied by the associated case weight and the results were summed to provide a baseline estimate of the total risk of injury for the population of occupants. Next, each occupant characteristic of interest was separately considered. For this analysis, a NASS dataset from 2007-2008 was used because recent NASS years contain data from the 2009 economic downturn, which decreased the exposure of preferentially vulnerable populations such as teenagers and the elderly, a pattern that is likely to be temporary. (Sivak, Schoettle et al. 2010)

To quantify the effects of age, the NASS-CDS dataset was altered so that all occupants with an age greater than a given cutoff had their age reset to the cutoff value (e.g. all occupants with an age greater than 65 were reset to 65 years old). The newly modified NASS-CDS dataset was then applied to the regression models again to estimate a risk for each occupant. The resulting risks were then multiplied by the associated case weights and the results were summed over occupants in the dataset. The percent difference between the resulting value and the baseline estimate of the number of occupants with serious-to-fatal injurywas then calculated, providing an estimate of percent reduction in occupants with serious-to-fatal injury. The process was repeated while varying the age “cutoff” between the 2.5th percentile and 97.5th percentile of the age distribution (i.e. 17 years old to 75 years old), providing estimates of the effect of age on reduction in AIS3+ injury. This process was repeated for different body regions and crash modes as appropriate to the original regression model. A similar process was used for BMI, where BMI was limited at integer values between 24 kg/m^2 and 45 kg/m^2 to obtain estimates of the effect of BMI on the percentages of occupants with AIS 3+ injury to different body regions from varying degrees of overweight to obese.

To quantify the effects of gender, the NASS-CDS dataset was altered so that all occupants were considered male. The newly modified dataset was then applied to the regression models as above to estimate a risk for the occupant. The resulting risk was multiplied by the associated case-weighting factor and the results were summed. The percent difference between the resulting value and the baseline estimate of the number of occupants with serious-to-fatal injury was then calculated, providing an estimate of percent reduction in occupants with serious-to-fatal injury to each body region where gender was a significant predictor in the regression model.

Confidence intervals on the predictions of the percent change in number of injured occupants were estimated using Monte Carlo simulation. With logistic regression, error on the linear predictor ($\hat{y}$) is normal witha single estimated standard deviation that is independent of the predicted value. To calculate the confidence interval, we randomly selected an offset for each case from the normal error distribution associated with the logit. This offset was added to the predicted value for that case under two conditions: 1) the original values of occupant characteristics, and 2) the adjusted values of occupant characteristics for each analysis. Each adjusted logit was then transformed to a probability of injury using the logistic transformation shown in Equation 1. That is, the value of $\hat{y}$ in Equation 1 for each case was entered as the original $\hat{y}$ plus the random error chosen for that case.

The difference in estimated risk between baseline and occupant-characteristic-adjusted conditions was then multiplied by the associated case weight and the results were summed across all occupants in the dataset. This process was repeated 1000 times for each model and the 2.5th and 97.5th percentiles of the resulting distribution of the predicted change in occupants with injury to each body region were used to determine 95% confidence intervals on the difference in injured occupants for baseline and the occupant-characteristic-adjusted scenario.

2.2.3 Estimating the Total Number of Occupants with AIS 3+ Injury due to Age,BMI, and Gender—Estimates of the total numbers of occupants with serious-to-fatal injuries to different body regions that are due to age, gender, and BMI were obtained by multiplying the total number of AIS 3+ injuries to a body region in a particular crash mode (from NASS-CDS 2007-2008) by the predicted changes in the percentage of occupants with AIS 3+ injury to that body region as a result of age, gender, or BMI. This last step is necessary because missing data (most commonly deltaV) prevents the statistical models that describe the effects of age on injury in crashes from being used on 30% of the relevant crashes in the dataset. Confidence intervals on the predicted numbers of occupants with AIS 3+ injury due to age, gender, and BMI were generated by multiplying the confidence intervals on percent changes by the associated total number of AIS 3+ injuries for each body region and crash mode combination. Note that this approach necessarily assumes that the missingness occurs at random. In fact, cases in CDS with missing deltaV have previously been shown to have higher injury rates (Kononen, Flannagan et al. 2011), but this means that our estimates of number of injuries are probably conservative.

3. Results

3.1 Sample Characteristics

The application of vehicle model year, vehicle type, and occupant age resulted in a dataset of 25,246 vehicle occupants. Removal of occupants with missing height or weight information, heavy trucks, buses or motorcycle occupants and those in frontal and side impact crashes that were missing deltaV reduced occupant number to 18,371 in the unweighted sample, which corresponds to a weighted sample of 6,011,375.

Table 1 lists the key predictors used in the regression models. Tables 2-4 demonstrate the distribution of key predictor variables in the dataset used in this study stratified by age, BMI and gender categories, respectively. Among age categories (Table 2), we found a significant difference in belt use and seat location, with younger crash-involved occupants less likely to use a seatbelt than older occupants andmore likely to be a passenger than middle-aged occupants. Younger and older occupants were also more likely to be driving passenger vehicles rather than utility vehicles or vans and were less likely to be in higher BMI categories. Middle-aged occupants were also less likely to be involved in high severity (i.e. deltaV) crashes for farside impacts than younger or older occupants.

Among BMI categories (Table 3), we found significant differences in age and gender, with higher percentages of males and middle-aged crash-involved occupants in higher BMI categories. Younger and Older occupants were less likely to be among the higher BMI categories. Low BMI occupants were more likely to be passengers. Higher BMI occupants were less likely to drive passenger cars and more likely to drive larger vehicles such as utility vehicles or vans. With respect to crash mode, lower BMI occupants were less likely to be involved in nearside crashes, while other crash modes didn't demonstrate significant differences by BMI category. Lower BMI occupants were also more involved in higher severity (i.e. higher deltaV) nearside crashes. No meaningful differences in crash severity were noted for frontal or farside impacts.

Between men and women (Table 4), men were more likely to be unbelted and occupying the driver position than women in crashes. Men were also more likely to be driving pickups or utility vehicles than women. Men were less likely to have a normal BMI (<25 kg/m^2) than women occupants in the dataset. With respect to crash mode, men were more likely to be involved in rollover crashes. No other significant crash mode differences were noted. Men were more likely involved in lower severity farside impacts than females, while no other meaningful differences were noted in crash severity.

3.2 Models of the Effects of Occupant Characteristics on Injury Risk

Logistic regression models predicting AIS 3+ injury by body region (head, spine, thorax, abdomen, upper extremity, lower extremity) and crash mode (frontal, nearside, farside and rollover), which have previously been reported in the literature by Ridella *et. al.*(2012) were recreated and are available in the accompanying appendix (Table A2, A3, A4, A5) along with a table demonstrating the baseline risks of AIS 3+ injury by crash mode and body region (Table A1). A summary table showing the occupant characteristics that were significant predictors of AIS 3+ injury risk is presented in Table 5. Age was a significant predictor for AIS 3+ injury risk for more body regions by crash type than either BMI or gender. Multiple significant effects of occupant characteristics and variables that interact with occupant characteristics were observed for some body regions, particularly the thorax and upper extremities in frontal crashes and head in nearside crashes, indicating that the effects of occupant characteristics are complex.

3.3 Effects of Occupant Characteristics on the Percentage of Occupants with Injury

Figure 1 describes the effects of occupant characteristics in terms of percent change in the number of occupants with severe injury to different body regions predicted to occur as limits are placed on the defining variable. In Figure 1a, the percent reduction in injury is modeled as the maximum age of the crash population is limited to progressively lower values, such that occupants above that age are modeled using the maximum age instead of their true (older) age. The results demonstrate that for every crash mode and body region shown, injury decreases substantially as the maximum age of the population decreases. Figure 1b shows similar plots for the percent reduction in injury as the maximum value for BMI is limited to progressively lower values. In frontal crashes, limiting BMI to progressively smaller values leads to substantial reduction in upper and lower extremity injuries. In nearside crashes, limiting BMI leads to a reduction in thorax injuries, but an increase in head injuries among this population. Figure 1c demonstrates the percent reduction in injury expected if all occupants in the crash were male, with evidence of substantial reductions in nearside and farside head injuries, frontal thorax, upper extremity and lower extremity injuries. Less substantial reductions were noted in rollover upper extremity injuries, and an increase in spinal injuries in rollover crashes was observed.

3.4 Estimating Total Number of Occupants with Severe Injury (AIS 3+) due to Age, BMI, and Gender

Figure 2 applies the predicted changes in percentage of occupants with severe injury to the NASS-CDS 2007-2008 dataset to estimate the decreases in numbers of occupants with severe injury if all occupants were male and if age and BMI were limited to their 5th percentile values (i.e. 17 years old and 19 kg/m^2). Table 6 provides the mean predicted decreases in number of occupants with injuries and the 95% confidence intervals on these estimates. For all crash modes limiting age results in 8,396 [95% CI 6,871-9,070] fewer head, 17,961 [95% CI 15,960 – 18,859] fewer thorax, 3,843 [95% CI 3,065 – 4,242] fewer spine, 3,578 [95% CI 1,402 – 4,439] fewer upper extremity and 4,584 [95% CI 4,012 – 4,995] fewer lower extremity injuries. Similarly, limiting BMI results in 2,069 [95% CI 1,107 – 2,775] fewer thorax,and 5,304 [95% CI 5,818 – 6,777] fewer lower extremity injuries. Finally, modeling all occupants as males results in 1,999 [95% CI 844 – 2,685] fewer head, 5,618 [95% CI 4,212 – 6,272] fewer thorax, 3,804 [95% CI 1,781 – 4,803] fewer upper extremity and 2,791 [95% CI 2,216 – 3,256] fewer lower extremity injuries.

4. Discussion

This is the first analysis that comprehensively estimates the impact of age, BMI and gender variations on the numbers of occupants in MVC's with serious to fatal injuries to different body regions in different crash modes. The results describe the effects in terms of the change in number of occupants with severe injury (AIS 3+) that would be expected if all other predictors of injury were held constant. Because of this, the results do not consider changes in exposure that would be expected because of associations between predictor variables (e.g., if all high BMI occupants became normal BMI occupants they would be more likely to drive passenger cars). However, the estimates of the numbers of injured occupants associated with age, gender, and BMI are an estimate of the theoretical benefits if an occupant protection system were changed to provide similar protection to occupants of all sexes, ages, and BMIs. As a result, the estimates in this paper can reasonably be used to identify the need for human surrogates to represent specific populations and the types of crash tests that these surrogates should be used in for testing. Results are also useful in prioritizing public health interventions related to occupants of motor vehicle crashes, including additional safety countermeasures, improved crash prevention testing parameters and public awareness campaigns focusing attention on vulnerable populations as well as promoting effective interventions for modifiable risk factors.

The trends in the distributions of predictor variables with age, gender, and BMI have important implications on the need for vehicle safety systems that account for the increased vulnerability associated with particular occupant characteristics. For example, older occupants were noted to be more likely to travel in passenger cars than light trucks, vans or utility vehicles; suggesting that investment in countermeasures to reduce the likelihood of injuries associated with aging, like thorax and head injuries in all crash modes may be most effectively targeted at passenger vehicles and in particular passenger vehicles tend to be driven by an older demographic. Because higher BMI occupants were less likely to drive passenger vehicles and more likely to occupy utility vehicles, trucks or vans, countermeasures to prevent injuries associated with BMI, such as lower extremity injuries in frontal crashes, may be of higher value in SUVs. The effects of occupant characteristics on injury to different body regions observed in this study are generally consistent with results of previous crash database analyses and biomechanical studies.

The increase in thoracic injuries for elderly occupants relative to younger occupants in similar crashes has been widely reported. (Morris, Welsh et al. 2002, Morris, Welsh et al. 2003, Kent, Henary et al. 2005) The increased risk of chest injuries is primarily from increased rib fractures and the accompanying intra-thoracic injuries. These injuries are more prevalent in older occupants because of age-related bone loss and reductions in fracture toughness. (Kent, Henary et al. 2005) Ultimately, elderly crash victims are less able to tolerate the effects of intra-thoracic injury, with less efficient oxygen exchange, decreased pain tolerance and increased stiffening of the chest wall that prohibits adequate clearance of secretions and increases infection risk.(Kent, Woods et al. 2008) Consistent with this mechanism and prior NASS-CDS crash analysis, (Ridella, Rupp et al. 2012) we found that risk of serious injury increases with age for all body regions and crash modes, with thorax injuries most prominent in frontal, nearside and farside crashes. Our finding that serious-to-fatal head injuries were more common in frontal and nearside crashes mirrors the findings of Ridella et al. and is consistent with Mallory's finding that elderly occupants are at higher risk for bleeding type head injuries, even at low crash severities. (Mallory 2010, Ridella, Rupp et al. 2012) Comparing age, BMI and gender effects on the numbers of occupants with AIS 3+ injuries to different body regions, the age effect substantially overwhelms BMI and gender for all crash modes and regions, signifying an urgent need to address injury in elderly crash victims, especially thorax and head injuries, with improved testing and occupant safety systems.

Obese occupants are at increased risk for severe injury due to anatomical and physiological variations that alter normal occupant and safety belt response during a crash. (Zhu, Layde et al. 2006, Turkovich and van Roosmalen 2010) Greater occupant mass increases kinetic energy, increasing forward hip/pelvis movement before adequate safety belt restraint (Viano, Parenteau et al. 2008, Kent, Forman et al. 2010, Turkovich and van Roosmalen 2010, Rupp, Flannagan et al. 2013) and decreases normal pitch forward during impact. (Kent, Forman et al. 2010) Thus, the increased lower extremity injuries in frontal crashes observed in our study likely results from increased hip excursion and a higher knee impact against the lower instrument panel. This increases knee-thigh-hip fractures and below the knee injury.(Wang, Bednarski et al. 2003, Kent, Forman et al. 2010, Rupp, Flannagan et al. 2010, Rupp, Flannagan et al. 2013) As the majority of nearside impacts usually have some associated component of frontal impact, the mechanism for the observed increase in obese occupants with nearside thoracic injuriesmay be similar to that observed in frontal crash cadaver studies where there is increased seatbelt loading on the more compliant and vulnerable lower thorax region and not on the stiffer upper thorax region.(Kent, Trowbridge et al. 2009) This has been shown to increase rib fractures, pulmonary contusions and thoracic injuries among obese occupants.(Boulanger, Milzman et al. 1992, Mock, Grossman et al. 2002, Moran, Rue et al. 2002, Zhu, Kim et al. 2010) Previous research has identified a conflicting relationship between obesity and severe abdominal injuries. Some authors find a protective effect from the adipose tissue “cushion”(Arbabi, Wahl et al. 2003, Wang, Bednarski et al. 2003) while others find increased abdominal injury and mortality.(Ryb and Dischinger 2008, Zarzaur and Marshall 2008) Zhu et al(2010) found a U shaped relationship, concluding that the protective effect that may be overcome by increased momentumas BMI increases. This relationship was not apparent in our study, which may be due to our inclusion of interaction effects (e.g. BMI*Vehicle Type) that were not accounted for in prior studies.

Men were less susceptible to thorax and upper/lower extremity injury in frontal crashes and less likely to sustain head injury in farside crashes in our analysis, consistent with previous findings that men and women experience crashes differently.(Evans 2001, Evans and Gerrish 2001, Bose, Segui-Gomez et al. 2011) Some authors argue that the shorter female stature and the tendency for women to sit more forward in the cabin may decrease the protection provided by standard safety devices, increasing the potential for lower extremity injuries and thorax injuries in frontal crashes.(Dischinger, Kerns et al. 1995, Crandall and Martin 1997, Bose, Segui-Gomez et al. 2011) Others suggest that additional mechanisms are at play, given that anthropometric data demonstrates a consistent stature difference between men and women throughout life, while injury risk changes over time, with greater risk for elderly females.(Evans 2001) We observed an interaction between gender and head injury with increased risk for severe-to-fatal head injury in females involved in farside crashes. This may be a result of shorter stature prompting seat position to be more forward for females than males and increasing the risk for women to be injured by the striking vehicle in a side impact. Despite the low contribution of gender effect to overall injury risk compared to BMI and age, more study is needed to understand these gender variations and the disparity in protection offered by current safety devices.

The effects of occupant characteristics on injury observed in this study indicate a need for improved human computational models that better represent different sets of occupant characteristics that can be used to identify the mechanisms and biomechanical factors that are associated with the observed effects of occupant characteristics. Specifically, the finding that the effect of BMI is largest in frontal crashes and on lower extremity injuries suggests that development of computational models of obese occupants should focus on this crash mode and injury. Further, the association between the body shape changes associated with obesity and poor belt fit (as well as more adipose tissue over the anterior pelvis) indicates that such models should have a humanlike external body shape.The increase in the risk and incidence of injuries to almost every body region and every crash model with increasing age indicates a broad need for computational models that represent elderly occupants for use in multiple modes of loading. Like computational models of obese occupants, these models should consider the differences in body shape associated with aging as well as the changes in skeletal geometry and failure characteristics associated with increasing age. Because thoracic injury (rib fracture) is a major contributor to the effects of age in all crash modes, computational models of older occupants should emphasize appropriate representation of age-related changes in rib geometry, costal cartilage mineralization, and tissue level failure characteristics. The finding that women are more likely to sustain thoracic and extremity injuries in frontal crashes than men suggests that frontal crash simulations with female computational models are needed to better understand whether the effect of gender is related to differences in body size, shape, skeletal geometry, or injury tolerance between men and women.

This analysis highlights the importance of improving occupant protection with specific targeted population interventions that reflect population variations in BMI, age and gender.For all crash modes, age was found to have the largest effect on injury, especially for the thorax and head regions. Despite the age effect, the obesity effect on lower extremity and thorax injuries and the differential injury findings among men and women need to be addressed. One potential intervention for the opposing effect of age and obesity on thoracic injuries is adaptive seat belt restraint systems that provide increased loading on obese occupants while decreasing the thoracic load on elderly occupants. Four point restraint systems and inflatable seatbelts have also been proposed for elderly occupants that will reduce or distribute chest loading. For obese occupants, knee airbags may help counter thelower extremity impact against the dashboard during a crash, limiting injury potential. Regardless, the introduction of new safety measures will require extensive physical and virtual testing to ensure that additional protection to limit occupant injuries among one occupant subgroup (e.g. elderly patients) doesn't adversely affect other subgroups (e.g. obese drivers).

Several analysis limitations are noted. Our analysis did not control for structural intrusion into the vehicle compartment. Although unlikely to affect the analysis, controlling for intrusion may reduce the effects of related variables such as deltaV and vehicle type. For a similar reason, the analysis did not control for airbag deployment, which has been shown to be a cause of upper extremity injuries (Hardy, Schneider et al. 2001) and may explain some of the upper extremity findings in this analysis. We did not consider crash direction within each crash type or the effects of subtypes of crashes due to small sample sizes and this may miss important relationships between predictor variables and injury. Height and weight data for uninjured occupants is self-reported in the NASS-CDS database. These reporting biases combined with more accurate data obtained for injured occupants may both overestimate increased injury risk underestimate decreased injury risk associated with gender and BMI. In addition, 30% of frontal, nearside and farside crashes in the NASS-CDS database are missing deltaV estimates, which has previously been shown to occur in those crashes with more severe injuries, multiple impacts and more often with trucks than other vehicles. (Kononen, Flannagan et al. 2011) This likely affects the estimates of the numbers of occupants sustaining injuries to different body regions but should not affect the relationship between the injury risk, body regions and predictors of risk.

5. Conclusion

This analysis estimates the relative impact of age, BMI and gender variations on the numbers of occupants in MVC's with serious to fatal injuries to different body regions in different crash modes. Results have important implications for the design of future safety occupant systems including such measures as adaptive restraint systems, inflatable seatbelts, and knee airbags, especially the finding that age provides the greatest relative contribution to occupant injury when compared to gender and BMI. Results also stress the importance of increased computational simulation with models that consider the variability in occupant characteristics to evaluate how safety design changes may influence protection for these occupants. Finally, analyses such as this one that aid inunderstanding the relative influences of occupant factors on crash related injury may influence how consumers will invest in safety options while purchasing a new vehicle (e.g. elderly drivers at risk for thorax injury may invest in an inflatable seatbelt option to decrease risk for thoracic injury).

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Appendix

Table A1

Risks of AIS 3+ Injury (%) with the associated 95% Confidence Interval by body region and crash mode.

	Head	Thorax	Spine	Abdomen	Upper Ex	Lower Ex	All Regions
Farside	0.10 (0.14, 0.06)	0.09 (0.13, 0.06)	0.02 (0.04, 0.01)	0.01 (0.03, 0.00)	0.02 (0.04, 0.01)	0.03 (0.04, 0.01)	0.20 (0.25, 0.15)
Frontal	0.18 (0.25, 0.12)	0.49 (0.65, 0.34)	0.10 (0.13, 0.07)	0.08 (0.12, 0.05)	0.31 (0.43, 0.19)	0.58 (0.71, 0.46)	1.32 (1.56, 1.09)
Nearside	0.19 (0.29, 0.10)	0.32 (0.40, 0.25)	0.02 (0.03, 0.01)	0.04 (0.05, 0.02)	0.05 (0.07, 0.02)	0.17 (0.22, 0.12)	0.54 (0.66, 0.41)
Rollover	0.08 (0.12, 0.04)	0.14 (0.25, 0.03)	0.02 (0.04, 0.01)	0.02 (0.04, 0.00)	0.03 (0.06, 0.01)	0.05 (0.07, 0.02)	0.24 (0.36, 0.13)
All Crash Modes	0.60 (0.73, 0.46)	1.07 (1.29, 0.86)	0.19 (0.23, 0.14)	0.17 (0.22, 0.12)	0.46 (0.60, 0.32)	0.83 (0.98, 0.69)	2.41 (2.73, 2.10)

Table A2

Frontal models

Parameter		Parameter Estimates					
		Head	Thorax	Spine	Abdomen	Upper Ex	Lower Ex
Intercept		−7.745*** (−8.52,−6.97)	−8.276*** (−10.4,−6.19)	−8.729*** (−9.8,−7.63)	−9.708*** (−11.3,−8.14)	−8.836** (−12.8,−4.9)	−8.741*** (−9.91,−7.57)
Belt Use (vs. unbelted)		−7.745*** (−8.52,−6.97)	−1.482* (−2.45,−0.51)	−1.14* (−1.83,0.44)	−1.574* (−2.61,−0.53)	−1.340* (−2.57,−0.11)	−1.784*** (−2.26,−1.30)
Vehicle Type (vs. passenger car)	Light truck					3.195* (0.40,5.99)	
	Utility					−2.822 (−7.18,1.54)	
	Van					−2.509 (−5.88,0.86)	
Age (yr.)		0.025*** (0.02,0.03)	0.031** (0.01,0.05)	0.044*** (0.03,0.06)	0.037* (0.01,0.06)	0.038*** (0.02,0.06)	0.020* (0.00,0.04)
BMI (kg/m^2)						0.015 (−0.09,0.12)	0.061** (0.03,0.09)
deltaV (mph)		0.114*** (0.09,0.14)	0.163*** (0.13,0.19)	0.090*** (0.07,0.11)	0.147*** (0.11,0.18)	0.126*** (0.10,0.15)	0.162*** (0.15,0.17)
Gender (vs. M)			−0.438 (−1.88,1.01)			2.143*** (1.19,3.10)	0.513*** (0.30,0.72)
BMI*Gender (vs. M)							
Age*Gender (vs. M)			0.026* (0.00,0.05)			−0.030* (−0.05,−0.01)	
Seat Position (vs. Driver)						1.065*** (1.50,0.63)	
BMI*Vehicle Type (vs. passenger car)	Light Truck					−0.107 (−0.22,0.00)	
	Utility					0.058 (−0.08,0.19)	
	Van					0.101 (−0.01,0.21)	
Multiple Severe Impacts (vs. none)		1.751* (0.64,2.87)					

** Note that predictors used within the regression models are summarized in Table 1 and the process for conducting the reverse stepwise regression is detailed in section 2.2.1 of the methods within the manuscript text.

*** A summary of those occupant characteristics or interaction terms that were significant and included within the subsequent analysis is presented in Table 5.

* $p<0.05$

** $p<0.001$

*** $p<0.0001$

Table A3

Nearside models.

Parameter		Parameter Estimates			
		Head	Thorax	Abdomen	Lower Ex
Intercept		−8.639*** (−10.54,−6.74)	−7.929*** (−9.17,−6.69)	−7.303*** (−8.00,−6.60)	−7.929*** (−9.17,−6.69)
Belt Use (vs. unbelted)		−1.254** (−1.95,−0.56)	−0.881 (−1.81,0.04)		−0.881 (−1.81,0.04)
Vehicle Type (vs. passenger car)	Light Truck		−0.087 (−0.95,0.77)		
	Utility		−0.470 (−1.35,0.41)		
	Van		−1.923* (−3.39,−0.45)		
Age (yr.)		0.052* (0.01,0.09)	0.025*** (0.01,0.04)		
BMI (kg/m^2)		0.029 (−0.03,0.09)	0.040* (0.01,0.07)		
deltaV (mph)		0.145*** (0.09,0.19)	0.212*** (0.16,0.26)	0.123*** (0.09,0.15)	0.025*** (0.01,0.04)
Gender (vs. M)		2.849* (0.12,5.58)			
BMI*Gender (vs. M)		−0.090* (−0.17,−0.01)			
Multiple Severe Impacts (vs. none)		−1.099* (0.34,1.86)		1.672* (0.42,2.92)	
L-/T-Type (vs. T-Type)				−16.067*** (−16.74,−15.39)	0.040* (0.01,0.07)

**Note that predictors used within the regression models are summarized in Table 1 and the process for conducting the reverse stepwise regression is detailed in section 2.2.1 of the methods within the manuscript text.

***A summary of those occupant characteristics or interaction terms that were significant and included within the subsequent analysis is presented in Table 5.

* $p<0.05$

** $p<0.001$

*** $p<0.0001$

Table A4

Farside Models

Parameter		Parameter Estimates	
		Head	Thorax
Intercept		−15.446*** (−22.12,−8.78)	−17.944*** (−23.11,−12.78)
Belt Use (vs. unbelted)		−2.279** (−3.48,−1.08)	
Vehicle Type (vs. passenger car)	Light truck	−2.619* (−4.53,−0.71)	−1.124* (−1.92,−0.33)
	Utility	−0.742 (−1.76,0.28)	−0.629 (−1.80,0.54)
	Van	−2.756* (−4.76,−0.75)	−1.155 (−2.87,0.56)
Age (yr.)		0.035** (0.01,0.05)	0.047** (0.02,0.07)
deltaV (mph)		0.196*** (0.15,0.24)	0.164*** (0.14,0.19)
Gender (vs. M)		1.643* (0.60,2.69)	
Height (cm)		0.041* (0.00,0.08)	0.050** (0.02,0.08)

**Note that predictors used within the regression models are summarized in Table 1 and the process for conducting the reverse stepwise regression is detailed in section 2.2.1 of the methods within the manuscript text.

***A summary of those occupant characteristics or interaction terms that were significant and included within the subsequent analysis is presented in Table 5.

* $p<0.05$

** $p<0.001$

*** $p<0.0001$

Table A5

Rollover Models

Parameter		Parameter Estimates				
		Head	Thorax	Spine	Upper Ex	Lower Ex
Intercept		−3.703*** (−4.42,−2.99)	−8.972*** (−10.23,−7.72)	−8.778*** (−9.98,−7.57)	−8.806*** (−10.16,−7.45)	−8.897*** (−9.81,−7.98)
Belt Use (vs. unbelted)		−2.057*** (−2.40,−1.71)	−2.499*** (−3.10,−1.90)	−1.738*** (−2.57,−0.91)	−1.435*** (−1.81,−1.06)	−3.462*** (−3.96,−2.97)
Vehicle Type (vs. passenger car)	Light Truck			−0.373 (−0.97,0.23)		
	Utility			−0.755* (−1.35,−0.16)		
	Van			−0.102 (−1.06,0.86)		
Age (yr.)		0.733*** (0.45,1.01)	0.020*** (0.01,0.03)	0.011 (−0.01,0.04)	0.030*** (0.02,0.05)	
Gender (vs. M)				−1.100 (−2.47,0.27)	0.811* (0.16,1.46)	
BMI*Gender (vs. M)						
Age*Gender (vs. M)				0.011 (−0.01,0.04)		
Multiple Severe Impacts (vs. none)		0.733*** (0.45,1.01)				
Number Quarter Turns (vs <2)	3-6	0.475 (−0.08,1.03)	3.941*** (2.45,5.43)	0.614* (0.09,1.14)	0.811* (0.16,1.46)	0.336 (−1.87,2.54)
	7-10	1.573*** (1.00,2.14)	2.156*** (1.31,3.00)	1.555* (0.07,3.05)	3.351** (1.53,5.18)	0.185 (−0.30,0.67)
	11-13	2.894*** (2.00,3.79)	3.941*** (2.45,5.43)	2.206*** (1.55,2.87)	0.811* (0.16,1.46)	0.336 (−1.87,2.54)
	>13	−8.972*** (−10.23,−7.72)	2.156*** (1.31,3.00)	−8.806*** (−10.16,−7.45)	−8.897*** (−9.81,−7.98)	1.683** (0.75,2.62)
First impact over occupant seat position				0.564* (0.09,1.04		

**Note that predictors used within the regression models are summarized in Table 1 and the process for conducting the reverse stepwise regression is detailed in section 2.2.1 of the methods within the manuscript text.

***A summary of those occupant characteristics or interaction terms that were significant and included within the subsequent analysis is presented in Table 5.

* $p<0.05$

** $p<0.001$

*** $p<0.0001$

Abbreviations

MVC	Motor Vehicle Crash
BMI	Body Mass Index
AIS	Abbreviated Injury Scale
ED	Emergency Department
UE	Upper Extremity
LE	Lower Extremity
NASS-CDS	National Automotive Sampling System-Crashworthiness data system
NHTSA	National Highway Traffic Safety Administration

REFERENCES

Arbabi S, Wahl WL, Hemmila MR, Kohoyda-Inglis C, Taheri PA, Wang SC. The cushion effect. J Trauma. 2003; 54(6):1090–1093. [PubMed: 12813327]

Association for the Advancement of Automotive Medicine. Abbreviated Injury Scale 90. 1998. 1998 Revision. Des Plains

Augenstein J, Perdeck E, Stratton J, Digges K, Bahouth G. Characteristics of crashes that increase the risk of serious injuries. Annu Proc Assoc Adv Automot Med. 2003; 47:561–576. [PubMed: 12941251]

Austin RA, Faigin BM. Effect of vehicle and crash factors on older occupants. Journal of Safety Research. 2003; 34(4):441–452. [PubMed: 14636666]

Bedard M, Guyatt GH, Stones MJ, Hirdes JP. The independent contribution of driver, crash, and vehicle characteristics to driver fatalities. Accid Anal Prev. 2002; 34(6):717–727. [PubMed: 12371777]

Blincoe, L.; Seay, A.; Zaloshnja, E. "The Economic Impact of Motor Vehicle Crashes".. 2000.

Bose D, Segui-Gomez M, Crandall JR. Vulnerability of female drivers involved in motor vehicle crashes: an analysis of US population at risk. Am J Public Health. 2011; 101(12):2368–2373. [PubMed: 22021321]

Boulanger BR, Milzman D, Mitchell K, Rodriguez A. Body Habitus as a Predictor of Injury Pattern after Blunt Trauma. Journal of Trauma-Injury Infection and Critical Care. 1992; 33(2):228–232.

CDC. [September 18, 2012] WISQARS (Web-based Injury Statistics Query and Reporting System).. 2010. from http://www.cdc.gov/injury/wisqars

CDC. Vital Signs: Nonfatal, motor vehicle-occupant injuries (2009) and seat belt use (2008) among adults—United States, MMWR. 2011.

Choban PS, Weireter LJ Jr. Maynes C. Obesity and increased mortality in blunt trauma. J Trauma. 1991; 31(9):1253–1257. [PubMed: 1920556]

Crandall, J.; Martin, P. Lower limb injuries sustained in crashes and corresponding biomechanical research.. Proceedings of the International Symposium on Real World Crash Injury Research; Leicestershire, England. 1997.

Dischinger PC, Kerns TJ, Kufera JA. Lower extremity fractures in motor vehicle collisions: the role of driver gender and height. Accid Anal Prev. 1995; 27(4):601–606. [PubMed: 7546071]

Evans L. Age and fatality risk from similar severity impacts. Journal of traffic medicine. 2001; 29(1/2):10–19.

Evans L. Female compared with male fatality risk from similar physical impacts. J Trauma. 2001; 50(2):281–288. [PubMed: 11242293]

Evans L, Gerrish PH. Gender and age influence on fatality risk from the same physical impact determined using two-car crashes. Society of Automotive Engineers. 2001

Hardy WN, Schneider LW, Rouhana SW. Prediction of airbag-induced forearm fractures and airbag aggressivity. Stapp Car Crash J. 2001; 45:511–534. [PubMed: 17458761]

Insurance Institute on Highway Safety. Fatality Facts 2010 - Gender. 2010 from http://www.iihs.org/research/fatality.aspx?topicName = Gender 2010.

Insurance Institute on Highway Safety. [September 19, 2012] Fatality Facts: Older People.. 2010. from http://www.iihs.org/research/fatality.aspx?topicName = Older people, 2010

Jehle D, Gemme S, Jehle C. Influence of obesity on mortality of drivers in severe motor vehicle crashes. Am J Emerg Med. 2012; 30(1):191–195. [PubMed: 21129887]

Kent R, Henary B, Matsuoka F. On the fatal crash experience of older drivers. Annu Proc Assoc Adv Automot Med. 2005; 49:371–391. [PubMed: 16179160]

Kent R, Trowbridge M, Lopez-Valdes FJ, Ordoyo RH, Segui-Gomez M. How many people are injured and killed as a result of aging? Frailty, fragility, and the elderly risk-exposure tradeoff assessed via a risk saturation model. Ann Adv Automot Med. 2009; 53:41–50. [PubMed: 20184831]

Kent R, Woods W, Bostrom O. Fatality risk and the presence of rib fractures. Ann Adv Automot Med. 2008; 52:73–82. [PubMed: 19026224]

Kent RW, Forman JL, Bostrom O. Is There Really a "Cushion Effect"?: A Biomechanical Investigation of Crash Injury Mechanisms in the Obese. Obesity. 2010; 18(4):749–753. [PubMed: 19798067]

Kononen DW, Flannagan CA, Wang SC. Identification and validation of a logistic regression model for predicting serious injuries associated with motor vehicle crashes. Accid Anal Prev. 2011; 43(1):112–122. [PubMed: 21094304]

Ma X, Laud PW, Pintar F, Kim JE, Shih A, Shen W, Heymsfield SB, Allison DB, Zhu S. Obesity and non-fatal motor vehicle crash injuries: sex difference effects. Int J Obes (Lond). 2011; 35(9):1216–1224. [PubMed: 21224830]

Mallory A. Head injury and aging: the importance of bleeding injuries. Ann Adv Automot Med. 2010; 54:51–60. [PubMed: 21050591]

Mock CN, Grossman DC, Kaufman RP, Mack CD, Rivara FP. The relationship between body weight and risk of death and serious injury in motor vehicle crashes. Accident Analysis and Prevention. 2002; 34(2):221–228. [PubMed: 11829292]

Moran, SG.; Rue, LW.; Reiff, DA.; Windham, ST.; Metzger, JS.; McGwin, G. Injury rates among restrained drivers in motor vehicle collisions: the role of body habitus. 2002.

Morris A, Welsh R, Frampton R, Charlton J, Fildes B. An overview of requirements for the crash protection of older drivers. Annu Proc Assoc Adv Automot Med. 2002; 46:141–156. [PubMed: 12361505]

Morris A, Welsh R, Hassan A. Requirements for the crash protection of older vehicle passengers. Annu Proc Assoc Adv Automot Med. 2003; 47:165–180. [PubMed: 12941224]

Neville AL, Brown CV, Weng J, Demetriades D, Velmahos GC. Obesity is an independent risk factor of mortality in severely injured blunt trauma patients. Arch Surg. 2004; 139(9):983–987. [PubMed: 15381617]

Newgard CD. Defining the "older" crash victim: the relationship between age and serious injury in motor vehicle crashes. Accid Anal Prev. 2008; 40(4):1498–1505. [PubMed: 18606283]

NHTSA. [April 1, 2012] Traffic Safety Facts 2010 Data: Alcohol-Impaired Driving.. 2012. from http://www-nrd.nhtsa.dot.gov/Pubs/811606.pdf

Ogden CL, Carroll MD, Kit BK, Flegal KM. Prevalence of obesity in the United States, 2009-2010. NCHS Data Brief. 2012; (82):1–8.

Ridella, SA.; Rupp, JD.; Poland, K. Age-related differences in AIS 3+ crash injury risk, types, causation and mechanisms.. Proceedings of the International Research Council on the Biomechanics of Injury conference; International Research Council on Biomechanics of Injury. 2012.

Rupp JD, Flannagan CA, Kuppa SM. Injury risk curves for the skeletal knee- thigh-hip complex for knee-impact loading. Accid Anal Prev. 2010; 42(1):153–158. [PubMed: 19887155]

Rupp JD, Flannagan CA, Leslie AJ, Hoff CN, Reed MP, Cunningham RM. Effects of BMI on the risk and frequency of AIS 3+ injuries in motor-vehicle crashes. Obesity (Silver Spring). 2013; 21(1):E88–97. [PubMed: 23505202]

Ryb GE, Dischinger PC. Injury severity and outcome of overweight and obese patients after vehicular trauma: a crash injury research and engineering network (CIREN) study. Journal of Trauma-Injury Infection and Critical Care. 2008; 64(2):406–411.

Sivak M, Schoettle B, Rupp J. Survival in fatal road crashes: body mass index, gender, and safety belt use. Traffic Inj Prev. 2010; 11(1):66–68. [PubMed: 20146145]

Turkovich, M.; van Roosmalen, L. A Preliminary Study on the Effects of Obesity on Occupant Response in Frontal Impact.. RESNA Annual Conference.; 2010.

United Nations. World Population Prospects: The 2010 Revision. Department of Economic and Social Affairs; New York: 2011.

Viano DC, Parenteau CS, Edwards ML. Crash Injury Risks for Obese Occupants Using a Matched-Pair Analysis. Traffic Injury Prevention. 2008; 9(1):59–64. [PubMed: 18338296]

Wang SC, Bednarski B, Patel S, Yan A, Kohoyda-Inglis C, Kennedy T, Link E, Rowe S, Sochor M, Arbabi S. Increased depth of subcutaneous fat is protective against abdominal injuries in motor vehicle collisions. Annu Proc Assoc Adv Automot Med. 2003; 47:545–559. [PubMed: 12941250]

Zarzaur BL, Marshall SW. Motor vehicle crashes obesity and seat belt use: A deadly combination? Journal of Trauma-Injury Infection and Critical Care. 2008; 64(2):412–419.

Zhu S, Kim JE, Ma X, Shih A, Laud PW, Pintar F, Shen W, Heymsfield SB, Allison DB. BMI and risk of serious upper body injury following motor vehicle crashes: concordance of real-world and computer-simulated observations. PLoS Med. 2010; 7(3):e1000250. [PubMed: 20361024]

Zhu SK, Layde PM, Guse CE, Laud PW, Pintar F, Nirula R, Hargarten S. Obesity and risk for death due to motor vehicle crashes. American Journal of Public Health. 2006; 96(4):734–739. [PubMed: 16537660]

Highlights

- We model relative effects of age, gender and BMI on AIS 3+ injury in motor vehicle crashes.
- Older age increased AIS 3+ injuries in all crash modes, especially thorax and head injuries.
- Higher BMI increased lower extremity and thorax injuries.
- Female gender was associated with more head, thorax and extremity injuries.
- Age provides the greatest relative contribution to occupant injury when compared to gender and BMI

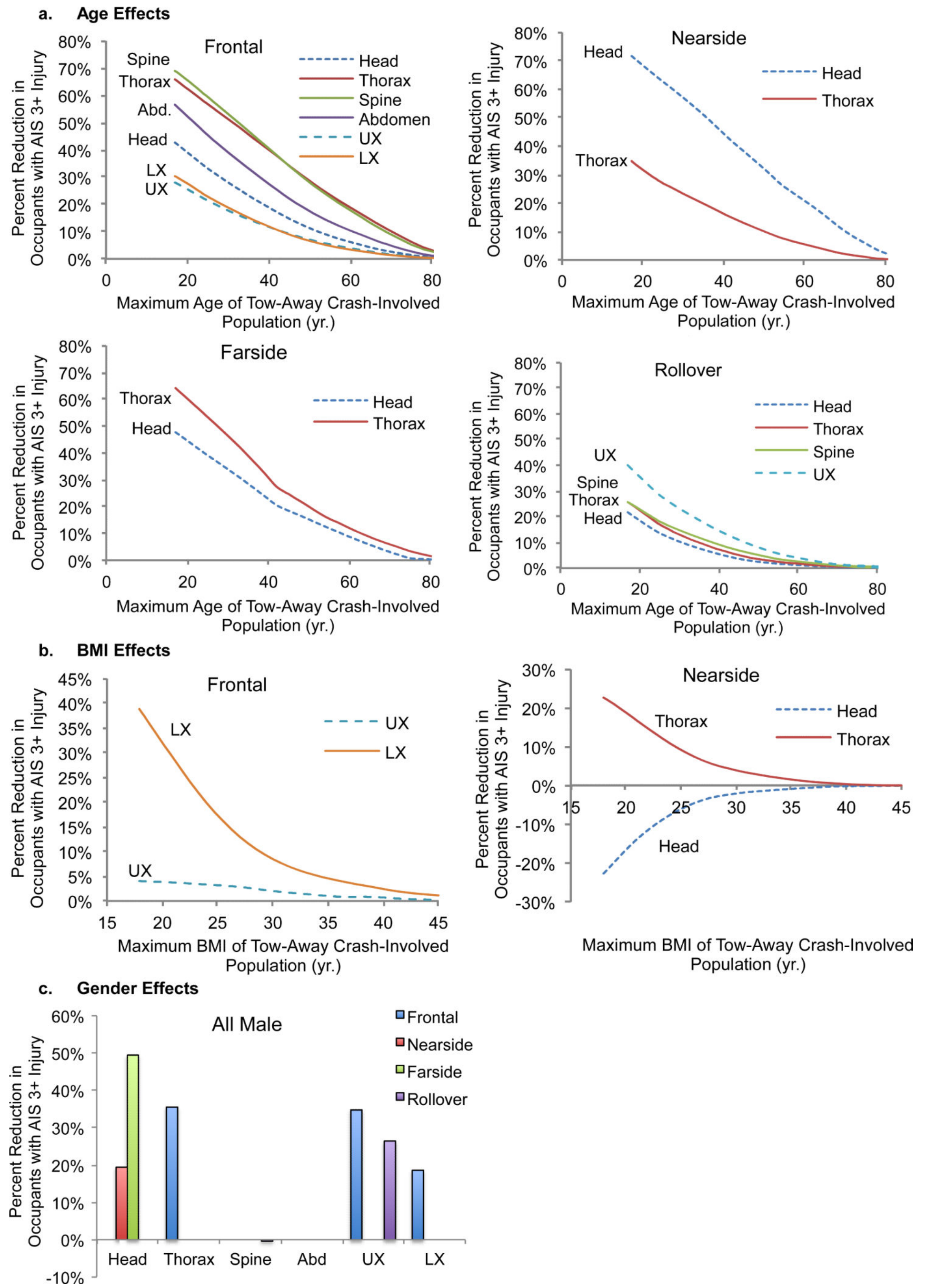

Figure 1.

Predicted percent changes in numbers of occupants with AIS3+ injury by body region as the maximum age, BMI and gender of the crash involved population is limited to different values.

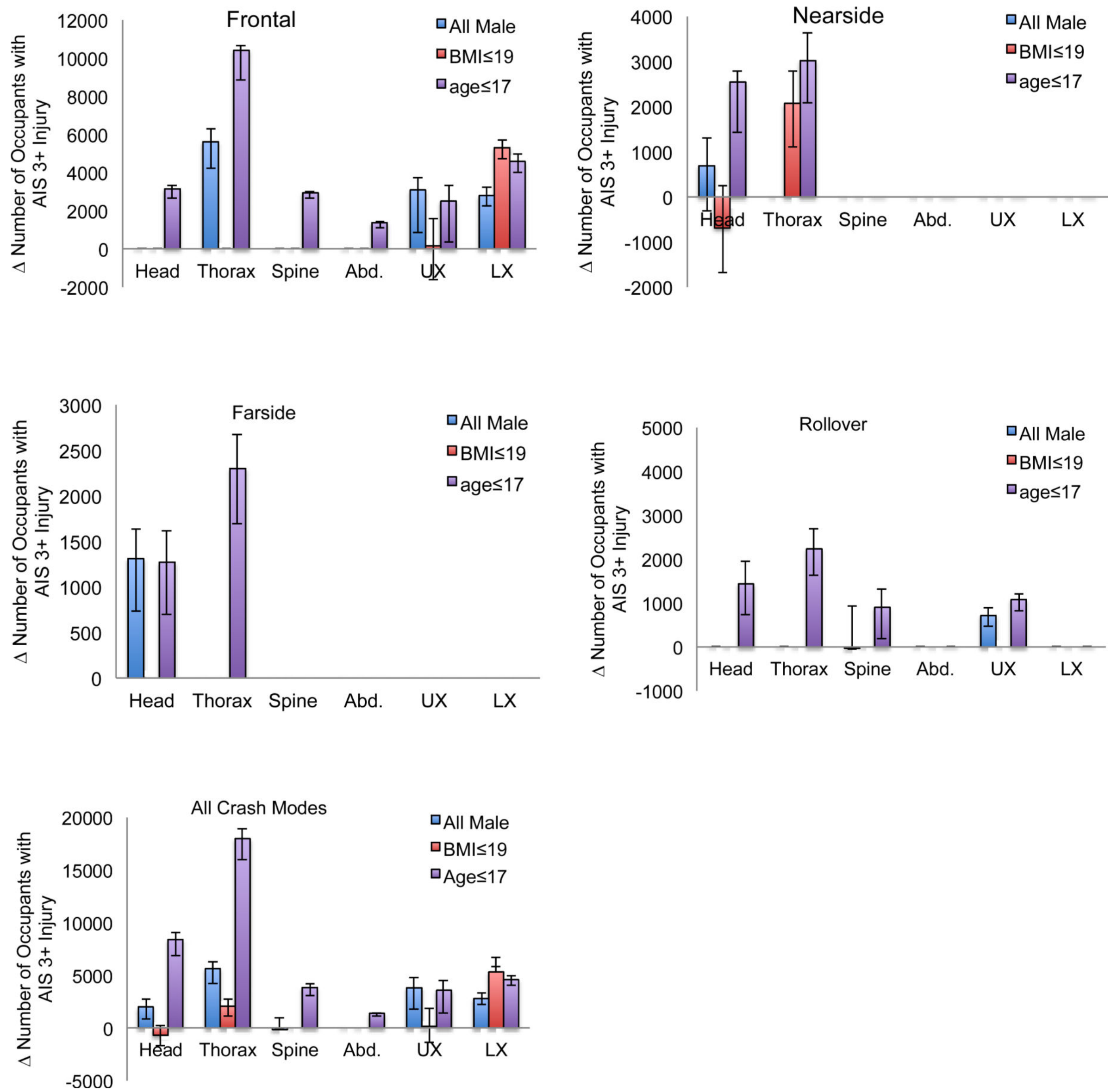

Figure 2.

Predicted decreases in numbers of occupants with AIS 3+ injury by body region and crash mode with age, gender, and BMI.

Table 1

Predictors used in the Regression Models

Predictor	Level
Age (yr)	Continuous
Gender	Male (reference), female
BMI (kg/m^2), BMI^2	Continuous
deltaV (km/h)	Continuous
Vehicle type	Passenger car (reference), light truck, utility vehicle, van
Belt use	Unbelted (reference), belted 3pt, belted other*
Seat location	Driver (reference), passenger
Height (cm)	Continuous
# of Quarter Turns (Rollover only)	Categorical (1-2, 3-6, 7-10, 11-13, >13)
Multiple Severe Impacts**	No (reference), Yes
Position of occupant relative to direction of roll	Same side (reference), Opposite side.
L-Type/T-Type (Near-/Farside Impacts Only)	T-Type (reference), L-Type

*Belted other refers to either a 3-point belt that is improperly used or older non 3 point seatbelts (e.g. lapbelts)

**For multiple severe impacts, the second impact must have been clearly distinguishable from the first impact, and the more severe impact was included for the regression analysis.

Table 2

Distribution of Key Predictors for NASS-CDS by Age Group (years)

		Age Group (yrs)					Rao-Scott Chi Square
		16-24	25-44	45-64	65-74	≥75	
Gender	Female	48%	48%	51%	47%	43%	$X^2(4)=4.8$ p=0.32
	Male	52%	52%	49%	53%	57%	
deltaV (kph), Frontal Impacts	ΔV <15	26%	28%	36%	37%	37%	$X^2(12)=16.2$, p=0.18
	15≤ ΔV <30	56%	56%	51%	44%	52%	
	30≤ ΔV <45	15%	14%	11%	17%	8%	
	ΔV > 45	3%	2%	2%	2%	3%	
deltaV (kph), Nearside Impacts	ΔV <15	38%	55%	60%	45%	38%	$X^2(12)=32.3$, p=0.001
	15≤ ΔV <30	46%	39%	35%	50%	50%	
	30≤ ΔV <45	14%	5%	4%	4%	7%	
	ΔV > 45	2%	1%	1%	1%	5%	
deltaV (kph), Farside Impacts	ΔV <15	43%	46%	65%	38%	37%	$X^2(12)=36.8$, p=0.0002
	15≤ ΔV <30	46%	43%	30%	49%	50%	
	30≤ ΔV <45	9%	10%	4%	13%	9%	
	ΔV > 45	2%	1%	1%	0%	4%	
N Quarter Turns (Rollover only)	1-2	54%	51%	60%	44%	35%	
	3-6	42%	44%	34%	53%	60%	
	7-10	4%	5%	6%	3%	5%	
	11-13	0%	0%	0%	0%	0%	
	>13	0%	0%	0%	0%	0%	
BMI	BMI < 18.5	4%	1%	1%	0%	1%	$X^2(16)=216.7$, p<0.0001
	18.5≤BMI<25	50%	32%	27%	24%	28%	
	25<BMI≤30	35%	46%	44%	51%	60%	
	30<BMI≤35	7%	13%	20%	17%	8%	
	BMI>35	4%	8%	8%	8%	3%	
Belt Use	3-point	87%	90%	92%	95%	94%	$X^2(4)=30.6$, p<0.0001
	No	13%	10%	8%	5%	6%	
Seat Location	Driver	79%	86%	84%	81%	80%	$X^2(4)=15.6$, p=0.007
	Passenger	21%	14%	16%	19%	20%	
Multiple Severe Impacts	No	96%	97%	97%	98%	98%	$X^2(4)=9.8$, p=0.044
	Yes	4%	3%	3%	2%	2%	
Vehicle Type	Car	71%	53%	51%	59%	75%	$X^2(12)=143.0$, p<0.0001
	Pickup	11%	17%	19%	9%	6%	
	Utility	16%	22%	20%	21%	9%	
	Van	2%	8%	10%	11%	10%	
Crash Mode	Farside	11%	13%	15%	18%	16%	$X^2(16)=35.4$, p=0.0009
	Frontal	60%	61%	60%	58%	57%	

		Age Group (yrs)					Rao-Scott Chi Square
		16-24	**25-44**	**45-64**	**65-74**	**≥75**	
	Nearside	12%	13%	17%	18%	18%	
	Rollover	17%	13%	8%	6%	9%	

* X^2(n): The number *n* in parentheses refers to the number of degrees of freedom.

Table 3

Distribution of Key Predictors for NASS-CDS Dataset by BMI group

		BMI Group (kg/m2)					Rao-Scott Chi Square
		BMI <18.5	18.5≤BMI<25	25<BMI≤30	30<BMI≤35	BMI>35	
Gender	Female	86%	64%	35%	44%	50%	$X^2(4)=240.4$ $p<0.0001$
	Male	14%	36%	65%	56%	50%	
deltaV (kph), Frontal Impacts	ΔV <15	46%	29%	32%	26%	26%	$X^2(12)=8.1$, $p=0.78$
	15≤ ΔV <30	39%	55%	52%	56%	60%	
	30≤ ΔV <45	13%	14%	13%	16%	12%	
	ΔV > 45	2%	2%	3%	2%	2%	
deltaV (kph), Nearside Impacts	ΔV <15	22%	47%	43%	74%	50%	$X^2(12)=44.8$ $p<0.0001$
	15≤ ΔV <30	50%	44%	47%	21%	40%	
	30≤ ΔV <45	13%	7%	9%	4%	8%	
	ΔV > 45	15%	2%	1%	1%	2%	
deltaV (kph), Farside Impacts	ΔV <15	68%	55%	41%	54%	53%	$X^2(12)=16.8$, $p=0.16$
	15≤ ΔV <30	25%	37%	48%	32%	39%	
	30≤ ΔV <45	6%	7%	9%	13%	8%	
	ΔV > 45	1%	1%	2%	1%	0%	
N Quarter Turns (Rollover only)	1-2	88%	53%	47%	53%	73%	
	3-6	11%	42%	49%	41%	25%	
	7-10	1%	5%	4%	6%	2%	
	11-13	0%	0%	0%	0%	0%	
	>13	0%	0%	0%	0%	0%	
Age Gp (yrs)	15-24	1%	4%	6%	7%	6%	$X^2(16)=216.7$, $p<0.0001$
	25-44	18%	33%	40%	38%	46%	
	45-64	11%	17%	23%	35%	28%	
	65-74	2%	3%	6%	3%	2%	
	≥75	68%	43%	25%	17%	18%	
Belt Use	3-point	91%	91%	90%	90%	89%	$X^2(4)=3.3$, $p=0.50$
	No	9%	9%	10%	10%	11%	
Seat Location	Driver	72%	80%	84%	86%	85%	$X^2(4)=41.0$, $p=<0.0001$
	Passenger	28%	20%	16%	14%	15%	
Multiple Severe Impacts	No	93%	97%	97%	97%	93%	$X^2(4)=12.0$ $p=0.0175$
	Yes	7%	3%	3%	3%	7%	
Vehicle Type	Car	71%	66%	56%	55%	53%	$X(12)=97.6$ $p<0.0001$
	Pickup	5%	9%	19%	18%	14%	
	Utility	15%	19%	18%	20%	22%	
	Van	9%	6%	7%	7%	11%	
Crash Mode	Farside	13%	16%	12%	11%	12%	$X^2(16)=23.9$, $p=0.0272$
	Frontal	50%	60%	60%	61%	62%	

		BMI Group (kg/m2)					Rao-Scott Chi Square
		BMI <18.5	18.5≤BMI<25	25<BMI≤30	30<BMI≤35	BMI>35	
	Nearside	6%	13%	14%	18%	13%	
	Rollover	31%	11%	14%	10%	13%	
Model Year	2000-2002	57%	56%	48%	53%	52%	$X^2(16)=30.0$, $p=0.0028$
	2003-2005	16%	22%	27%	22%	20%	
	2006-2008	24%	18%	20%	20%	23%	
	2009-2011	3%	4%	5%	5%	5%	

* $X^2(n)$: The number *n* in parentheses refers to the number of degrees of freedom.

Table 4

Distribution of Key Predictors for NASS-CDS Dataset by gender

		Gender		Rao-Scott Chi Square
		F	M	
deltaV (kph), Frontal Impacts	ΔV <15	30%	29%	$X^2(3)=6.2$, p=0.10
	15≤ΔV <30	56%	52%	
	30≤ ΔV <45	12%	16%	
	ΔV > 45	2%	3%	
deltaV (kph), Nearside Impacts	ΔV <15	47%	53%	$X^2(3)=1.61$ p=0.66
	15≤ΔV <30	44%	38%	
	30≤ ΔV <45	7%	8%	
	ΔV > 45	2%	1%	
deltaV (kph), Farside Impacts	ΔV <15	45%	55%	$X^2(3)=13.6$ p=0.003
	15≤ΔV <30	46%	35%	
	30≤ ΔV <45	8%	8%	
	ΔV > 45	1%	2%	
N Quarter Turns (Rollover only)	1-2	56%	52%	
	3-6	39%	44%	
	7-10	5%	4%	
	11-13	0%	0%	
	>13	0%	0%	
Age Gp (yrs)	15-24	31%	31%	$X^2(4)=4.7$, p=0.31
	25-44	37%	37%	
	45-64	23%	22%	
	65-74	5%	5%	
	≥75	4%	5%	
Belt Use	3-point	92%	88%	$X^2(1)=4.5$, p<0.0001
	No	8%	12%	
Seat Location	Driver	80%	86%	$X^2(1)=59.3$, p<0.0001
	Passenger	20%	14%	
Multiple Severe Impacts	No	92%	88%	$X^2(1)=1.59$, p=0.21
	Yes	8%	12%	
Vehicle Type	Car	65%	54%	$X^2(3)=108.9$ p<0.0001
	Pickup	5%	24%	
	Utility	22%	16%	
	Van	8%	6%	
Crash Mode	Farside	14%	12%	$X^2(3)=15.3$, p=0.0014
	Frontal	64%	57%	
	Nearside	13%	15%	
	Rollover	9%	16%	

		Gender		Rao-Scott Chi Square
		F	M	
Model Year	2000-2002	35%	38%	$X^2(4)=5.3$, p=0.15
	2003-2005	53%	47%	
	2006-2008	10%	13%	
	2009-2011	2%	2%	
BMI	BMI < 18.5	4%	1%	$X^2(4)=240.9$, p<0.0001
	18.5≤BMI<25	47%	25%	
	25<BMI≤30	31%	54%	
	30<BMI≤35	11%	14%	
	BMI>35	7%	6%	

* $X^2(n)$: The number *n* in parentheses refers to the number of degrees of freedom.

Table 5

Summary of Age, Gender, and BMI Effects by Body Region and Crash Mode.

	Head	Thorax	Abdomen	Spine	UpperEx	LowerEx
Frontal	Age	Age Gender Age*Gender	Age	Age	Age BMI Gender Age*Gender BMI*VehicleType	Age Gender BMI
Nearside	Age BMI Gender BMI*Gender	Age BMI	None	N/A	N/A	None
Farside	Age Gender	Age	N/A	N/A	N/A	N/A
Rollover	Age	Age	Age	Age Gender Age*Gender	Age Gender	None

N/A: Not Applicable because the underlying NASS-CDS sampled contained an insufficient number of AIS 3+ injuries (<100) to generate a model.

Table 6

Mean and 95% Confidence Intervals on Predicted Decreases in Numbers of Occupants with Injury by Body Region and Crash Mode.

Age≤17	**Head**	**Thorax**	**Spine**	**Abdomen**	**UX**	**LX**
Frontal	3,145 (2,651 - 3,296)	10,407 (8,859 - 10,656)	2,940 (2,651 – 2,956)	1,368 (1,062 - 1,417)	2,501 (341 - 3,352)	4,584 (4,012 - 4,995)
Nearside	2,545 (1,426 - 2,775)	3,020 (2,083 - 3,645)				
Farside	1,270 (693 - 1,616)	2301 (1,693 – 2,679)				
Rollover	1,435 (732 - 1,946)	2,233 (1,633 – 2,692)	902 (180 –1,302)		1,077 (814 - 1,208)	
Total, age≤17	8,396 (6,871 - 9,070)	17,961 (15,960 – 18,859)	3,843 (3,065 – 4,242)	1,368 (1,062 – 1,417)	3,578 (1,402 - 4,439)	4,584 (4,012 – 4,995)

BMI<19	**Head**	**Thorax**	**Spine**	**Abdomen**	**UX**	**LX**
Frontal					161 (−1,618 – 1,572)	5,304 (4,729 – 5,688)
Nearside	−688 (−1,678 - 259)	2,069 (1,107 - 2,775)				
Farside						
Rollover						
Total, BMI<19	−688 (−1,678 - 259)	2,069 (1,107 - 2,775)			161 (−1,401 – 1,789)	5,304 (4,729 – 5,688)

All Male	**Head**	**Thorax**	**Spine**	**Abdomen**	**UX**	**LX**
Frontal		5,618 (4,212 – 6,272)			3,089 (832 – 3,755)	2,791 (2,216 – 3,256)
Nearside	689 (−311 – 1,290)					
Farside	1,311 (731 - 1,640)					
Rollover			−12 (−45 - 919)		715 (459 - 877)	
Total, Male	1,999 (844 - 2,685)	5,618 (4,212 - 6,272)	−12 (−45 - 919)		3,804 (1,781 – 4,803)	2,791 (2,216 – 3,256)

Totals	**Head**	**Thorax**	**Spine**	**Abdomen**	**UX**	**LX**
Age≤17	8,396 (6,871 - 9,070)	17,961 (15,960 - 18,859)	3,843 (3,065 – 4,242)	1,368 (1,062 – 1,417)	3,578 (1,402 - 4,439)	4,584 (4,012 - 4,995)
BMI≤19	−688 (−1,678 - 259)	2,069 (1,107 - 2,775)			161 (−1,401 - 1,789)	5,304 (4,729 – 5,688)
Gender=M	1,999 (844 - 2,685)	5,618 (4,212 - 6,272)	−12 (−45 - 919)		3,804 (1,781 - 4,803)	2,791 (2,216 - 3,256)