# THE ROLES OF VEHICLE FOOTPRINT, HEIGHT, AND WEIGHT IN CRASH OUTCOMES: APPLICATION OF A HETEROSCEDASTIC ORDERED PROBIT MODEL

By

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## ABSTRACT

This paper uses a heteroscedastic ordered probit model to distinguish the effects of vehicle weight, footprint and height on the severity of injuries sustained by vehicle occupants while controlling for many occupant, roadway and other characteristics. Model results suggest that the impacts of physical vehicle attributes on crash outcomes depend on the number of involved vehicles, and typically are more significant in one-car crashes than in two-car crashes. While larger-footprint vehicles and shorter vehicles are estimated to reduce the risk of serious injury for their occupants in single-vehicle crashes, they appear to be less crashworthy in two-vehicle collisions. Heavier vehicles are anticipated to be more crashworthy regardless of crash type. Under evolving U.S. fuel economy standards, moderate changes in light-duty-vehicle weights, footprints, and heights are estimated to have relatively small impacts on crash severities, while other factors, such as seat belt use, driver intoxication, and the presence of roadway curvature and grade influence crash outcomes much more noticeably.

## KEY WORDS

Crash modeling, Injury severity, Heteroscedastic ordered probit, Vehicle footprint, Vehicle weight, Vehicle height, Fuel economy standards.

## INTRODUCTION

Until recently, the United States' Corporate Average Fuel Economy (CAFE) standards had remained largely unchanged since their 1975 introduction. Recognizing two classes of light-duty vehicles (LDVs), the standards were stricter for passenger cars than for trucks, including minivans, pickups and sport utility vehicles (SUVs). Originally intended to distinguish cars for personal use from light-duty trucks (LDTs) for work use, this designation has exceeded its vision, in the face of manufacturing and consumer preference shifts. Between model years (MYs) 1987 and 2003, the share of LDT sales rose from 28 percent to 50 percent of U.S. LDV sales, while LDV fleet fuel efficiency dropped 4.6 percent (NHTSA 2004). In a lagged response to market shifts, the nation's 2007 Energy Independence Security Act mandated an increase in fuel economy standards based on vehicle footprint (wheelbase times track width). While the European Union, Japan and China mandate weight-based fuel economy standards (An et al. 2011), the U.S, National Highway Traffic Safety Administration (NHTSA) proposed fuel economy standards (effective for MY 2011) based on footprint to avoid incentivizing manufacturers to increase weight on vehicles to avoid stricter standards. Proponents argue that such standards encourage the use of light-weight materials while preserving vehicle size, reflecting consumers' preference for larger vehicles while preserving rollover stability (NTHSA 2005). It is thought that maintaining "cushion" space while reducing vehicle weight can reduce injury risk, a view reinforced by Van Auken and Zellner's (2005) findings. Critics, including many automotive manufacturers, maintain that heavier vehicles are safer (Hakim 2004), a stance supported by several past studies (Crandall and Graham 1989, Farmer et al. 1997, Bedard et al. 2002, Kahane 2003).

In order to appreciate – and distinguish – the crash-severity impacts of vehicle weight, footprint, height, among other vehicle attributes, this paper analyzes occupant injury outcomes using an ordered-response model. Crash data from the National Automotive Sampling System's General Estimates System (NASS GES) were combined with vehicle characteristic data from the Insurance Institute for Highway Safety's Highway Loss Data Institute (HLDI) to examine the relevance of several vehicle attributes while controlling for environmental and occupant characteristics (e.g. speed limits, weather conditions, roadway design, occupant age and gender).

## PREVIOUS RESEARCH

Researchers concerned with traffic safety have examined the factors influencing crash injury severity using a wide variety of statistical methods and data sets. The use of police-reported crash data is standard, with many studies focusing on just two distinct injury outcomes (e.g., no injury versus injury and/or death). For example, Shibata and Fukuda (1994) were among the earliest to apply (binary) logistic regression to crash risk analysis, evaluating factors such as driving without a license, alcohol use, speed, seat belt use, and helmet use on fatality risks. Farmer et al. (1997) used a logistic regression to examine injury type and severity in relation to occupant location, gender, age, and seat belt use, angle of impact, vehicle weight, and body style, and concluded that occupants of heavier vehicles were less likely to sustain serious injuries. Krull et al. (2000) used logistic regression methods to analyze the effects of rollover on driver injury severity in addition to roadway, vehicle and driver factors, and concluded that pickup trucks are more crashworthy than passenger cars. Toy and Hammitt (2003) used logistic regression to predict the effects of vehicle type, crash configuration (of two-vehicle crashes), and other vehicle attributes on risk of serious injury and death, finding that SUVs, vans and, in particular, pickups were both more crashworthy and aggressive. They also concluded that increasing vehicle mass in passenger cars increases crashworthiness and aggressiveness.

Models that recognize more than two crash injury outcomes can be modeled using multinomial logit (MNL), multinomial probit (MNP), ordered logit (OL), and/or ordered probit (OP) models. Among these, OL and OP, which recognize the ordinal (rather than simply categorical) nature of injury severity, are by far the most popular. For example, Abdel-Aty (2003) used OP models to analyze the effect of age, gender, seat belt use, point of impact, speed, and vehicle type on injury severity level at multiple locations and concluded that drivers of passenger cars experience higher injury severity levels. Distinguishing between one-vehicle and two-vehicle crash types, Kockelman and Kweon (2002) examined the effect of vehicle type (among other attributes) on injury severity and concluded that pickups and SUVs are less safe than passenger cars under single-vehicle crash conditions, while the reverse is true in two-vehicle crashes. As an extension to the traditional OP model, de Lapparent (2008) employed a bivariate OP model (with two responses, simultaneously) to relate use of seat belt and injury sustained, while accounting for correlation in the error terms of seat belt choice and injury severity (in an effort to account for endogeneity). Since seat belt use is likely correlated with risk aversion, traditional models may well overestimate the effectiveness of seat belts in reducing injury risk and severity. De Lapparent (2008) observed that demographic characteristics of car users play important roles in the decision to fasten seat belts and in later injury levels.

Application of traditional OL and OP models implied that underlying error-term variances are constant, or homoscedastic. O'Donnell and Connor (1996) have parameterized error terms as a function of occupant age, vehicle speed, MY, and time of crash in order to address this weakness of traditional models. Using a similar framework, Wang and Kockelman (2005) compared the results of OL and heteroscedastic ordered logit (HOL) models, after parameterizing error-term variance as a function of speed limit, vehicle type, and vehicle curb weight for single- and two-vehicle crash types. They found that while heavier vehicles are both more crashworthy and aggressive, a weight increase of 1000 pounds of all U.S. vehicles did not significantly influence crash outcomes. On the other hand, if all passenger cars were to become light duty trucks, incapacitating and fatal injuries would rise dramatically. This analysis closely resembles their approach, while also controlling for a driver's alcohol use, vehicle MY, footprint and height.

While prior studies have studied the impact of vehicle weight on crash outcome, few have examined the effect of vehicle footprint. An early study by Evans and Frick (1992) developed linear regressions relating the driver fatality ratio against simply wheelbase and weight ratios for two groups of vehicles, (those of MY 1979 and earlier and those of MY 1980 and later). For two-car crashes, they concluded that, given identical wheelbases, drivers of lighter vehicles sustain greater fatality risk. They also concluded that there is no relationship between wheelbase and fatality risk after controlling for mass. Bedard et al. (2002) used logistic regression to determine the independent contributions of various driver, crash, and vehicle characteristics to fatality risk of drivers in single-vehicle crashes, finding size to be the vehicle attribute most closely related to injury severity (with a 10 inch increase in wheelbase estimated to reduce the odds of fatality by 10 percent). More recently, Wenzel (2010) used ordinary least squares (OLS) regression to estimate fatality risk (defined by the number of driver fatalities per million registered vehicles from MY 2003 to 2007) as a function of weight and footprint using the National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS) data. He found a weak relationship between footprint and death rates, after controlling for driver age and gender, and crash location (but neglecting driving distances). Again, only fatal injuries are considered in his study, like the others. In contrast, this work looks at the likelihood of all crash outcomes, while simultaneously controlling for a wide assortment of attributes.

## MODEL STRUCTURE

The ordinal nature of injury severity categories (as chosen by crash-reporting police officers) makes this important variable suitable for ordered regression analysis. In the standard OP and OL models, an assumption of homoscedastic (constant-variance) error terms can result in incorrect standard errors and biased parameter estimates (Yatchew and Griliches 1985). The heteroscedastic ordered probit (HOP) model used here allows one to parameterize the variance of OP error terms in order to reflect the variations in uncertainty that come with different crash types (Williams 2009, Wang and Kockelman 2005).

Each crash-victim's observed injury category, $y$, is a function of the associated but latent (unobserved) and continuous severity measure, $y^*$. Let $\mu_0 = 0$ and $\mu_j$ ($j$=1, 2, 3) denote the four severity thresholds that determine the five observed $y$ values, as follows:

$y$ = 0 (no injury) if $y^* \leq 0$,

$y$ = 1 (possible injury) if $0 < y^* \leq \mu_1$,

$y$ = 2 (non-incapacitating injury) if $\mu_1 < y^* \leq \mu_2$,

$y$ = 3 (incapacitating injury) if $\mu_2 < y^* \leq \mu_3$, and

$y$ = 4 (fatal injury) if $y^* > \mu_3$.

Let $x$ denote the vector of explanatory variables that affect injury severity $y^*$ such that:

$$y^* = x'\beta + \varepsilon \tag{1}$$

where $\beta$ is the associated vector of parameters and error term $\varepsilon$ accounts for other, unobserved factors affecting injury severity (such as pavement roughness, actual vehicle speed, and driver alertness at time of crash). The probability of observed $y$ taking on injury severity $j$ for the $i^{th}$ crash-victim observation can be expressed as follows (see, e.g., Greene 2011):

$$P(y_i = j) = \Phi\left(\frac{\mu_j - x_i\beta}{\sigma_i}\right) - \Phi\left(\frac{\mu_{j-1} - x_i\beta}{\sigma_i}\right) \tag{2}$$

where $\Phi(\quad)$ represents the standard normal cumulative distribution function and variance $\sigma_i{}^2$ may be parameterized as a (non-negative) function of observation-specific attributes ($z_i$), as follows:

$$\sigma_i{}^2 = [\exp(z_i\gamma)]^2 \tag{3}$$

Here, $z_i$ represents the set of variables explaining the error terms' variance and $\gamma$ represents the associated coefficients. In the OP model, $\gamma$ is restricted to zero, ensuring homoscedasticity (or constant variance). This paper employs the more flexible HOP specification, parameterizing variance as a function of statistically significant explanatory variables. Coefficients of explanatory variables are estimated via maximization of the following likelihood function using LIMDEP statistical software (Greene 2011):

$$L = \prod_{i=1}^{N} \left[ \sum_{j=1}^{J} \delta(y_i = j) \left( \Phi\left(\frac{\mu_j - x_i\beta}{\sigma_i}\right) - \Phi\left(\frac{\mu_{j-1} - x_i\beta}{\sigma_i}\right) \right) \right]^{w_i} \quad (4)$$

where $\delta(y_i = j)$ serves as an indicator variable equaling one if $y_i = j$ and zero otherwise, and weight, $w_i$, is a population expansion factor provided in the NASS GES, as described below.

## DATA DESCRIPTION

This paper relies on year 2007 through 2009 NASS GES data matched with additional vehicle-specific characteristics (obtained using HLDI's database) based on abbreviated vehicle identification numbers (VINs)[1]. The GES relies on a select sample of police accident reports (PARs) from 400 police jurisdictions within 60 geographic sites called Primary Sampling Units (PSUs) across 26 states. PARs are selected in a stratified fashion, first among PSUs, then police jurisdictions, and lastly among reported crashes. Approximately 45,000 PARs are selected each year for recording into NASS GES, representing about 0.7 percent of the PARs filed annually. In order to calculate national crash estimates, each GES crash record includes a weight (Equation 4's $w_i$) representing the product of the inverse of the (estimated) probability of selecting that PAR at each of the three sampling stages (NHTSA 1991). Unreported crashes, likely those involving only moderate property damage and no significant personal injury, are not directly represented in the GES data set (Blincoe et al. (2002) estimated 50% of property-only damage crashes go unreported in the U.S.)[2].

Despite some statistical uncertainty associated with the variable reporting of different crash types and the geographic heterogeneity of the data, NASS GES provides a large sample covering all types of crashes, unlike National Highway Traffic Safety Administration's Fatality Analysis Reporting System (FARS) data, which only includes fatal crashes. While the GES data set is large (containing 161,809 crash records and 401,020 corresponding occupant-based observations over the three-year period), key variables missing in significant numbers include occupant age (6.3 percent missing) and gender (4.1 percent), alcohol use (8.2 percent), seat belt usage (13.4 percent), speed limit (15.2 percent), roadway division type (13.9 percent), horizontal alignment (3.5 percent) and vertical grade (21.4 percent). Moreover, crashes involving three or more vehicles account for 14.9 percent of the occupant-based observations, and do not provide information on each collision partner, so they were not used here (where the focus is on single-vehicle and two-vehicle crashes). Among the 2007 through 2009 GES-reported crashes, 58.6 percent of vehicles reported a VIN, and HLDI's decoding software successfully matched 86.2 percent of these to provide additional vehicle characteristics, such as MY, curb weight, wheel base, length, width, and

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[1] VINs in the NASS GES contain the first 12 to 13 of the total 17 standard characters, in order to protect owner anonymity.

[2] Police-reported injury levels may also be poor indicators of the actual or Modified Abbreviated Injury Scale (MAIS) level, following medical evaluation. For example, Farmer (2003) found that 41 percent of injuries reported by U.S. police as incapacitating received MAIS ratings of "minor injury" by health care professionals using NASS Crashworthiness Data System (CDS).

height. It should be noted that U.S. VIN values were not standardized before MY 1981, so such vehicles are also not present in the final data records analyzed here.[3]

After merging GES crash data with HLDI vehicle characteristics, 26,421 occupant observations for one-vehicle crashes and 72,139 occupant observations for two-vehicle crashes contained all required variables, as summarized in Table 1. These represent 29.2 percent of one-vehicle crash occupants and 28.8 percent of two-vehicle crash occupants of the NASS GES sample data. In looking at this reduced data set, one sees that fatal injuries are slightly underrepresented in the data analyzed (2.0 percent for one-vehicle crashes versus 2.3 percent in the original data set and 0.3 percent for two-vehicle crashes versus 0.5 percent in the original data set) while incapacitating injuries are slightly overrepresented (19.4 percent for one-vehicle crashes versus 16.9 percent in the original data set and 7.7 percent for two-vehicle crashes versus 6.0 percent in the original data set). Younger occupants also appear slightly overrepresented in the one-vehicle crashes (mean age is 31.5 years versus 32.5 years in the original data set). One-vehicle crashes on higher-speed-limit roadways appear slightly overrepresented (mean speed limit of 44.9 miles per hour versus 44.3 in the original data set) and two-vehicle crashes are slightly overrepresented on lower-speed-limit roadways (41.5 miles per hour average, versus 41.9 in the original data set).

## RESULTS

As shown in Table 2, both OP and HOP models were estimated for occupant injury severity in one- and two-vehicle crashes in LIMDEP. Results of a Likelihood Ratio Test (LRT) between the OP and the HOP models suggest that heteroscedasticity exists in both crash types, with the HOP model statistically preferred over the OP model ($p < 0.0001$). Defining a predicted injury severity level as the most probable $y$ for each occupant, the one- and two-vehicle HOP models correctly predict 50.6 and 67.4 percent of the actual observed injury severity levels, respectively.

All vehicle, occupant, and environmental characteristics relevant to injury severity were tested as regressors for the choice model. Statistically insignificant ($p > 0.10$) candidate variables include base price, minimum and maximum horsepower of the vehicle, vehicle type, curb weight of collision partner in two-vehicle crashes, whether the accident was a rollover type, whether the accident occurred on an interstate highway, and vehicle occupancy. Discarded from the model one at a time, many of these variables are correlated with and accounted for by variables retained in the model, such as the height and footprint of the primary vehicle and its collision partner, the occupant's seat position, crash-site speed limit, and roadway geometry. Vehicle wheelbase and track width, which are directly used to determine footprint, were also not used due to high correlation to footprint. Unfortunately, other potential variables affecting occupant injury severity such as vehicle center of gravity, seat position-specific airbag deployment and whether the vehicle is equipped with electronic stability control were not available in the data set.

Though estimated coefficients on explanatory variables are similar for OP and HOP models in both the one- and two-vehicle crash models, the variance specification (Eqn 3) of the HOP models also yielded statistically significant coefficients for occupant age, crash-site speed limit, primary vehicle MY, primary vehicle height, and primary vehicle and collision partner footprints, suggesting that these can impact the

[3] Vehicles of MY 1980 and beyond would be over 27 years old in this data set, or more than 70 percent older than the average light-duty vehicle lifespan in the U.S. (Lu 2006).

spread of latent severity $y^*$. Due to the large number of occupant-based observations (particularly in two-vehicle crashes), additional variables were shown to be statistically significant in explaining injury severity variance. However, inconsistent explanatory variables for variance across one- and two-vehicle models were rejected for intuition (e.g. it is counterintuitive that being female would affect the range of $y^*$ in two-vehicle crashes but not one-vehicle crashes). Furthermore, as roadway division type and geometry are related to speed limit, they are excluded from the variance specification due to the inclusion of speed limit. The effects of roadway design variables are still accounted for in the choice specification, but offer no intuitive reason to be included in the variance specification.

Crashing in a vehicle with a large footprint and colliding with a vehicle with a large footprint are estimated to increase the variation in occupant injury outcomes (and thus, generally, the likelihood of a fatal crash), certeris paribus. On the other hand, a newer vehicle tends to lessen variance in occupant injury severity in both one- and two-vehicle crashes and a taller primary vehicle tends to lessen variance in injury severity in two-vehicle crashes. The overall implications of variations in each explanatory variable – reflecting both changes in mean $y^*$ and its variance (Eqns. 1 and 3) – are explored in some detail below.

**Vehicle Size Effects**

*Weight*

In both one- and two-vehicle crashes, the models predict that occupants of lighter vehicles will sustain greater risk of injury. For one-vehicle crashes, increasing each observation's vehicle's weight by one standard deviation (870.8 pounds) – while holding all other variables constant – is predicted to decrease the likelihood of serious injury (defined as $y$ = 3 or 4) by 0.0059 (or a change of -0.59 absolute percentage points), from 0.0639 to 0.0580 (or -9.3 percent of the base likelihood), and decrease the likelihood of fatal injury ($y$ = 4) by 0.0007 (or a change of -.07 absolute percentage points), from 0.0057 to 0.0050 (or -12.7 percent of the base likelihood). For two-vehicle crashes, increasing the primary vehicle's weight by one standard deviation (867.0 pounds) drops the model-predicted probability of incurring serious injury by 0.0009 (or -4.5 percent) and fatal injury by 0.0001 (or -6.0 percent). The marginal effects of increasing vehicle curb weight by one standard deviation for each injury severity level are shown in Tables 3 and 4 for one- and two-vehicle crashes, respectively. Such findings are consistent with the literature, which finds in favor of a heavier vehicle's occupants, ceteris paribus (e.g., Evans and Frick 1994). However, as Wang and Kockelman (2005) point out, vehicle type (e.g., SUV versus passenger car) is very important, with cars having an advantage, if weight is preserved.

*Footprint*

The relationship between injury severity and footprint is not as straightforward. Unable to account for variance in error terms, the OP model predicts that an increase in vehicle footprint decreases risk in all injury categories. This relationship remains true for one-vehicle crashes in the HOP model, consistent with findings by Bedard et al. (2002). However, the HOP model tells a different story for two-vehicle crashes: occupants in bigger vehicles are predicted to have lower risks for non-incapacitating injuries, though the likelihood of incapacitating or fatal injury increases. As shown in Table 3, in one-vehicle crashes, a one standard deviation increase in vehicle footprint (9.3 square feet) while holding all other variables constant is predicted to decrease the risk of all injury categories, dropping serious injury risk by

0.0060 (-9.4 percent) and fatality risk by 0.0003 (-4.9 percent). For two-vehicle crashes, a one standard deviation increase in primary-vehicle footprint (9.2 square feet) is estimated to decrease non-incapacitating injury risk by 0.0007 (-1.9 percent) while increasing risk of serious injury and death by 0.5 and 6.4 percent, respectively (see Table 4). The HOP model's flexibility allows tail probabilities (for incapacitating and fatal outcomes) to fall though the average predicted injury severity (E($y^*$)) may rise.

The model also predicts larger-footprint partner vehicles to be more aggressive in two-vehicle crashes, if their weight and height are unchanged. Increasing the footprint of the collision partner by one standard deviation (9.2 square feet) and holding all else constant is predicted to increase the risk of serious injury by 0.0010 (4.5 percent) and fatality by 0.0001 (11.3 percent), as shown in Table 4. According to 2009 FARS, 48.1 percent of all accident fatalities occur in one-vehicle crashes. Then, accounting for both crashworthiness and aggressiveness effects of vehicle footprint, a one-standard-deviation increase in vehicles' footprints in both single- and two-vehicle crashes is predicted to increase fatality probability by 6.0 percent. The slight decrease in fatality risk appears to favor smaller-footprint vehicles across the fleet, which may appeal to transportation planners, environmentalists, and engineers, among others, given constraints on parking and lane–space, as well as emissions considerations. However, a calculation of crash outcome changes by type, multiplied by NHTSA's injury costs per person (Blincoe et al. 2002), suggest these crash share changes net out in terms of economic cost, with a negligible overall crash-cost change across the fleet (-1.0 percent). Nevertheless, models are abstractions of reality and imperfect. There may be other attributes at play (e.g., driver aggression or manufacture design details correlated with certain attributes) that can bias parameter coefficients or otherwise limit inference.

While the estimated percentages shared above suggest that vehicle owners and manufacturers (and regulators) may do well to shoot for a high–weight, low-footprint target (to reduce fatal crash risks), it is obviously tricky to make vehicles smaller but heavier: there is a fairly strong linear relationship between curb weights and footprints (sample $R^2 = 0.73$, and $\rho = +0.85$). Of course, the United States' new CAFE requirements may lead in the opposite direction: lower-weight vehicles for higher fuel economy, but larger footprints to avoid having to improve fuel economy too much (within each vehicle-size class). President Obama's recent plan to increase average fuel economy to 55 miles per gallon (based on EPA test cycles) by 2025 continues with footprint-based targets, with smaller vehicles having higher targets than larger ones (The White House 2011). Bomberg et al. (2009) suggested that a 10 percent decrease in vehicle mass can improve fuel economy by 1.9 miles per gallon. If a 10-percent footprint increase ("upsizing") accompanies the 10-percent weight reduction ("downweighting"), fatality risk is predicted here to fall by .0015 (or -9.1 percent) in one-vehicle crashes but increase by .0001 (13.8 percent) in two-vehicle crashes. When accounting for both one- and two- vehicle crashes, the models predict overall fatalites to rise by 2.8 percent, while fuel use and greenhouse gas (and other) emissions may fall significantly.

*Height*

The effect of a vehicle's height on injury severity varies by crash type here. Taller vehicles are estimated to be less crashworthy in one-vehicle crashes and more crashworthy in two-vehicle crashes. For one-vehicle crashes, increasing vehicle height by one standard deviation (8.3 inches) while holding all other variables constant increases predicted risk of serious injury by 0.0101 (15.8 percent) and fatality by 0.0013 (22.9 percent), as shown in Table 3. These results seem consistent with several previous studies that control for vehicle type (rather than height). In single-vehicle crashes, Wang and Kockelman (2005) found minivans and pickups to be less crashworthy for their occupants, Kockelman and Kweon (2002) found pickups and SUVs less crashworthy (perhaps due to their higher rollover likelihoods, which is a very dangerous crash type), White (2004) found light trucks to be less crash-worthy, and Ulfarsson and Mannering (2004) found drivers of pickups, SUVs and minivans sustain more severe injuries (than car drivers). This effect appears to reverse in two-vehicle crashes, where increasing the primary vehicle's height by one standard deviation (8.1 inches) is predicted to decrease the probability of an occupant sustaining serious injury by 0.0010 (-5.1 percent) and death by 0.0001 (-9.1 percent). The height of the collision partner is shown by the models to have a negligible impact on injury risk: A one standard deviation (8.1 inches) increase in the collision partner's height (holding all other variables constant) is predicted to increase fatal outcomes for the primary vehicle's occupants by 1.8 percent. The models' estimates imply that the popular notion of taller vehicles being safer may unwarranted (especially when considering rollover tendencies and outcomes of one-vehicle crashes) and that fears of increased risk when crashing into a taller crash partner may be exaggerated.

When accounting for both types of crashes, increasing all vehicles' heights by one standard deviation is estimated to increase overall death probability by 7.2 percent (or 0.0006). The result implies that the popularity of SUVs in recent years may be pushing fatality rates up (despite the overall fall in fatal crash counts[4]). As footprint-based CAFE standards no longer incentivize manufacturers to design taller vehicles to qualify for less stringent fuel economy requirements (under the protected status of a light-duty truck definition), the possibility of a shorter vehicle fleet is predicted to decrease overall fatality risks across all crash types. *Model Year*

Safety technology factors such as the availability of air bags, anti-lock and automatic brakes, adaptive headlamps, lane departure warning systems, and electronic stability control[5] contribute significantly to occupant safety (affecting crash outcomes and/or crash rates). The data do not include information on each vehicle's adoption of specific vehicle safety technologies, so the MY variable must serve as an overall indicator for vehicle improvements (as well as vehicle condition). In both one- and two-vehicle crashes, the models predict occupants in more recent MY vehicles to sustain lower injury and fatality risk and experience less variance in injury severity outcomes. The marginal probability changes in injury levels (see Tables 3 and 4) from the models show that increasing the vehicle MY in one-vehicle crashes by one standard deviation (5.2 years) is predicted to decrease fatality probability by 12.7 percent and in two-vehicle crashes ($\sigma$=5.2 years), predicted to decrease fatality probability by 5.2 percent. Kockelman and Kweon (2002) also found that occupants in newer vehicles sustained less severe injuries.

**Seating and Seat Belt-Use Effects**

As expected, the models predict seat belts play a key role in preventing injury and death. In one- and two-vehicle crashes, fatality likelihood is predicted to increase by 0.0296 (92.1 percent) and 0.0065 (an astounding 264.9 percent), respectively, when a fully belted (lap and shoulder) occupant removes his/her

[4] Traffic crash fatalities peaked in 2005 at 43,150, the highest since 1990. Since 2005, traffic fatalities have been falling, coinciding with a downturn in the U.S. economy and rising unemployment. Similar declines in crash fatalities also occurred in the economic recessions in the early 1980's and 1990's (NHTSA 2010).

[5] ESC systems are required on all new 2012 passenger vehicles sold in the U.S. and dual front-seat air bags have been mandated since 1989. Automatic braking systems were first introduced in the US by Mercedes in 2003; Nissan introduced lane departure warning systems to the U.S. in 2004.

belt. The safety benefits of seat belts have been confirmed in many previous studies (e.g., Shibata and Fukuda 1994, Farmer et al. 1997, Krull et al. 2000, Bedard et al. 2002 and Abdel-Aty 2003)

In one-vehicle crashes, occupants seated in the second row are generally predicted to be safer than those sitting in the first row (25 percent less chance of being killed). Wang and Kockelman (2005) also found second row seats to be safer, though for both one- and two- vehicle crashes. In two-vehicle crashes, due to the possibility of dangerous side- and rear-impact crashes, the model predicts the driver's seat as the safest position, consistent with findings by O'Donnell and Connor (1996). In both crash types, the front row passenger's side (right) seat is predicted to be the most dangerous position for fatality risk, similar to Smith and Cummings' (2004) finding.

**Roadway and Environmental Factor Effects**

As expected, the likelihood of a crash resulting in injury and fatality rises on roadways with higher speed limits (due to greater kinetic-energy-dissipation needs upon impact). The predicted probability changes by injury severity level due to one standard deviation increase in speed limit are shown in Tables 3 and 4. Though such results are consistent with previous studies (e.g., Farmer et al. 1997, Zhang et al. 2000, Krull et al. 2000, Khattak et al. 2002, and Wang and Kockelman 2005), speed limit is not a perfect indicator of actual vehicle travel speeds at the time of crash. Data on vehicle speeds at time of crash (from on-board speed detection systems) would be valuable to have.[6]

One-way roads appear safest, reducing fatality by 93.9 percent when compared to roadways with no division and 85.4 percent when compared to roadways with a physical divider in one-car crashes (54.3 percent and 45.7 percent for two-vehicle crashes. Physical dividers can reduce the frequency of head-on crashes, which tend to be quite severe. Such results are consistent with findings by Eluru et al. (2010) and Abdel-Aty and Keller (2005). Consistent with many previous studies (e.g., Dissanayake and Lu 2002, Abdel-Aty 2003, Wang and Kockelman 2005 and Eluru et al. 2010), the presence of horizontal curvature tends to increase predicted fatality risk, particularly for one-vehicle crashes (by 75.8 percent). The presence of vertical grades also increases fatal injury likelihoods in one-vehicle crashes, though less dramatically as shown in Tables 3. Surprisingly, the model also predicts the presence of vertical grades to decrease (-9.1 percent) fatality risks in two-vehicle crashes as shown in Table 4.

Adverse weather's influence on injury severity in two-car crashes was not found to be statistically significant. Interestingly, one-vehicle crashes that occur during adverse weather conditions appear to generally be safer for occupants, with their fatality shares falling by 0.0017 (-28.9 percent). This is arguably attributable to drivers exerting extra caution during bad weather conditions, and slowed speeds resulting in safer (though generally more, per mile traveled) crashes. This result is consistent with findings by Khattak et al. (2002) and Wang and Kockelman (2005). Also consistent with Wang and Kockelman's findings (2005), the crashes during daylight are predicted to be less safe for one-vehicle crash occupants but more safe for two-vehicle crashes, as witnessed by the opposing signs of the marginal probabilities in Tables 3 and 4.

**Occupant Attributes**

[6] Of some interest is the fact that roadways designed for higher speed limits tend to have wider lanes and shoulders, less horizontal and vertical curvature, more stringent access control, and a host of other factors that tend to reduce crash rates, per mile travelled (see, e.g., Kockelman et al. 2006).

The effect of age on crash injury severity is predicted to be more dramatic for one-vehicle crashes than two-vehicle crashes. For example, a one standard deviation increase in the occupant's age (holding all other variables constant) is predicted to increase fatality risk by 16.3 in one-vehicle crashes and 8.6 percent in two-vehicle crashes (absolute probability changes are shown in Tables 3 and 4). The finding that older occupants experience more injurious outcomes is consistent with the work of Farmer et al. (1997), Bedard et al. (2002), Dissanayake and Lu (2002), Abdel-Aty (2003), and Wang and Kockelman (2005). Younger occupants may be more fit, and their bodies (and bones) more flexible.

Women are more likely to be injured and die in crashes than men. Holding all other attributes at mean values, women are estimated here to be 43.0 percent more likely to die in a one-vehicle crash and 47.5 percent more likely in a two-vehicle crash (than their male counterparts). Almost all previous studies have found women to be more prone to injury in vehicle crashes (see, e.g. Kockelman and Kweon 2002).

Alcohol use by a vehicle's *driver* has significant impacts on the occupant's injury severity risks, particularly in one-car crashes. For one-vehicle crashes, which are three times as likely to involve a driver under the influence of alcohol as multiple-vehicle crashes (NHTSA 2008), such driver status increases the average occupant's injury fatality risk by 0.0084 (197.3 percent). In two-vehicle crashes, a driver's alcohol use/abuse increases the occupant's predicted fatality risk by 0.0007 (49.0 percent). The altered vision, decreased inhibition, and lack of concentration and coordination caused by alcohol use all contribute to higher injury and fatality rates in a crash, as noted by Shibata and Fukuda (1994), Krull et al. (2000) and Bedard et al. (2002).

## CONCLUSIONS

The impact of CAFE standards on crash safety has long been a hotly contested topic (see, e.g. Crandall and Graham 1989). Historically, the debate has been over the relationship between vehicle weight and crash severity. With the United States' recent introduction of footprint-based fuel economy standards, the attention shifts somewhat, to the importance of vehicle length and width – and their product, footprint. By employing an HOP model specification, this study examines the effects of different vehicle characteristics (MY, weight, footprint, and height) on crash severity while controlling for a wide variety of occupant and environmental variables (age, gender, alcohol use, roadway geometry, speed limit, weather and light conditions, seating position, and seat belt use).

Results illuminate many of the tradeoffs that exist for vehicle design attributes and occupants involved in one- and two-vehicle crashes. Vehicle weight, footprint, and height are all estimated to play a more significant role in injury risk (particularly fatality risk) in one-vehicle crashes than in two-vehicle crashes. Everything else constant, occupants of heavier, larger-footprint and shorter vehicles tend to sustain the lowest risk of fatal injury in one-vehicle crashes. Vehicle weight impacts are similarly directed – but less sizable – in two-vehicle crashes; however, occupants of smaller-footprint and taller vehicles are predicted to face less injury and fatality risk than those in larger-footprint and shorter vehicles. While the result regarding height in two-vehicle crashes may be as expected (since taller vehicles can override shorter vehicles and avoid much of the vehicle crumpling that occurs), *overall* fatality rates are predicted to rise by 7.2 percent following an approximate 8 inch increase in the light-duty-vehicles' fleet height.

Importantly, overall increases in vehicle weights, footprints, and heights across the NASS GES-represented fleet of crashed vehicles had small impacts on fatality risk, suggesting that manufacturer modifications to meet attribute-based CAFE standards may have little impact on crash severity. Other factors, such as seat belt use, alcohol use, roadway geometry and roadway division type are estimated to exert far greater impacts on crash outcomes. Such findings underscore the importance of seat-belt laws, anti-drinking-and-driving campaigns, and roadway design in facilitating safer travel.

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### TABLE 1 Variable Definitions and Summary Statistics

| Variable | Variable Description | One-Vehicle Crashes | | Two-Vehicle Crashes | |
|---|---|---|---|---|---|
| | | Mean | Std Dev | Mean | Std Dev |
| CURBWT | Curb weight of the vehicle, in lbs | 3550 | 870.8 | 3551 | 867.0 |
| FOOTPRINT* | Footprint of the vehicle, in square feet (SF) | 56.0 | 9.33 | 56.1 | 9.2 |
| HEIGHT# | Height of the vehicle, in inches | 62.3 | 8.28 | 62.2 | 8.11 |
| MODELYR* | Model year of the vehicle | 2000 | 5.19 | 2001 | 5.15 |
| PFOOTPRINT# | Footprint of collision partner, in SF | - | - | 56.0 | 9.16 |
| PHEIGHT | Height of collision partner, in inches | - | - | 62.0 | 8.08 |
| FRTRIGHT | 1 if seated in the front row other than driver's seat (front middle or right); 0 otherwise | 0.165 | 0.371 | 0.156 | 0.363 |
| SECLEFT | 1 if seated in the second row behind driver (left side); 0 otherwise | 0.042 | 0.201 | 0.041 | 0.197 |
| SECRIGHT | 1 if seated in the second row middle or left; 0 otherwise | 0.069 | 0.254 | 0.069 | 0.253 |
| OTHERSEAT | 1 if seated in any seat other than above, such as third row or cargo area; 0 otherwise | 0.010 | 0.097 | 0.007 | 0.084 |
| FULLBELT | 1 if occupant uses both lap and shoulder belts; 0 otherwise | 0.785 | 0.411 | 0.873 | 0.333 |
| PARTBELT | 1 if occupant uses either lap or shoulder belt, but not both; 0 otherwise | 0.015 | 0.123 | 0.013 | 0.114 |
| OTHERBELT | 1 if occupant uses restraining system other than lap or shoulder belt, e.g. child safety seat | 0.060 | 0.238 | 0.080 | 0.271 |
| SPDLIMIT* | Speed limit at the crash site, in mph | 44.9 | 14.6 | 41.5 | 10.23 |
| SPDSQRT | Square of the crash site's speed limit, in $mi^2/hr^2$ | - | - | 1825 | 907 |
| DIVIDE | 1 if the two way roadway is divided by median strip or barrier; 0 otherwise | 0.345 | 0.475 | 0.384 | 0.486 |
| NODIVIDE | 1 if the two way roadway is not physically divided (including TWLTLs); 0 otherwise | 0.609 | 0.488 | 0.568 | 0.495 |
| STRAIGHT | 1 if the roadway is straight; 0 otherwise | Base variable for horizontal curve | | | |
| CURVE | 1 if the roadway is curved; 0 otherwise | 0.270 | 0.444 | 0.069 | 0.254 |
| HILL | 1 if the roadway is on a hill; 0 otherwise | 0.296 | 0.456 | 0.181 | 0.385 |
| DARK | 1 if dark, dusk or dawn at time of crash; 0 otherwise | 0.474 | 0.499 | 0.239 | 0.427 |
| BADWEATHER | 1 if the weather is adverse (rain, sleet, snow, fog, etc.); 0 otherwise | 0.174 | 0.379 | 0.126 | 0.332 |
| AGE | Occupant age, in years | 31.5 | 17.2 | 35.2 | 19.3 |
| AGESQRT | Square of the occupant's age, in $years^2$ | 1289 | 1399 | 1609 | 1623 |
| FEMALE | 1 if the occupant is female; 0 otherwise | 0.423 | 0.494 | 0.501 | 0.500 |
| ALCOHOL | 1 if the vehicle's *driver* was reported on the PAR as under influence of alcohol; 0 otherwise | 0.148 | 0.356 | 0.020 | 0.141 |

Notes:

*This variable is used in the heteroscedasticity specification for one- and two-vehicle crashes.
#This variable is used in the heteroscedasticity specification for two-vehicle crashes.

"P**" variables are crash partner attributes, in two-vehicle crashes. Base crash condition is a male driving his vehicle unbelted, on a level, one-way road during light, good-weather conditions, not under the influence of alcohol (as reported by police officers responding to the crash).

## TABLE 2 HOP Model Results

| Variable | One-Vehicle Crashes | | Two-Vehicle Crashes | |
|---|---|---|---|---|
| | Coefficient | t-statistic | Coefficient | t-statistic |
| *Injury severity measure* | | | | |
| Constant | 7.42 | 10.091 | 6.72 | 7.762 |
| CURBWT | -2.52E-05 | -4.659 | -3.11E-05 | -4.919 |
| FOOTPRINT | -5.20E-03 | -11.744 | -4.72E-03 | -8.398 |
| HEIGHT | 4.11E-03 | 10.044 | -1.28E-03 | -2.331 |
| MODELYR | -3.78E-03 | -10.239 | -3.47E-03 | -7.987 |
| PFOOTPRINT | - | - | -1.41E-03 | -3.791 |
| PHEIGHT | - | - | 9.88E-04 | 2.678 |
| FRTRIGHT | 0.0238 | 4.499 | 0.1235 | 21.143 |
| SECLEFT | -0.0447 | -4.097 | 0.0741 | 5.840 |
| SECRIGHT | -0.0506 | -5.284 | 0.0901 | 8.850 |
| OTHERSEAT | 0.0705 | 4.138 | 0.0388 | 1.240 |
| FULLBELT | -0.3918 | -55.080 | -0.4293 | -32.599 |
| PARTBELT | -0.3305 | -19.717 | -0.3865 | -18.230 |
| OTHERBELT | -0.3591 | -30.498 | -0.3730 | -23.226 |
| SPDLIMIT | 5.84E-03 | 33.633 | 0.0103 | 7.762 |
| SPDSQRT | - | - | -1.10E-04 | -7.305 |
| DIVIDE | 0.0975 | 8.569 | 0.1120 | 12.575 |
| NODIVIDE | 0.1048 | 9.753 | 0.1256 | 14.896 |
| CURVE | 0.0916 | 21.232 | 0.0334 | 4.884 |
| HILL | 0.0374 | 8.762 | -0.0142 | -2.554 |
| DARK | -0.0348 | -8.833 | 0.0495 | 9.305 |
| BADWEATH | -0.0548 | -11.512 | - | - |
| AGE | -2.15E-03 | -4.271 | 7.80E-03 | 15.177 |
| AGESQRT | 2.72E-05 | 4.456 | -5.33E-05 | -9.249 |
| FEMALE | 0.0589 | 14.927 | 0.1056 | 23.578 |
| ALCOHOL | 0.1756 | 27.192 | 0.1111 | 5.700 |
| Variance | | | | |
| SPDLIMIT | -1.03E-03 | -1.924 | 6.34E-03 | 13.265 |
| AGE | 1.55E-03 | 3.602 | -8.14E-04 | -3.172 |
| MODELYR | -6.00E-04 | -21.684 | -6.95E-04 | -25.408 |
| FOOTPRINT | 4.84E-03 | 5.880 | 5.36E-03 | 6.468 |
| HEIGHT | - | - | -2.64E-03 | -2.908 |
| PFOOTPRINT | - | - | 4.71E-03 | 8.452 |
| *Threshold* | | | | |
| $\mu_0$ | 0.000 | - | 0.000 | - |
| $\mu_1$ | 0.170 | 33.435 | 0.297 | 50.240 |
| $\mu_2$ | 0.422 | 38.684 | 0.545 | 55.581 |
| $\mu_3$ | 0.882 | 38.911 | 1.151 | 39.477 |
| Number of Observations | 26421 | | 72139 | |
| LRI | 0.3224 | | 0.4485 | |

Note: All coefficients shown are statistically significant at the 10 percent level (p-value < 0.10) except those shown with an asterisk (*).

**TABLE 3 Variable Marginal Effects in One-Vehicle Crashes**

| Variable | Marginal Effect (Change of Probabilities Versus Base Case) | | | | |
|---|---|---|---|---|---|
| | No Injury | Possible Injury | Non-Incapacitating Injury | Incapacitating Injury | Fatal Injury |
| *Continuous Variables (with 1 Standard Deviation Increase)* | | | | | |
| CURBWT | 0.0170 | -0.0046 | -0.0065 | -0.0052 | -0.0007 |
| FOOTPRINT | 0.0285 | -0.0111 | -0.0113 | -0.0058 | -0.0003 |
| HEIGHT | -0.0274 | 0.0069 | 0.0103 | 0.0088 | 0.0013 |
| MODELYR | 0.0157 | -0.0040 | -0.0060 | -0.0050 | -0.0007 |
| SPD_LIMIT | -0.0688 | 0.0176 | 0.0262 | 0.0219 | 0.0031 |
| AGE | -0.0048 | -0.0010 | 0.0014 | 0.0035 | 0.0009 |
| *Seat Position (versus Driver's Seat)* | | | | | |
| FRTRIGHT | 0.0004 | -0.0001 | -0.0001 | -0.0001 | 2.39E-06 |
| SECLEFT | 0.0341 | -0.0095 | -0.0130 | -0.0102 | -0.0014 |
| SECRIGHT | 0.0384 | -0.0107 | -0.0147 | -0.0114 | -0.0015 |
| OTHERSEAT | -0.0579 | 0.0138 | 0.0217 | 0.0193 | 0.0030 |
| *Restraint Use (versus No Seat Belt Use)* | | | | | |
| FULLBELT | 0.3573 | -0.0483 | -0.1230 | -0.1564 | -0.0296 |
| PARTBELT | 0.3074 | -0.0346 | -0.1032 | -0.1415 | -0.0282 |
| OTHERBELT | 0.3313 | -0.0409 | -0.1126 | -0.1488 | -0.0289 |
| *Roadway Division (versus One Way Road)* | | | | | |
| DIVIDE | -0.0712 | 0.0210 | 0.0273 | 0.0203 | 0.0026 |
| NODIVIDE | -0.0769 | 0.0225 | 0.0295 | 0.0221 | 0.0028 |
| *Horizontal Alignment (versus Straight Road)* | | | | | |
| CURVE | -0.0741 | 0.0187 | 0.0281 | 0.0239 | 0.0035 |
| *Vertical Grade (versus Level Road)* | | | | | |
| HILL | -0.0297 | 0.0077 | 0.0113 | 0.0094 | 0.0013 |
| *Light Condition (versus Daylight)* | | | | | |
| DARK | 0.0273 | -0.0072 | -0.0104 | -0.0085 | -0.0012 |
| *Adverse Weather (versus Good Weather)* | | | | | |
| BADWEATH | 0.0422 | -0.0116 | -0.0161 | -0.0128 | -0.0017 |
| *Gender (versus Male)* | | | | | |
| FEMALE | -0.0543 | 0.0071 | 0.0183 | 0.0235 | 0.0053 |
| *Alcohol Use (versus No Alcohol Use)* | | | | | |
| ALCOHOL | -0.1504 | 0.0323 | 0.0560 | 0.0536 | 0.0084 |

## TABLE 4 Variable Marginal Effects in Two-Vehicle Crashes

| Variable | Marginal Effect (Change of Probabilities Versus Base Case) | | | | |
|---|---|---|---|---|---|
| | No Injury | Possible Injury | Non-Incapacitating Injury | Incapacitating Injury | Fatal Injury |
| *Continuous Variables (with 1 Standard Deviation Increase)* | | | | | |
| CURBWT | 0.0048 | -0.0026 | -0.0013 | -0.0009 | -4.58E-05 |
| FOOTPRINT | 0.0036 | -0.0030 | -0.0007 | 0.0001 | 0.0001 |
| HEIGHT | 0.0036 | -0.0015 | -0.0011 | -0.0010 | -0.0001 |
| PFOOTPRINT | -0.0011 | -0.0004 | 0.0005 | 0.0009 | 0.0001 |
| PHEIGHT | -0.0015 | 0.0008 | 0.0004 | 0.0003 | 1.50E-05 |
| MODELYR | 0.0035 | -0.0018 | -0.0010 | -0.0007 | -3.96E-05 |
| SPD_LIMIT | -0.0051 | 0.0011 | 0.0018 | 0.0021 | 0.0002 |
| AGE | -0.0097 | 0.0054 | 0.0026 | 0.0016 | 0.0001 |
| *Seat Position (versus Driver's Seat)* | | | | | |
| FRTRIGHT | -0.0662 | 0.0338 | 0.0186 | 0.0130 | 0.0007 |
| SECLEFT | -0.0380 | 0.0200 | 0.0105 | 0.0071 | 0.0004 |
| SECRIGHT | -0.0469 | 0.0244 | 0.0130 | 0.0089 | 0.0005 |
| OTHERSEAT | -0.0192 | 0.0103 | 0.0053 | 0.0035 | 0.0002 |
| *Restraint Use (versus No Seat Belt Use)* | | | | | |
| FULLBELT | 0.2901 | -0.1138 | -0.0869 | -0.0828 | -0.0065 |
| PARTBELT | 0.2682 | -0.1021 | -0.0809 | -0.0789 | -0.0063 |
| OTHERBELT | 0.2610 | -0.0983 | -0.0788 | -0.0776 | -0.0063 |
| *Roadway Division (versus One Way Road)* | | | | | |
| DIVIDE | -0.0499 | 0.0279 | 0.0133 | 0.0083 | 0.0004 |
| NODIVIDE | -0.0568 | 0.0315 | 0.0152 | 0.0096 | 0.0005 |
| *Horizontal Alignment (versus Straight Road)* | | | | | |
| CURVE | -0.0173 | 0.0090 | 0.0048 | 0.0033 | 0.0002 |
| *Vertical Grade (versus Level Road)* | | | | | |
| HILL | 0.0071 | -0.0038 | -0.0019 | -0.0013 | -0.0001 |
| *Light Condition (versus Daylight)* | | | | | |
| DARK | -0.0255 | 0.0133 | 0.0071 | 0.0048 | 0.0003 |
| *Gender (versus Male)* | | | | | |
| FEMALE | -0.0530 | 0.0282 | 0.0145 | 0.0097 | 0.0005 |
| *Alcohol Use (versus No Alcohol Use)* | | | | | |
| ALCOHOL | -0.0616 | 0.0307 | 0.0175 | 0.0127 | 0.0007 |

**Chart (a). One-Vehicle Crash Injury Likelihood by Weight, Footprint and Height (all other variables constant)**

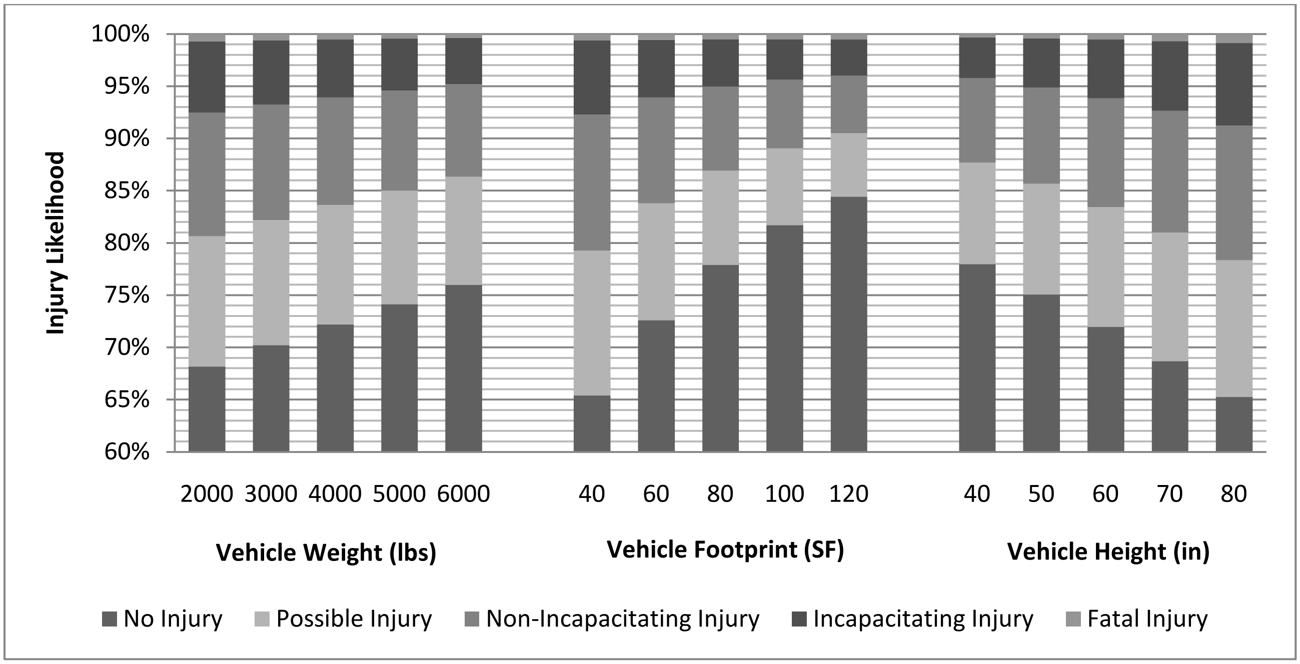


**Chart (b). Two-Vehicle Crash Injury Likelihood by Primary Vehicle's Weight, Footprint and Height (all other variables constant)**

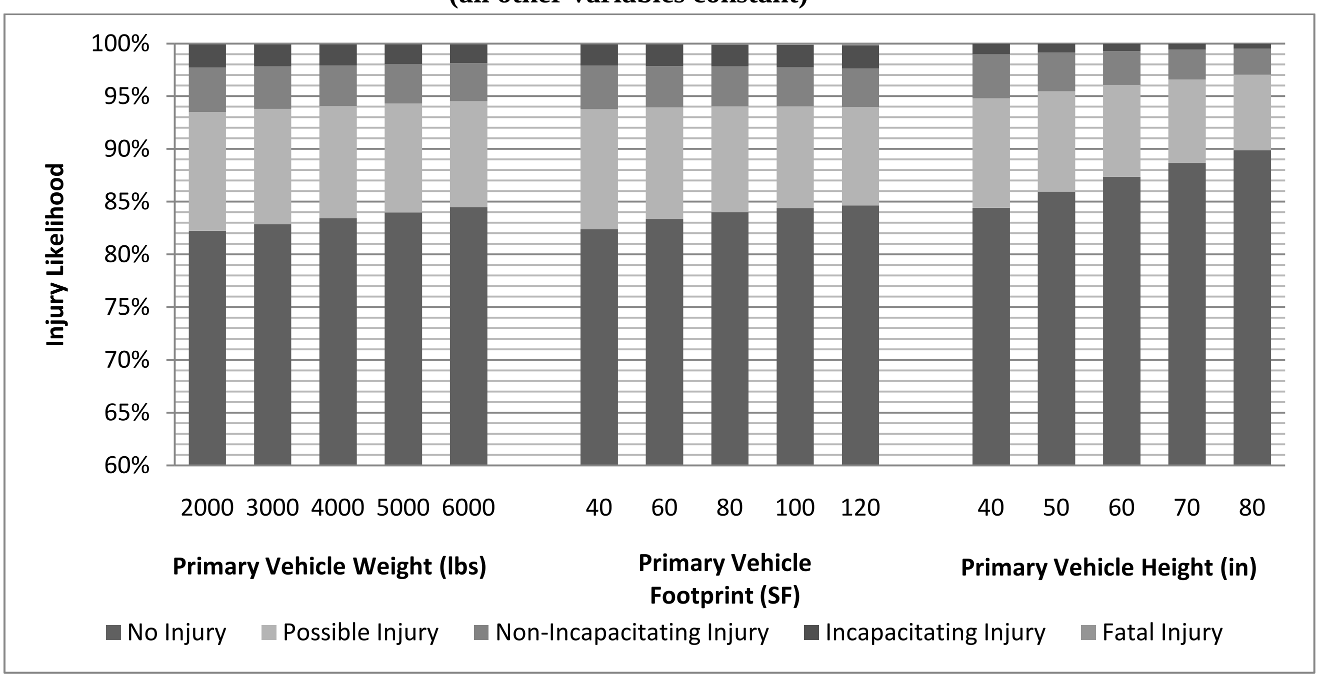


**FIGURE 1 Model-Predicted Probabilities of Occupant Injury by Vehicle Characteristics**