Risk Analysis, Vol. 23, No. 4, 2003

Safety Impacts of SUVs, Vans, and Pickup Trucks in Two-Vehicle Crashes

Edmond L. Toy[1]* and James K. Hammitt[2]

Policy makers, vehicle manufacturers, and consumers have shown growing concern about the relative safety of sport utility vehicles (SUVs), vans, pickups, and cars. Empirical analysis of real-world crashes is complicated by the possibility that apparent relationships between vehicle type and safety may be confounded by other factors, such as driver behavior and crash circumstances. This study compares different vehicle types with respect to their crashworthiness (self-protection) and aggressivity (risk to others) in crashes between two passenger vehicles. The U.S. Crashworthiness Data System is used to analyze detailed information on 6,481 drivers involved in crashes during 1993–1999. Logistic regression analysis is used to model the risk of serious injury or death to a driver, conditional on a crash occurring. Covariates include the body type of each vehicle in the crash; the driver's age, gender, and restraint use; and the configuration of the crash. A unique feature of this study is the use of "delta-v" to represent the joint effects of vehicle mass and crash severity. While estimated effects are somewhat sensitive to the injury severity level used as the outcome variable, SUVs, vans, and pickups appear to be more aggressive and may be more crashworthy than cars. Effects of pickups are most pronounced. Drivers in pickups face less risk of serious injury than car drivers (odds ratio [OR], 0.35; 95% confidence interval [CI], 0.20–0.60), and drivers who collide with pickups experience more than twice the risk than those who collide with a car (OR, 2.18; 95% CI, 1.03–4.62). While vehicle mass and crash severity contribute to the apparent crashworthiness and aggressivity of passenger vehicles, other vehicle characteristics associated with body type (e.g., the stiffness and height of the underlying structure of the vehicle) also influence safety risks.

KEY WORDS: Aggressivity; crash severity; crashworthiness; motor vehicle; sport utility vehicle

1. INTRODUCTION

Consumer demand for light trucks and vans (LTVs) has grown substantially over the past two decades. This category of vehicles, which includes sport utility vehicles (SUVs), vans, and pickup trucks, now comprises nearly half of all new passenger vehicle sales in the United States.(1) The popularity of LTVs is due partly to the public's perception that they are more crashworthy than cars (i.e., LTV occupants have a better chance of surviving a traffic crash than car occupants).(2) This potential advantage, however, may come at the price of greater aggressivity, (i.e., the design of LTVs may increase the risk to others on the road). The safety implications of LTVs have gained prominence as consumers become increasingly interested in vehicle safety, insurers restructure premiums

[1] U.S. Office of Management and Budget, Washington, DC. This research was conducted while Dr. Toy was affiliated with the Harvard Center for Risk Analysis and reflects the author's personal views. This study does not represent the views of OMB or the Administration.

[2] Center for Risk Analysis and Department of Health Policy and Management, Harvard School of Public Health, Boston, Massachusetts.

* Address correspondence to Edmond L. Toy at etoy@post.harvard.edu.

to reflect vehicle body type, and regulators and manufacturers seek modifications to vehicle designs for the sake of safety.[3–5]

Recent empirical studies appear to confirm these perceptions about LTV safety.[6–9] For every 1,000 two-vehicle crashes in which one vehicle is a large SUV, there are an estimated 3.68 driver fatalities in the other vehicle involved in the crash ("collision partner"). In contrast, for crashes involving a large car, only 1.39 fatalities occur in the collision partner. In head-on crashes between cars and SUVs, there are four times as many deaths among the drivers of cars as among the drivers of SUVs.[6]

There are a variety of possible explanations for these empirical results. Given the well-established relationship between vehicle mass and safety,[10,11] one obvious explanation is the generally greater mass of LTVs, which can increase both their crashworthiness and aggressivity. In addition, LTVs often differ from cars in other characteristics that can influence risk, such as "stiffness" and "geometry." Such vehicle characteristics have been studied less extensively and have more subtle effects than vehicle mass but may be important in the context of crashes involving LTVs.[12] Other nonvehicle factors may also contribute to the observed safety impacts of LTVs. For example, LTVs are more likely to be driven on high-speed rural roads than are cars, which increases crash severity.[13] Factors like crash severity, driver behavior, and crash circumstances may confound the relationship between vehicle type and serious injury risk but often have not been well addressed in studies about the safety of LTVs.

This investigation compares the relative effects of LTVs and cars on the risk (probability) of serious and fatal injury to drivers involved in crashes between two passenger vehicles. It explores empirically the effects of vehicle body type, controlling for vehicle mass, crash severity, and other factors related to drivers and crash circumstances. A unique feature of this study is the use of "delta-v" (Δv, change in velocity) to control for the joint effects of mass and crash severity. This study may help regulators and vehicle designers to identify the important factors that influence risk in order to target risk reduction interventions more precisely.

2. METHODS

2.1. Data Source

Data were obtained from the Crashworthiness Data System (CDS), a computerized database maintained by the U.S. National Highway Traffic Safety Administration (NHTSA) as part of its National Accident Sampling System. The primary advantage of using CDS is that it contains data on delta-v, which is used here as a proxy for mass and crash severity.

CDS is a nationally representative sample of all police-reported crashes in the United States that involved a car or LTV that was towed away from the crash scene due to vehicle damage. CDS includes crashes that result in minor, serious, and fatal injuries. Most other analyses have focused only on fatalities and are based on the Fatality Analysis Reporting System. Although fatalities are of most interest, they are comparatively rare, occurring in only about 0.6% of all traffic crashes reported to the police. CDS is the most detailed national database of traffic crashes. A CDS investigation may include post-crash vehicle inspections, interviews with crash victims, and review of medical records. Data for about 5,000 crashes are collected each year.[14,15]

Data from CDS were extracted for all drivers involved in two-vehicle crashes between LTVs and/or cars for which information on injury severity was available. Vehicle body type (i.e., cars, SUVs, vans, and pickups) is categorized by CDS investigators based on visual inspections, police reports, and interviews. The sample was further limited to crashes that occurred during 1993–1999; crashes before this period were not considered because the classification system for injury severity used for CDS was modified in 1993.[16] In addition, the sample was restricted to drivers who were in a vehicle of model year 1990 or more recent so that only reasonably modern cars are considered.

There are 10,075 observations satisfying these criteria ("full sample"); each two-vehicle crash may contribute one or two observations to the sample. For model estimation, 3,594 observations are excluded due to missing values for any of the independent variables (described below); the "regression sample" consists of 6,481 observations. All models reported below are estimated using the regression sample so that comparison of the various model results reflects changes in the model form rather than changes in the sample.

2.2. Conceptual Framework

Fig. 1 illustrates the conceptual framework for the analysis of serious and fatal injury risk to a driver involved in a two-vehicle crash. The framework is based on existing literature that identifies factors that can influence risk.

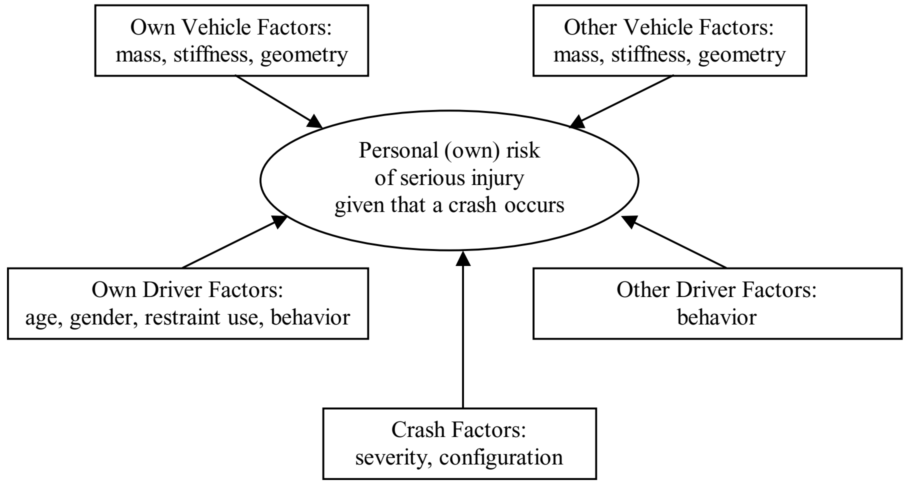

Fig. 1. Conceptual framework.

The first type of factor that may influence risk relates to the driver's own vehicle characteristics.[6] Vehicle mass has a well-established influence on risk; greater mass is associated with decreased risk in two-vehicle crashes.[17,18] The stiffness of the vehicle depends on the underlying structure of the vehicle (e.g., a ladder frame design is stiffer than a unibody design). In two-vehicle crashes, large differences in stiffness can result in the less stiff vehicle absorbing the bulk of the crash energy. The geometry may also influence risk; this refers generally to the location (particularly the height) of load-bearing structures within the vehicle. Differences in geometry can lead to one vehicle overriding the protective structures of the other vehicle. Although ground clearance or "ride height" of a vehicle may be indicative of its geometry, the two concepts are not identical. On average, LTVs have greater mass, are stiffer, and ride higher than cars.[6]

Second, a driver's risk may be affected by the *other* vehicle's characteristics (i.e., the other vehicle's mass, stiffness, and geometry).

Third, the characteristics of the driver may also influence risk. Demographic characteristics, such as age and gender, may affect risk.[10] For example, older drivers may be less tolerant of crash forces, increasing the risk of injury, all else being equal. The driver's restraint use (e.g., wearing a seat belt or the presence of an air bag) can have a protective effect. Another factor is driver behavior, which refers broadly to whether a vehicle was being driven recklessly or safely and therefore influences the severity of the crash.

Fourth, a driver's risk can be influenced by the behavior of the *other* driver.

The fifth and final category, shown in Fig. 1, includes crash factors. The severity of the crash strongly affects injury risk.[10,19,20] Intuitively, crash severity is associated with the relative speed of the vehicles at impact, which may in turn be influenced by the type of road where the crash took place (e.g., speeds on rural roads are usually higher than on urban roads) and the manner in which a vehicle was being driven (e.g., whether alcohol was involved).[10,13] In addition, the configuration of the crash-involved vehicles (e.g., head-on vs. side impact) can influence health outcomes.

2.3. Analytical Approach

Logistic regression methods are used. The dichotomous outcome is whether a driver was seriously injured or killed. Injury severity is measured using the Abbreviated Injury Scale (AIS), which assigns to each injury a value from 1 (minor injuries) to 6 (maximum, untreatable injuries); a value of 3 is considered a "serious injury."[21] The maximum AIS value is used if the driver suffered multiple injuries. Fatalities that occur within 30 days of the crash are considered as serious injuries regardless of the AIS level. Only the health outcomes of drivers are considered, since all vehicles have exactly one driver.

Development of the regression model was guided by the conceptual framework shown in Fig. 1. Independent variables were chosen to control for potentially confounding factors and were based on the availability of data within CDS.

CDS contains several types of information on the characteristics of both vehicles. At a general level, each vehicle is characterized by its body type (i.e., car, SUV, van, or pickup) using a series of indicator variables. These variables enable estimation of the effects of *own* vehicle body type and *other* vehicle body type on the driver's injury outcome, which correspond, respectively, to the crashworthiness of the driver's vehicle and the aggressivity of the other vehicle. The indicator variables for the driver's vehicle body type are denoted as Own SUV, Own Van, and Own Pickup (the comparator is the driver in a car), while the collision partner's vehicle body type is labeled as Other SUV, Other Van, Other Pickup (the comparator is a collision partner that is a car). More finely detailed categories (e.g., compact and full-size pickups) lead to small sample sizes and are not used in this analysis.

As suggested by Fig. 1, vehicles may be characterized more specifically based on their mass, stiffness, and geometry. Data on the masses of both vehicles involved in a crash are available within CDS, and this analysis uses the ratio of the masses to incorporate the effects of mass on driver risk. This variable is defined as the curbweight of the driver's vehicle divided by the curbweight of the collision partner. Curbweight is the mass of a vehicle, excluding occupants and cargo, and is based on manufacturers' vehicle specifications. Increasing values of mass ratio are expected to be associated with reduction in risk. Data on vehicle stiffness and geometry are not available within CDS. Because we control for mass ratio, the indicator variables for vehicle body type serve as proxies for other unobserved vehicle characteristics, such as stiffness and geometry.

Driver-related factors include the driver's age (measured in years), gender, and restraint use. Restraint use is coded using indicator variables for whether the driver properly used a seat belt (manual or automatic) and whether a driver-side air bag was present.

Crash-related factors include the crash severity and crash configuration. The vehicles' relative velocity at the moment of impact is not available, so other measures of crash severity are necessary. This analysis uses delta-v. Delta-v is defined for each vehicle as the change in velocity during the time between initial contact and the time at which the vehicles achieve a common velocity, which is assumed to occur at the moment of maximum deformation.[22,23] In simple crashes (e.g., full frontal collisions with no rotation; other crash types require more complex equations), physical principles imply that

$$\Delta V_1 = \sqrt{\frac{2E_A M_2}{M_1 (M_1 + M_2)}} \quad \text{and}$$

$$\Delta V_2 = \sqrt{\frac{2E_A M_1}{M_2 (M_1 + M_2)}},$$

where M_i is the mass of vehicle i and E_A is the total energy absorbed by both vehicles through the crushing process. Moreover,

$$E_A = \frac{1}{2}\left(\frac{M_1 M_2}{M_1 + M_2}\right) V_R^2,$$

where V_R is the relative velocity of the two vehicles at the moment of impact.

CDS crash investigators estimate E_A using (1) measurements of the extent and location of deformation in the crash-involved vehicles and (2) results of laboratory experiments in which vehicles are crash-tested into fixed barriers, generally as part of NHTSA's ongoing New Car Assessment Program.

Delta-v is a function of the masses of the two vehicles and their relative velocity. Therefore, it can be used in the regression model to represent the joint effects of the vehicles' masses and the severity of the crash (in the sense of the relative velocity of the vehicles). It is not analytically feasible to separate the effects of mass and crash severity based only on delta-v values. In the context of the conceptual framework shown in Fig. 1, delta-v reflects the influence of the mass of both vehicles and the behavior of both drivers.

Other approaches have been used to control for crash severity. For example, the posted speed limit at the site of the crash has been used as a crude proxy of crash severity.[12] In addition, the double pair comparison method, which provides a method for standardizing crash conditions in the absence of severity information, has been used to investigate the effects of driver characteristics on fatality risks.[10,24] We believe that the method adopted here is preferable because delta-v is a more direct measure of crash severity than the posted speed limit and other alternatives.

To capture the effect of crash configuration on serious injury risk, a series of three indicator variables represents the general area of damage to the driver's vehicle (left side, right side, and rear; the comparator is a frontal crash).

The analysis is implemented using Stata statistical software.[25] Stata's survey logistic regression analysis capabilities are used to account for the multiple-stage sampling procedure used for CDS.[26] The probability weights supplied in CDS are used.

3. RESULTS

Table I presents descriptive statistics for variables used in the regression. Weighted means and the standard deviations (for continuous variables) are shown. Approximately 21% of the observations represent

Table I. Descriptive Statistics

Variables	Full Sample[a] Mean	Full Sample[a] N	Regression Sample[b] Mean	Regression Sample[b] N
Serious injury to driver (%)	2.15	10,075	2.59	6,481
Own vehicle body type (%)				
Own SUV	7.26	10,075	5.56	6,481
Own Van	6.91	10,075	6.15	6,481
Own Pickup	10.14	10,075	9.44	6,481
Other vehicle body type (%)				
Other SUV	9.12	10,075	9.62	6,481
Other Van	7.63	10,075	6.45	6,481
Other Pickup	15.71	10,075	12.68	6,481
Age, years (std. dev.)	35.99 (16.28)	10,057	35.64 (17.30)	6,481
Male (%)	47.71	10,067	47.19	6,481
Seat belt used (%)	90.19	9,400	89.73	6,481
Air bag present (%)	61.14	9,987	60.38	6,481
Mass ratio (std. dev.)	1.01 (0.31)	9,585	1.00 (0.33)	6,481
Delta-v, km/hr (std. dev.)	19.60 (9.12)	7,564	19.73 (9.04)	6,481
Left-side impact (%)	17.90	8,707	18.03	6,481
Right-side impact (%)	16.78	8,707	17.26	6,481
Rear impact (%)	7.80	8,707	8.10	6,481

[a]The full sample contains observations that have information on the injury outcome of drivers involved in crashes between two-passenger vehicles between 1993 and 1999, and the driver was in a vehicle of model year 1990 or more recent.
[b]The regression sample is the subset of observations from the full sample that does not have a missing value for any of the listed variables.

drivers who were in LTVs. This fraction is smaller than the nearly 50% share of new passenger vehicles that are LTVs because (1) the share of vehicles that are LTVs was smaller in earlier model years (i.e., early 1990s), and (2) older model years account for a disproportionate share of collisions because they were on the road for a longer part of the period from which the data are drawn. The distribution of crashes differs between the full sample and the regression sample, in part due to the exclusion of observations with missing values. For example, the regression sample has a smaller proportion of LTVs and contains more crashes in which the driver was seriously injured. Approximately 90% of drivers used seat-belts, based on vehicle inspections, review of hospital records, and interviews. This fraction is higher than the 69% rate found in government observational studies.[27]

Results are presented for several different regression models, which differ by the independent variables that are included. The first model includes independent variables only for the body types of both vehicles. Additional independent variables are added to subsequent models. The progression of these models illustrates the effects of potentially confounding factors on the estimated effects of vehicle body type. The odds ratios (ORs) and 95% confidence intervals (CI) estimated from each model are shown in Table II.

Model 1. In this model, the risk of serious injury to a driver is characterized as a function of only the vehicle body types of both vehicles involved in the crash. The crashworthiness of LTVs is not significantly different from that of cars (as indicated by the statistically insignificant ORs for the body type of the driver's vehicle, Own SUV, Own Van, and Own Pickup). Vans and pickups are associated with statistically significant aggressivity effects (as indicated by the ORs for Other Van and Other Pickup that are significantly greater than 1). This model suggests that a driver faces about 1.7 times more risk (i.e., higher odds of serious injury) if the other vehicle in the crash is a van rather than a car, and about 3.7 times more risk if the other vehicle is a pickup. The aggressivity of SUVs is not significantly different from cars. However, this model does not attempt to control for any confounding factors, so the estimated effects of vehicle body type may be biased.

To examine the effects of missing variables, Model 1 was reestimated using the full sample. The crashworthiness of LTVs remained statistically insignificant (ORs for Own SUV, Own Van, and Own Pickup are 0.76, 0.66, and 0.74, respectively). Pickups maintain their statistically significant aggressivity effects, though at a less pronounced level (OR for Other Pickup is 2.52). No significant aggressivity effect is found for SUVs or vans. The similarity of results for

Table II. Logistic Regression Results

	Odds Ratios[a,b] (95% Confidence Intervals)				
Independent Variables	Model 1	Model 2	Model 3	Model 4	Model 5
Own vehicle body type					
Own SUV	1.18 (0.54–2.59)	1.03 (0.64–1.66)	1.35 (0.92–1.99)	1.00 (0.48–2.07)	0.97 (0.43–2.17)
Own Van	0.77 (0.43–1.39)	0.71 (0.41–1.21)	0.91 (0.49–1.68)	0.65 (0.38–1.13)	0.66 (0.38–1.13)
Own Pickup	0.94 (0.68–1.30)	0.71 (0.47–1.07)	0.87 (0.65–1.17)	0.39* (0.25–0.60)	0.35* (0.20–0.60)
Other vehicle body type					
Other SUV	1.18 (0.74–1.88)	1.24 (0.74–2.08)	1.02 (0.54–1.92)	1.21 (0.68–2.17)	1.42 (0.90–2.23)
Other Van	1.70* (1.05–2.77)	1.50 (0.90–2.52)	1.20 (0.66–2.18)	1.23 (0.62–2.43)	1.15 (0.62–2.12)
Other Pickup	3.67* (1.92–7.01)	3.63* (1.94–6.80)	3.14* (1.62–6.08)	2.54* (1.16–5.58)	2.18* (1.03–4.62)
Age		1.02* (1.00–1.03)	1.02* (1.01–1.03)	1.03* (1.01–1.05)	1.02* (1.00–1.05)
Male		0.98 (0.66–1.44)	1.01 (0.69–1.48)	0.95 (0.63–1.44)	0.96 (0.72–1.28)
Seat belt		0.25* (0.14–0.44)	0.25* (0.14–0.43)	0.36* (0.19–0.68)	0.37* (0.20–0.70)
Air bag		0.76 (0.37–1.57)	0.82 (0.43–1.60)	0.81 (0.36–1.84)	0.76 (0.32–1.81)
Mass ratio			0.37* (0.16–0.88)		
Delta-v				1.12* (1.10–1.14)	1.13* (1.10–1.16)
Left-side impact					3.45* (1.90–6.26)
Right-side impact					0.69 (0.33–1.44)
Rear impact					0.05* (0.02–0.11)

Note: Dependent variable is log(odds) that driver is seriously injured or killed.
[a]Sample size is 6,481.
[b]The asterisk (∗) indicates an odds ratio that is significant at the 5% level.

the full sample and regression sample suggests that the exclusion of observations with missing data from the regression sample does not substantially bias the results.

Model 2. In addition to vehicle body types, this model allows for consideration of four other variables: the driver's age, gender, and seat-belt use, and the presence of an air bag. Risk increases with age and decreases with seat-belt use, which is consistent with existing literature.(10) An alternative metric of age, an indicator variable for whether the driver was 65 years or older, was examined but found not to change materially the estimated effects for vehicle body type. The results indicate that seat-belt use reduces risk by 75%. The 95% confidence interval (a range of 56–86% reduction in OR) is reasonably close to previous NHTSA estimates of seat-belt effectiveness (automatic and manual seat belts reduce a driver's serious injury risk by 49% and 67%, respectively).(27) The smaller risks for males and air-bag presence are consistent with existing literature, but these effects are not statistically significant.(10) The estimated effects of vehicle body type are similar to those obtained with Model 1, suggesting that driver-related factors in Model 2 do not strongly confound the relationship between vehicle body type and risk.

Model 3. This model allows for the additional consideration of the ratio of the vehicles' masses. When the driver's vehicle is twice as heavy as the other vehicle, the driver's serious injury risk is reduced by 63% (OR for mass ratio is 0.37). The results continue to indicate that pickups are more aggressive than cars, though at a less pronounced level than in Model 2 (the OR decreases from 3.63 to 3.14). This suggests that vehicle mass contributes to the apparent aggressivity of pickups, but that other vehicle characteristics, such as stiffness and geometry, also contribute. Alternative variables to represent mass (e.g., the ratio of the mass of one vehicle to the total mass of both vehicles) were examined but were found not to have a material effect on the conclusions.

Model 4. In this model, delta-v is added to the regression to represent the joint effects of crash severity and vehicle mass; the mass ratio variable is excluded. The results suggest that a one-unit change in delta-v (1 km/hr) increases serious injury risk by 12%. Crash severity appears to be a confounding factor in estimates of the effects of vehicle body type. The aggressivity of pickups is reduced compared to Model 3 (OR for Other Pickup decreases from 3.14 to 2.54), and a crashworthiness effect for pickups emerges in this model (OR for Own Pickup is 0.39). Driver's age and seat-belt use continue to have statistically significant effects. In an alternative model, mass ratio was included as an additional independent variable. This had no effect on the effects estimated for Model 4, and the effect of mass ratio was insignificant, indicating that mass ratio does not have an effect that is measurably independent of delta-v (results not shown). In addition, inclusion of a variable for the square of delta-v did not materially affect the results.

Model 5. This model contains additional variables to represent the crash configuration. The results show that a driver whose vehicle is struck on the left side faces substantially greater risk compared to a frontal crash, while a rear impact is associated with less risk. Crash configuration appears to have a moderate effect as a confounding factor on vehicle type. The results for the other variables differ somewhat from the Model 4 results, yet the qualitative message remains that pickups appear to be more crashworthy and more aggressive than cars.

Several sensitivity analyses were conducted using this model form. First, the effect of roll-over crashes was examined. Government statistics show that rollovers are particularly deadly (they occur in about 2% of all crashes but account for about 20% of fatalities) and they occur to LTVs more than twice as often as to cars.[28] The model was reestimated using only those observations where the driver's vehicle did not roll over (240 observations from the regression sample were dropped). The estimated odds ratios do not change markedly, with the exception that Own Van is associated with a statistically significant crashworthiness effect (the OR and 95% CI for Own Van is 0.52 [0.33–0.83]).

Second, the sensitivity of the results to the inclusion of fatalities was examined. In the results presented so far, the outcome measure is whether the driver suffered a serious injury, defined as an AIS level of 3 or higher, or whether a fatality occurred (regardless of the AIS level). Model 5 was reestimated using an outcome variable based solely on AIS level (results not shown), and the estimated effects of the independent variables were essentially unchanged. This result is not surprising since cases in which a driver suffered only an AIS level 1 or 2 injury and died are rare.

Third, the cut-off for the injury severity level used to define a positive outcome was examined. Rather than using an AIS level of 3 as the cut-off for defining a positive outcome, it is possible to examine other cut-off levels: AIS 1 (corresponding to "minor" injuries), AIS 2 (moderate), AIS 4 (severe), AIS 5 (critical), and AIS 6 (maximum). Table III shows the logistic regression results for models with these different AIS levels as the outcome. Because injury frequency declines sharply with severity, the (weighted) fraction of observations that are positive (i.e., exceed the AIS

Table III. Sensitivity to the Injury Severity Level of the Outcome Measure

	Odds Ratios[a,b] (95% Confidence Intervals)					
Independent Variables	Outcome: AIS 1–6	Outcome: AIS 2–6	Outcome: AIS 3–6	Outcome: AIS 4–6	Outcome: AIS 5–6	Outcome: AIS 6
Own vehicle body type						
Own SUV	1.10 (0.68–1.78)	0.57 (0.31–1.03)	0.97 (0.43–2.17)	1.34 (0.61–2.95)	2.66* (1.14–6.20)	0.55 (0.06–5.06)
Own Van	0.96 (0.55–1.69)	0.84 (0.27–2.60)	0.66 (0.38–1.13)	0.45 (0.10–2.09)	0.78 (0.15–4.02)	0.88 (0.13–6.19)
Own Pickup	0.91 (0.42–2.00)	0.59 (0.23–1.50)	0.35* (0.20–0.60)	0.30* (0.18–0.49)	0.49* (0.24–1.00)	0.60 (0.15–2.35)
Other vehicle body type						
Other SUV	1.16 (0.47–2.84)	1.67 (0.75–3.71)	1.42 (0.90–2.23)	4.27* (2.64–6.91)	5.16* (1.73–15.39)	5.19* (1.11–24.20)
Other Van	1.10 (0.64–1.91)	1.45 (0.57–3.67)	1.15 (0.62–2.12)	2.56* (1.53–4.28)	3.96* (2.14–7.32)	2.93* (1.03–8.30)
Other Pickup	0.84 (0.51–1.36)	1.53 (0.88–2.65)	2.18* (1.03–4.62)	2.82 (0.86–9.18)	2.44* (1.12–5.34)	1.55 (0.68–3.56)
Age	1.02* (1.00–1.03)	1.02* (1.00–1.04)	1.02* (1.00–1.05)	1.03* (1.01–1.05)	1.03* (1.03–1.04)	1.04* (1.03–1.05)
Male	0.35* (0.28–0.44)	0.77 (0.53–1.11)	0.96 (0.72–1.28)	2.27* (1.06–4.89)	1.66* (1.06–2.59)	1.35 (0.64–2.83)
Seat belt	0.29* (0.15–0.58)	0.47* (0.29–0.77)	0.37* (0.20–0.70)	0.24* (0.11–0.51)	0.15* (0.11–0.20)	0.17* (0.12–0.25)
Air bag	1.46 (0.94–2.27)	0.90 (0.55–1.47)	0.76 (0.32–1.81)	0.64 (0.29–1.41)	0.49* (0.27–0.90)	0.54 (0.28–1.03)
Delta-v	1.10* (1.06–1.13)	1.12* (1.10–1.14)	1.13* (1.10–1.16)	1.15* (1.13–1.18)	1.16* (1.14–1.18)	1.15* (1.13–1.17)
Left-side impact	1.61* (1.15–2.26)	1.48 (0.89–2.46)	3.45* (1.90–6.26)	10.72* (3.87–29.73)	7.62* (4.56–12.73)	7.73* (4.15–14.40)
Right-side impact	0.61 (0.36–1.02)	0.95 (0.58–1.56)	0.69 (0.33–1.44)	2.65* (1.59–4.42)	4.09* (2.82–5.95)	3.56* (2.30–5.51)
Rear impact	0.54 (0.23–1.25)	0.07* (0.02–0.30)	0.05* (0.02–0.11)	0.22* (0.08–0.60)	0.41 (0.16–1.07)	0.49 (0.19–1.26)
Weighted fraction of positive observations	0.573	0.083	0.026	0.008	0.005	0.003

[a]Sample size is 6,481.
[b]The asterisk (∗) indicates an odds ratio that is significant at the 5% level.

injury level cut-off) decreases dramatically when more serious injuries are used as the cut-off. The results suggest that vans and pickups are more crashworthy than cars, but only pickups have statistically significant crashworthiness effects. In contrast, there is no consistent result for the crashworthiness of SUVs across outcomes. The results also suggest that SUVs, vans, and pickups are more aggressive than cars across nearly all AIS levels, although the effects for SUVs and vans are statistically significant only at the more severe injury levels. The effect of delta-v is remarkably similar across AIS levels.

4. DISCUSSION

Two important issues complicate the empirical analysis of the safety impacts of LTVs. First, physical vehicle characteristics that influence safety (i.e., mass, stiffness, and geometry) are often correlated. Although there is substantial heterogeneity within vehicle types, LTVs on average have greater mass, stiffer vehicle structures, and higher ride height than cars.(6) Unless these characteristics are examined explicitly, it is difficult to distinguish whether the apparent safety effects of LTVs are due to their mass, stiffness, geometry, or some combination.

A second complicating issue is the existence of potentially confounding factors that may bias the estimated relationship between vehicle type and the probability of serious injury. One such factor may be crash severity. For example, LTVs tend to be driven on rural roads at high speeds more often than cars.(13) Previous studies of fatality risks of cars and LTVs have either not controlled for crash severity,(6) or proxies for crash severity were used, such as the posted speed limit for the road where the crash occurred.(12)

This analysis attempts to address these issues. The regression model distinguishes the influence of mass from the influence of other vehicle characteristics. The regression model also controls for a variety of potentially confounding factors. Delta-v is used to control for the joint effects of vehicle mass and crash severity.

The results indicate that vehicle characteristics other than mass have a measurable effect on risk. This supports a previous study, which hypothesized that stiffness and geometry influence safety risks but did not quantify the magnitude of their effects.(6) Our analysis did not isolate the independent effects of stiffness, geometry, and any other correlated vehicle characteristics that influence safety. This study provides empirical evidence to vehicle designers and policy makers that there are vehicle design elements other than mass that can be modified to improve traffic safety. From a policy perspective, modifications to stiffness and geometry may be more acceptable than changes to vehicle mass.

The results also show the importance of taking confounding factors into account. In Model 1, in which vehicle body types are the sole predictors of risk, LTVs are not associated with statistically significant crashworthiness effects, while vans and pickups are associated with significant aggressivity effects. Yet these estimated effects are biased due to the omission of confounding variables.

Additional models include controls for driver characteristics, delta-v, and crash configuration. Driver age, gender, and restraint use do not appear to seriously confound the relationship between vehicle body type and risk. Inclusion of delta-v and crash configuration does change the estimated vehicle body type effects. A crashworthiness effect is found for pickups: drivers experience 65% less risk in pickups than in cars. Controlling for mass and confounding variables decreases the estimated aggressivity of pickups. The OR for Other Pickup is 2.18, compared to 3.67 estimated in the model without statistical controls.

The results show that delta-v is an important confounding factor in the relationship between vehicle body type and risk, as suggested by the different ORs for body type when delta-v is and is not included in the models (the effect goes beyond that which can be explained by mass ratio alone). Delta-v acts as a confounder because it is associated with vehicle body type. To examine this association, we conducted a linear regression in which the dependent variable was delta-v and the independent variables were body type and mass ratio. Own Pickup and Other Pickup both have positive coefficients that are significant at the 5% level (coefficients and 95% CIs are 4.44 [3.29–5.60] and 2.25 [0.81–3.69], respectively; no other vehicle body types have coefficients that are statistically significant). That is, a driver in a pickup experiences a higher delta-v compared to being in a car, and a driver who is involved in a collision with a pickup experiences a greater delta-v than if the collision partner were, instead, a car. Crash severity differs systematically for pickups, possibly due to the effect of different driving behaviors and crash circumstances. Thus, if delta-v is not controlled for, the crashworthiness of pickups is underestimated, while the aggressivity of pickups is overestimated.

Sensitivity analyses show that the estimated effects of body type vary with the level of injury severity used to define the outcome variable. Controlling for mass, crash severity, and other factors, vans and pickups appear to be more crashworthy than cars across all injury severity levels, but the effect is statistically significant only for pickups. Evidence for the crashworthiness of SUVs does not show a clear trend, and whether SUVs are more or less crashworthy than cars is sensitive to the criterion of injury used. The analysis also shows that SUVs, vans, and pickups have aggressivity effects across injury levels. The aggressivity of SUVs and vans is statistically significant only for the more severe injuries; this is generally consistent with the literature that focuses on fatality risks.

There are several important limitations to this analysis. First, 36% of the observations were not used in the regressions due to missing variables. On the one hand, the estimated gross effects of body type (i.e., not controlling for other factors, as in Model 1) do not appear to be substantially biased by omitting observations with missing data. However, missing data may have reduced the precision of the estimated effects. Nevertheless, care should be exercised in generalizing the results of this study beyond the samples used to estimate the models. Moreover, due to the strong influence of delta-v on injury outcomes and the frequency with which these values are missing, imputation of missing values should be considered in future research on vehicle safety.

Second, delta-v is an imperfect measure of crash severity.[29–31] The accuracy of the inferred value of delta-v depends on the degree of similarity between a real-world crash and the laboratory crash test on which the inference is based. Some types of crashes (e.g., frontal offset crashes) may not be accurately modeled. Despite these shortcomings, delta-v remains the most direct measure of crash severity.

This analysis does not address several broader issues related to the safety of LTVs and cars. The study examines the risk of serious injury conditional on a two-vehicle crash occurring; the probability of crash involvement by LTVs and cars is not analyzed. The relationship between LTVs, cars, and roll-over crashes is not investigated.

In summary, two primary findings emerge. First, this study confirms that differences in vehicle mass influence the apparent increased crashworthiness and aggressivity of LTVs relative to cars. It also finds that characteristics other than mass—most likely stiffness and geometry—influence the safety impacts of LTVs. Controlling for mass and crash severity, SUVs, vans, and pickups all appear to increase risks to drivers of other vehicles, but only pickups appear to reduce risks to their own drivers. The finding that vehicle design elements other than mass affect crash outcomes suggests that policy makers and vehicle manufacturers should consider these elements when crafting approaches to improve safety. Second, the results show that factors such as crash severity confound the relationship between severe injury risk and vehicle body type. Results that do not account for confounding factors should be interpreted cautiously. Future research should supplement the regression models reported here with vehicle-specific information on stiffness and geometry. Such information could yield more precise estimates of different vehicle characteristics and their relative influence.

ACKNOWLEDGMENTS

Support for this research was provided by the National Highway Traffic Safety Administration, the Harvard Center for Risk Analysis, and the Agency for Healthcare Research and Quality. The authors wish to thank John Graham, who provided helpful comments while serving as Director of the Harvard Center for Risk Analysis.

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