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An Analysis of the Relationship between Casualty Risk Per Crash and Vehicle Mass and Footprint for Model Year 2000-2007 Light-Duty Vehicles

Preliminary report prepared for the Office of Energy Efficiency and Renewable Energy, US Department of Energy

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Executive Summary

NHTSA recently completed a logistic regression analysis (Kahane, 2011) updating its 2003 and 2010 studies of the relationship between vehicle mass and US fatality risk per vehicle mile traveled (VMT). The new study updates the previous analyses in several ways: updated FARS data for 2002 to 2008 involving MY00 to MY07 vehicles are used; induced exposure data from police reported crashes in several additional states are added; a new vehicle category for car-based crossover utility vehicles (CUVs) and minivans is created; crashes with other light-duty vehicles are divided into two groups based on the crash partner vehicle's weight, and a category for all other fatal crashes is added; and new control variables for new safety technologies and designs, such as electronic stability controls (ESC), side airbags, and methods to meet voluntary agreement to improve light truck compatibility with cars, are included.

In a companion report (Wenzel, 2011b), we use the updated databases NHTSA has created to replicate their findings on the relationship between vehicle weight, size (actually footprint, or vehicle wheelbase times track width), and US fatality risk per vehicle miles traveled (VMT), for model year 2000 to 2007 light-duty vehicles involved in fatal crashes between 2002 and 2008. The data are examined in slightly different ways, to get a deeper understanding of the relationship between reductions in vehicle mass and footprint, and overall safety.

This report compares the logistic regression results of the NHTSA analysis of US fatality risk per VMT with an analysis of 13-state fatality risk and casualty risk per crash. This analysis differs from the NHTSA analysis in two respects: first, it analyzes risk per crash, using data on all police-reported crashes from thirteen states, rather than risk per estimated VMT; and second, it analyzes casualty (fatality plus serious injury) risk, as opposed to just fatality risk. There are several good reasons to investigate the effect of mass and footprint reduction on casualty risk per crash. First, risk per VMT, accounts for two effects that influence whether a person is killed or seriously injured in a crash: how well a vehicle can be, or actually is, driven (based on its handling, acceleration, and braking capabilities) to avoid being involved in a serious crash (crash avoidance), and, once a serious crash has occurred, how well a vehicle protects its occupants from fatality or serious injury (crashworthiness). By encompassing both of these aspects of vehicle design, risk per VMT gives a complete picture of how vehicle design can promote, or reduce, road user safety. On the other hand, risk per crash isolates the second of these two safety effects, crashworthiness, by examining the effect of mass and footprint reduction on how well a vehicle protects its occupants once a crash occurs.

Second, estimating risk on a per crash basis only requires using data on police-reported crashes from states, and does not require combining them with data from other sources, such as vehicle registration data and VMT information, as in NHTSA 2011. Because only sixteen states currently record the vehicle identification number of vehicles involved in police-reported crashes, which is necessary to determine vehicle characteristics, and only thirteen states also report the posted speed limit of the roadway on which the crash occurred, extending the analysis to casualties (fatalities plus serious/incapacitating injuries; i.e. level "K" and "A" injuries in police reports) reduces the statistical uncertainty of analyzing just fatalities per crash. Finally, a serious incapacitating injury can be just as traumatic to the victim and her family, and costly from an economic perspective, as a fatality. Limiting the analysis to the risk of fatality, which is an extremely rare event, ignores the effect vehicle design may have on reducing the large number of incapacitating injuries that occur each year on the nation's roadways. All risks in this report are societal risk, including fatalities and serious injuries in the case vehicle and any crash partners, and include not only driver casualties but passenger and non-occupant casualties as well.

However, the frequency of police-reported crashes per VMT and of casualties per police-reported crash can both be influenced, in opposite directions, by the probability that a collision event becomes a police-reported crash. If collisions of certain vehicles are slightly less likely to be reported, because these vehicles are either somewhat less damage-prone or are uninsured, this would tend to increase the observed detrimental effect of mass reduction on reported crashes per VMT and conversely decrease its detrimental effect on casualties per reported crash. By contrast, fatalities or casualties per VMT would be not be affected by crash-reporting rates, because the crash-reporting rate is not part of the formula for calculating risk. The extent to which any reporting bias of non-injury crashes exists, the observed effects for police-reported crashes per VMT might not correspond exactly to the "effect of mass reduction on crash avoidance" and the observed effects for casualties per police-reported crash might not correspond exactly to the "effect of mass reduction on crashworthiness." We suspect that large pickups are less likely to suffer damage in non-injury crashes than other vehicle types; and that older, less expensive, or uninsured vehicles are less likely to report crash damage to police. In addition, one vehicle crashes are more likely to suffer from this reporting bias, as there is no crash partner who may file an insurance claim.

Table ES.1 summarizes the results of our analysis of the effect of vehicle mass or footprint reduction on the two components of risk per VMT, crash frequency (number of crashes per VMT) and crashworthiness (risk per crash), for both fatality and casualty risk, using data from 13 states. We convert the percent change in the <u>log-odds</u> of casualty or fatality per crash output from the SAS LOGIST procedure to the <u>percent change in the probability</u> of casualty or fatality per crash. This conversion has no effect on the output regression coefficients when the change in the log-odds of casualty is small, but substantially increases the percent change for explanatory variables that have a large effect on the log-odds of casualty. Effects that are statistically significant are shown in red in the table; significance is based on the 95% confidence interval derived from the standard error of the output of the SAS LOGIST procedure, converted to a percent probability interval.

Table ES.1 indicates that for cars and light trucks, the effects from the two components, crash frequency and crashworthiness, roughly add together to result in the overall effect on fatality risk per VMT. For example, a 100-lb reduction in the mass of lighter cars leads to a 1.84% increase in crash frequency (columns B), while mass reduction leads to a 0.76% decrease in the number of fatalities per crash (column C); the net effect is only a 1.08% increase in the risk of fatality per VMT (column D). For CUVs/minivans, the relationship is different; mass reduction leads to a 0.71% increase in crash frequency, as well as a 0.87% increase in the number of fatalities per crash; however, the net result, a 1.29% increase in the number of fatalities per VMT, is less than the sum of the two components.

Table ES.1 indicates that mass reduction increases crash frequency (columns B and E) in all five vehicle types, with larger increases in lighter-than-average cars and light-duty trucks. As a result, mass reduction has a more beneficial effect on crashworthiness, or casualty risk per crash (column F), than on casualty risk per VMT (column G), and on fatality risk per crash (column C) than on fatality risk per VMT (column D). Mass reduction actually decreases casualty risk per crash (column F) in all vehicles except light cars, and in three of the four cases these reductions are statistically significant, albeit small. Footprint reduction increases crash frequency (columns B and E) in cars and light trucks, but slightly reduces crash frequency in CUVs/minivans; footprint reduction does not have a statistically-significant effect on casualty risk per crash (column F), and only for fatality risk per crash (column C) for light trucks. In general mass or footprint reduction has a smaller effect on casualty risk per crash (column F) than on fatality risk per crash (column C).

The effect of mass reduction on 13-state casualty risk per VMT (column G) is quite consistent with that NHTSA estimated for US fatality risk per VMT (column A), although the effect is estimated to be slightly larger for lighter cars and lighter light trucks, and slightly smaller for heavier cars, heavier light trucks, and CUVs/minivans.

In contrast with NHTSA's findings on US fatality risk per VMT (column A), mass reduction <u>reduces</u> casualty risk per crash (column F) for four of the five vehicle types, and three of these four reductions are statistically significant. Mass reduction results in a small but insignificant increase in casualty risk per crash for lighter cars. And footprint reduction results in much smaller, and not statistically significant, effects on casualty risk per crash (column F) than on US fatality risk per VMT (column A).

Many of the control variables included in the logistic regressions are statistically significant, and have a large effect on fatality or casualty risk per crash, although not as large an effect as on fatality risk per VMT. For example, a car's mass could be reduced by 2,300 lbs while adding ABS without increasing its casualty risk per crash. While the effect of mass reduction may result in a statistically-significant increase in risk in certain cases, the increase is small and is overwhelmed by other known vehicle, driver, and crash factors.

Control variables for ABS and ESC in cars, AWD in light trucks and CUVs/minivans, and drivers aged 14 to 30 have a larger effect on crash frequency than fatality risk per crash. On the other hand, whether a vehicle is a two-door car, SUV, or heavy-duty pickup, side airbag variables in cars, and middle-aged drivers have a larger effect on fatality risk per crash than on crash frequency. Whether a driver is male has essentially no effect on crash frequency, but surprisingly causes a statistically significant increase in fatality risk once a crash occurs. Driving at night on high-speed rural roads, also has a surprisingly much lower effect on crash frequency than on fatality risk given a crash.

In contrast with NHTSA's results for US fatalities per VMT, allowing footprint to vary along with weight results in little change in the effect of mass reduction on casualty risk per crash than when footprint is held constant; however, the detrimental effect of mass reduction on casualty risk per crash in lighter cars is increased just enough to make it statistically significant. When mass is allowed to vary along with footprint, footprint reduction slightly reduces the already small detrimental effect on casualty risk per crash (Alternative 1 in Table ES.2; further addressed in Section 3 of this report). As with NHTSA's analysis of fatality risk per VMT, mass reduction does not consistently increase casualty risk per crash across all footprint deciles for any combination of vehicle type and crash type. Mass reduction increases casualty risk per crash in a majority of footprint deciles for 10 of the 27 crash and vehicle combinations, but few of these increases are statistically significant. On the other hand, mass reduction decreases risk in a majority of footprint deciles for 14 of the 27 crash and vehicle combinations.

Similar to our findings on US fatality risk per VMT, after accounting for all of the control variables in the logistic regression model, except for vehicle mass and footprint, we find that the correlation between mass and the casualty risk per crash by vehicle model is very low. There also is no significant correlation between the residual, unexplained risk and vehicle weight. These results corroborate our earlier finding that, even after accounting for many vehicle, driver, and crash factors, the variance in risk by vehicle model is quite large and unrelated to vehicle weight (addressed in more detail in Section 4).

Other changes in the data and variables used in the regression models result in only slight changes in the effect of mass or footprint reductions on casualty risk per crash, as summarized in Table ES.2. For example:

- Regression analyses using police-reported crash data from states must use control variables to account for differences in definitions of "serious" or "incapacitating" injuries, and reporting requirements, across states. Removing the 12 state control variables results in a large reduction in casualty risk per crash from mass reduction in all five vehicle types, a large increase in risk from footprint reduction in cars and CUVs/minivans, and a small reduction in risk from footprint reduction in light trucks (Alternative 2 in Table ES.2). Including only two variables to control for states with high and low casualty risk per crash substantially reduces the effect of mass and footprint reduction on casualty risk (Alternative 3 in Table ES.2), while including the 12 control variables for individual states reduces the effect a little bit more. These results indicate that excluding control variables for the state in which a crash occurred from a regression model using state police-reported crash data can give inaccurate estimates of the effect of mass or footprint reduction on casualty risk per crash (addressed in Section 5.1).

- Calculating risk as casualty crashes, rather than total casualties, per crash results in little change in the effect of mass reduction on risk, but does increase the small detrimental effect of footprint reduction in cars on risk, and makes it statistically significant (Alternative 4 in Table ES.2; addressed in Section 5.2).

- Adding control variables for vehicle manufacturer results in mass reduction increasing casualty risk per crash in cars, but increasing the small <u>beneficial</u> effect of mass reduction in light trucks and CUVs/minivans. Accounting for vehicle manufacturer causes a reduction in footprint to reduce casualty risk per crash in cars, but increase casualty risk per crash in light trucks and CUVs/minivans (Alternative 5 in Table ES.2; addressed in Section 5.3).

- As we found in our assessment of NHTSA's analysis of US fatality risk per VMT, including calendar year variables in the regression models appears to weaken the benefit of side air bags in cars and CUVs/minivans, and compatibility measures and ESC in light trucks. These variables also appear to minimize the increased risk of SUVs and heavy-duty pickup trucks. Excluding the calendar year variables from the regression models slightly reduces the beneficial effect of mass reduction on casualty risk per crash in light trucks and CUVs/minivans, and slightly increases the detrimental effect of footprint reduction on casualty risk per crash in cars (Alternative 6 in Table ES.2; addressed in Section 5.4).

- Including all-wheel-drive, sports, and police cars, and fullsize vans results in virtually no change in the effect of mass or footprint reduction on casualty risk per crash for cars or light trucks (Alternative 7 in Table ES.2; addressed in Section 5.5).

- Adding data from three additional states, including vehicles with unreported model year, correcting VIN transcription errors, and expanding the analysis to calendar years 2000, 2001, and 2008, increases the number of state crash records by about 40 percent. Including these data in the regression analyses results in the effect of mass reduction in lighter cars being slightly more detrimental, and the effect of mass reduction in heavier cars, all light trucks, and CUVs/minivans being slightly less beneficial. Including these data slightly reduces the small detrimental effect of footprint reduction on casualty risk per crash for cars, increases the beneficial effect for light trucks, and increases the detrimental effect for CUVs/minivans. However, increasing the sample size included in the regression analysis by 40% does not noticeably reduce the confidence intervals around the point estimates (Alternative 8 in Table ES.2; addressed in Section 5.6).

In conclusion, casualty risk per crash is not necessarily a better metric than fatality risk per VMT for evaluating the effect of mass or footprint reduction on risk; rather, it provides a different perspective in assessing the benefits or drawbacks of mass and footprint reduction on safety in vehicles. However, it does allow the risk per VMT to be separated into its two components, crash frequency and risk per crash. Our analysis indicates that much of the detrimental effect of mass or footprint reduction on risk can be attributed to the tendency for mass or footprint reduction to increase crash frequency, rather than to reduce vehicle crashworthiness (risk once a crash has occurred).

As with our analysis of US fatalities per VMT, this report concludes that the effect of mass reduction on casualty risk per crash is small, and tends to be overwhelmed by other control variables, such as vehicle type, specific safety technologies, and crash conditions such as whether the crash occurred at night, in a rural county, or on a high-speed road. This report indicates that the effects are only slightly sensitive to what variables and data are included in the regression analysis. Finally, as in our analysis of US fatality risk per VMT, this report shows that after accounting for many vehicle, driver, and crash variables there remains a wide variation in casualty risk per crash by vehicle make and model, and this variation is unrelated to vehicle mass.

It is important to recognize that the results of this study are based on the relationship of vehicle mass and footprint on risk for recent vehicle designs (model year 2000 to 2007). These relationships may or may not continue into the future as manufacturers utilize new vehicle designs and incorporate new technologies, such as more extensive use of strong lightweight materials and specific safety technologies.

Table ES.1. Effect of mass and footprint reduction on two components of fatality and casualty risk per VMT, crash frequency (crashes per VMT) and crashworthiness (risk per crash); effects in red are statistically significant (see text)

Variable	Case vehicle type	A. NHTSA US fatalities per VMT	B. 13-state crashes per VMT	C. 13-state fatalities per crash	D. 13-state fatalities per VMT	E. 13-state crashes per VMT	F. 13-state casualties per crash	G. 13-state casualties per VMT
Mass reduction	Cars < 3106 lbs	1.43%*	1.84%	-0.76%	1.08%	1.84%	0.15%	1.76%
	Cars > 3106 lbs	0.48%	1.23%	-2.44%	-1.42%	1.23%	-0.91%	0.32%
	LTs < 4594 lbs	0.52%	1.42%	-1.98%	-0.43%	1.42%	-0.37%	1.41%
	LTs > 4594 lbs	-0.40%	0.93%	-1.22%	-0.46%	0.93%	-0.69%	-0.22%
	CUV/ minivan	-0.47%	0.71%	0.87%	1.29%	0.71%	-0.13%	-0.02%
Footprint reduction	Cars	1.89%	1.05%	1.24%	2.80%	1.05%	0.32%	2.00%
	LTs	-0.02%	1.15%	0.73%	1.92%	1.15%	-0.04%	1.13%
	CUV/ minivan	1.73%	-0.37%	-2.25%	-1.54%	-0.37%	0.33%	1.52%

* Based on NHTSA's estimation of uncertainty using a jack-knife method, only mass reduction in cars less than 3,106 lbs has a statistically significant effect on US fatality risk.

Table ES.2. Effect of mass and footprint reduction on 13-state casualty risk, under alternative regression model specifications and using additional data; effects in red are statistically significant (see text)

Variable	Case vehicle type	13-state casualties per police-reported crash	1. Excluding, mass or footprint variable	2. Excluding state control variables	3. Including only two state control variables	4. Casualty crashes per crash	5.Including vehicle make variables	6. Excluding CY variables	7. Including sports, squad, AWD cars and fullsize vans	8. Including all additional data
Mass reduction	Cars < 3106 lbs	0.15%	0.36%	-0.78%	-0.06%	0.24%	1.13%	0.12%	0.16%	0.30%
	Cars > 3106 lbs	-0.91%	-0.67%	-1.91%	-1.32%	-0.85%	0.55%	-1.07%	-0.88%	-0.60%
	LTs < 4594 lbs	-0.37%	-0.41%	-0.46%	-0.44%	-0.32%	-0.54%	0.07%	-0.50%	-0.06%
	LTs > 4594 lbs	-0.69%	-0.72%	-1.85%	-0.79%	-0.67%	-0.76%	-0.34%	-0.93%	-0.60%
	CUV/ minivan	-0.13%	0.02%	-1.95%	-0.43%	-0.25%	-0.58%	0.29%	-0.13%	-0.14%
Footprint reduction	Cars	0.32%	-0.05%	1.78%	0.55%	0.55%	-0.37%	0.68%	0.32%	0.19%
	LTs	-0.04%	-0.44%	-0.84%	-0.09%	0.19%	0.22%	-0.24%	0.10%	-0.21%
	CUV/ minivan	0.33%	0.20%	3.58%	0.46%	0.74%	1.35%	0.26%	0.33%	0.40%

Table of Contents

List of Tables and Figures

1. Introduction

NHTSA recently completed a logistic regression analysis updating its 2003 and 2010 studies of the relationship between vehicle mass and US fatality risk per vehicle mile traveled (VMT; Kahane, 2011). The new study updates the previous analyses in several ways: updated FARS data for 2002 to 2008 involving MY00 to MY07 vehicles are used; induced exposure data from police reported crashes in several additional states are added; a new vehicle category for car-based crossover utility vehicles (CUVs) and minivans is created; crashes with other light-duty vehicles are divided into two groups based on the crash partner vehicle's weight, and a category for all other fatal crashes is added; and new control variables for new safety technologies and designs, such as electronic stability controls (ESC), side airbags, and methods to meet voluntary agreement to improve light truck compatibility with cars, are included.

In a companion report (Wenzel, 2011b), we use the updated databases NHTSA has created to replicate their findings on the relationship between vehicle weight, size (actually footprint, or vehicle wheelbase times track width), and US fatality risk per vehicle miles traveled (VMT), for model year 2000 to 2007 light-duty vehicles involved in fatal crashes between 2002 and 2008. The data are examined in slightly different ways, to get a deeper understanding of the relationship between reductions in vehicle mass and footprint, and overall safety.

This report compares the logistic regression results of the NHTSA analysis of US fatality risk per VMT with an analysis of 13-state casualty risk per crash. This analysis differs from the NHTSA analysis in two respects: first, it analyzes risk per crash, using data on all police-reported crashes from thirteen states, rather than risk per estimated VMT; and second, it analyzes casualty (fatality plus serious injury) risk, as opposed to fatality risk. There are several good reasons to investigate the effect of mass and footprint reduction on casualty risk per crash.

First, risk per VMT, which NHTSA has studied extensively, accounts for two effects that influence whether a person is killed or seriously injured in a crash: how well a vehicle can be driven (based on its handling, acceleration, and braking capabilities) to avoid being involved in a serious crash (crash avoidance), and, once a serious crash has occurred, how well a vehicle protects its occupants from fatality or serious injury (crashworthiness). By encompassing both of these aspects of vehicle design, risk per VMT gives a complete picture of how vehicle design can promote, or reduce, road user safety. On the other hand, risk per crash isolates the second of these two safety effects, crashworthiness, by examining the effect of mass and footprint reduction on how well a vehicle protects its occupants once a crash occurs. In general, NHTSA safety regulations focus on crashworthiness (e.g. crash test requirements and NCAP star ratings, seatbelt and airbag requirements, and roof crush standards), although some standards require the installation of technologies, such as automated braking systems (ABS) and electronic stability control (ESC), that improve a vehicle's crash avoidance.

Second, estimating risk on a per crash basis requires using data on police-reported crashes from states. Although NHTSA generates a national sample of police-reported crashes, the National Automotive Sampling System, General Estimates System (NASS GES), that can be used to estimate per crash risks on a national basis, the database is relatively small and may be biased towards crashes that occur in relatively urban areas. Only sixteen states currently record the vehicle identification number of all vehicles involved in police-reported crashes, which is necessary to determine the model year, make, and model of each vehicle, in order to assign its correct curb weight, footprint, type, and installed safety features (such as side airbags, ABS, ESC, and all-wheel drive). The sixteen states that report VIN information represent about one-third of the country, so estimating fatality risk per crash from these sixteen states increases the statistical uncertainty of the analysis, relative to that from estimating fatality risk per VMT using all US fatalities.[1] Extending the analysis to casualties (fatalities plus serious/incapacitating injuries) reduces the statistical uncertainty of analyzing just fatalities per crash. In addition, a serious incapacitating injury can be just as traumatic to the victim and her family, and costly from an economic perspective, as a fatality. Limiting the analysis to the risk of fatality, which is an extremely rare event, ignores the effect vehicle design may have on reducing the large number of incapacitating injuries that occur each year on the nation's roadways.

In an earlier report LBNL compared fatality risk per vehicle registration-year and casualty risk per crash, using the same database of all police-reported crashes in five states (Wenzel, 2011a). For the most part, the trend in casualty risk by vehicle type is quite similar to that of fatality risk, when vehicle registration-years are used as the measure of exposure, although casualty risks are substantially lower than fatality risks for sports cars and for pickups. The trend in casualty risk by vehicle type is similar regardless of whether vehicle registration years or police-reported crashes are used as the measure of exposure. Casualty risks for subcompact and compact cars are relatively lower per crash than per vehicle, while casualty risks for large and import luxury cars, minivans, large SUVs, and pickups are relatively higher per crash than per vehicle. We accounted for miles driven by vehicle make and model using odometer readings from vehicle emission inspection and maintenance programs in four of the five states. For most vehicle types, adjusting casualty risk per vehicle registration-year for miles driven has little to no effect (although the adjustment does substantially increase casualty risk for sports cars, which are driven many fewer miles than other vehicles, by 30%, and slightly reduces casualty risk for fullsize vans and ¾-ton pickups, which are driven more miles than the average vehicle).

In summary, casualty risk per crash is not necessarily a better metric than fatality risk per VMT; rather, it provides a different perspective in assessing the benefits or drawbacks of mass and footprint reduction on safety in vehicles. Unless noted otherwise, all casualty risks in this report are societal risk, including fatalities and serious injuries in the case vehicle and any crash partners, and include not only driver casualties but passenger casualties as well.

Section 2 of this report replicates the logistic regression models NHTSA used in its analysis of US fatality risk per VMT, and compares the effect of mass and footprint reduction on US fatality risk per VMT, 13-state fatality risk per crash, and 13-state casualty risk per crash. Section 3 examines in more detail the multi-collinearity between vehicle mass and footprint, and methods to address that multi-collinearity when assessing their effect on casualty risk per crash. In Section 4 we examine the relationship between vehicle mass and casualty risk per crash by

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[1] This report further limits the analysis to the thirteen states that provide the posted speed limit of the roadway on which the crash occurred, an important variable NHTSA uses in its regression models that approximates the travel speed of the vehicles involved in the crash. In Section 5 we run a sensitivity analysis using data from the three additional states that report VIN but not posted speed limit, using a technique developed by NHTSA to impute the posted speed limit based on the type of roadway on which the crash occurred (NHTSA, 2003).

vehicle model, before and after accounting for differences in driver characteristics, crash locations, and other vehicle attributes. In Section 5 we test alternative specifications of the regression models, in order to examine the sensitivity of our results to different model specifications, and using additional data.

2. 13-state fatality and casualty risk per crash

For its analysis of the effect of changes in vehicle mass on US fatality risk per VMT, NHTSA used information on all US traffic fatalities, from the Fatality Analysis Reporting System (FARS). For the measure of exposure, NHTSA used a subset of non-culpable vehicles involved in two-vehicle crashes from police-reported crash data from thirteen states; NHTSA refers to this subset of vehicles as "induced exposure" cases. The induced exposure cases provide information on driver and crash characteristics for vehicles that are not involved in fatal crashes, as in the FARS data. NHTSA developed weighting factors to scale the induced exposure vehicles up to national level vehicle registrations. NHTSA then multiplied the vehicle registration-years by annual vehicle miles traveled (VMT) factors it developed by vehicle type and age, from odometer data provided by RL Polk. For more details on NHTSA's data and methodology, refer to Kahane, 2011.

In this section we use basically the same logistic regression models NHTSA developed for their analysis of US fatality risk per VMT to assess the effect of mass and footprint reduction on 13-state fatality and casualty risk per crash, using data from all police-reported crashes in thirteen states. We also examine in detail the effect mass and footprint reduction have on 13-state casualty risk per crash in each type of crash, as well as the effects the various other vehicle, driver, and crash condition variables have on casualty risk per crash.

2.1. Data and methods

For its analysis NHTSA used FARS data on fatal crashes, and police-reported crash data from 13 states, for MY00 to MY07 light-duty vehicles between calendar years 2002 and 2008. NHTSA used a subset of nonculpable vehicles in two-vehicle crashes as a measure of induced exposure; these records provide distributions of on-road vehicles by vehicle year, make, and model, driver age and gender, and crash time and location (day vs. night, rural vs. urban counties, and high-speed roads). Each induced exposure record is then given a registered vehicle weighting factor, so that each induced exposure record represents a number of national vehicle registrations; the sum of the weighting factors equals the number of vehicles registered in the country. Each record is also given a VMT weighting factor, based on vehicle year, make/model, and age, using odometer data provided by R.L. Polk. The data can be used to estimate US fatality risk per registered vehicle or vehicle miles traveled (VMT).

NHTSA compiled a database of the following vehicle attributes, by model year, make and model: curb weight and footprint (wheelbase times track width), as well as the presence of all-wheel drive and automated braking systems. NHTSA added several new variables for new safety technologies and designs: electronic stability controls (ESC), four types of side airbags, and two methods to comply with the voluntary manufacturer agreement to better align light truck bumpers to make them more compatible with other types of vehicles.

To reflect changes in the vehicle mix since the 2003 study, NHTSA added a third vehicle category, car-based crossover utility vehicles (CUVs) and minivans. It also added two new crash types, for a total of nine: crashes with other light-duty vehicles are divided into two groups based on the crash partner vehicle's weight, and all other fatal crashes (involving more than two vehicles, etc.). The analysis involves running a logistic regression model with total crash fatalities as the dependent variable for each of the nine crash types and the three vehicle types, for a total of 27 regressions. Because all fatalities in the crash are used, the risks reflect societal risk, rather than just the risk to the occupants of the case vehicle. The induced exposure cases are weighted by the number of vehicle registrations and the annual mileage, so that the models are estimating the effect of changes in the control variables on US fatalities per vehicle mile traveled (VMT).

Table 2.1 shows the control variables NHTSA used in its regression models, for each of the case vehicle types. For cars and trucks, NHTSA uses two variables (UNDRWT00, OVERWT00) for vehicle weight, allowing the effect of weight on risk to vary for lighter and heavier cars and trucks. The determination of the two weight classes is based on the average weight for each vehicle type: 3,106 lbs for cars and 4,594 lbs for light-duty trucks. Because there are fewer CUVs and minivans in the database, NHTSA uses a single variable, LBS100, for CUV/minivan weight. As in the 2003 and 2010 analyses, eight variables for driver age and gender are used. In the 2003 analysis, NHTSA excluded the driver airbag control variables in the regressions for rollovers and crashes with pedestrians. In the 2011 analysis, NHTSA includes the control variable ROLLCURT airbags only in the regression models for rollover crashes involving cars or CUVs/minivans; regression models of pedestrian crashes do not include any control variables for airbags; and the control variables for CURTAIN, COMBO, and TORSO airbags are included in regression models for all other crashes involving cars or CUVs/minivans. No airbag variables were included in the regression models for light trucks.

Table 2.1. Control variables used in regression models, by subject vehicle type

Control variable	Cars	LTVs	CUVs/minivans
UNDRWT00	C	C	
OVERWT00	C	C	
LBS100			C
FOOTPRINT	C	C	C
TWODOOR	D		
SUV		D	
HD_PKP		D	
BLOCKER1		D	
BLOCKER2		D	
MINIVAN			D
ROLLCURT *	C		C
CURTAIN *	C		C
COMBO *	C		C
TORSO *	C		C
ABS	C		C
ESC	C	C	C
AWD		C	C
DRVMALE	C	C	C
M14_30	C	C	C
M30_50	C	C	C
M50_70	C	C	C
M70_96	C	C	C
F14_30	C	C	C
F30_50	C	C	C
F50_70	C	C	C
F70_96	C	C	C
NITE	D	D	D
RURAL	D	D	D
SPDLIM55	D	D	D
HIFAT_ST	D	D	D
VEHAGE	C	C	C
BRANDNEW	D	D	D
CY2002	D	D	D
CY2003	D	D	D
CY2004	D	D	D
CY2005	D	D	D
CY2007	D	D	D
CY2008	D	D	D

C: continuous variable

D: dummy variable, coded as either 1 or 0

* The control variable for ROLLCURT airbags is only used in regression models of rollover crashes involving cars or CUVs/minivans; regression models of pedestrian crashes do not include any control variables for airbags; the control variables for CURTAIN, COMBO, and TORSO airbags are included in regression models for all other crashes involving cars or CUVs/minivans.

Rather than reporting coefficients for the variables of interest (curb weight and footprint) from a single regression model across all crash types, NHTSA reports a weighted average of the coefficients from the nine regression models run for each of the nine crash types. NHTSA uses a "baseline" distribution of fatalities across the crash types, to represent the expected distribution of fatalities in the 2017 to 2025 timeframe of the new CAFE and GHG emission standards. Similar to the 2003 study, NHTSA derives the baseline fatalities from MY04-09 vehicles in crashes between 2004 and 2008. NHTSA then adjusts this baseline distribution downward to account for the assumption that all vehicles in the 2017-2025 timeframe will have ESC installed. The assumptions used for this adjustment are taken from a NHTSA analysis that found that ESC reduces fatal rollovers by 56% in cars and 74% in light trucks; fixed-object impacts by 47% in cars and 45% in light trucks; and other non-pedestrian crashes by 8% in both cars and light trucks.[2] These assumptions treat crossover SUVs and minivans as light trucks rather than cars. This "post-ESC" distribution of fatalities by crash type is then multiplied by the regression coefficients for each crash type to create the weighted average effect of each control variable on risk. Table 2.2 shows the baseline distribution of fatalities, by case vehicle type and crash type, which are used to create the overall coefficient estimates weighted by the results from the regressions for each crash type.

For our analysis of fatality and casualty risk per crash, we divided all crashes in the 13-state databases into the nine crash categories, and three vehicle types, used by NHTSA in its 2011 study, for the most part using the same criteria. One important difference is that NHTSA considered only "first-events" in classifying one-vehicle crashes as rollovers; vehicles that struck an object (or another vehicle) prior to rolling over are not included in NHTSA's "rollover" category. However, since all thirteen states do not consistently code "first" vs. "most harmful" events in the same manner, as is done in FARS, we included all vehicles involved in single-vehicle rollover crashes in our "rollover" category, regardless of whether they struck an object prior to rolling over.

Table 2.2 and Figure 2.1 compare the distribution of light-duty vehicle crashes in the U.S. from the NHTSA 2011 report with those from the 13 states. The US fatal crash involvements in Table 2.2 include those from 2008, while the fatal and casualty crash involvements from the thirteen states do not, as 2008 data were available from only five of the states.[3] Note that there are higher fractions of "other" crashes (that is, crashes involving more than two vehicles, or for which not all information was available) in the 13-state data; for example, 22% of U.S. fatal car crash involvements in FARS are in the "other" category, while 29% of fatality crash involvements, and 34% of casualty crash involvements, in the thirteen states are in the "other" category. The distributions of vehicles involved in crashes in Figure 2.1 exclude the "other" crash category, so that the fractions of all other types of crashes equal 100% for each vehicle type.

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[2] Sivinski R. (2011). *Update of NHTSA's 2007 Evaluation of the Effectiveness of Light Vehicle Electronic Stability Control (ESC) in Crash Prevention*, NHTSA Technical Report No. DOT HS 811 486. Washington, DC: National Highway Traffic Safety Administration. http://www-nrd.nhtsa.dot.gov/Pubs/811486.pdf.

[3] We reran the regressions on US fatalities excluding calendar year 2008, to determine what effect excluding these data has on the results from our casualty regressions using the 13-state data. The results of this analysis are summarized in Appendix A.

Table 2.2. Fatal and casualty crash involvements for model year 2000 to 2007 passenger cars in 2002 to 2008

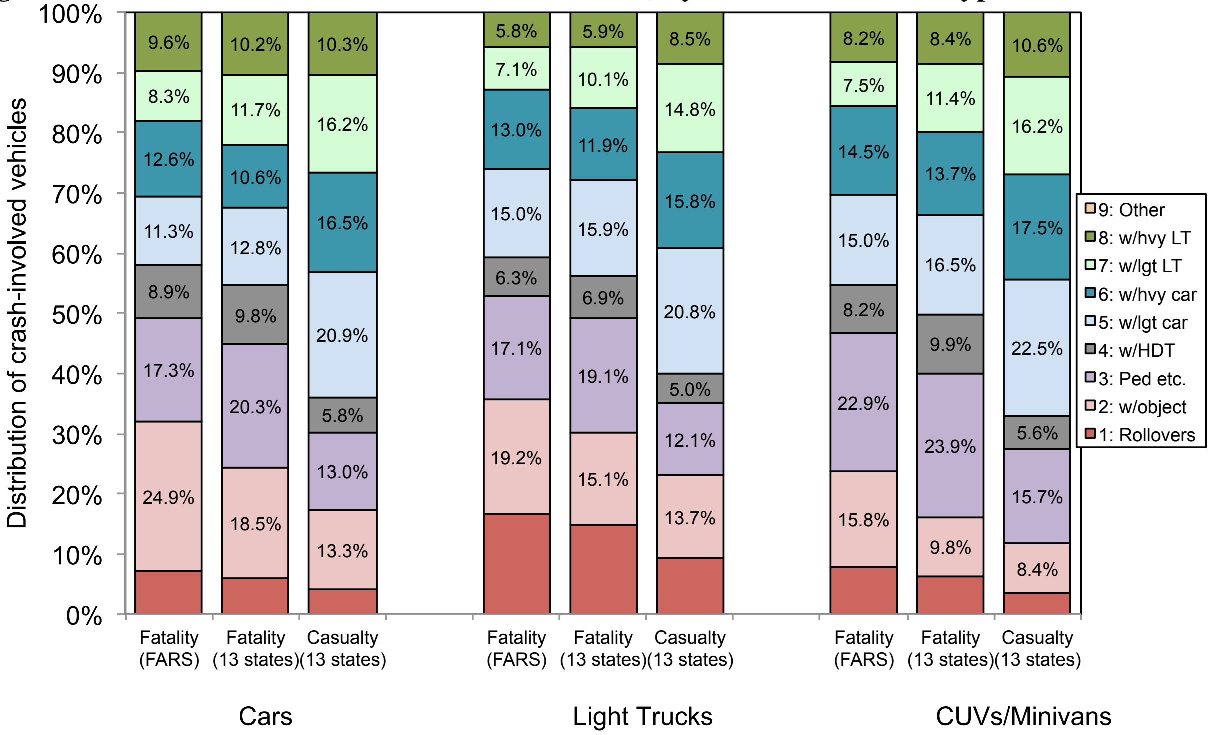
	Fatal crash involvements (FARS)			Fatal crash involvements (13 states)			Casualty crash involvements (13 states)		
Crash type	Cars	LTVs	CUVs/ minivans	Cars	LTVs	CUVs/ minivans	Cars	LTVs	CUVs/ minivans
1: Rollovers	2,709	6,269	660	489	1,083	122	2,851	4,632	533
2: w/object	9,373	7,272	1,319	1,527	1,089	187	9,372	6,812	1,300
3: Ped etc.	6,514	6,493	1,904	1,676	1,380	458	9,168	6,002	2,442
4: w/HDT	3,346	2,371	680	811	500	190	4,064	2,469	868
5: w/lgt car	4,258	5,667	1,245	1,058	1,149	317	14,719	10,330	3,503
6: w/hvy car	4,746	4,928	1,211	874	859	263	11,664	7,882	2,727
7: w/lgt LT	3,149	2,670	622	963	728	219	11,446	7,381	2,521
8: w/hvy LT	3,622	2,196	685	842	426	161	7,267	4,228	1,652
9: Other	10,487	9,407	2,810	3,296	2,728	824	35,959	25,298	8,668
Total	48,204	47,273	11,136	11,536	9,942	2,741	106,510	75,034	24,214
1: Rollovers	5.6%	13.3%	5.9%	4.2%	10.9%	4.5%	2.7%	6.2%	2.2%
2: w/object	19.4%	15.4%	11.8%	13.2%	11.0%	6.8%	8.8%	9.1%	5.4%
3: Ped etc.	13.5%	13.7%	17.1%	14.5%	13.9%	16.7%	8.6%	8.0%	10.1%
4: w/HDT	6.9%	5.0%	6.1%	7.0%	5.0%	6.9%	3.8%	3.3%	3.6%
5: w/lgt car	8.8%	12.0%	11.2%	9.2%	11.6%	11.6%	13.8%	13.8%	14.5%
6: w/hvy car	9.8%	10.4%	10.9%	7.6%	8.6%	9.6%	11.0%	10.5%	11.3%
7: w/lgt LT	6.5%	5.6%	5.6%	8.3%	7.3%	8.0%	10.7%	9.8%	10.4%
8: w/hvy LT	7.5%	4.6%	6.2%	7.3%	4.3%	5.9%	6.8%	5.6%	6.8%
9: Other	21.8%	19.9%	25.2%	28.6%	27.4%	30.1%	33.8%	33.7%	35.8%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Figure 2.1 indicates that there is a smaller portion of fatal car crashes with stationary objects, heavy cars, and rollover crashes in the thirteen states (18.5%, 10.6%, and 5.9%, respectively) than in the entire US (24.9%, 12.6%, and 7.2%, respectively). On the other hand, there are more fatal car crashes in crashes with pedestrians/pedalcycles, light cars, light and heavy light-duty trucks, and heavy-duty trucks in the thirteen states (20.3%, 12.8%, 11.7%, 10.2%, and 9.8%, respectively) than in the US (17.3%, 11.3%, 8.3%, 9.6%, and 8.9%, respectively). These trends hold for light trucks and CUVs/minivans as well.

In the thirteen states, there are higher fractions of crashes involving rollovers, stationary objects, pedestrians/pedalcycles, and heavy trucks, and fewer crashes with other light-duty vehicles, when the crashes result in a fatality rather than a casualty. This suggests that rollovers and crashes with stationary objects, pedestrians/pedalcycles, and heavy-duty trucks are more likely to result in fatalities, as opposed to incapacitating injuries, than crashes with another light-duty vehicle.

The distributions of fatal and casualty crashes involving cars in the thirteen states are quite similar to those involving CUVs and minivans; however, CUVs and minivans tend to be involved in fewer crashes with stationary objects (9.8% of all fatal crashes) than cars (18.5% of all fatal crashes). Light trucks tend to have more fatal/casualty crashes in rollovers and crashes with lighter cars (15.0% and 15.9% of all fatal crashes, respectively) than cars do (5.9%, and 12.8% of all fatal crashes, respectively), but relatively fewer crashes with stationary objects (15.1%, vs. 18.5% for cars) and heavier light trucks (6.9%, vs. 9.8% for cars).

Figure 2.1. Distribution of crash-involved vehicles, by vehicle and crash type



Note in Table 2.2 that there are many fewer fatal crash involvements in the thirteen states (e.g., 11,536 cars) than in the US FARS (48,204 cars). Extending the analysis to include incapacitating injuries substantially increases the number of casualty crash involvements in the thirteen states (to 106,510 cars). The focus of this report is on the effect of mass and footprint reduction on casualty risk using data from the thirteen states, although we do compare the effect on fatality risk in the next section. And in Section 5 we analyze the effect of extending the analysis to sixteen states, and adding other crashes to the analysis.

To the extent possible, we used the same assumptions as in the NHTSA analysis, in many cases using the same SAS programs. For example, we used the VIN decoder programs developed by NHTSA to determine model year, make, and model of each vehicle in the state crash data, and added detailed vehicle characteristics such as body style, curb weight, footprint, ABS, AWD, passive restraint systems, etc. And we used the NHTSA definitions to classify vehicles into five types (light cars, heavy cars, light light-duty trucks, heavy light-duty trucks, and CUVs/minivans), as well as the nine types of crashes described above. This was done in order to allow for a more direct comparison of the results from the two studies, as well as with other studies using very similar databases and approaches.

However, it was necessary to diverge from the NHTSA analysis in several respects. First, NHTSA used a subset of non-culpable vehicles in two-vehicle crashes from police-reported crash data from the thirteen states to assign driver and environment control variables to national vehicle registration years (from Polk). NHTSA selected non-culpable vehicles in two-vehicle crashes to determine induced exposure crash involvements. Each of these vehicles was assigned a weight representing the national registration-years for each particular year, make and model.

NHTSA developed other weights for total VMT based on a database of vehicle odometer readings by vehicle year, make and model, also obtained from Polk. For our analysis of risk per crash, we use all vehicles in the state databases, including those involved in one-vehicle crashes and the vehicle NHTSA determined to be responsible for the crash in two-vehicle crashes. Therefore both the number of fatalities or casualties, and the number of crashes, come from the same datasets. For our analysis of risk per VMT, we again use the number of fatalities or crashes from the thirteen state databases, coupled with the VMT weights that NHTSA derived from the induced exposure crash involvements, national vehicle registrations, and average vehicle odometer readings. Because NHTSA apparently included all induced exposure involvements in creating their VMT weights, and did not exclude those that resulted in a fatality, we are able to use NHTSA's VMT weights in our regression models of 13-state risk per VMT. However, NHTSA used national Polk registration data to scale the induced exposure crashes from the thirteen states to the national level. Since we only include casualties occurring in the thirteen states, this scaling is not necessary for our analysis. In the future we hope to obtain VMT weights adjusted to total registration-years in the thirteen states, rather than in the entire US, for our analyses of risk per VMT.

Second, as noted above, NHTSA included fatal crash involvements from FARS for 2008, even though 2008 data were available from only six of the thirteen states NHTSA used to develop the induced exposure records. For the remaining seven states, NHTSA assumed the distribution of induced exposure crashes in 2008 were identical to those in 2007.[4] Rather than extending this assumption to the fatality and casualty crashes from the seven states without 2008 data, we limited our initial analysis to crash data through 2007.

To make our results most comparable to NHTSA's results for US fatalities per VMT, we also excluded the following records from our initial analysis:

- sports cars, police cars, and all-wheel drive cars;
- vehicles whose reported model year did not match the model year decoded from the VIN;
- vehicles whose model year was not reported in the state crash data (with the exception of all crash records from Washington, which NHTSA included in their analysis of induced exposure crashes);
- vehicles involved in police-reported crashes in 2008 (in six states);
- vehicles that had apparent VIN transcription errors that we corrected so that the reported model year matched the VIN model year.[5]

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[4] NHTSA made similar assumptions for years of state crash data that were not available, such as 2002 data from Pennsylvania and 2002 and 2003 data from Michigan.

[5] The apparent transcription errors are based on comparing the reported model year with the characters in the 9th and 10th VIN position. If the reported model year matched a common transcription error (such as a "5" entered as an "S") then we translated the character in the 10th VIN position to match the reported model year. If the reported model year matched the character entered in position 9, we shifted the character in position 9, and all subsequent characters, to the right one position. These VIN adjustments are described in more detail in Appendix B.

Including these records, as well as police-reported crash data from three states that NHTSA did not include in its analysis of induced exposure crashes, increases the number of vehicles analyzed by about 40% of mass and footprint reduction on risk. We test how including all of these records in the regression analyses would change the effect of mass and footprint reduction on casualty risk per crash in Section 5.

2.2. Accounting for the state in which the crash occurred

In its regression models of US fatality risk per VMT, NHTSA included the control variable HIFAT_ST, which identifies states with high fatality rates per million vehicle-years. We investigated the effect of replacing this single control variable with two variables, for states with high and with low fatality risks per crash, as well as with 12 control variables for each state used in the analysis except Florida.

Figures 2.2 and 2.3 show the unadjusted fatality and casualty risk per crash in 16 states. Figure 2.2 indicates that fatality risk per crash is the highest in Florida, Pennsylvania, and Wyoming, and the lowest in Michigan, Illinois, and New Jersey. Figure 2.3 suggests that casualty risk per crash is the highest in Alabama, Florida, Maryland, and Wyoming, and the lowest in Georgia, Michigan, New Jersey, and Washington. Note that driver casualty risks per crash have been fairly constant over time in most states, with the exception of Maryland and New Mexico, which exhibit fairly large, consistent reductions in casualty risk each year. We have no explanations for this trend in these two states.

Figure 2.2. Driver fatality risk per 100,000 crashes in 16 states

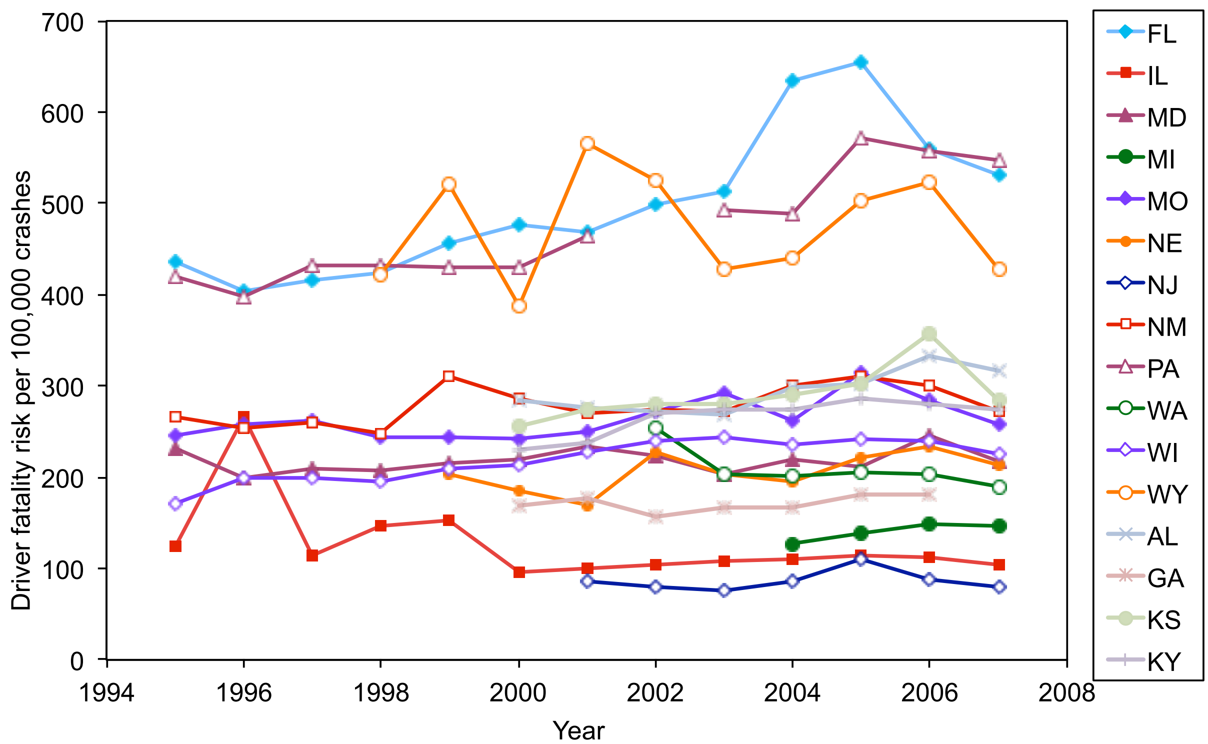
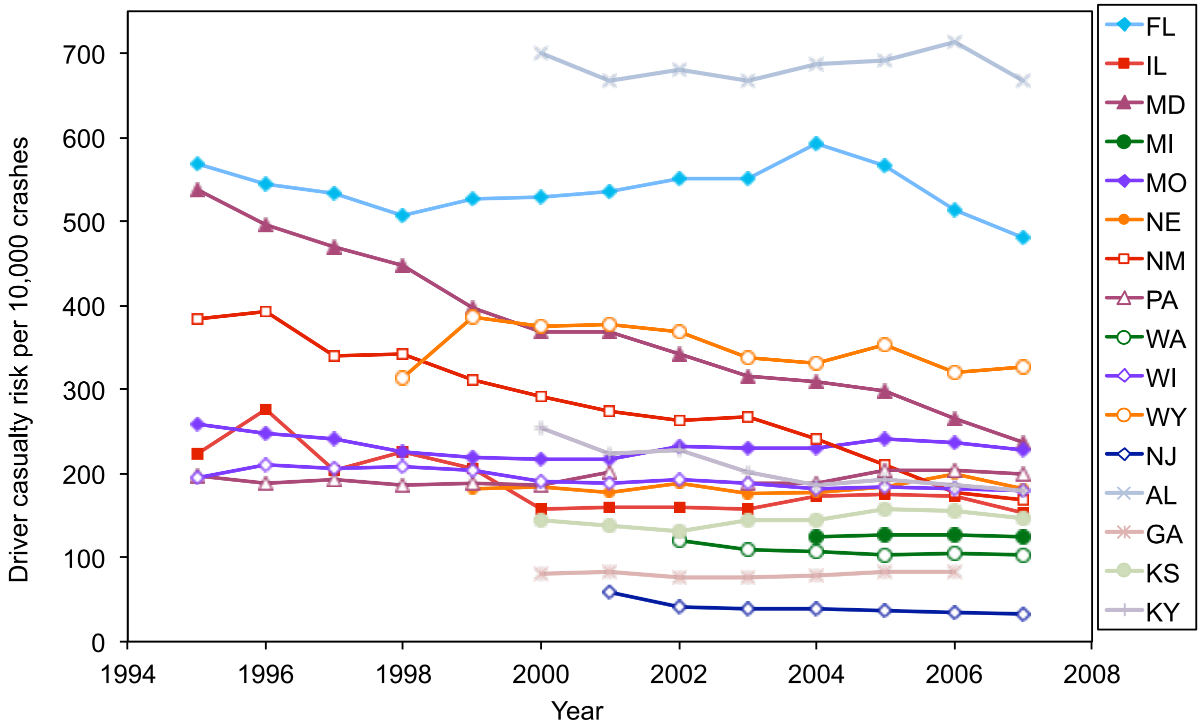
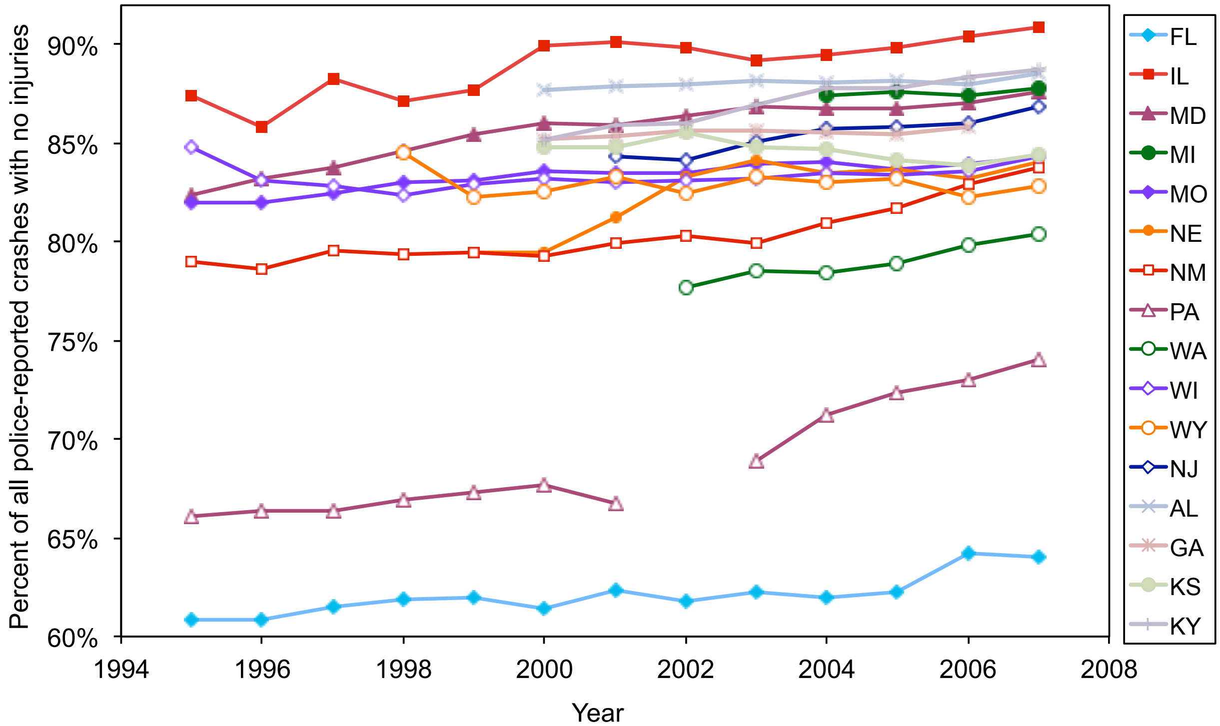


Figure 2.3. Driver casualty risk per 10,000 crashes in 16 states



The relatively high or low risks shown for some states in Figures 2.2 and 2.3 do not necessarily reflect more dangerous driving conditions in those states; rather, they reflect either different definitions of "incapacitating", "serious", or "major" injuries, or different reporting requirements or reporting bias in those states. For example, Pennsylvania is unique in that it reports "moderate" injuries in addition to "major" and "minor" injury; as a result, there are relatively few "major" injuries reported in Pennsylvania, which increases its casualty risk per crash relative to other states. In Florida, there is no property damage threshold over which a crash is required to be included in the state crash database; in most other states crashes resulting in property damage in excess of $500 must be reported. In Figure 2.4, only about 60% of all crashes in the Florida database are non-injury crashes, whereas 80% to 90% of the crashes in most other states are non-injury crashes. As a result, risks per crash are higher in Florida than in almost any other state.

Figure 2.4. Percent of police-reported crashes that are non-injury crashes, in 16 states



Based on Figures 2.2 through 2.4, we replaced the HIFAT_ST variable NHTSA used for analysis of US fatalities per VMT with 12 variables identifying each state except Florida for our analysis of fatality and casualty risks per crash. We examine how replacing the 12 state control variables with only two variables for high- and low-injury states would change the effect of mass and footprint reduction on risk in Section 5.

2.3. Effect of mass and footprint reduction on fatality and casualty risk per crash

All of the regression coefficients presented in the NHTSA 2011 report are the direct output from the SAS LOGIST procedure (with the exception of those for the mass and footprint variables UNDRWT00, OVERWT00, LBS100, and FOOTPRNT, which NHTSA often multiplies by -1 so that they reflect the effect of a reduction in vehicle mass or footprint; we use the same convention throughout this report). The output from the SAS LOGIST procedure reflects the percent change in the log-odds of casualty (or fatality) per crash for a one-unit increase in the explanatory variable. In order to obtain the percent change in the probability of casualty (or fatality) per crash, the SAS outputs need to be converted from log-space to linear space, and from odds to probabilities. We use the equation $e^x - 1$, where x is the logistic regression coefficient from the SAS output, to make this conversion. This conversion has no effect on the output regression coefficients when the change in the log-odds of casualty is small; however it substantially increases the percent change for explanatory variables that have a large effect on the log-odds of casualty (such as the crash location variables). For example, the casualty risk per crash from a lighter than average car involved in a rollover crash has a 1.64 times higher log-odds of casualty if it occurs in a rural county; after conversion, this crash has a 416 percent higher probability of casualty if it occurs in a rural county (EXP(1.64) - 1 = 4.16). Unless noted otherwise, the confidence intervals shown in this report are calculated the same way; that is, using the standard error of the log-odds output of the SAS LOGIST procedure to derive the 95% confidence interval of the log-odds coefficient, and to display it as a percent probability interval.

Figure 2.5 presents the regression coefficients of the effect of reductions in mass and footprint on US fatality risk per ten billion VMT, from the NHTSA 2011 analysis (in light blue). The coefficients for each of the nine crash types are weighted by the distribution of NHTSA's estimated 2016 baseline fatal crash involvements, after adjustment for full ESC penetration. The figure indicates that mass reduction increases societal[6] fatality risk by about one percent for cars and lighter-than-average light trucks, while mass reduction leads to a slight reduction in fatality risk for the heavier light trucks and CUV/minivans. The 95% confidence intervals in the figure indicate that the changes in risk for lighter cars, and both categories of light-duty trucks, are statistically significant. The confidence intervals shown in the figure, and all figures in this report, represent the weighted average standard error from the SAS output, times 1.96. NHTSA does not report these confidence intervals in its 2011 report; rather it uses a jack-knife technique to estimate the range in uncertainty around the point estimates. The resulting confidence intervals are larger than those shown in this report.

Figure 2.5 compares the effect of mass and footprint reduction on US fatalities per billion VMT (from NHTSA 2011, in blue) with that on 13-state fatality risk (in red), and 13-state casualty risk (in green), per police-reported crash. The effect for each of the nine crash types is weighted by the expected distribution of fatal or casualty crashes in 2016, after full adoption of ESC, just as in the NHTSA 2011 report. Mass reductions in cars and light trucks, while holding footprint constant, results in a consistent reduction in state fatality risk per crash; the reductions are statistically significant for all but the lighter cars. Mass reduction in CUVs and minivans leads to a statistically insignificant increase in state fatality risk per crash. Footprint reductions in cars and light trucks result in statistically significant increases in state fatality risk per crash, while footprint reduction in CUVs and minivans results in a relatively large but insignificant reduction in risk.

The results for 13-state fatality risk per crash (shown in red) in Figure 2.5 are quite different from the results NHTSA obtained for US fatality risk per VMT (shown in blue), which found that mass reduction, while holding footprint constant, increased risk for cars and lighter light trucks, and slightly reduced risks for the heavier light trucks and CUVs/minivans. The different results for fatality risk per VMT versus per crash could be attributed to at least three factors.

- First, as discussed above, the effect of mass reduction on fatality risk per VMT is the combined effect of a vehicle's crash avoidance and its crashworthiness; the ability of a vehicle to avoid a crash altogether, and the extent to which a vehicle protects its occupants once a serious crash occurs. The net detrimental effect of mass reduction on fatality risk per VMT for cars and lighter light-duty trucks may be the result of a large

[6] All of the fatality risks reported in the 2011 NHTSA report are societal risk, that is fatalities to all vehicle occupants and non-occupants involved in the crash are included. Unless specified otherwise (i.e. in Section 6, when we examine the effect of side impact airbags on risk to car occupants, and steps manufacturers have taken to improve light truck compatibility on the risk light trucks impose on other vehicle occupants, in two-vehicle crashes), all risks in this report also are societal risk.

detrimental effect of mass reduction on these vehicles' crash avoidance, combined with a smaller, beneficial effect of mass reduction on crashworthiness. We address this possibility below.

- Second, the differences between the effect of mass reduction on US fatality risk per VMT versus 13-state fatality risk per crash could be the result of differences in the mass/footprint relationship with risk in the thirteen states vs. in the country as a whole.

- Finally, the differences between fatality risk per VMT and casualty risk per crash could indicate that casualties are much less sensitive to mass reductions than fatalities, and that vehicle mass reduction somehow reduces casualties but not fatalities.

Figure 2.5 indicates that mass reductions generally result in smaller effects on casualty risk per crash than on fatality risk per crash. Mass reductions result in small statistically significant reductions in casualty risk per crash for heavier cars and all light trucks, a small but not statistically significant reduction in risk for CUVs/minivans, and a small but not statistically significant increase in risk for lighter cars. The effect of footprint reduction on casualty risk per crash also is much smaller than its effect on fatality risk per crash, with small and not statistically significant increases in casualty risk per crash for cars and CUVs/minivans.

Figure 2.6 shows the same data as Figure 2.5, but for 13-state fatality and casualty risk per VMT, not per crash, using the VMT weights developed by NHTSA using national registration data and induced exposure crashes in the thirteen states. Comparing Figure 2.6 with Figure 2.5, one sees that the effects of mass and footprint reduction on risk per VMT are quite a bit larger than the effects on risk per crash. The difference is so large that a reduction in risk per crash becomes an increase in risk per VMT, for mass reduction in lighter cars in terms of fatality risk (shown in red), and for mass reduction in heavier cars and lighter light-duty trucks in terms of casualty risk (shown in green).

Figure 2.6 also indicates that the effect on fatality risk per VMT from the 13-state data (shown in red) are comparable to the effect on national fatality risk per VMT (shown in blue), for mass reduction in only lighter cars and heavier light-duty trucks. The mass and size effects on casualty risk per VMT from the thirteen states (shown in green) are comparable to the effects on US fatality risk per VMT (shown in blue) for mass reduction in lighter and heavier cars, and heavier light-duty trucks, and for footprint reduction in cars and CUVs/minivans.

The improved similarity in the US and 13-state risks expressed in terms of VMT exposure in Figure 2.6 suggests that the large differences between US fatality risk per VMT and 13-state fatality risk per crash in Figure 2.5 are the result of changing the measure of exposure from per VMT to per crash, and not because the relationships between mass and footprint reductions and risk in the thirteen states are different from those relationships in the entire US (the second possible explanation for the differences in fatality risk per VMT vs. per crash, summarized above). Figure 2.7 compares the effect of mass and footprint reduction on the two components of risk, the number of crashes per VMT (crash frequency, the inverse of crash avoidance, shown in orange) and the fatality risk per crash (crashworthiness, shown in light red), with their effect on fatality risk per VMT (shown in dark red), from the 13-state crash data.

Figure 2.5. Effect of mass and footprint reduction on three types of risk, by vehicle type

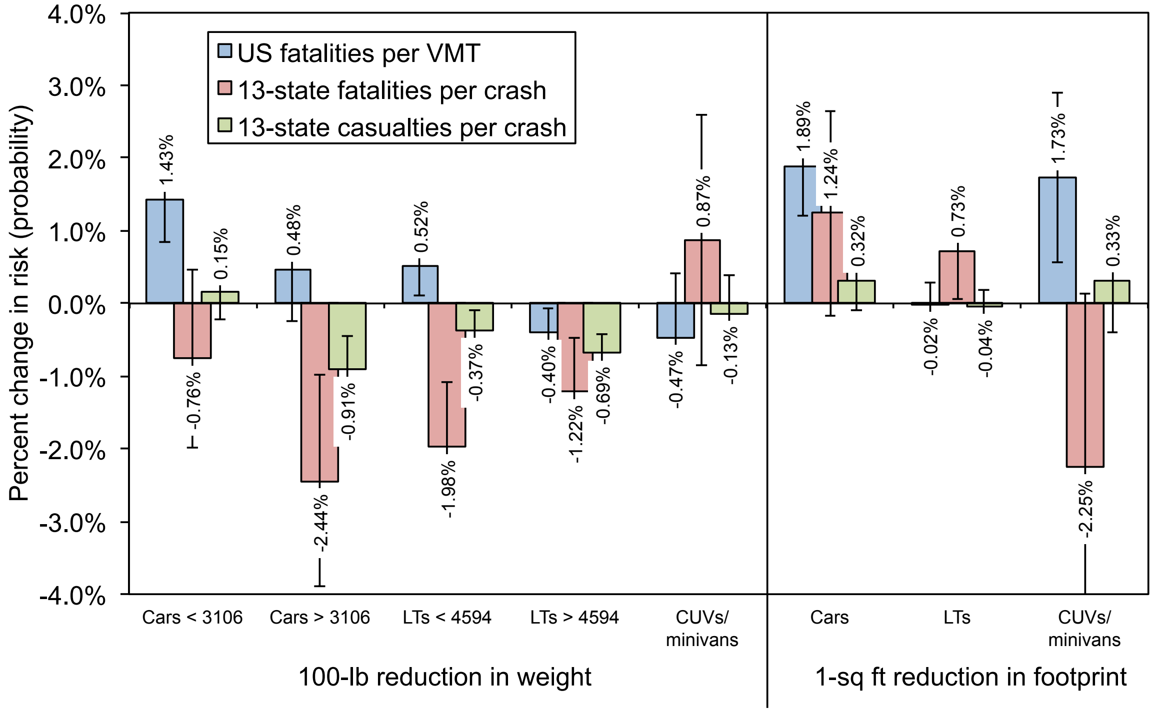
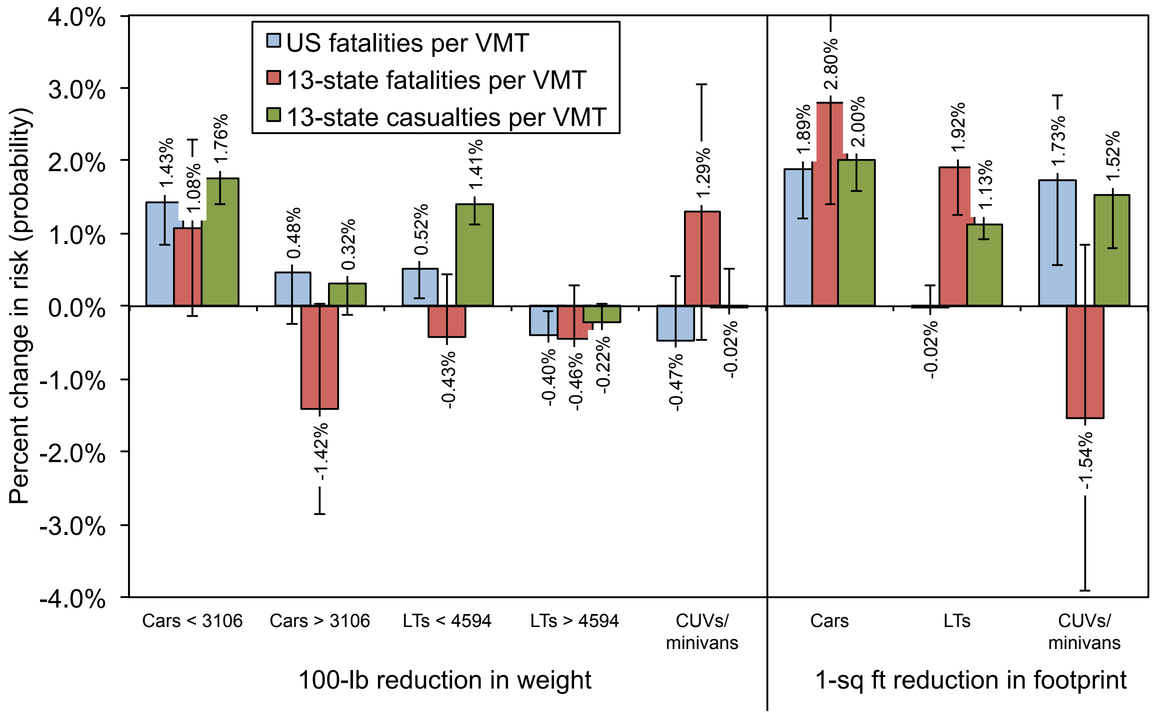


Figure 2.6. Effect of mass and footprint reduction on three types of risk per VMT, by vehicle type



The results in Figure 2.7 for crash frequency and crashworthiness were obtained using the same regression models, with the dependent variable changed from fatalities per VMT to crashes per VMT (for crash frequency) or fatalities per crash (for crashworthiness). For cars and light trucks, the effects from the two components roughly add together to result in the overall effect on fatality risk per VMT. For example, a 100-lb reduction in the mass of lighter cars leads to a 1.84% increase in crash frequency (the number of crashes per VMT), while mass reduction leads to a 0.78% decrease in the number of fatalities per crash (or a 0.76% increase in crashworthiness); the net effect is only a 1.08% increase in the risk of fatality per VMT. For CUVs/minivans, the relationship is different; mass reduction leads to a 0.71% increase in crash frequency, as well as a 0.87% increase in the number of fatalities per crash (or decrease in crash worthiness); however, the net result, a 1.29% increase in the number of fatalities per VMT, is less than the sum of the two components.

Figure 2.7. Effect of mass and footprint reduction on crashes per VMT (vehicle crash frequency), fatalities per crash (vehicle crashworthiness), and fatalities per VMT, by vehicle type

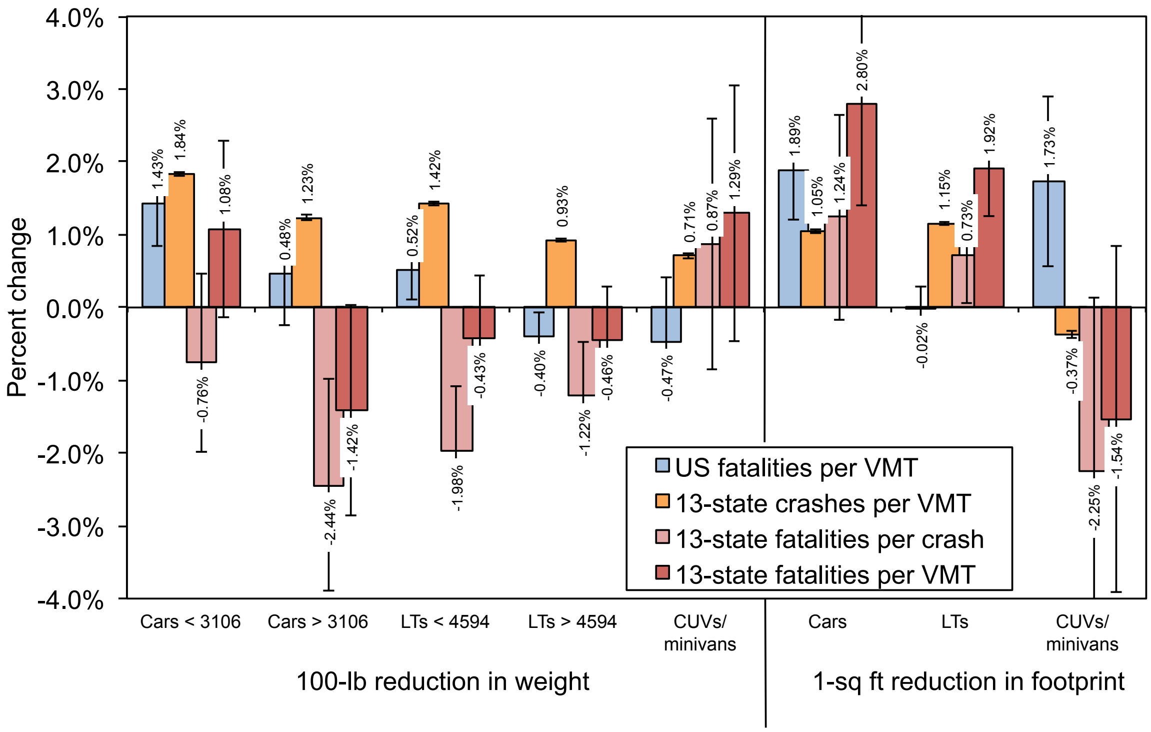
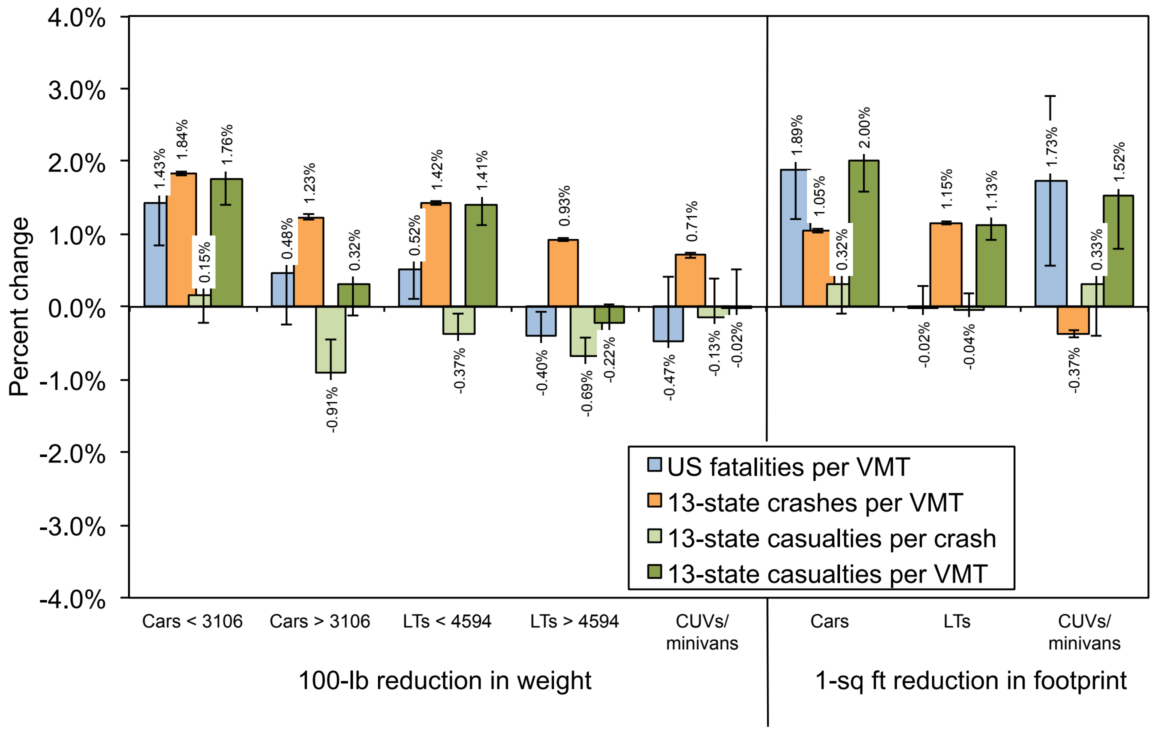


Figure 2.7 indicates that a reduction in car and light truck footprint increases both the number of crashes per VMT and the number of fatalities per crash (or decreases both the crash avoidance and crashworthiness), with the overall effect on fatalities per VMT roughly the sum of the two components. Footprint reduction in CUVs/minivans leads to a decrease in both the number of crashes per VMT and the number of fatalities per crash, with the net reduction in fatalities per VMT less than the sum of the two components.

Comparing the effect of mass and footprint reduction on crashes per VMT, from Figure 2.7, with the casualty risks per crash, from Figure 2.6, obtains similar results for casualty risks per VMT in Figure 2.6: the net effect of mass or footprint reductions on casualty risk per VMT is roughly the sum of the effect of mass or footprint reduction on crash avoidance and on crashworthiness, at least for cars and light trucks, as shown in Figure 2.8.

Figure 2.8. Effect of mass and footprint reduction on crashes per VMT (vehicle crash frequency), fatalities per crash (vehicle crashworthiness), and fatalities per VMT, by vehicle type

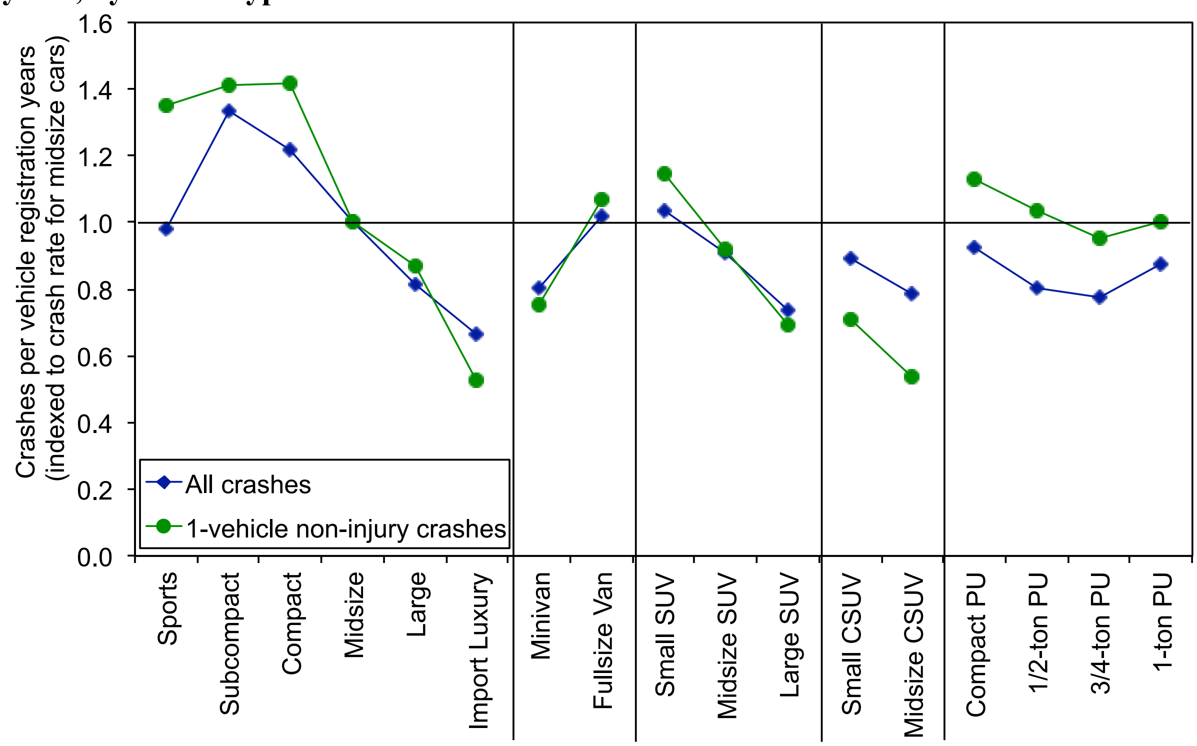


There is a possibility that reporting bias in the state police-reported crash data may influence the results of crash frequency and casualty risk per crash. Non-injury crashes may be under-reported for certain vehicle and crash types, such as large pickups that are less likely to suffer damage, and that older, less expensive, uninsured vehicles that are less likely to report crash damage to police, or one vehicle crashes in which there is no crash partner that requires a police-report in order to file an insurance claim. If collisions of certain vehicles or crashes are slightly less likely to be reported, this would tend to increase the observed detrimental effect of mass reduction on reported crashes per VMT and conversely decrease its detrimental effect on casualties per reported crash. (By contrast, fatalities or casualties per VMT would be not be affected by crash-reporting rates, because the crash-reporting rate is not part of the formula for calculating risk.) The extent to which any reporting bias of non-injury crashes exists, the observed effects for police-reported crashes per VMT might not correspond exactly to the "effect of mass reduction on crash avoidance" and the observed effects for casualties per police-reported crash might not correspond exactly to the "effect of mass reduction on crashworthiness."

We suspect that one-vehicle, non-rollover, non-injury crashes by pickup trucks are under-reported in the state crash data. Two-vehicle crashes are more likely to be reported, because two parties are involved, while rollover and injury crashes are more likely to be reported because they tend to be more severe. If pickup truck owners were not reporting one-vehicle non-injury crashes, we would expect the crash rate per registered vehicle for pickup trucks in one-vehicle non-injury crashes to be lower relative to that of other vehicles than in all crashes. Figure 2.9 compares the number of one-vehicle, non-injury crashes per 10,000 vehicle registration years, and the number of all crashes per 1,000 registration years, by vehicle type; crash rates for each type of crash are indexed to that for midsize cars. The data are from an earlier analysis, using police-reported crash data from only five states (Wenzel, 2011a). Pickup trucks have relatively higher crash rates in one-vehicle non-injury crashes (in green) than in all crashes combined (in blue), relative to the crash rates of other types of vehicles. This suggests that pickup truck owners are not under-reporting the type of crash least likely to be reported, one-vehicle, non-injury crashes, in the state crash databases.

We plan to expand this analysis to the crash data from the 13 states, and investigate further the extent to which crashes involving certain types of vehicles, or certain types of crashes, are under-reported in the state crash data.

Figure 2.9. One-vehicle, non-injury crashes and all crashes per 10,000 vehicle registration-years, by vehicle type and state



Recall that the risks and crashes per VMT in Figures 2.6 through 2.8 use the VMT weights developed by NHTSA using national registration data and induced exposure crashes in the thirteen states. To more accurately calculate fatality risk per VMT for the thirteen states, we need to obtain vehicle registration data, by calendar year, and vehicle model year and model, for the thirteen states, and develop new VMT weights to represent total VMT in the thirteen states, as opposed to the national VMT weights NHTSA used in their analysis and here.

Figure 2.5 shows the effect of mass and footprint reduction on risk per police-reported crash; Figure 2.10 shows their effect on fatality risk per serious crash (shown in brown), with "serious crashes" defined as any police-reported crash that resulted in a casualty to a vehicle occupant or non-occupant. The figure suggests that using serious, or casualty, crashes, rather than all police-reported crashes, as the measure of exposure has only a slight change in the effect of mass and footprint reduction on risk.

Figure 2.10. Effect of mass and footprint reduction on three types of risk, by vehicle type

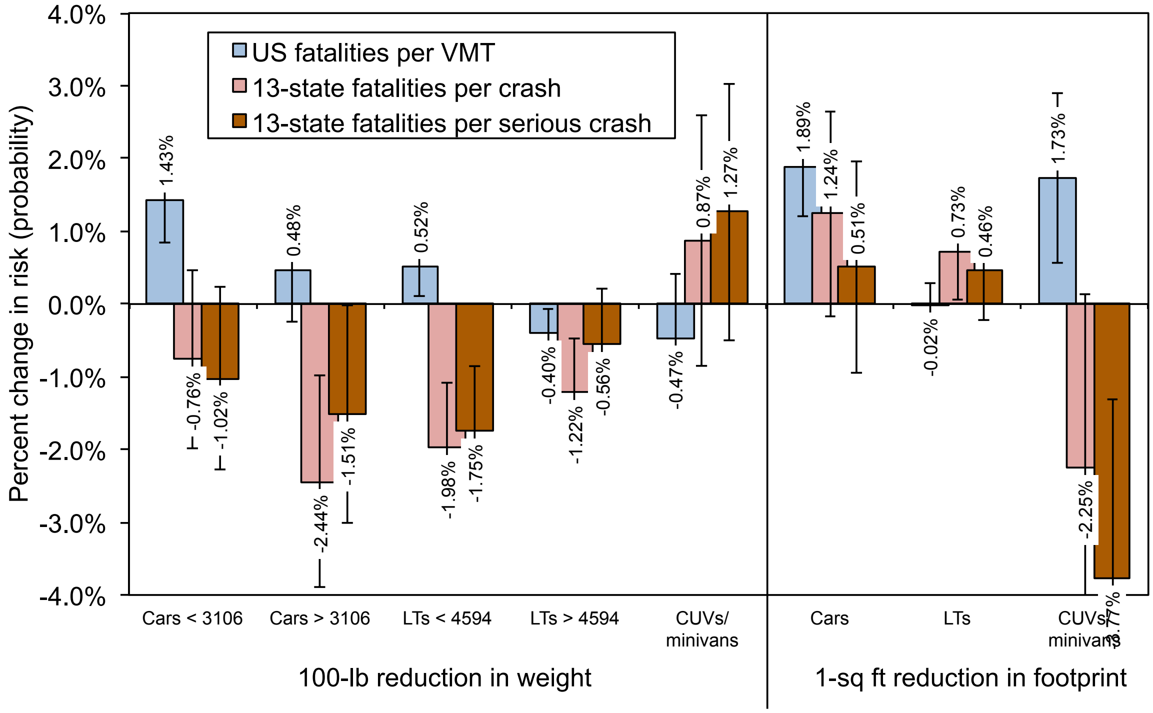
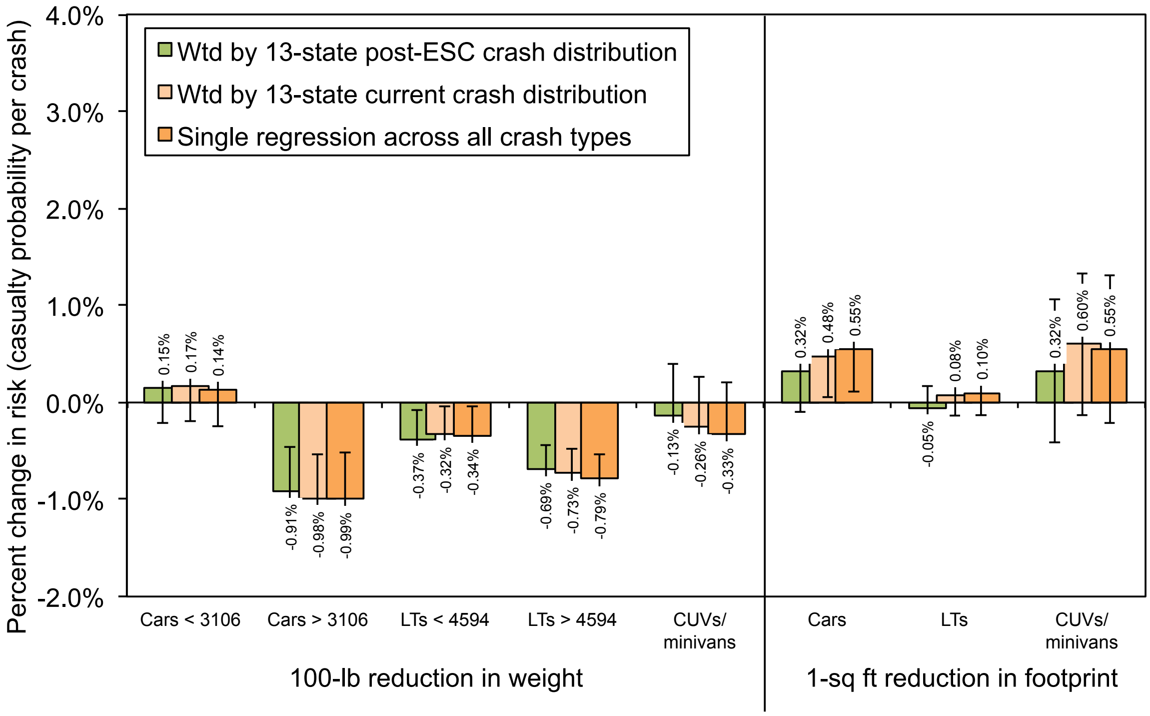


Figure 2.11 compares the effect of mass and footprint reduction on 13-state casualty risk per crash, after accounting for full adoption of ESC by 2017 (in green, from Figure 2.5) with the results from the nine regression models by crash type weighted by the current distribution of crashes (light orange). Full penetration of ESC in the on-road fleet (going from the light orange to green columns in the figure) results in little change in the effect of mass reduction on casualty risk per crash for cars and light trucks, but slightly reduces the detrimental effect of mass reduction on risk for CUVs and minivans (from a reduction in risk of 0.26% to a reduction of 0.13%). On the other hand, accounting for the change in the distribution of crashes after full ESC penetration slightly reduces the penalty from a reduction in footprint for cars (from a 0.48% increase in risk to a 0.32% increase in risk) and CUVs/minivans (from a 0.60% increase in risk to a 0.32% increase in risk). Using the anticipated distribution of crashes once all vehicles are equipped with ESC results in little change in the effect of mass and footprint reduction on casualty risk per crash.

Results from a single regression analysis across all nine crash types are also shown in Figure 2.11 (in dark orange). The effects of mass and footprint reduction on casualty risk per crash using a single regression model are quite similar to those when the effects by crash type are weighted by the current distribution of crashes (shown in light orange in the figure).

Figure 2.11. Effect of mass and size reduction on 13-state casualty risk per crash by vehicle type, across all crash types and weighted average effect in each type of crash

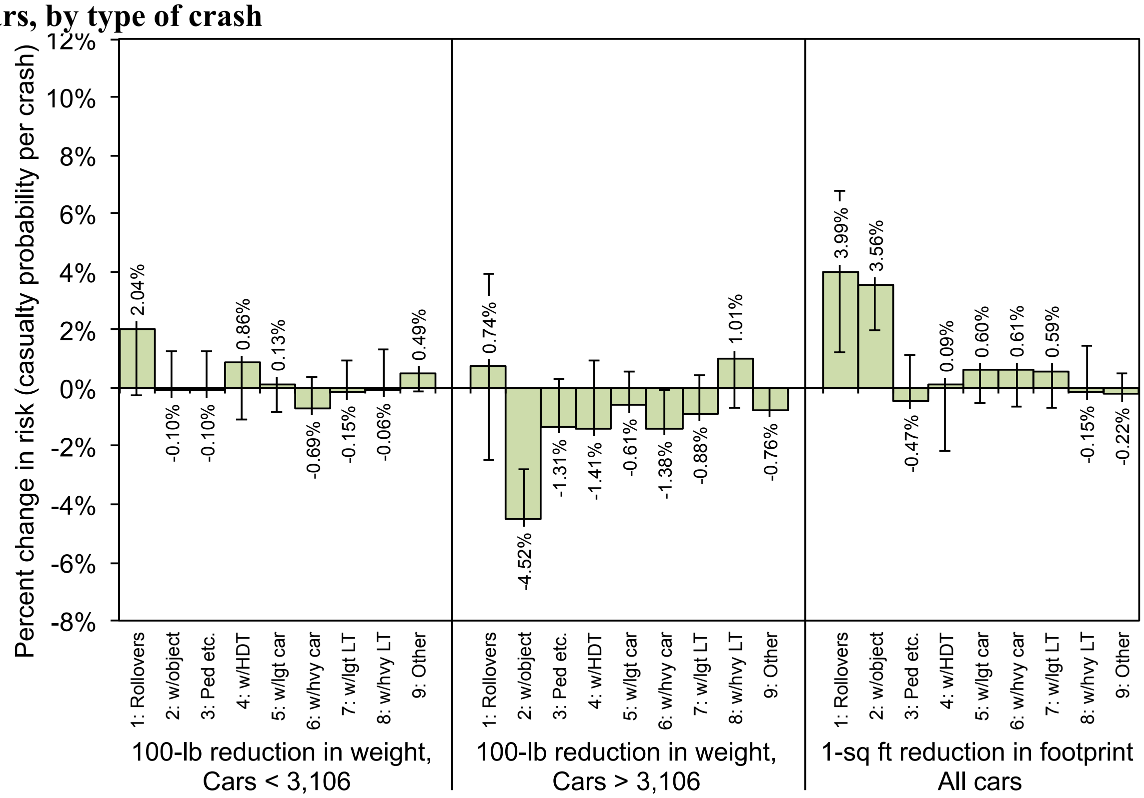


Figures 2.12 through 2.14 show the effect of changes in mass or footprint on casualty risk per crash, by type of crash. Figure 2.12 indicates that mass reduction results in a large (4.52%) reduction in risk only in crashes with objects for heavier cars; this large reduction in risk is somewhat offset by increases in risk in car rollover crashes (by 2.04% for lighter cars, and by 0.74% for heavier cars). On the other hand, footprint reductions in cars result in a large increase in risk in rollovers (3.99%) and crashes with objects (3.56%). Because full ESC adoption is expected to substantially reduce the number of rollover and crashes with objects, and footprint reduction substantially increases casualty risk in these types of crashes, removing many of these types of crashes by 2017 will reduce the overall detrimental effect of footprint reduction in cars (from 0.48% to 0.32% as shown in Figure 2.11).

Figure 2.12 shows the effect of mass and footprint reductions on risk in light trucks, by type of crash. In general, although relatively small, more of the effects of mass or footprint reduction on risk tend to be statistically significant for light trucks than for cars. Mass reduction results in a relatively large (2.81%) reduction in casualty risk in rollovers for heavier light-duty trucks. A possible explanation for why mass reduction reduces risk in rollovers is that once a vehicle rolls over, a lighter vehicle applies less force on its roof than a heavier vehicle. We see the same beneficial effect of mass reduction in casualty rollover risk in CUVs/minivans, in Figure 2.13

(7.20%). As with cars, footprint reduction increases risk in rollovers and crashes with objects (by 2.14% and 1.11%, respectively) in light-duty trucks, and to an even greater extent (by 12.6% and 5.61%, respectively) in CUVs/minivans. The large, detrimental effects of footprint reduction on casualty risk in rollovers and crashes with objects account for the decrease in the effect of footprint reduction on risk after removing many of these types of crashes in Figure 2.11 (from a 0.08% increase in risk to a 0.05% reduction in risk for light trucks, and from a 0.60% to a 0.32% reduction in risk for CUVs/minivans).

Figure 2.12. Effect of mass and footprint reduction on 13-state casualty risk per crash in cars, by type of crash



Light truck mass reduction leads to statistically significant reductions in casualty risks in crashes with pedestrians/cyclists, lighter light-duty trucks, and, for the heavier light-duty trucks, heavier cars and lighter trucks. For light trucks, as well as CUVs/minivans, mass reduction results in statistically significant increases, while footprint reduction leads to decreases, in casualty risk in crashes with heavy-duty trucks.

Curiously, mass reduction in CUVs/minivans leads to a large increase in casualty risk (2.03%) in crashes with lighter light-duty trucks, but a large decrease in risk (4.34%) in crashes with heavier light-duty trucks, as shown in Figure 2.14. Footprint reduction in CUVs/minivans leads to a large increase in casualty risk (5.54%) in crashes with heavier light-duty trucks.

Figure 2.13. Effect of mass and footprint reduction on 13-state casualty risk per crash in light trucks, by type of crash

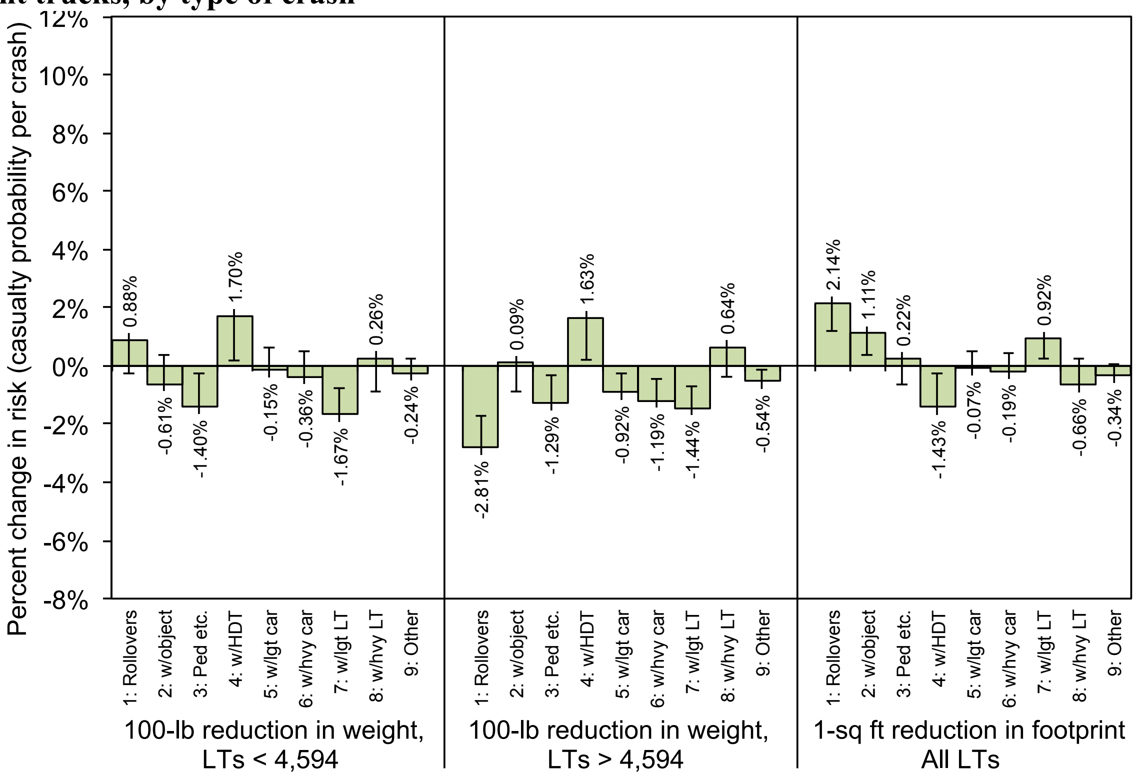
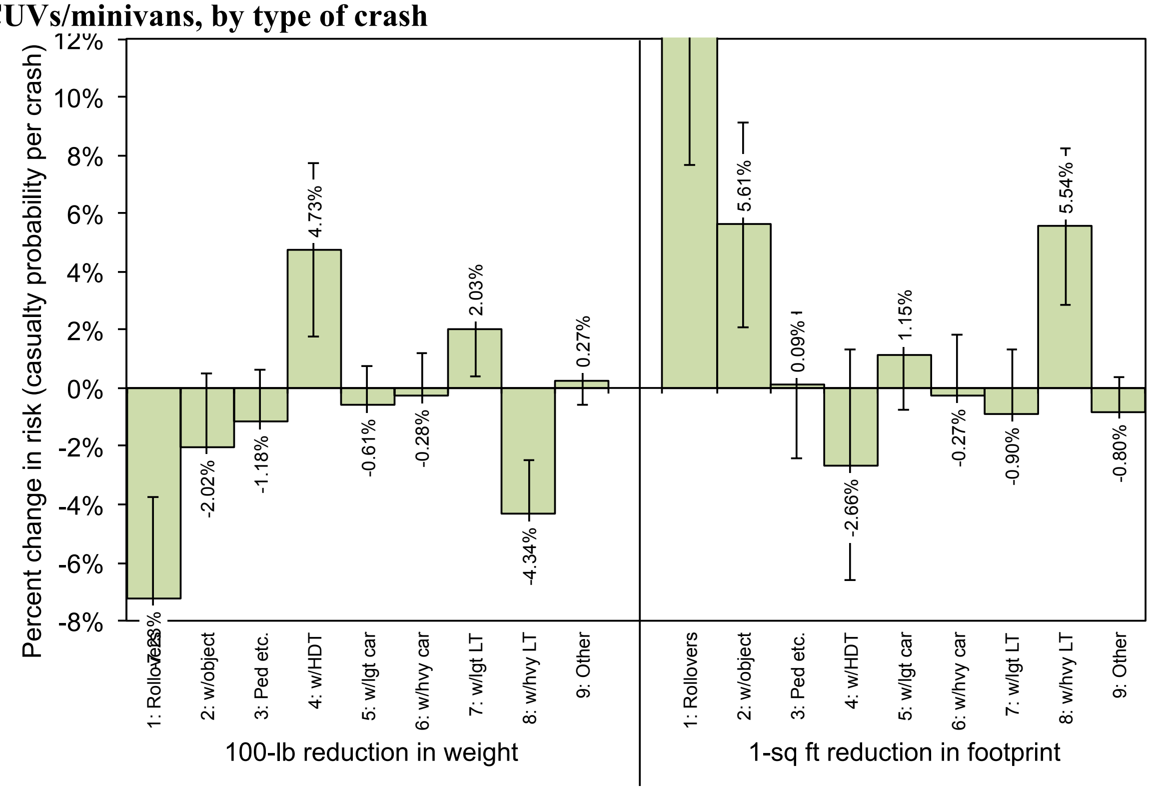
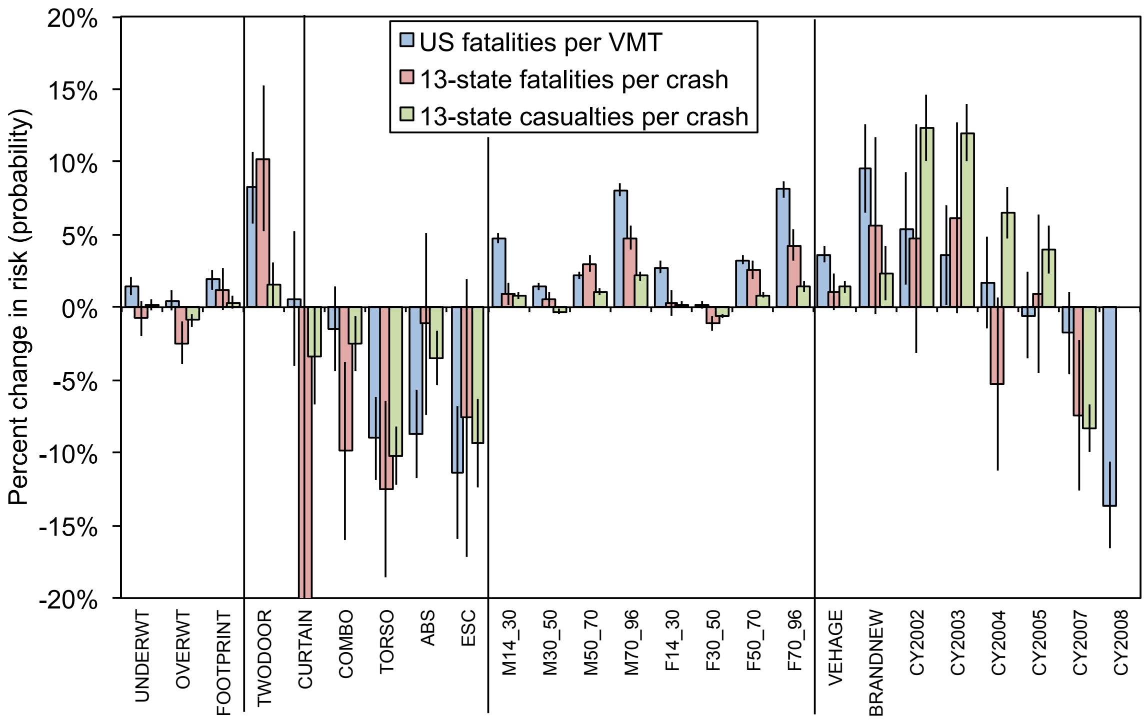


Figure 2.14. Effect of mass and footprint reduction on 13-state casualty risk per crash in CUVs/minivans, by type of crash



Figures 2.15 through 2.20 compare the effect of changes in the other vehicle, driver, and crash control variables on US fatality risk per VMT, from the NTHSA 2011 analysis (in light blue), with their effects on 13-state fatality (light red) and casualty risk (in light green) per crash. Figure 2.15 indicates that while 2-door cars continue to have a much higher fatality risk per crash than 4-door sedans, this effect essentially disappears in terms of casualty risk per crash. Curtain and combo side airbags have a much larger positive safety benefit in terms of fatality risks per crash than in terms of fatality risk per VMT; the beneficial effects of torso side airbags, ABS, and ESC are similar among the three types of risk, with the exception of ABS in fatality risk per crash. The driver age and gender variables have a smaller effect on fatality risk per crash, and a much smaller effect on casualty risk per crash, than on fatality risk per VMT; this suggest that much of the driver effect on risk contributes to the occurrence of a serious crash, and not the crashworthiness of the vehicle once a crash has occurred. Nevertheless, risk increases for the oldest drivers, even in terms of casualty risk per crash. The effects of vehicle age and brand new vehicles on the risks per crash are much smaller than on fatality risk per VMT. Likewise the effect of the calendar year variables also are smaller on risks per crash, and the consistent reduction in risk over time observed in fatality risk per VMT is not as strong in terms of fatality risk per crash. The calendar year variables are examined in more detail in Section 5.3.

Figure 2.15. Effect of mass and footprint reduction, and selected control variables, on 13-state casualty risk per crash, passenger cars



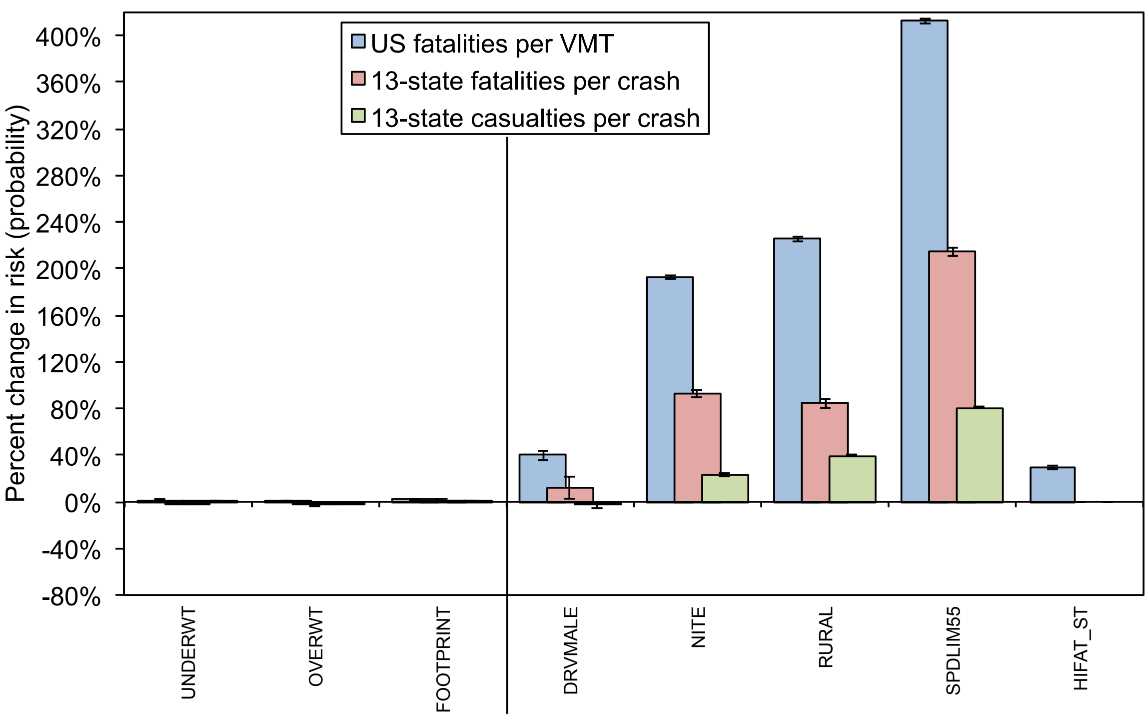
Note that the three vehicle variables of interest, UNDRWT, OVERWT, and FOOTPRINT, all have a much lower effect on risk than almost all of the control variables in Figure 2.15. For instance, a 100-lb reduction in curb weight for an underweight car is expected to increase casualty risk per crash by only 0.15%, while installing ABS would reduce risk by 3.5%.

Therefore, the regression results suggest that, in theory, the mass of a lighter car could be reduced by as much as 2,300 lbs while adding ABS, without increasing casualty risk per crash.

The control variables in Figure 2.16 have a much bigger effect on risk than the mass or footprint reduction variables, or the control variables presented in Figure 2.15. Male drivers and driving at nighttime, on rural roads, and on roads with posted speed limits above 55 mph have a smaller effect on fatality risk per crash, and a much smaller effect on casualty risk per crash, than on fatality risk per VMT; in fact, once a crash occurs, male drivers have essentially the same risk of casualty as female drivers. This suggests that the detrimental effect of male drivers has to do with their higher tendency of getting into a serious crash rather than their sensitivity to injury once a serious crash has occurred. Similarly, driving at night, on rural and high-speed roads, has a bigger effect on whether a vehicle is involved in a crash, than on how well a vehicle protects its occupants once a crash has occurred. Even so, these three variables do substantially increase the likelihood of casualty once a crash occurs.

As discussed above, the NHTSA regression of US fatality risk per VMT included a variable for high-fatality states; our regression models for fatality and casualty risk per crash include twelve variables for each state in the database. We analyze the effect of each state on fatality and casualty risk per crash in Section 5.1

Figure 2.16. Effect of mass and footprint reduction, and selected control variables, on 13-state casualty risk per crash, passenger cars



Figures 2.17 and 2.18 present the effect of the control variables on the three types of risk in crashes involving light trucks. SUVs have a much lower, and heavy-duty pickups a much higher, fatality risk per crash than regular pickups, which is opposite of the effects for fatalities per VMT and casualties per crash. And while AWD provides a large safety benefit in terms of

fatalities per VMT, it results in increased risk in terms of fatalities or casualties per crash. The other variables in Figure 2.17 have similar effects for the three types of risk, with the exception of three of the four female driver age variables, that show lower fatality risk per crash than for a 50-year old female.

Figure 2.19 indicates that minivans have a slightly lower fatality risk per VMT, a slightly higher fatality risk per crash, and a substantially higher casualty risk per crash, than CUVs. The three side airbag variables show inconsistent effects across the three types of risk for CUVs and minivans. ABS and ESC tend to provide a higher safety benefit in terms of fatality risk per crash, and a lower benefit in terms of casualty risk per crash. AWD provides a large safety benefit in terms of fatality risk per VMT, and a smaller benefit in terms of casualty risk per crash, but increases fatality risk per crash. As with cars and light trucks, the increased risk for elderly drivers in CUVs/minivans is smaller in terms of casualty risk per crash than in terms of fatality risk per VMT or per crash, while the effects of vehicle age and brand new vehicles on casualty risk per crash is negligible.

Figure 2.17. Effect of mass and footprint reduction, and selected control variables, on 13-state casualty risk per crash, light trucks

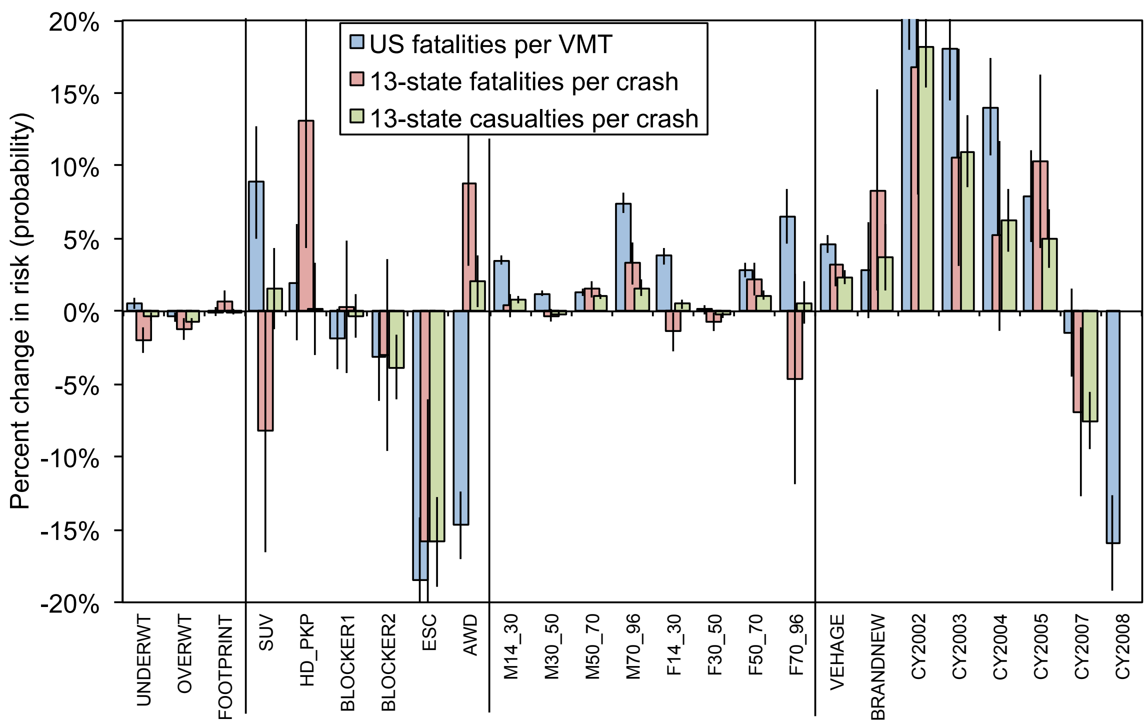


Figure 2.18. Effect of mass and footprint reduction, and selected control variables, on 13-state casualty risk per crash, light trucks

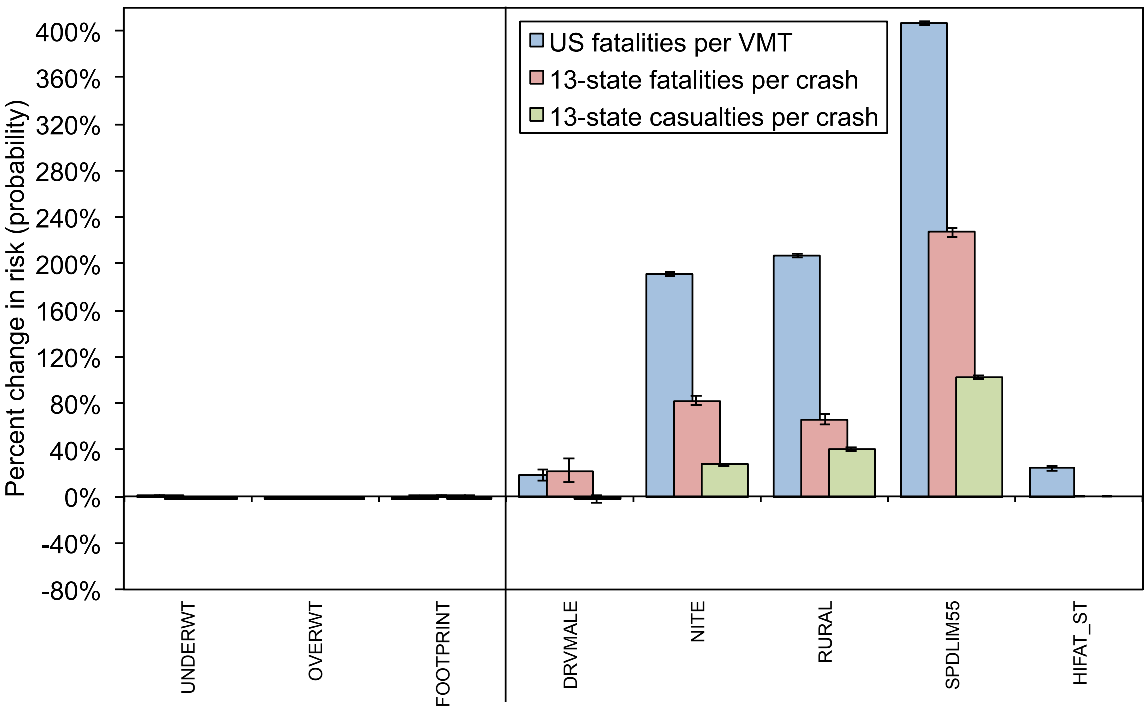


Figure 2.19. Effect of mass and footprint reduction, and selected control variables, on 13-state casualty risk per crash, CUVs and minivans

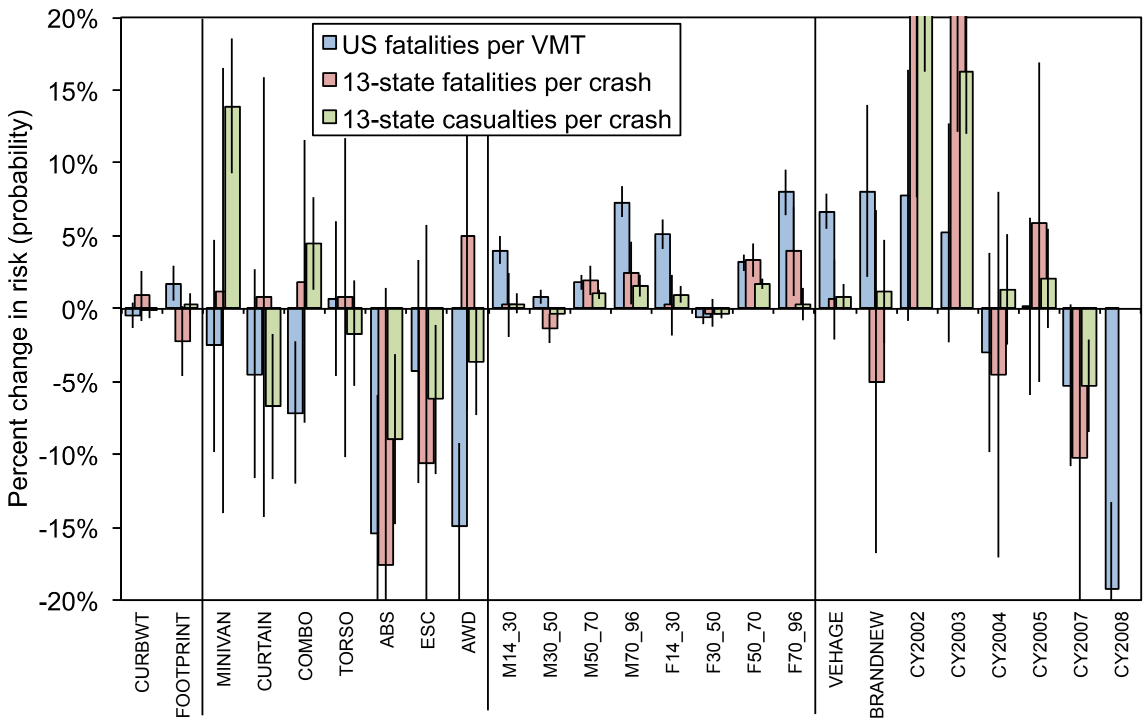
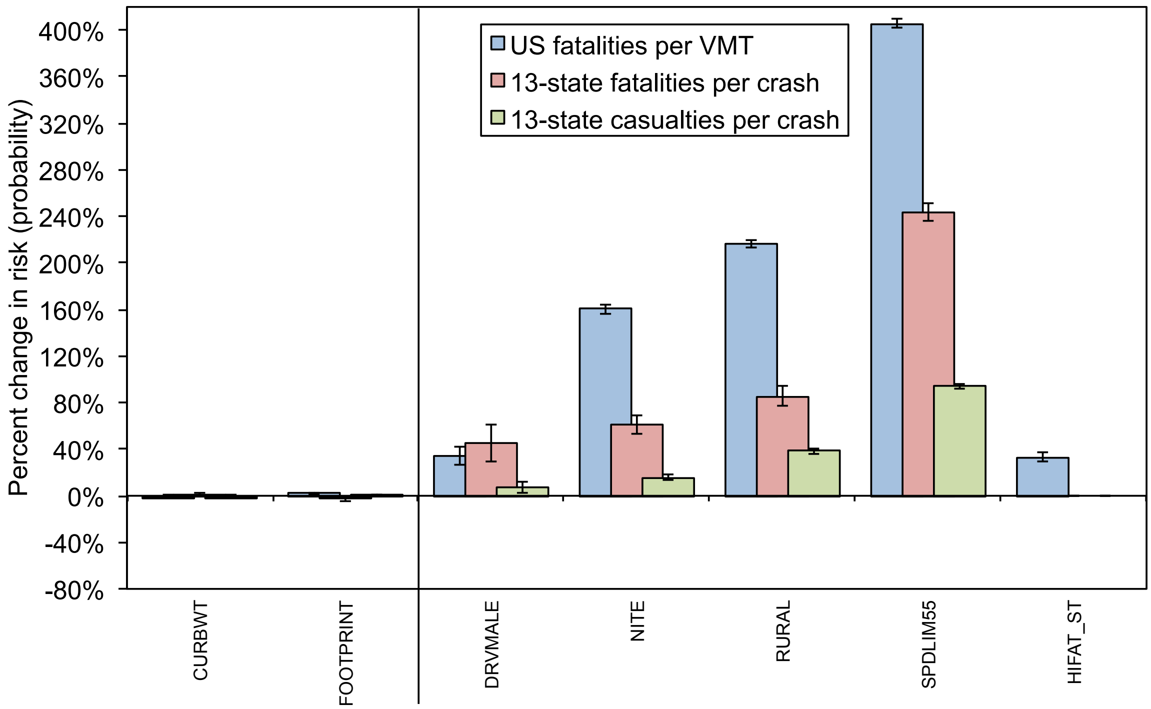


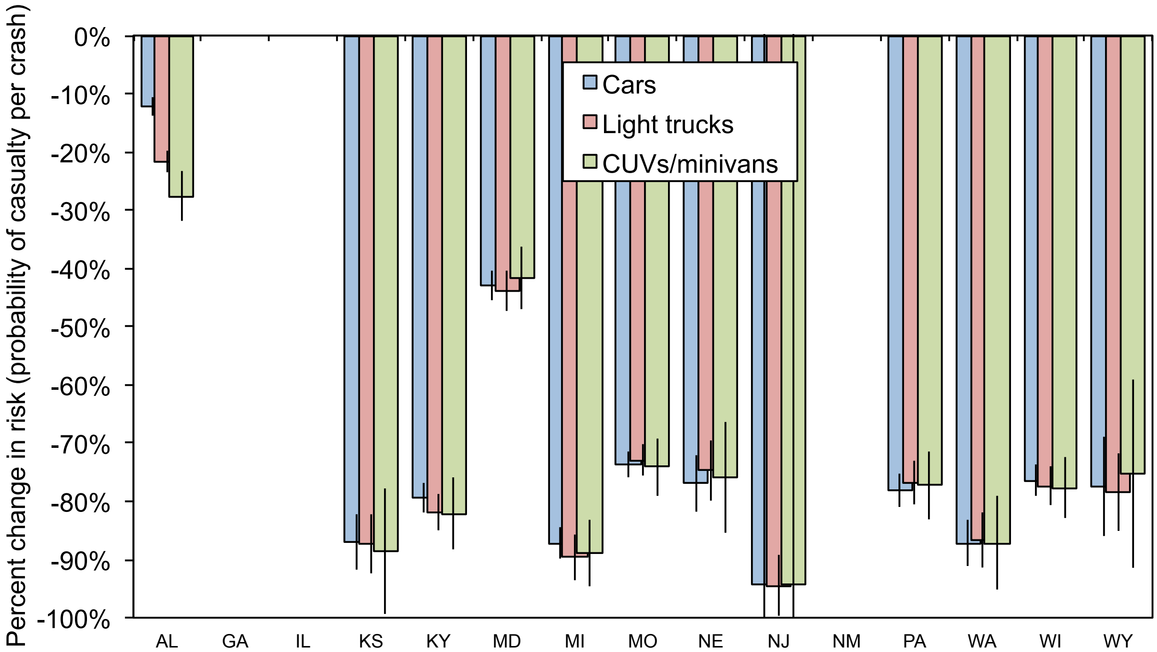
Figure 2.20. Effect of mass and footprint reduction, and selected control variables, on 13-state casualty risk per crash, CUVs and minivans



The effects of male drivers and crash characteristics on risks per crash for light trucks (Figure 2.18) and CUVs/minivans (Figure 2.20) are quite similar to those for cars (Figure 2.16). For all vehicle types, most of the vehicle, driver, and crash location variables shown in Figures 2.15 through 2.20 have a much greater effect on the three types of risk than reductions in vehicle mass or footprint.

Figure 2.21 shows the effect of each of the state control variables on casualty risk per crash, relative to the risks in Florida, by vehicle type. Note that in Figure 2.21 the model predicts a 10% to 25% lower casualty risk in Alabama than in Florida, while Figure 2.3 above indicates that Alabama has a roughly 25% higher casualty risk per crash than Florida. This discrepancy may be explained by the regression model also accounting for where crashes occurred in each state: over half of all police-reported crashes in Alabama occurred on roads in rural areas, which tend to have higher risks than crashes in urban areas, whereas only 15% of all crashes in Florida were in rural areas. After accounting for the greater amount of driving in dangerous rural areas in Alabama, the regression model indicates that driving in Alabama is actually 10% to 25% safer, depending on the type of vehicle, than driving in Florida. Similarly, the regression model predicts that a vehicle has a 75% lower casualty risk per crash in Wyoming than in Florida, while Figure 2.3 above indicates that the casualty risk per crash in Wyoming is only about 40% lower than that in Florida. All driving in Wyoming is in rural areas.

Figure 2.21. Effect of state in which the crash occurred on 13-state casualty risk per crash, by vehicle type



Figures 2.22 through 2.24 show the effect of the vehicle, driver, and calendar year control variables on the two components of fatality risk per VMT (shown in dark red), crash frequency (shown in orange) and fatality risk per crash (shown in light red). ABS and ESC in cars, AWD in light trucks and CUVs/minivans, and drivers aged 14 to 30 have a larger effect on crash frequency than risk per crash, while two-door cars, SUVs, and heavy-duty pickups, the side airbag variables in cars, and middle-aged drivers have a smaller effect on crash frequency than risk given a crash. Surprisingly, for CUVs/minivans, the side airbag variables reduce crash frequency but have little effect on fatality risk per crash, ABS has the same benefit in reducing crash frequency as fatality risk, and ESC has essentially no effect on crash frequency but a large benefit in reducing fatality risk. For light trucks, ESC has about the same benefit in reducing crash frequency as in reducing fatality risk given a crash. The control variables for CY2002 and CY2003 show a large reduction in crash frequency, but a large <u>increase</u> in risk given a crash, for all three types of vehicles.

Figures 2.25 and 2.26 show the effect of driver gender and the crash time and location, and the state control variables, on the two components of risk, crash frequency and fatality risk given a crash. The data are shown for passenger cars only, but the results are very similar for all three vehicle types. Male drivers have essentially no effect on crash frequency, but cause a statistically significant increase in fatality risk once a crash occurs, which is surprising. The age/gender variables in Figures 2.22 through 2.24 probably account for the risky behavior typical of male drivers; however, one would expect that, given a crash, males would have a lower fatality risk than females, as females are thought to be more susceptible to fatality or serious injury than males. The crash and location variables, driving at night on high-speed rural roads, have a much lower effect on crash frequency than on fatality risk given a crash. This also is somewhat surprising, as crash risk is thought to be greater under these three driving conditions, but apparently the severity of the crashes that occur under these conditions is greater than their effect on crash frequency.

Figure 2.22. Effect of mass and footprint reduction, and selected control variables, on 13-state crashes per VMT, fatality risk per crash, and fatality risk per VMT, passenger cars

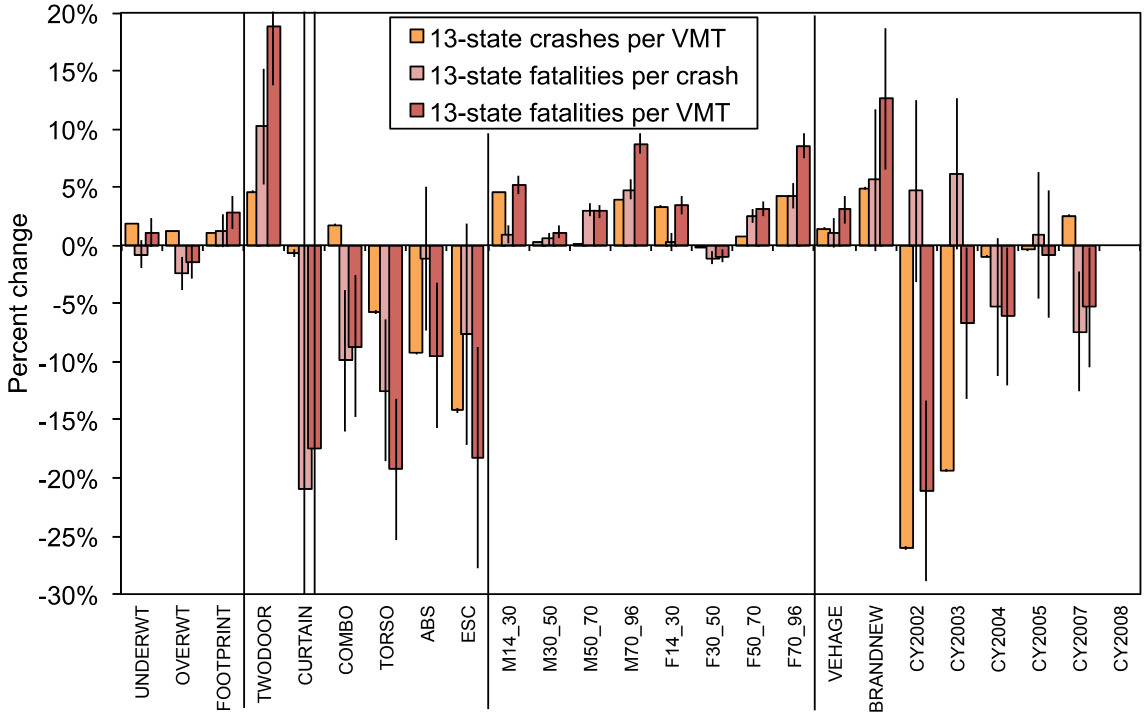


Figure 2.23. Effect of mass and footprint reduction, and selected control variables, on 13-state crashes per VMT, fatality risk per crash, and fatality risk per VMT, light trucks

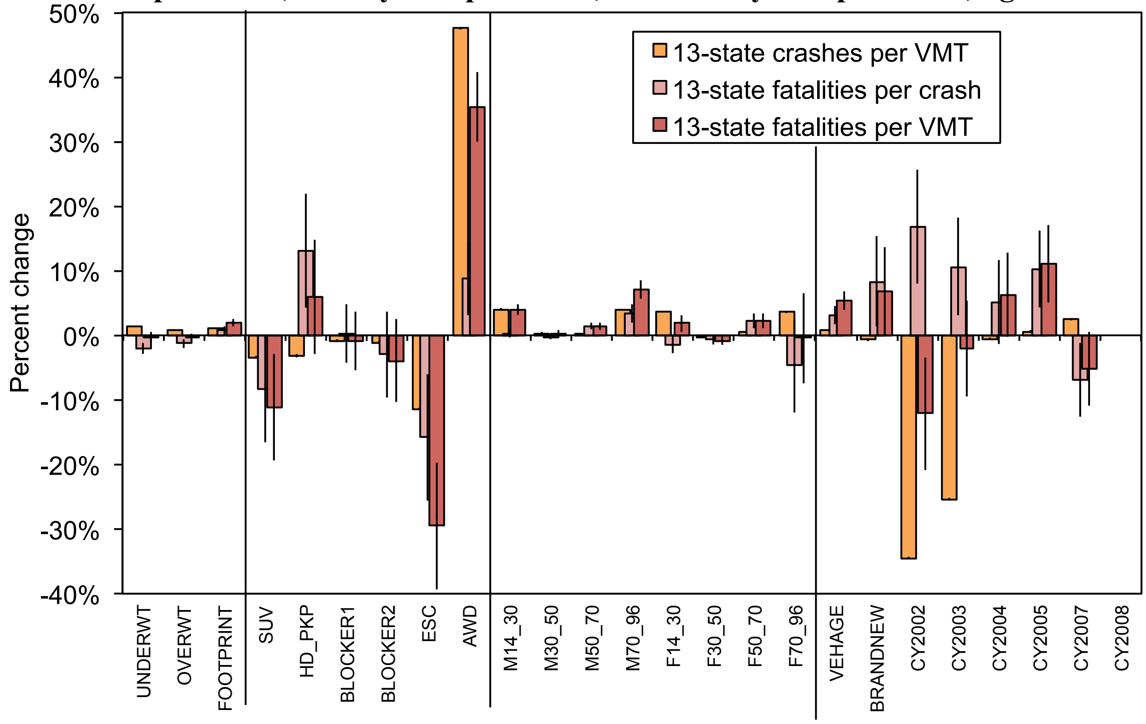


Figure 2.24. Effect of mass and footprint reduction, and selected control variables, on 13-state crashes per VMT, fatality risk per crash, and fatality risk per VMT, CUVs/minivans

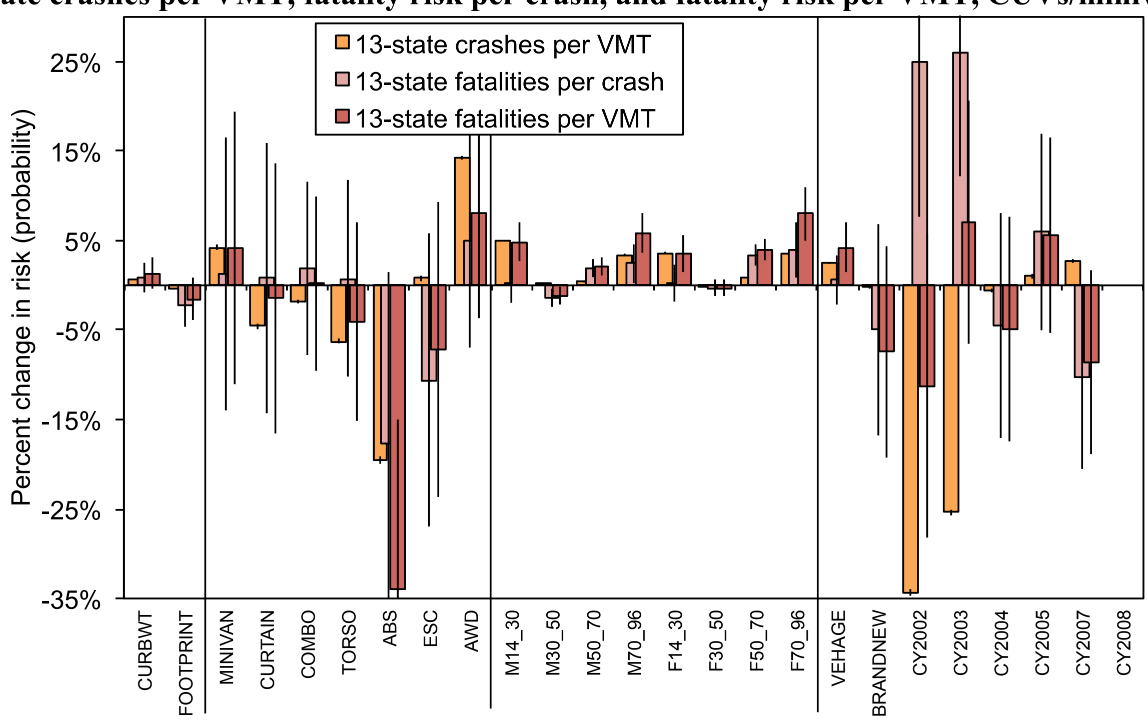


Figure 2.25. Effect of mass and footprint reduction, and driver gender and crash time/location control variables, on 13-state crashes per VMT, fatality risk per crash, and fatality risk per VMT, passenger cars

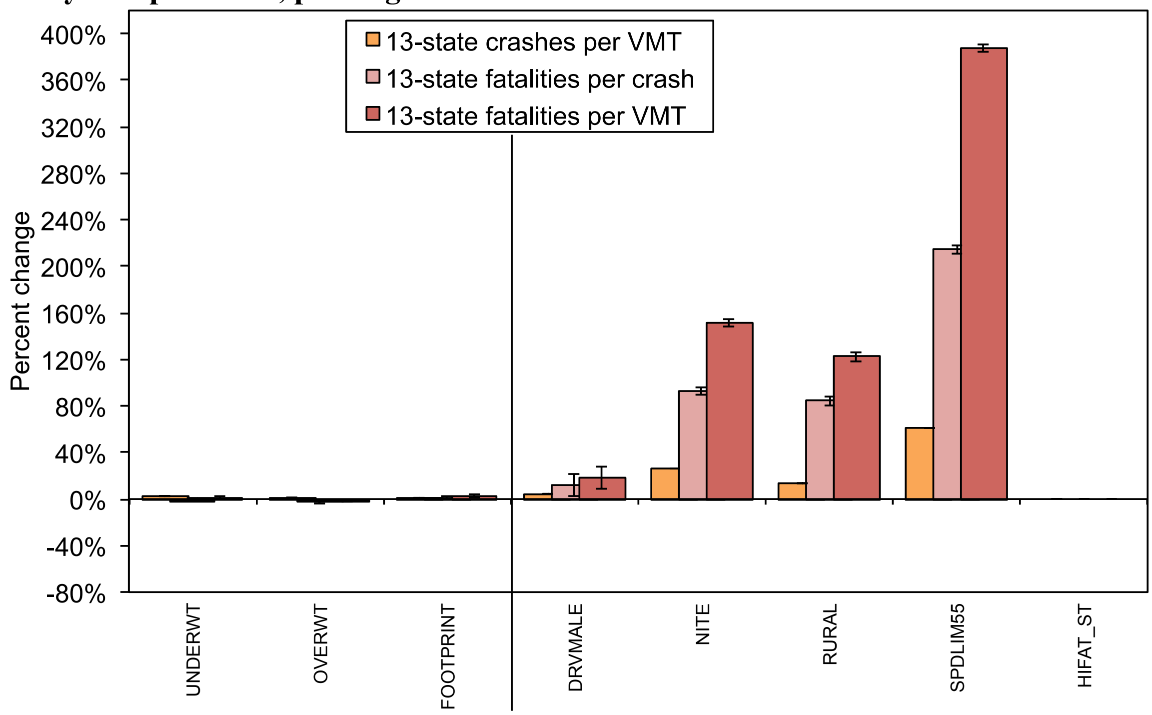
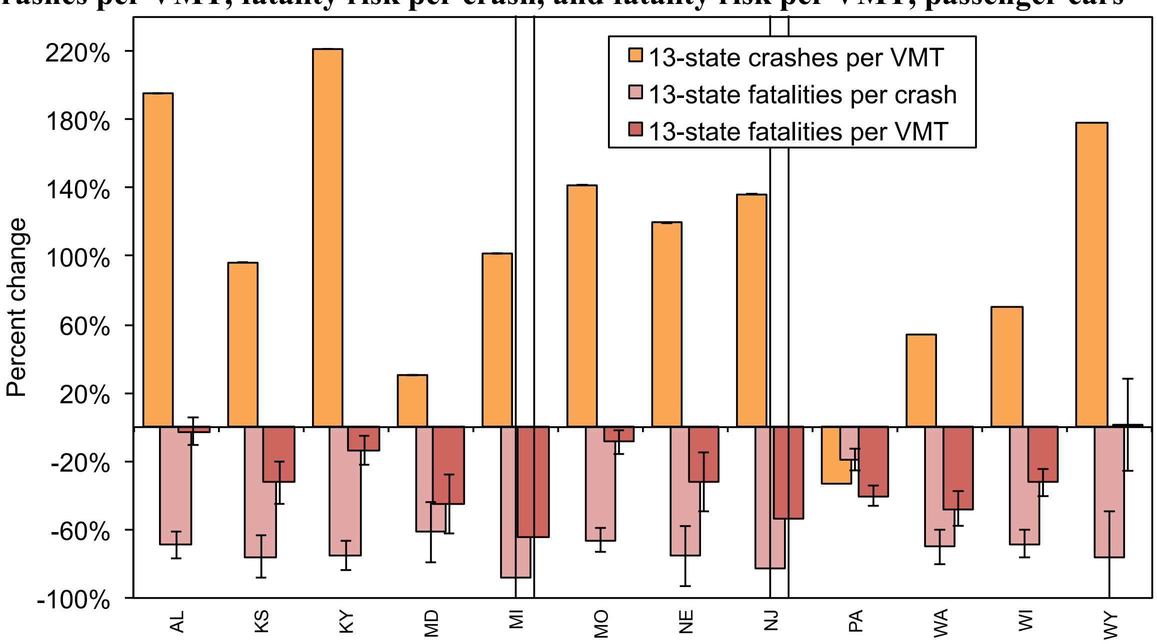


Figure 2.26. Effect of mass and footprint reduction, and state control variables, on 13-state crashes per VMT, fatality risk per crash, and fatality risk per VMT, passenger cars



3. Multi-collinearity between vehicle mass and footprint

In its 2003 and 2010 analysis NHTSA resisted including vehicle mass and size (in that case, wheelbase and track width) in the same regression model, because the two variables were strongly correlated with each other. Including two or more highly-correlated variables in the same regression model can lead to biased or incorrect results. However, in its 2011 analysis, NHTSA does include vehicle mass and footprint in the same regression models. Figure 3.1 shows the correlation between curb weight and footprint by vehicle model; only the most popular 275 models, with at least 10 billion VMT or 100 fatalities in the US fatality database NHTSA used for its 2011 analysis, are included in the figure (106 car models, 131 light truck models, and 38 CUV/minivan models). The figure indicates that curb weight and footprint are more highly correlated for cars (R^2 of 0.87) than for light trucks (R^2 of 0.65) or CUVs/minivans (R^2 of 0.60). Figure 3.2 shows the same data as Figure 3.1, but uses six vehicle types. Here the correlation ranges from over 0.80 for 4-door cars, pickups, and SUVs, to less than 0.70 for CUVs and 2-door cars, to only 0.26 for minivans. The correlation of 0.65 for all light trucks (pickups and SUVs) combined in Figure 3.1 is improved when these two types of trucks are analyzed separately in

Figure 3.1. Correlation between vehicle curb weight and footprint, by vehicle model and three vehicle types

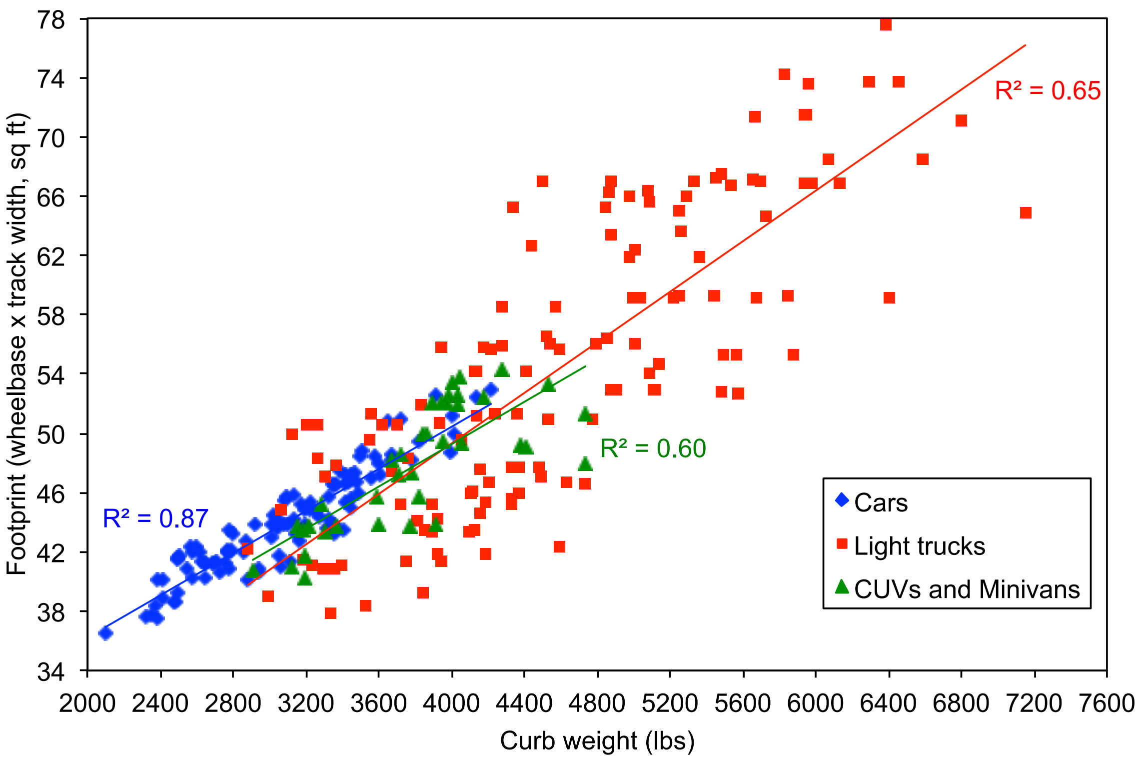


Figure 3.2: 0.86 for pickups and 0.81 for SUVs in Figure 3.2. On the other hand, separating CUVs from minivans improves the correlation between curb weight and footprint for CUVs (0.66) but not for minivans (0.26). The correlation is so poor for minivans in part because of the Kia Sedona, which has a much higher weight (4,730 lbs) for its footprint (51.3 sq ft) than other minivans; removing this model improves the correlation for minivans to 0.78.

Figure 3.2. Correlation between vehicle curb weight and footprint, by vehicle model and seven vehicle types

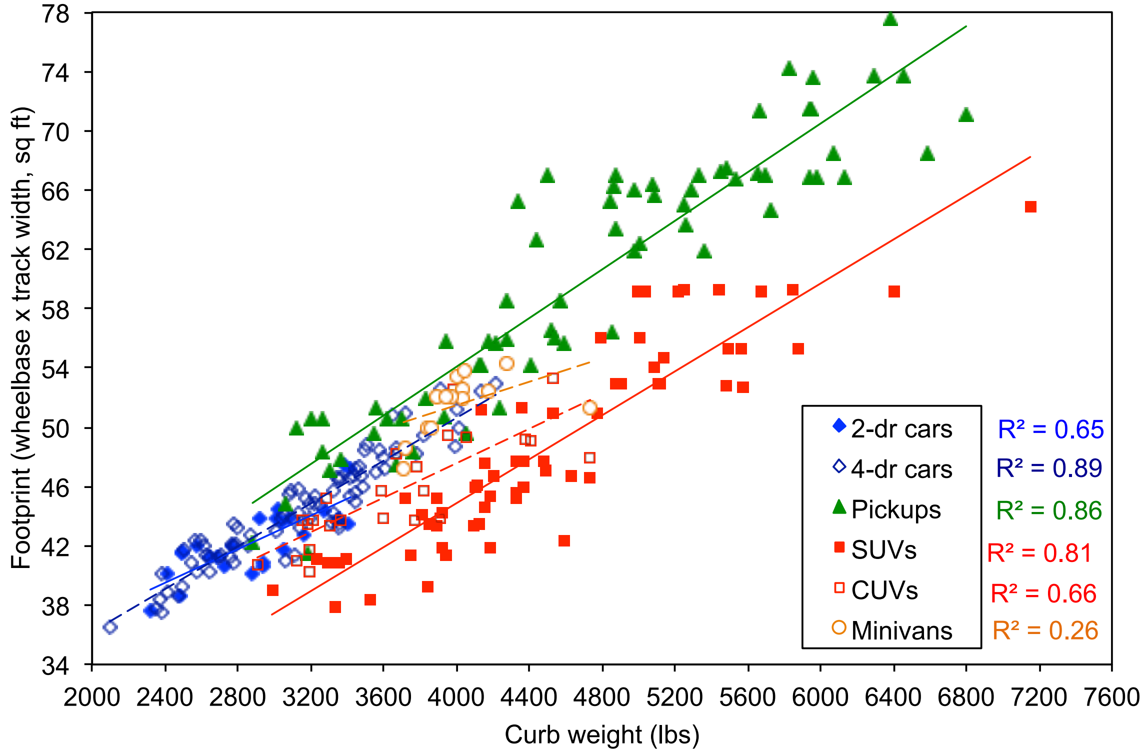
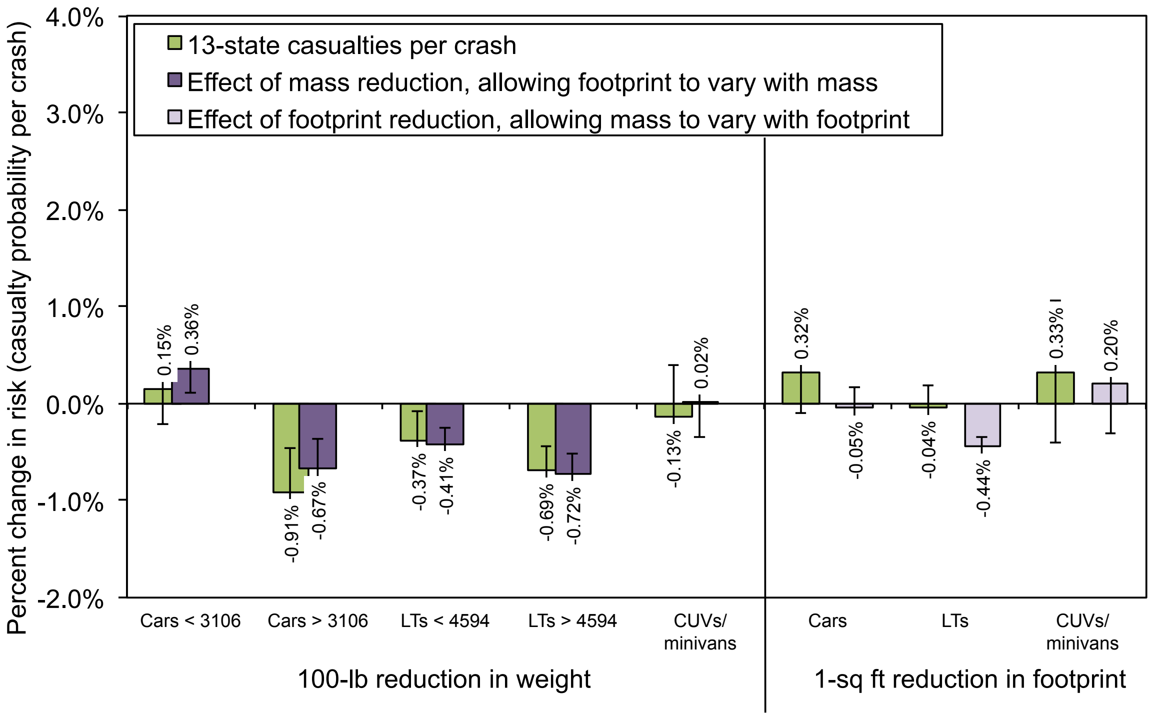


Figure 3.3 compares the results from the regression models for 13-state casualty risk per crash, in light green from Figure 2.5, with two alternative model specifications to test the sensitivity of the results. The first sensitivity, in dark purple, includes the weight variables in the regression model but excludes the footprint variable; this model tests the effect of mass reduction while allowing footprint to vary with vehicle mass. This sensitivity slightly increases the risk from a 100-lb mass reduction in lighter cars (from 0.15% to 0.36%) and CUVs/minivans (from a 0.13% decrease in risk to a 0.02% increase in risk), and reduces the beneficial effect of mass reduction in heavier cars (from a 0.91% to a 0.67% reduction in risk); however, there is essentially no change in casualty risk per crash in light-duty trucks. The effects of mass reduction when footprint is allowed to vary with mass for casualty risk per crash are quite different from the effects for fatality risk per VMT. In an earlier analysis (Figure 3.3, LBNL, 2011a), we showed that mass reduction results in much larger increases in fatality risk per VMT when footprint is allowed to vary with mass, than when footprint is held constant, at least for cars and CUVs/minivans. Here, with risk measured as casualty risk per crash, mass reductions result in only slightly larger increases in risk when footprint is allowed to vary with mass (shown in dark purple), than when footprint is held constant (shown in green).

Figure 3.3. Effect of reduction in mass or footprint on 13-state casualty risk per crash, by vehicle type: holding footprint constant, allowing footprint to vary with mass, and allowing mass to vary with footprint

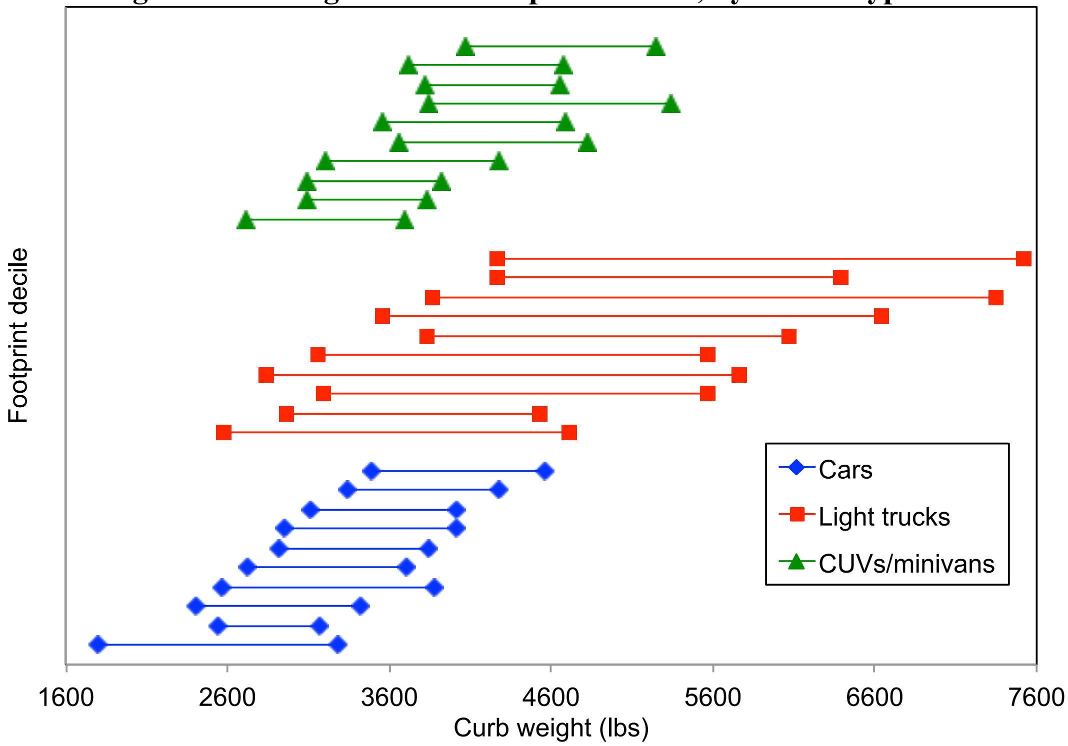


The second sensitivity keeps footprint in the regression model, but removes mass, and is shown in light purple in Figure 3.3. Allowing vehicle mass to be reduced with footprint reduces the effect of footprint reduction on casualty risk per crash in all three vehicle types: from a 0.32% increase to a 0.05% decrease in risk for cars, from a 0.04% decrease to a 0.44% decrease in risk for light trucks, and from a 0.33% increase to a 0.20% increase for CUVs/minivans. Figure 3.3 suggests that including both mass and footprint in the same regression model results in only slight changes in the effect of mass and footprint reductions on casualty risk per crash.

In its 2011 analysis NHTSA examined the relationship between curb weight and fatality risk for deciles of vehicles with roughly the same footprint. Figure 3.4 shows the range in curb weights for the footprint deciles NHTSA used for the three vehicle types. The figure shows that there is a large degree of overlap in the curb weights of vehicles with roughly the same footprint; this is an indication that the correlation between curb weight and footprint may be strong but is not absolute.

NHTSA ran a new regression model with all of the control variables except footprint, for each crash and vehicle type, and footprint decile, a total of 270 regression models; the two mass variables, UNDERWT00 and OVERWT00, originally used for cars and light trucks were replaced by a single mass variable LBS100. NHTSA listed the number of the regression models for the ten footprint deciles in which the regression coefficient on vehicle mass was positive; that is, where a mass reduction would be harmful and increase fatality risk.

Figure 3.4. Range in curb weight for the footprint deciles, by vehicle type



We replicate this analysis for 13-state casualty risk in Table 3.1, which includes the number of footprint deciles in which the coefficient on vehicle mass is statistically significant. There are four columns for each vehicle type in Table 3.1; the first two indicate the number of footprint deciles in which a reduction in vehicle mass increases casualty risk per crash, and the number that are statistically significant. Red print indicates cases in which three or more footprint deciles have significant coefficients. The second two columns for each vehicle type indicate the number of footprint deciles in which a reduction in vehicle mass reduces casualty risk per crash, and the number that are statistically significant. For example, in car rollover crashes, mass reduction increases casualty risk in six footprint deciles, but only one of those increases is statistically significant. On the other hand, light truck mass reduction reduces casualty risk in rollover crashes in five footprint deciles, and four of those five are statistically significant. Table 3.1 indicates that mass reduction does not consistently result in increased casualty risk for vehicles with similar footprint. Mass reduction increases casualty risk in a majority of footprint deciles for 10 of the 27 crash and vehicle combinations, but few of these increases are statistically significant. On the other hand, mass reduction reduces risk in a majority of footprint deciles for 14 of the 27 crash and vehicle combinations, although few of these reductions are statistically significant.

Table 3.1. Number of footprint deciles in which mass reduction increases or decreases 13-state casualty risk per crash, by vehicle and crash type

	Cars				Light trucks				CUVs/Minivans			
Crash type	Number of deciles with increasing risk	Number of deciles with estimates that are statistically significant	Number of deciles with decreasing risk	Number of deciles with estimates that are statistically significant	Number of deciles with increasing risk	Number of deciles with estimates that are statistically significant	Number of deciles with decreasing risk	Number of deciles with estimates that are statistically significant	Number of deciles with increasing risk	Number of deciles with estimates that are statistically significant	Number of deciles with decreasing risk	Number of deciles with estimates that are statistically significant
1: Rollovers	6	1	4	1	5	4	5	2	4	0	6	2
2: w/object	2	1	8	1	6	2	4	0	5	0	5	0
3: w/ped etc.	3	0	7	1	2	0	8	1	4	1	6	2
4: w/HDT	3	2	7	1	6	2	4	0	6	1	4	0
5: w/lgt car	7	1	3	2	6	3	4	2	5	0	5	1
6: w/hvy car	4	1	6	3	4	1	6	4	7	1	3	0
7: w/lgt LT	4	2	6	2	1	0	9	2	7	0	3	0
8: w/hvy LT	4	2	6	2	8	2	2	1	3	2	7	2
9: Other	2	1	8	4	3	2	7	2	6	3	4	2

The data in Table 3.1 give no information on the size of the effect of mass reduction on casualty risk per crash in the footprint deciles. Figures 3.5 through 3.7 show the percent change in casualty risk from mass reduction for each footprint decile, by vehicle type, for six of the nine crash types (rollovers, and crashes with stationary objects, cars, and light trucks). Figure 3.5 indicates that mass reduction increases casualty risk in car rollover crashes by about 15% in deciles nine and ten, but reduces casualty risk by nearly 35% in decile eight. Figure 3.7 indicates that mass reduction in CUVs/minivans reduces casualty risk in rollovers in six of the footprint deciles, and that these reductions are quite large (over 40%), and statistically significant, for footprint deciles four, nine and ten. Figures 3.5 through 3.7 suggest that there are no consistent trends in the effect of mass reduction on risk when vehicles are grouped by footprint decile.

Figure 3.5. Effect of car mass reduction on 13-state casualty risk per crash, by footprint decile and crash type

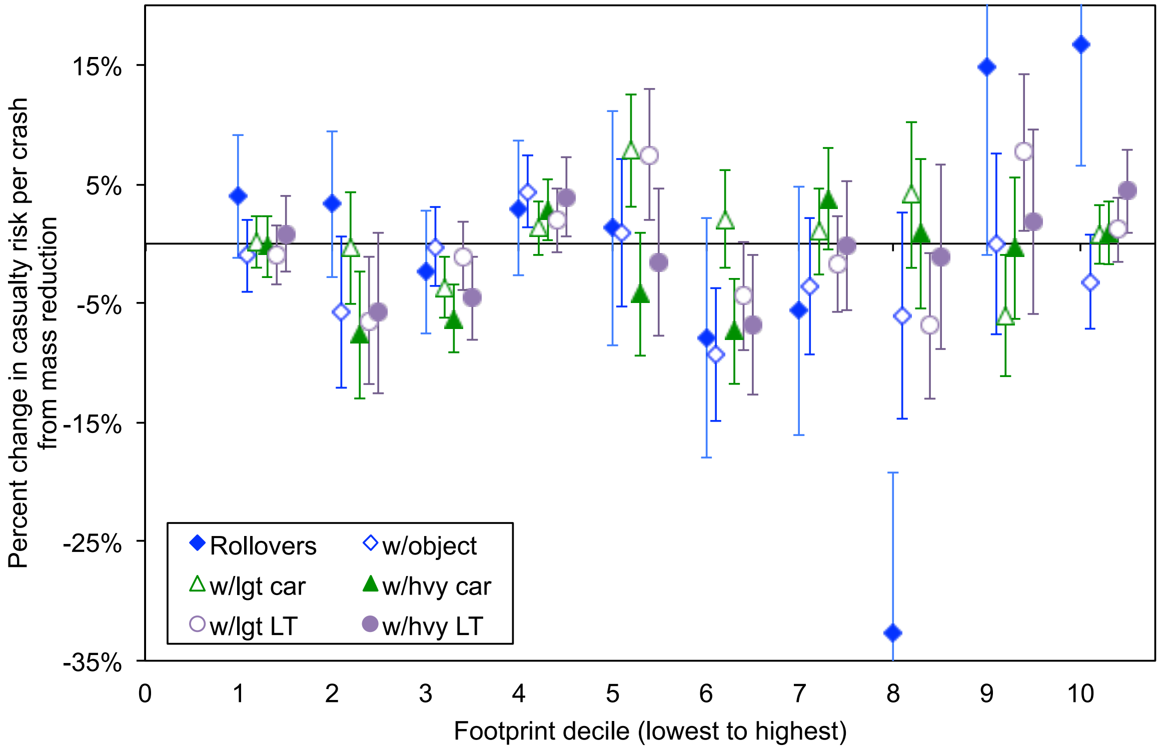


Figure 3.6. Effect of light truck mass reduction on 13-state casualty risk per crash, by footprint decile and crash type

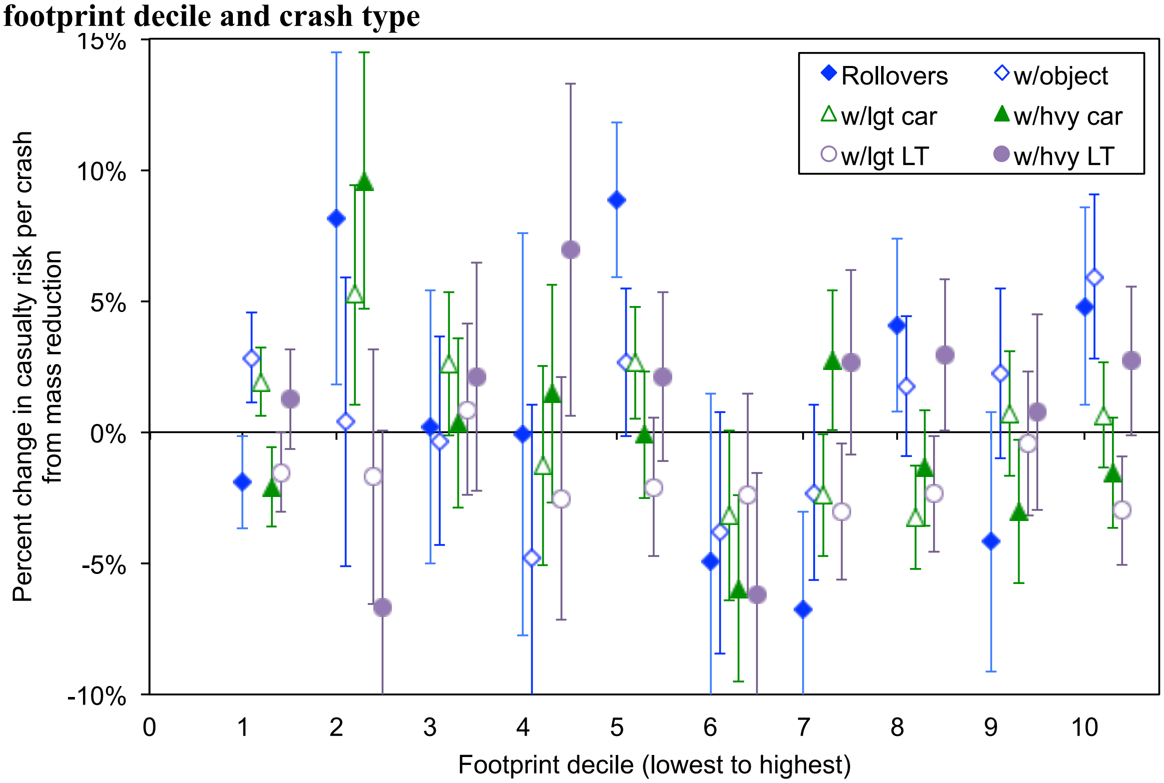
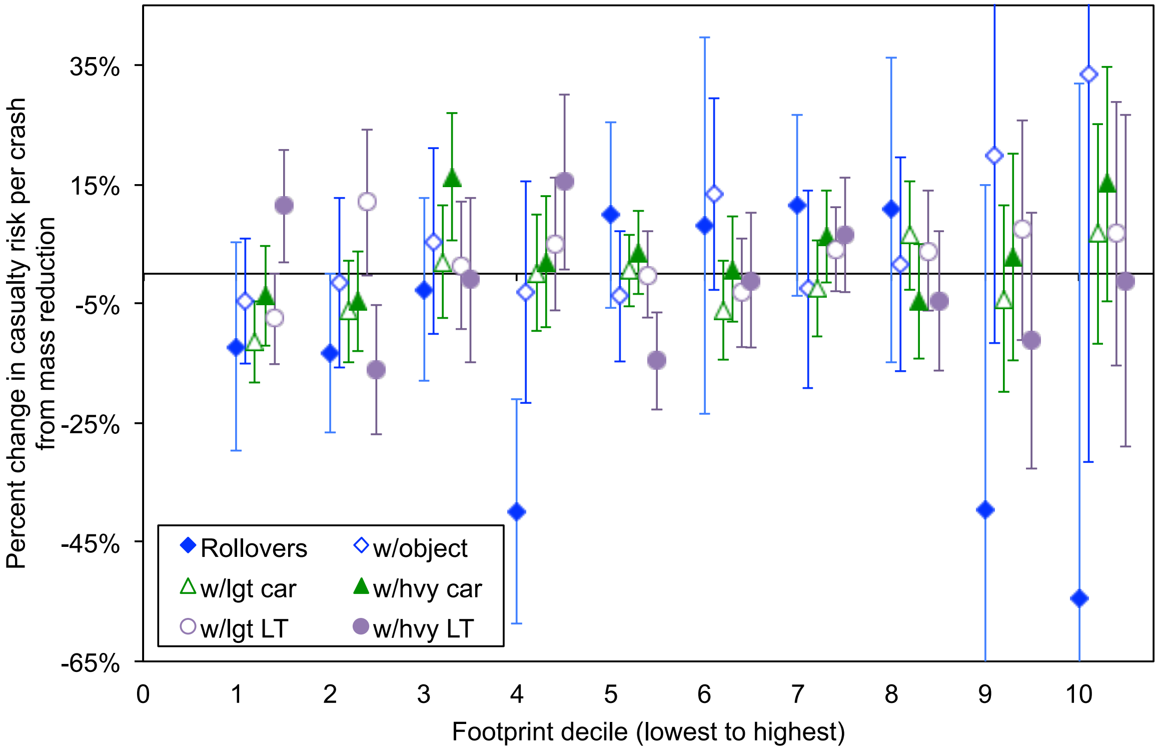


Figure 3.7. Effect of CUV/minivan mass reduction on 13-state casualty risk per crash, by footprint decile and crash type



4. Casualty risk by vehicle model

In this section we examine the variance in societal casualty risk by average vehicle mass and by vehicle model, both before and after accounting for the vehicle, driver and crash variables NHTSA includes in its regression models of US fatality risk per VMT. Figure 4.1 plots unadjusted 13-state casualty risk per crash against average curb weight, with vehicles grouped into 100-lb increments of vehicle curb weight. Figure 4.1 indicates that casualty risk per crash decreases slightly as curb weight increases for light trucks less than 5,900 lbs, and increases with increasing mass for light trucks greater than 5,900 lbs; there is no trend between car mass and casualty risk. There also is a large degree of variability for cars, the lighter light trucks, and CUVs/minivans, as indicated by the R^2 values below 0.20.

Figures 4.2 through 4.4 show the relationship between unadjusted casualty risk per crash and mass by more detailed vehicle type. Figure 4.2 indicates that the relationship between curb weight and casualty risk per crash is weaker for 4-door cars than for 2-door cars, with risk actually increasing with increasing mass for 4-door cars between 3,600 and 4,200 lbs. Figure 4.3 suggests that for large pickups (3/4- and 1-ton pickups) casualty risk increases as curb weight increases. And Figure 4.4 indicates that the relationship between casualty risk and curb weight is strong. with a dramatic reduction in casualty risk as mass increases and a relatively high degree of correlation, for minivans, and CUVs when they are divided into those below and above 3,600 lbs.

Figure 4.1. Relationship between 13-state casualty risk per crash and curb weight, with vehicles grouped into 100-lb increments of curb weight, by vehicle type

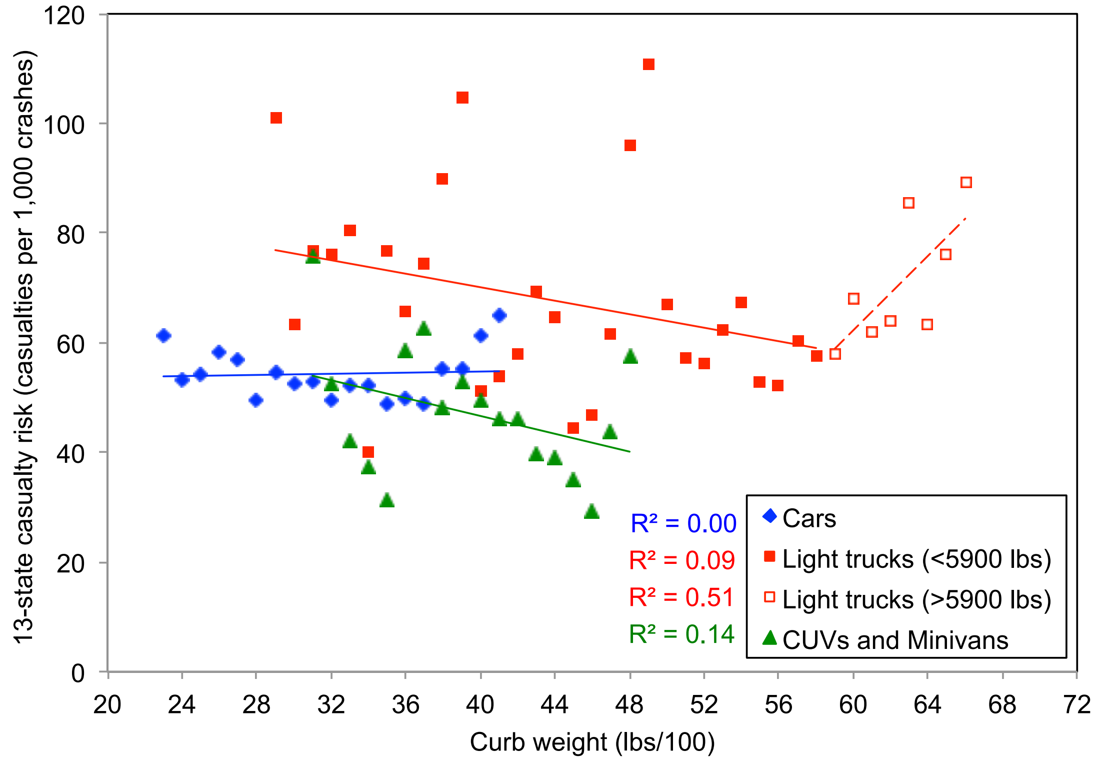


Figure 4.2. Relationship between 13-state casualty risk per crash and curb weight, with vehicles grouped into 100-lb increments of curb weight, passenger cars

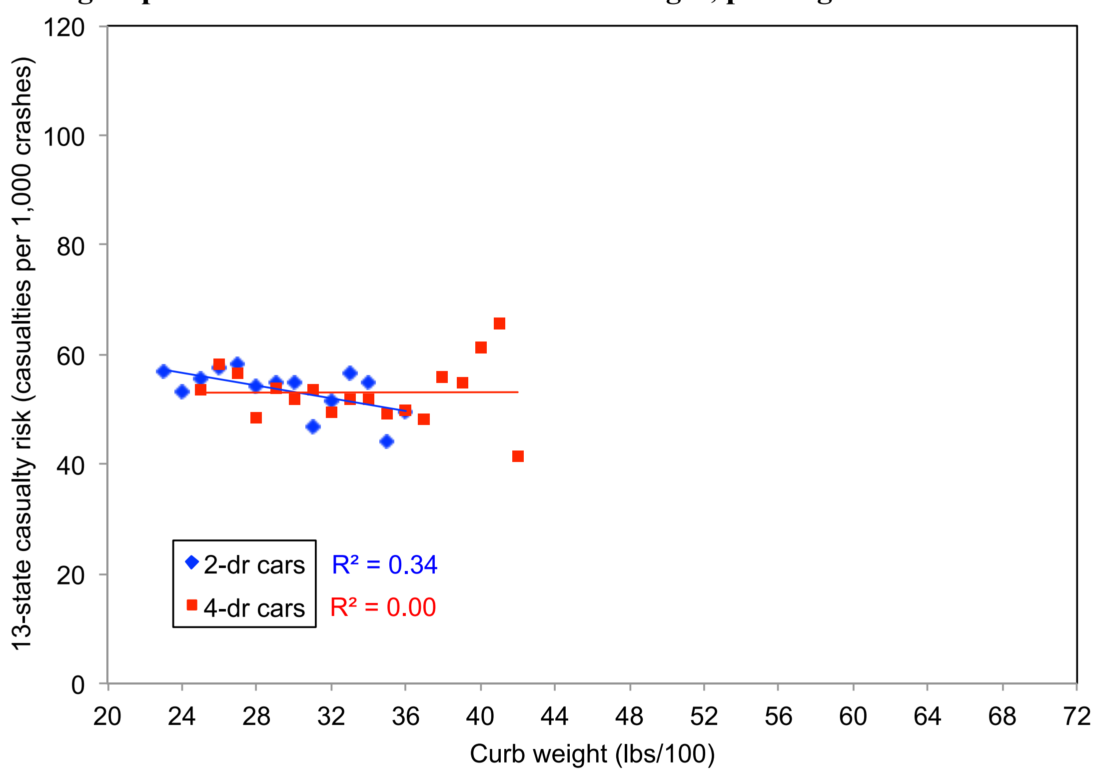


Figure 4.3. Relationship between 13-state casualty risk per crash and curb weight, with vehicles grouped into 100-lb increments of curb weight, light trucks

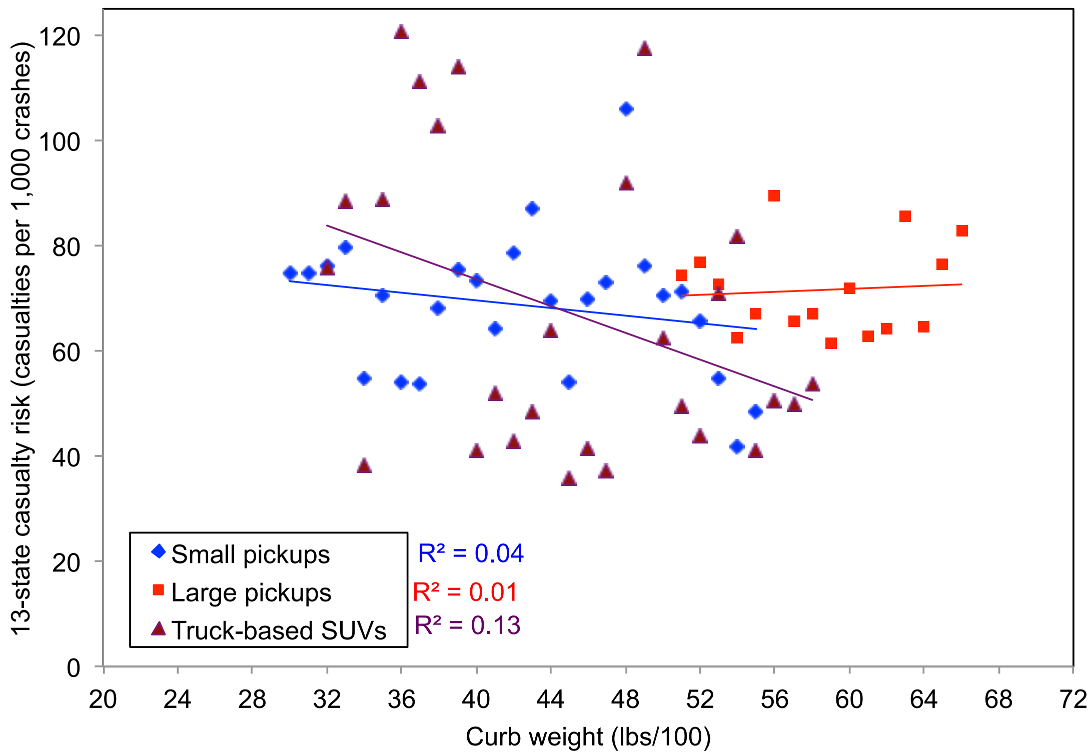


Figure 4.4. Relationship between 13-state casualty risk per crash and curb weight, with vehicles grouped into 100-lb increments of curb weight, CUVs and minivans

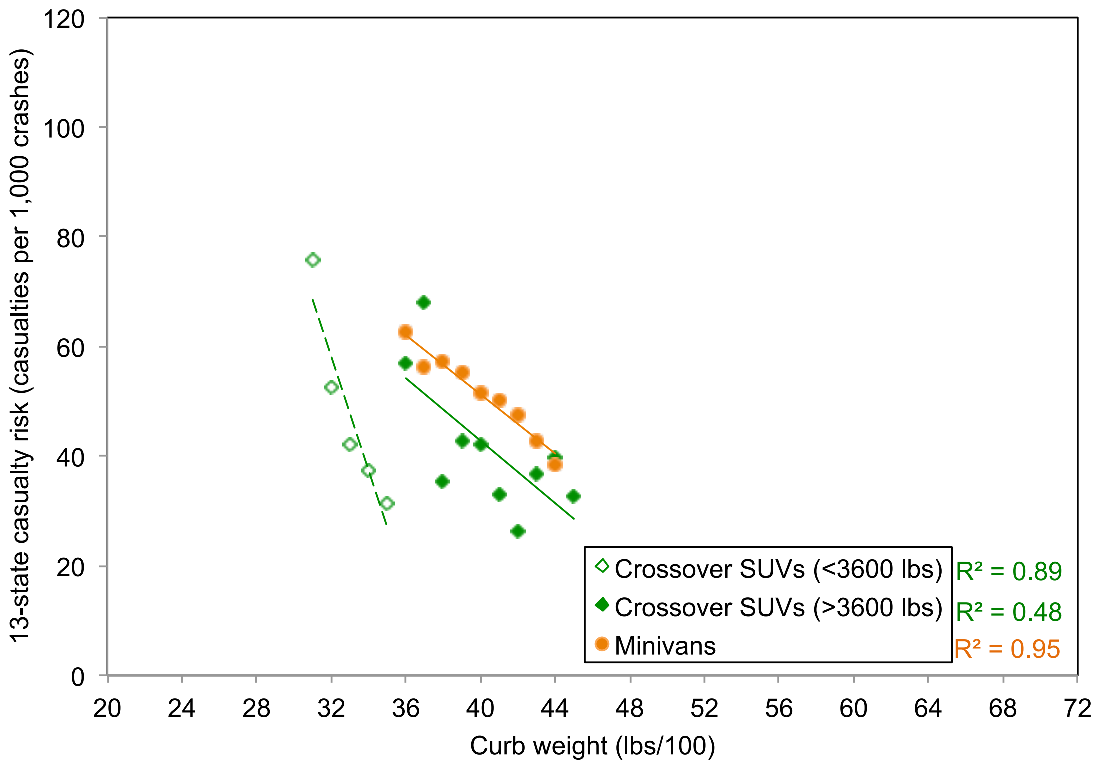
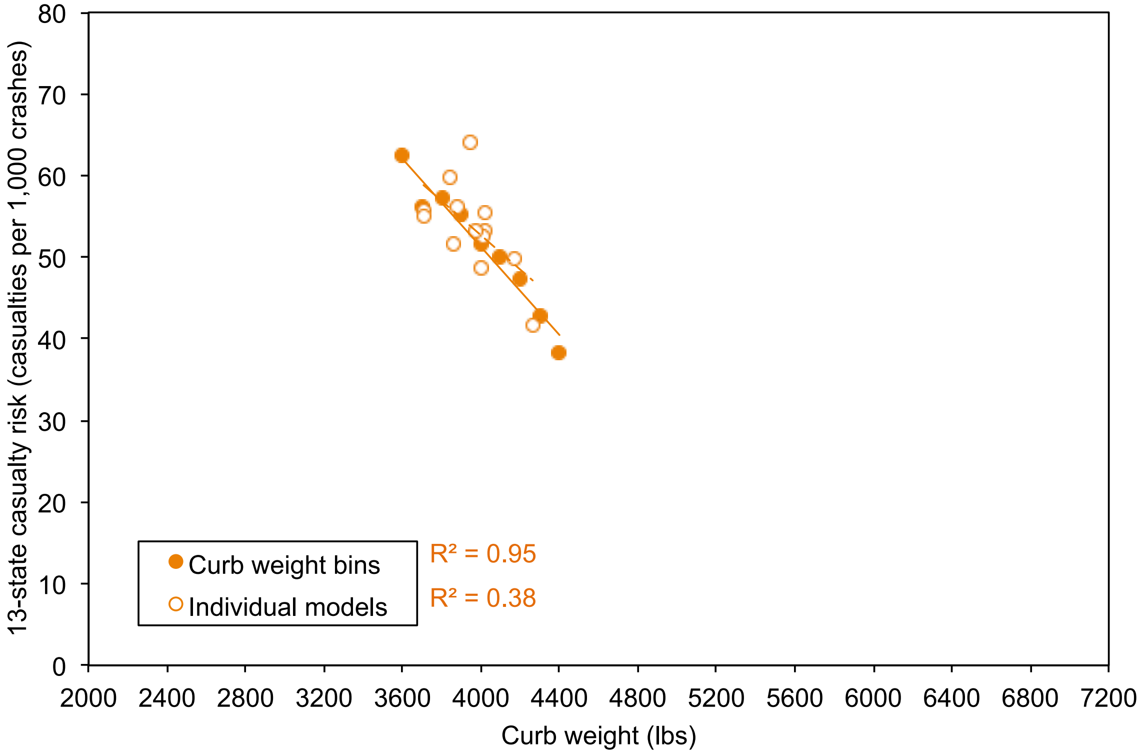


Figure 4.5 shows the danger of using the average risks of groups of individual models, such as by curb weight bins. The filled symbols in the figure represent the relationship between minivan casualty risk and curb weight when the data are grouped into bins of curb weight, from Figure 4.4; this analysis shows a high correlation between risk and curb weight. However, if the relationship between risk and curb weight of the 13 most popular individual minivan models, which represent over 90% of the minivan casualties and crashes, are plotted, the correlation is much lower, with the R^2 dropping to 0.38.[7]

Figure 4.5. Relationship between 13-state casualty risk per crash and curb weight for minivans, by average risk for 100-lb increments of curb weight and individual models



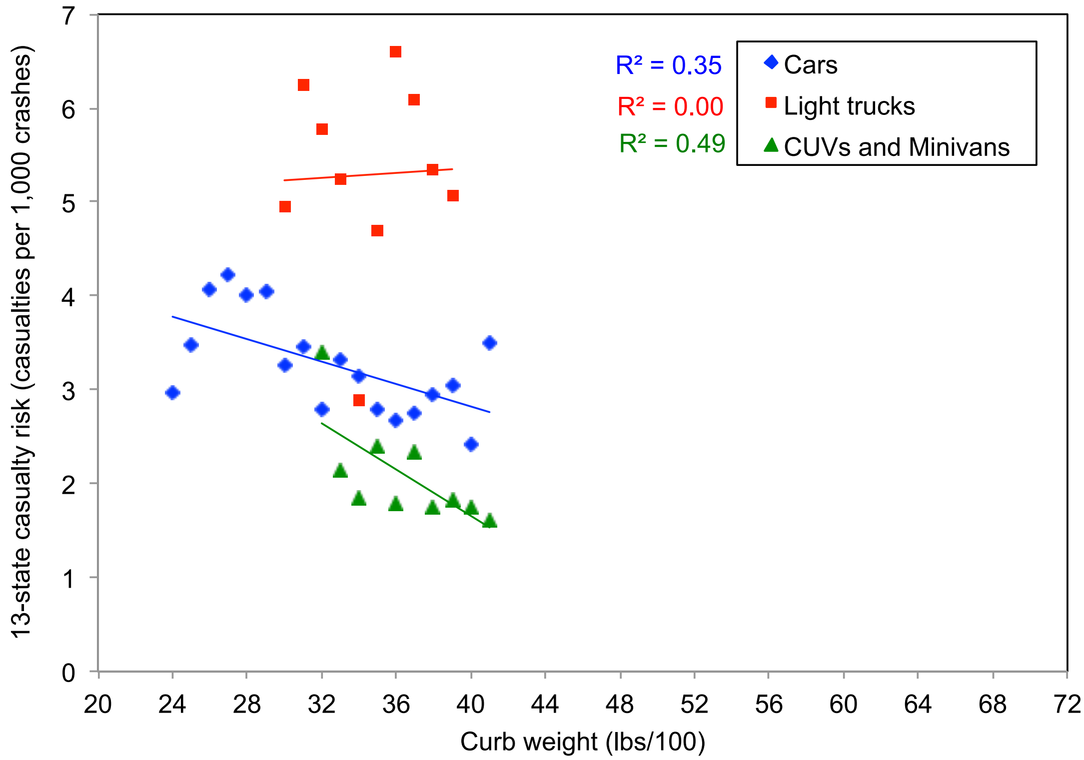
It is possible that the relationship between vehicle mass and casualty risk is stronger in certain types of crashes. Figure 4.6 presents the relationship between 100-lb increments in curb weight and casualty risk in one-vehicle crashes with a stationary object, the type of crash in which vehicle mass is thought to provide occupants the most protection. For cars and CUVs/minivans, casualty risk in crashes with stationary objects does decline as mass increases; the strength of this relationship is greater in crashes with stationary objects than in all types of crashes (Figure 4.1). In the case of light trucks, there is no relationship or correlation between casualty risk in crashes with stationary objects and mass.

Note that, for a given vehicle weight, light trucks have a higher casualty risk per crash in crashes with stationary objects than cars or CUVs/minivans. Since there are no crash partner casualties in crashes with stationary objects, we suspect that light trucks have a higher risk than cars in Figure

[7] Figure 4.5 actually excludes one additional popular minivan model, which has the highest casualty risk (67 per 1,000 crashes) and weight (4,741 lbs) of the minivan models shown; including this model would make the correlation between casualty risk and curb weight even lower.

4.6 because of their tendency to roll over, their increased use on more dangerous rural roads, and perhaps more passenger casualties in light trucks than in cars.

Figure 4.6. Relationship between 13-state casualty risk per crash in crashes with stationary objects and curb weight, by vehicle type

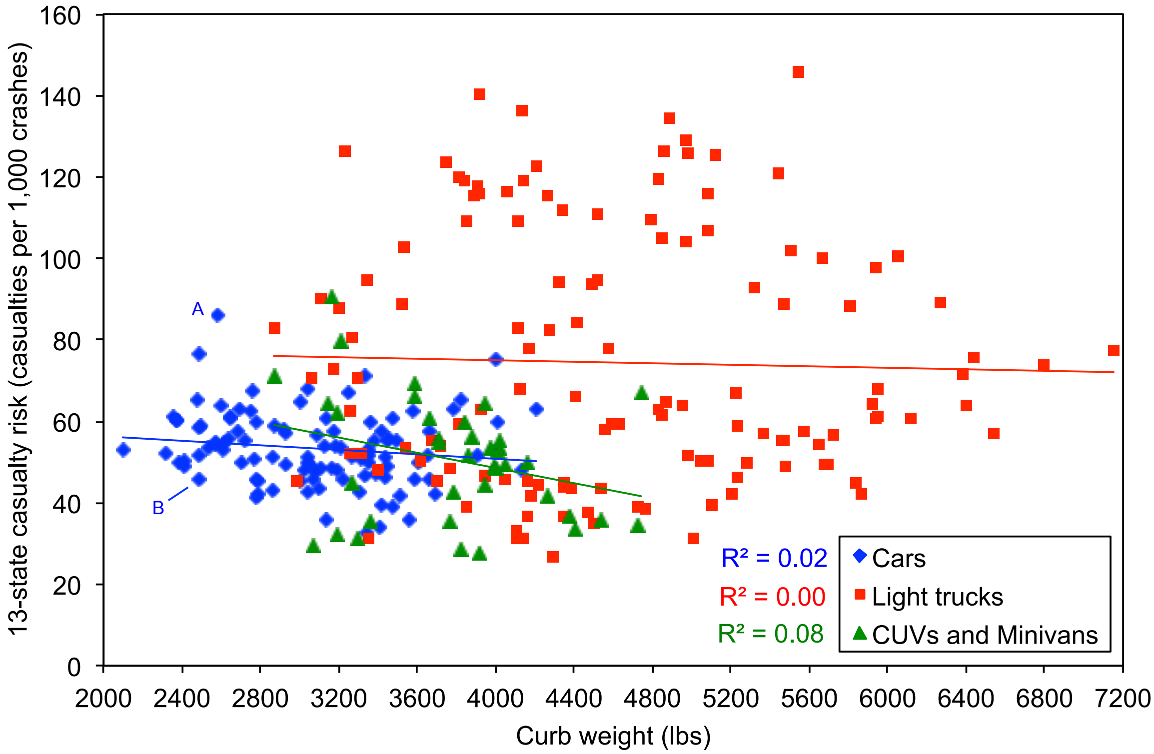


Figures 4.1 through 4.6 show that grouping vehicles into 100-lb mass increments indicates that, for some vehicle types, casualty risk per crash decreases as mass increases. Figure 4.7 shows the relationship between vehicle mass and casualty risk by individual vehicle model. Only 275 models with at least 10 billion VMT, or at least 100 fatalities, based on the NHTSA 2011 analysis, are included (106 car models, 131 light truck models, and 38 CUV/minivan models); these models represent over 90% of all casualties and crashes. Here we see that casualty risk declines slightly with increasing mass for cars, light trucks, and CUVs/minivans.

Although casualty risk gradually declines with increasing mass, the extremely low R^2 values (all less than 0.10) indicate that there is essentially no relationship between mass and casualty risk per crash, for any of the three types of vehicles, and that there is a very large range in casualty risk for individual vehicle models at a given weight. For example, the vehicle model labeled A in the figure, which weighs 2,579 lbs, has a casualty risk of 86 per 1,000 crashes, while model B, which weighs slightly less (2,487 lbs), has a casualty risk of only 46.

Of course, differences in vehicles (footprint, two- vs. four-doors, and presence of side impact air bags, automated braking systems, or electronic stability controls), drivers (age and gender), and crash characteristics (at night, on high-speed roads, or in rural vs. urban areas or high-casualty risk states) by vehicle model may explain some of the large range in casualty risk by vehicle

Figure 4.7. 13-state casualty risk per crash and curb weight, by vehicle model



weight. To account for these various variables, we reran the logistic regression models including all of the driver, crash, and vehicle control variables except vehicle mass and footprint, across all types of crashes for each of the three vehicle types. We then calculated the predicted casualty risk per crash for each vehicle in the 13-state crash database. We multiplied the logistic regression coefficients for all driver, crash, and vehicle variables except mass and footprint by the characteristics of each vehicle, to obtain the predicted number of casualties per vehicle, and then summed across vehicle make and model. We then divided the total number of predicted fatalities in each make and model by the number of crashes for that make and model, to obtain predicted risk, the number of predicted casualties per police-reported crash. We exclude footprint as well as mass in the predicted risks we calculate from the regression coefficients, as the two vehicle attributes are moderately correlated.

While Figure 4.7 shows the unadjusted casualty risks by vehicle modes, Figure 4.8 shows the risks predicted by the regression model coefficients for all control variables except vehicle mass and footprint. Figure 4.8 indicates that, after controlling for the all of the driver, crash, and vehicle variables used in the logistic regression model except vehicle mass and footprint, there still is a large range in casualty risk per crash across vehicle models of similar weight, for all three vehicle types. Figure 4.9 shows the remaining residual, or unexplained, casualty risks after accounting for all variables except vehicle mass and footprint. In essence Figure 4.9 shows that there is no relationship between vehicle mass and the remaining, unexplained casualty risk after accounting for driver, crash and all other vehicle attributes.

Figure 4.8. Predicted 13-state casualty risk per crash after accounting for all driver, crash, and vehicle variables except mass and footprint, vs. curb weight

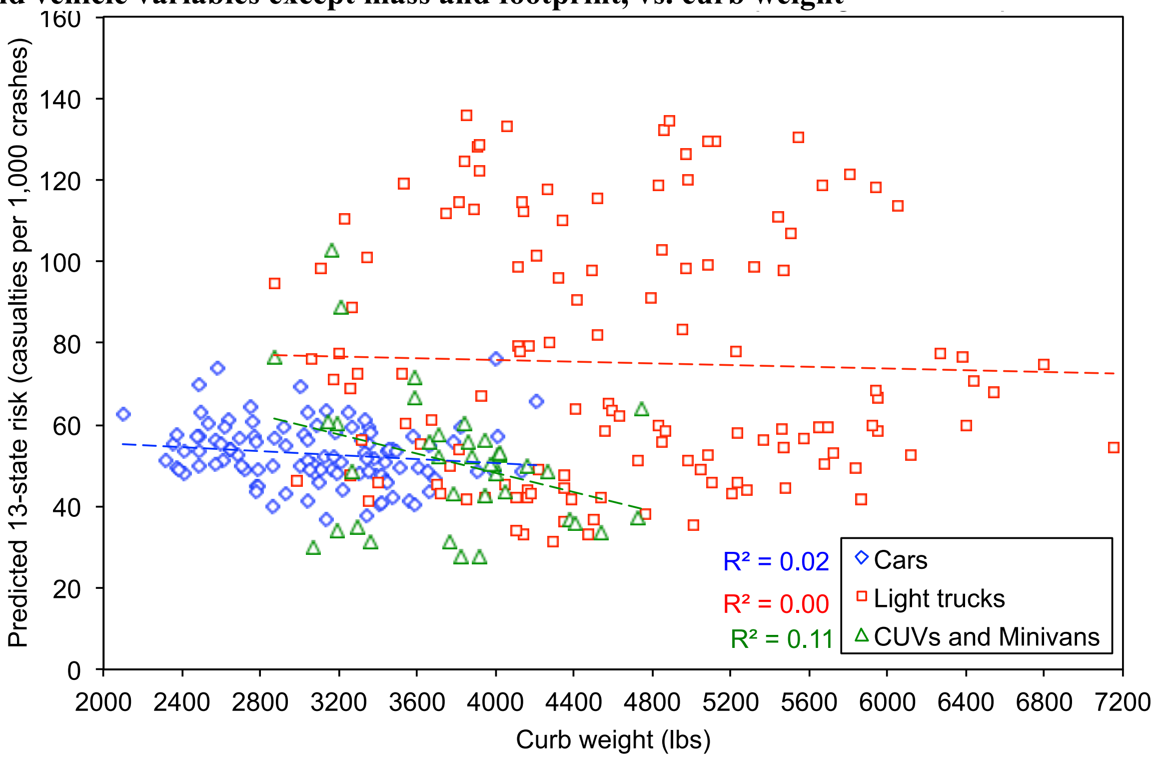


Figure 4.9. Residual 13-state casualty risk per crash after accounting for all driver, crash, and vehicle variables except mass and footprint, vs. curb weight

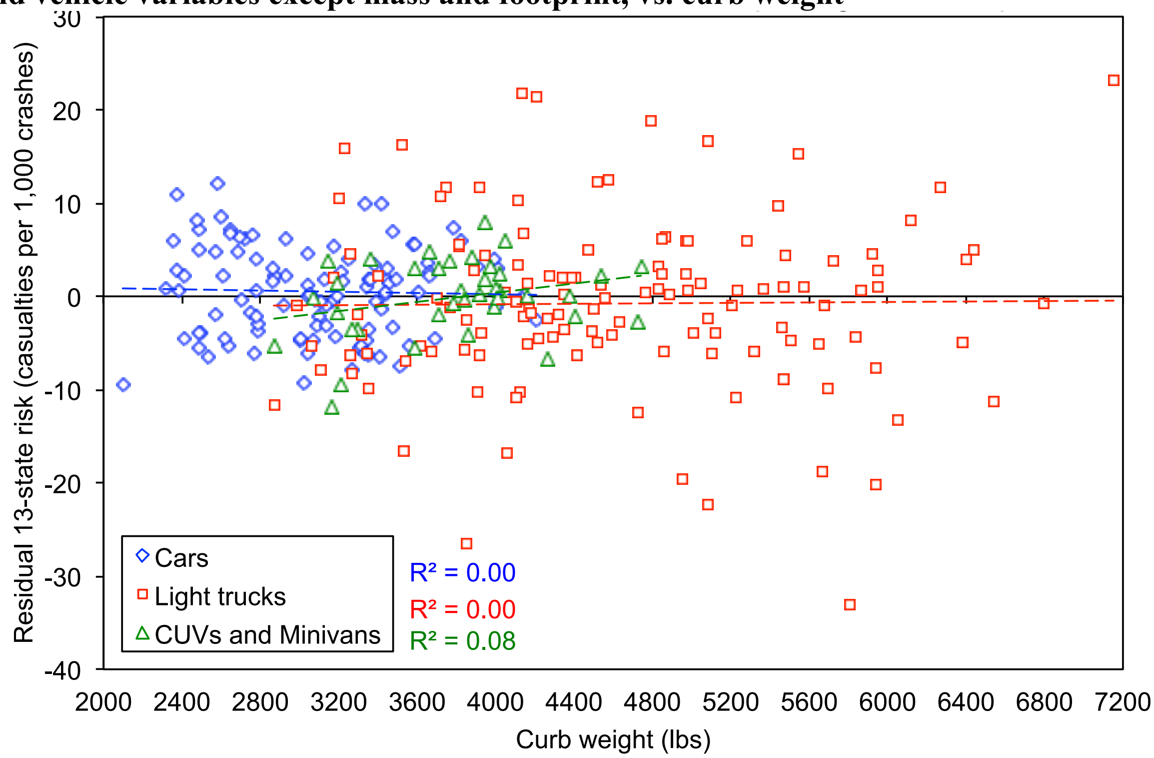


Table 4.1 summarizes the relationships between predicted and residual casualty risk and vehicle curb weight that are presented in Figures 4.7 through 4.9. In addition to the correlation between casualty risk and curb weight, the table shows the slope of the linear regression line drawn through the risks by vehicle model, which represents the percent change in casualty risk per 100-pound reduction in mass or 1-square foot reduction in footprint. The relationship for the three vehicle types is shown at the top of the table, followed by those for the seven detailed vehicle subtypes (with small, i.e. compact and ½-ton, pickups shown separately from heavy-duty, i.e. ¾- and 1-ton, pickups), and finally the five vehicle type and weight groups NHTSA used in its regression analyses. Cases where there is a positive relationship between casualty risk and vehicle mass reduction, i.e. where mass reduction leads to reduction in casualty risk, are shown in red in the table; there are no cases where the correlation between risk and weight by vehicle model exceeds 0.30.

Table 4.1 indicates that casualty risk consistently increases as mass is reduced for almost all vehicle types, although the correlation between casualty risk and weight is negligible in almost all cases. The exception is CUVs, where casualty risk increases by 1.6% per 100-lbs of mass reduction, with the correlation between actual and predicted casualty risk and mass is moderate, with an R^2 of over 0.21. Table 4.2 presents the same information as Table 4.1, but for the relationship between casualty risk and vehicle footprint reduction, with the similar results: casualty risk increases slightly as footprint is reduced, with negligible correlation between casualty risk and footprint reduction.

Table 4.1. Relationship between actual, predicted, and residual 13-state casualty risk per crash, and vehicle <u>mass</u> reduction, after accounting for all driver, crash, and vehicle variables except mass and footprint, by vehicle type and model

Vehicle type	Actual 13-state casualty risk per crash		Predicted risk		Residual risk	
	R^2	Slope	R^2	Slope	R^2	Slope
Cars	0.02	0.3%	0.02	0.2%	0.00	0.0%
Light trucks	0.00	0.1%	0.00	0.1%	0.00	0.0%
CUVs/minivans	0.08	0.9%	0.11	1.2%	0.08	-0.2%
2-dr cars	0.02	0.3%	0.02	0.2%	0.00	0.0%
4-dr cars	0.02	0.3%	0.02	0.2%	0.00	0.1%
Small pickups	0.00	0.1%	0.03	0.6%	0.26	-0.5%
Heavy-duty pickups	0.00	0.1%	0.03	0.9%	0.11	-0.8%
SUVs	0.00	0.2%	0.00	0.3%	0.01	-0.1%
CUVs	0.21	1.6%	0.22	1.9%	0.08	-0.3%
Minivans	0.03	-0.4%	0.05	-0.4%	0.00	0.0%
Cars < 3106	0.07	1.0%	0.04	0.6%	0.03	0.4%
Cars > 3106	0.06	-0.8%	0.04	-0.6%	0.03	-0.3%
LTs < 4594	0.00	0.4%	0.01	0.6%	0.02	-0.2%
LTs > 4594	0.01	0.6%	0.02	0.7%	0.00	-0.1%
CUVs/ minivans	0.08	0.9%	0.11	1.2%	0.08	-0.2%

Table 4.2. Relationship between actual, predicted, and residual 13-state casualty risk per crash, and vehicle footprint reduction, after accounting for all driver, crash, and vehicle variables except mass and footprint, by vehicle type and model

Vehicle type	Actual 13-state casualty risk per crash		Predicted risk		Residual risk	
	R^2	Slope	R^2	Slope	R^2	Slope
Cars	0.02	0.3%	0.02	0.3%	0.00	0.1%
Light trucks	0.01	-0.3%	0.01	-0.3%	0.01	0.1%
CUVs/minivans	0.00	0.0%	0.01	0.3%	0.07	-0.3%
2-dr cars	0.03	0.4%	0.00	0.1%	0.03	0.4%
4-dr cars	0.02	0.3%	0.02	0.3%	0.00	0.0%
Small pickups	0.03	-0.5%	0.00	-0.1%	0.17	-0.4%
Heavy-duty pickups	0.15	-1.7%	0.12	-2.0%	0.01	0.3%
SUVs	0.01	-0.6%	0.01	-0.5%	0.02	-0.2%
CUVs	0.04	1.0%	0.05	1.3%	0.06	-0.3%
Minivans	0.14	1.2%	0.28	1.2%	0.00	0.0%
Cars < 3106	0.10	1.4%	0.02	0.5%	0.11	0.9%
Cars > 3106	0.05	-0.8%	0.02	-0.4%	0.07	-0.4%
LTs < 4594	0.01	-0.5%	0.01	-0.6%	0.00	0.1%
LTs > 4594	0.01	-0.3%	0.01	-0.5%	0.02	0.2%
CUVs/ minivans	0.00	0.0%	0.01	0.3%	0.07	-0.3%

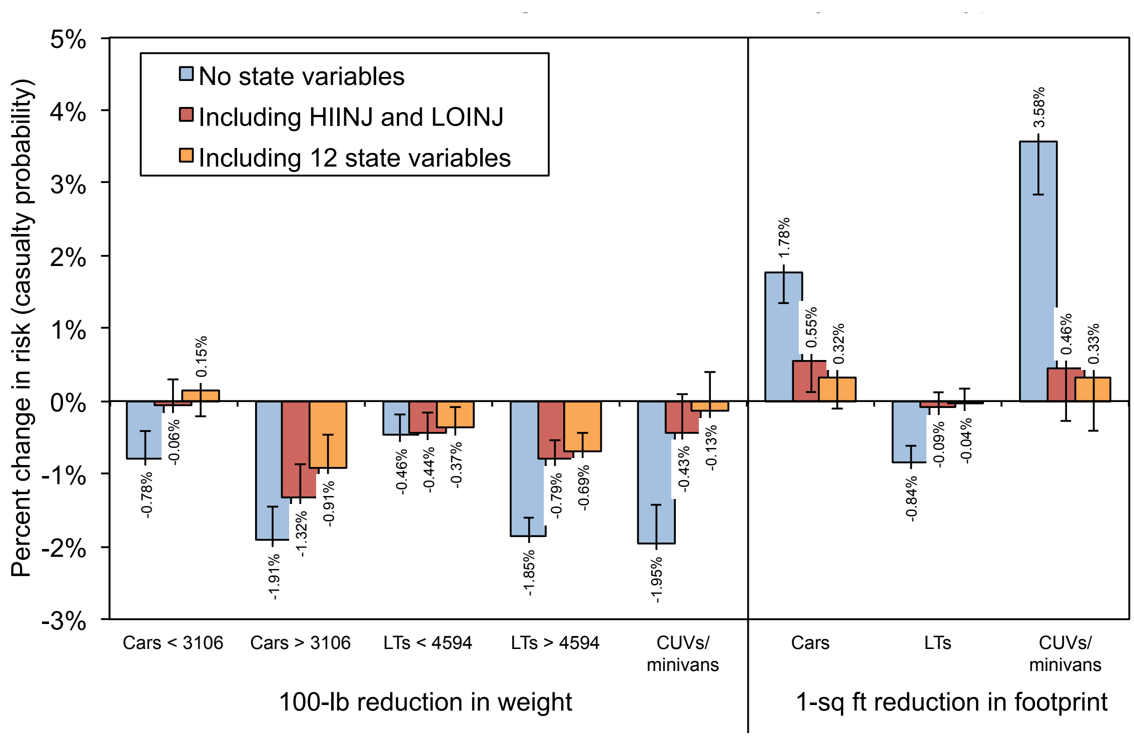
5. Sensitivity of 13-state casualty risk per crash results to data used and model specification

In this section we examine the sensitivity of our results on the effect of mass and footprint on 13-state casualty risk per crash. We examine the effect of different methods of accounting for the state in which the crash occurred, and how the effect of mass or footprint reduction changes after accounting for vehicle manufacturer, after excluding the calendar year control variables, and after adding additional data to the analysis.

5.1. State control variables

As discussed above, we included 12 control variables to account for the different reporting requirements in each state, as well as other differences in risk per crash among states. Figure 5.1 compares the effect of this approach with two other approaches: not accounting for state at all in the analysis, and using only two control variables, HIINJ and LOINJ, to identify states with relatively high (Alabama, Florida, Maryland, and Wyoming,) and relatively low (Michigan, New Jersey, and Washington) casualty risk per crash (see Figure 2.3, above). Figure 5.1 indicates that mass reduction has a much larger beneficial effect, and footprint reduction a much more detrimental effect in cars and CUVs/minivans, when one excludes the state in which the crash occurred from the regression models (shown in blue). Including only the two variables to control for state, HIINJ and LOINJ, substantially reduces the effect of mass and footprint reduction on casualty risk per crash (shown in red); including the 12 control variables for individual states reduces the effect a little bit more (shown in orange).

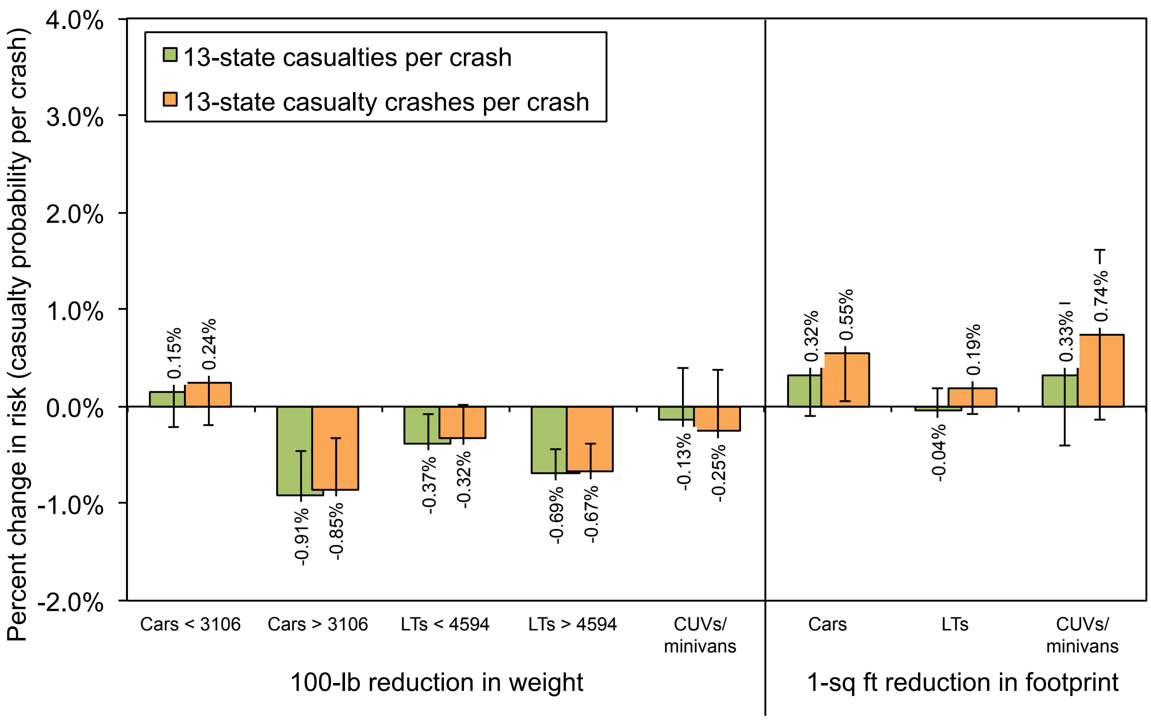
Figure 5.1. Effect of mass and footprint reduction on 13-state casualty risk per crash by vehicle type, under three methods of controlling for the state in which the crash occurred



5.2. Alternative measure of exposure

Figure 5.2 compares the effect of mass and footprint reduction on the risk of a casualty crash, rather than the risk of all casualties that occurred in the crash. In other words, the casualty crash cases are not weighted by the total number of casualties, either in the case vehicle or in its crash partner. In his review of the previous NHTSA studies, Paul Green suggested that analyzing risk at the crash, rather than person, level might be a better approach; each fatal case would be a single independent observation, and may serve to increase any under-estimation of the uncertainty around the parameter estimates. As shown in Figure 5.2, this alternative measure of risk, the risk of a casualty crash per all police-reported crashes (shown in dark orange) slightly increases the detrimental effect of mass reduction on risk in cars and light trucks, but slightly decreases the effects on risk in CUVs/minivans. The risk of casualty crash per police-reported crash results in larger increases in the detrimental effect of footprint reduction in all three types of vehicles.

Figure 5.2. Effect of mass and footprint reduction on 13-state casualties and casualty crashes per crash, by vehicle type

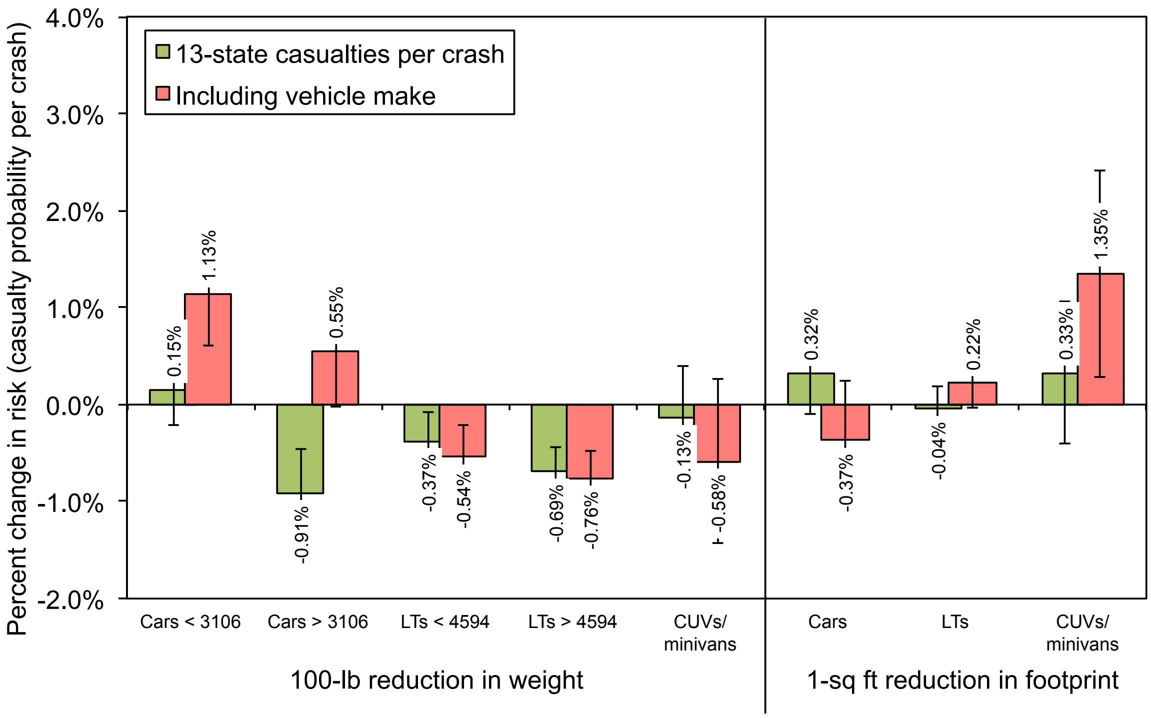


5.3. Vehicle manufacturer

The analysis by vehicle model in Section 4 indicates that the variables included in the regression models account for only a fraction of the variability in risk. We suspect that other, more subtle differences in vehicle models, or driver behavior, may explain the large remaining variability in risk. We tested that assumption by adding 18 dummy variables based on the vehicle nameplate manufacturer. GM brands (Buick, Cadillac, Chevrolet, GMC, Oldsmobile, Pontiac, and Saturn) are treated as the default value, since combined they represent the most vehicles by manufacturer, in terms of both casualties and police-reported crashes. The six Chrysler brands (Jeep, Chrysler, Dodge, Plymouth, AM General and Sprinter) and the three Ford brands (Ford, Lincoln, Mercury) were combined in a single Chrysler and Ford category. The luxury brands of Toyota, Honda, and Nissan (Lexus, Acura, and Infiniti, respectively) were treated as separate manufacturers. A small number of low-volume manufacturers were grouped into a separate Other manufacturer category.

Figure 5.3 compares the effect of adding variables for each of the 18 manufacturers (shown in red) to the regression models estimating casualty risk per crash from the thirteen states in Figure 2.5 above (shown in light green). Accounting for vehicle manufacturer results in a large increase in the harmful effect of mass reduction for cars, but increases the beneficial effect of mass reduction in light trucks and CUVs/minivans. Accounting for vehicle manufacturer has the opposite result on the effect of footprint reduction on risk: the effect of footprint reduction becomes beneficial for cars, but more detrimental for light trucks and strongly detrimental CUVs/minivans.

Figure 5.3. Effect of mass and footprint reduction on 13-state casualty risk per crash by vehicle type, after controlling for vehicle manufacturer



5.4. Calendar year variables

One interesting effect of the regression models is the reduction in casualty risk per crash over time, as indicated by the coefficients for the calendar year control variables. The reduction is consistent, and of roughly the same magnitude, for each vehicle type, as shown in Figure 5.4. The calendar year variables account for changes in both case vehicles and their crash partners, as well as the crash environment, over time, changes that are not explicitly included as other control variables in the regression models. In its 2011 report NHTSA interprets the trend of reduced risk over time as a reflection of general improvements in vehicle and roadway safety, increase in curb weight of crash partners, and, in particular, improvement in light truck design to reduce their tendency to rollover.

Figure 5.5 shows the effect on light truck casualty risk per crash, by type of crash, over time; for the most part, these results are consistent with fatality risk per VMT over time, reported in LBNL 2011b. The figure indicates that the effect of the calendar year variables on light truck risk is strong for crashes with light cars and lighter light-duty trucks. NHTSA believes that this may be the result of the removal over time of very light and unsafe cars and light trucks as potential crash partners for light trucks. However, there also are consistent decreases over time in light truck risk in crashes with heavy-duty trucks, and other (mostly multi-vehicle) crashes, as well as in crashes with heavier cars, although the effect is not as large. NHTSA suspects that the risk associated with light trucks involved in crashes with heavy-duty trucks has decreased over time because heavy-duty truck activity decreases as the economy has faltered. The economic recession in 2008 may have reduced the number of heavy-duty trucks traveling roadways, and thus available as potential crash partners with light-duty vehicles.

Figure 5.4. Effect of calendar year variables on 13-state casualty risk per crash, by vehicle type

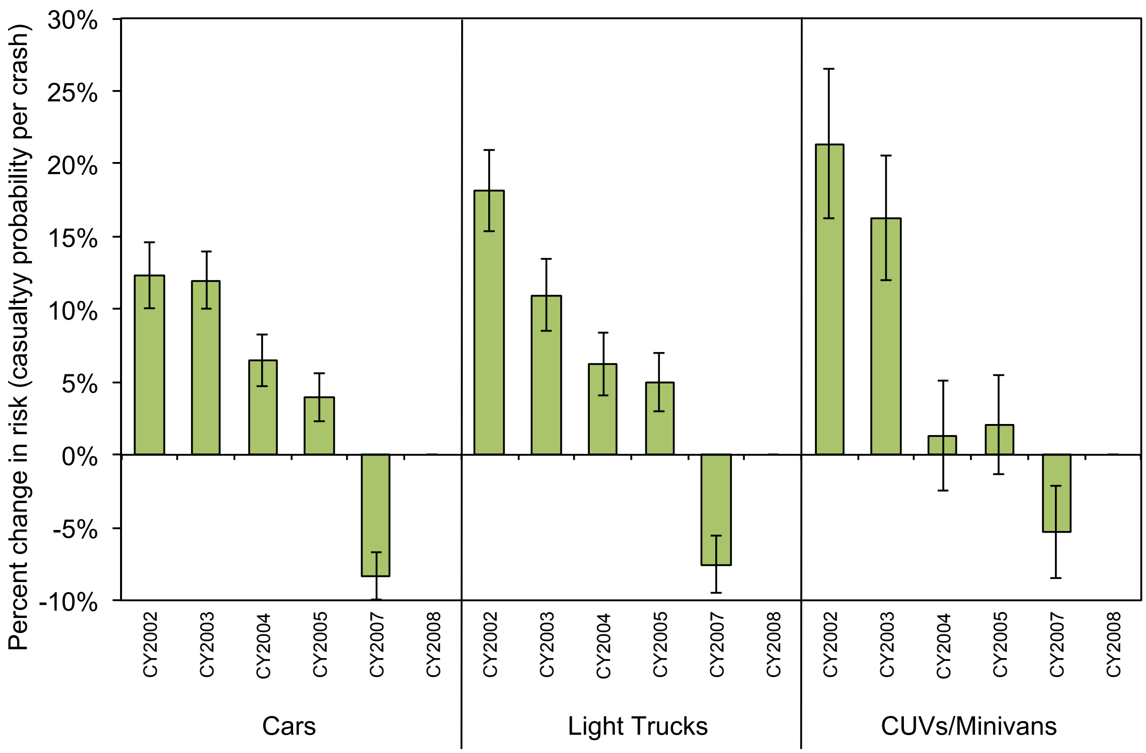
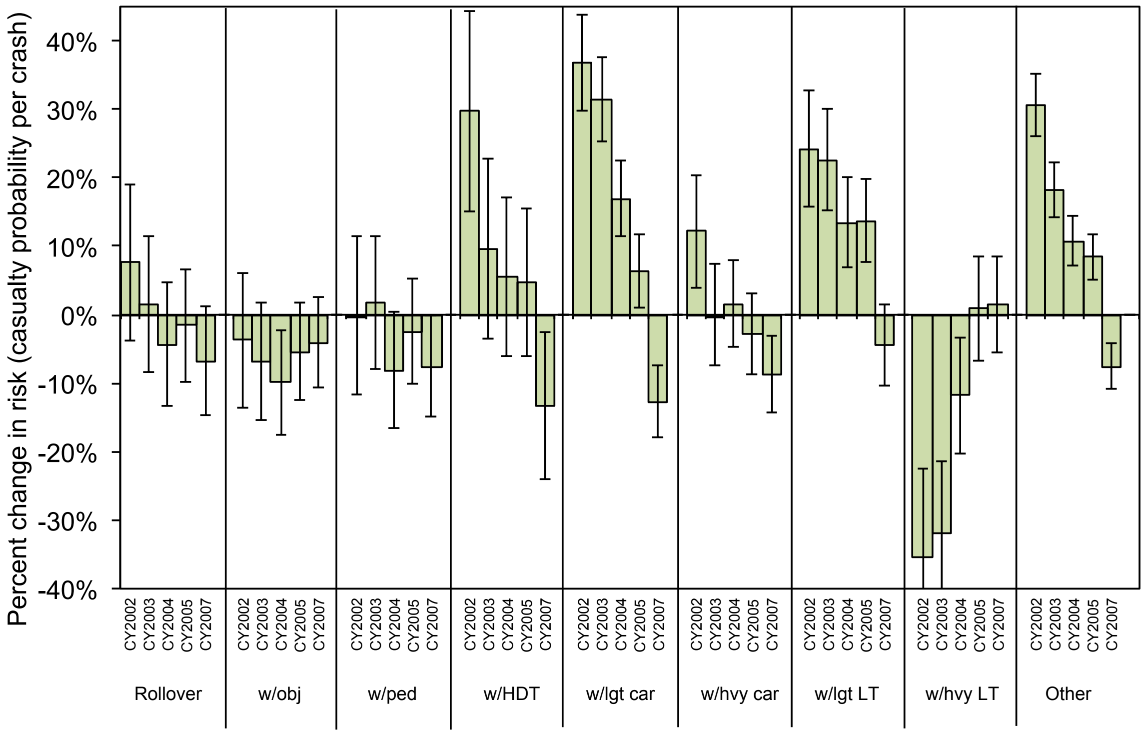


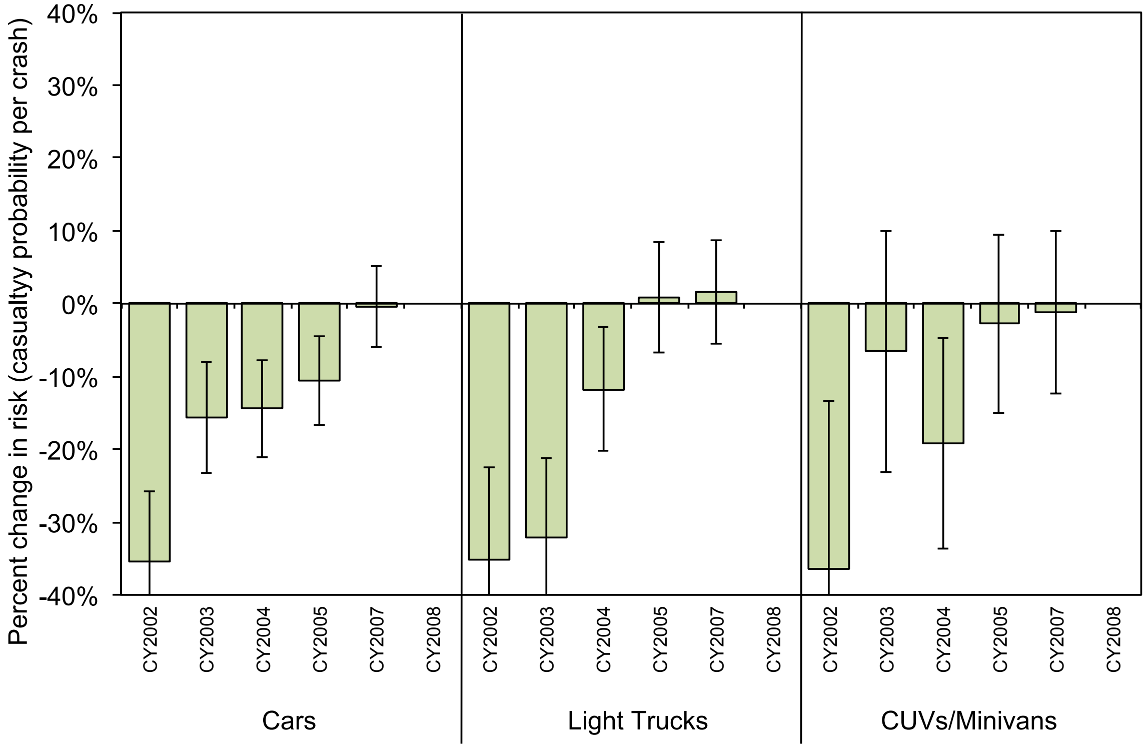
Figure 5.5. Effect of calendar year variables on light truck risk, by crash type



Note that there is no consistent trend in light truck casualty risk per crash in rollover crashes; NHTSA believes that the decline in light truck rollover fatality risk per VMT over time (reported in LBNL 2011b) may be the result of manufacturers increasing static stability factor or other aspects of light truck design to reduce their likelihood to rollover. These changes would not be expected to reduce risk of casualty (or fatality) in light trucks once a rollover has occurred, and Figure 5.5 does not show a consistent reduction in rollover risk per crash.

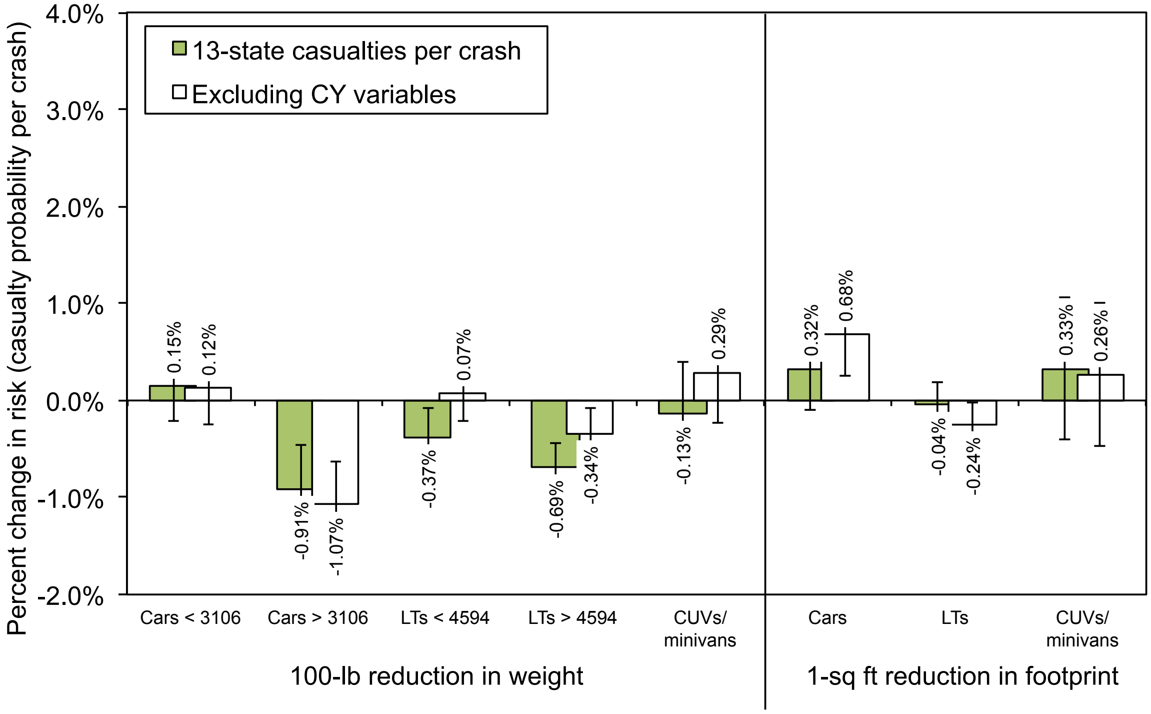
Another difference is that light truck casualty risk per crash consistently increases over time in crashes with heavier light-duty trucks, whereas the earlier analysis (of the effect of calendar year on US fatality risk per VMT) showed no consistent increase over time in fatality risk in crashes with heavier light-duty trucks. Figure 5.6 indicates that this is a consistent trend across all three types of case vehicles. We have no explanation for why casualty risks per crash are dramatically lower in crashes with heavier light-duty trucks than in crashes with other types of light-duty vehicles, or why risks in these types of crashes appear to be increasing over time.

Figure 5.6. Effect of calendar year variables on crashes with heavier light-duty trucks, by case vehicle type



Figures 5.7 through 5.10 show the effect of removing the calendar year variables from the regression model of 13-state casualty risk per crash (shown in light green). Figure 5.7 indicates that excluding the calendar year variables has little effect on the effect of mass reduction in cars, or for footprint reduction in CUVs/minivans. However, removing the calendar year variables reduces the beneficial effect of mass reduction in trucks and CUVs/minivans; and increases the detrimental effect of footprint reduction in cars but increases the beneficial effect of footprint reduction in light trucks.

Figure 5.7. Effect of mass and footprint reduction on 13-state casualty risk per crash by vehicle type, including and excluding calendar year variables



Figures 5.8 through 5.10 show what effect removing the calendar year variables has on the vehicle control variables; there is little to no effect on the driver or crash control variables (not shown). Figures 5.8 through 5.10 indicate that removing the calendar year variables has a large effect on the curtain airbag variable in cars and CUVs/minivans, and the SUV, HD pickup, BLOCKER2, and ESC variables in light trucks. In addition, the figures indicate that removing the calendar year variables lowers the effect of vehicle age, and whether a vehicle is brand new, on casualty risk per crash in all three vehicle types. Figures 5.7 through 5.10 suggest that inclusion of the calendar year variables in the regression models dilutes the effect of airbag technologies in cars and CUVs and minivans, the added risk in SUVs and heavy-duty pickups, and the beneficial effect of ESC in light trucks in general, while over-stating the effect of vehicle age in all three vehicle types.

Figure 5.8. Effect of selected control variables on car risk, including and excluding calendar year variables

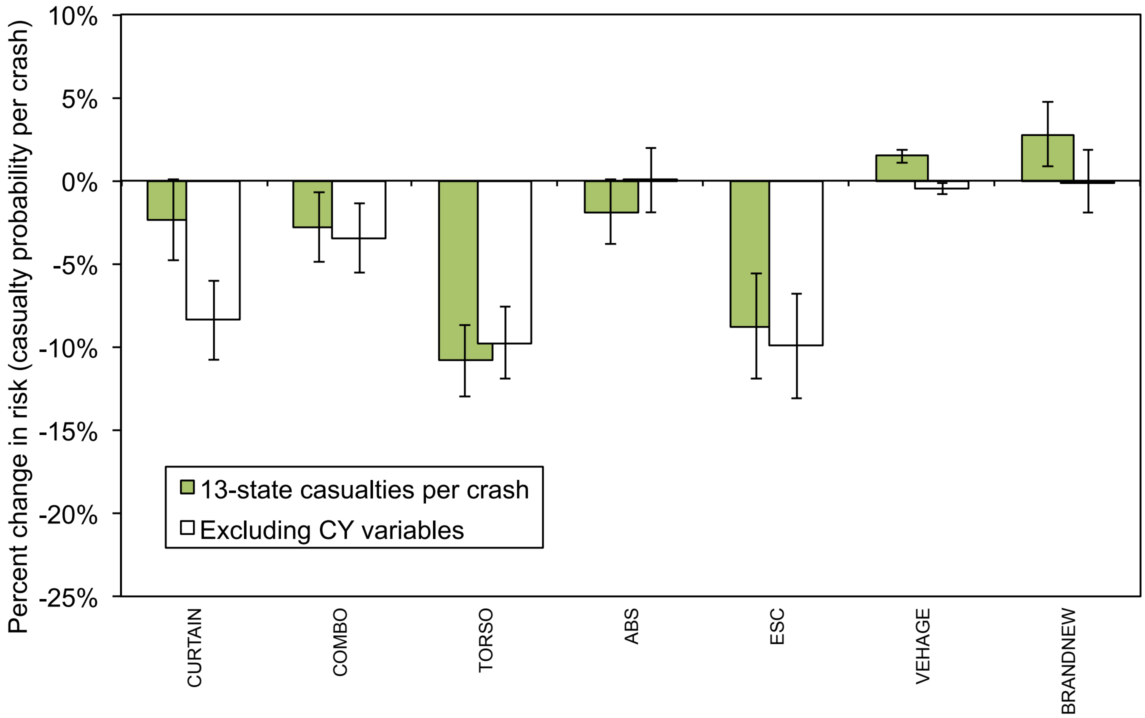


Figure 5.9. Effect of selected control variables on light truck risk, including and excluding calendar year variables

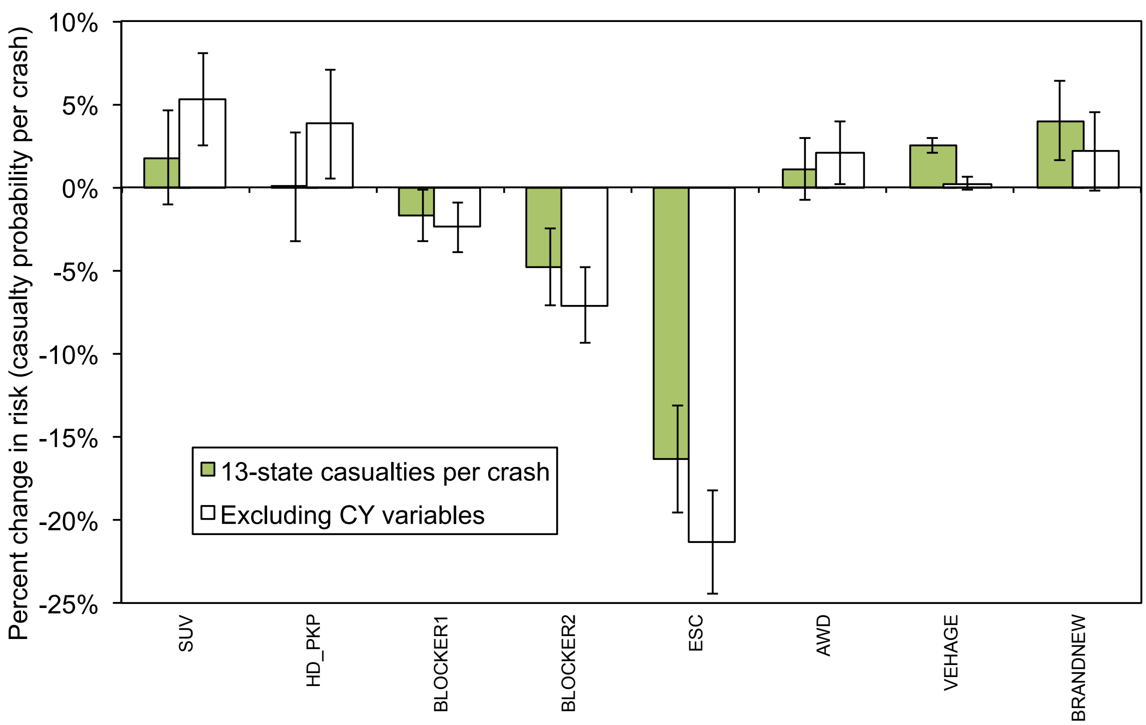
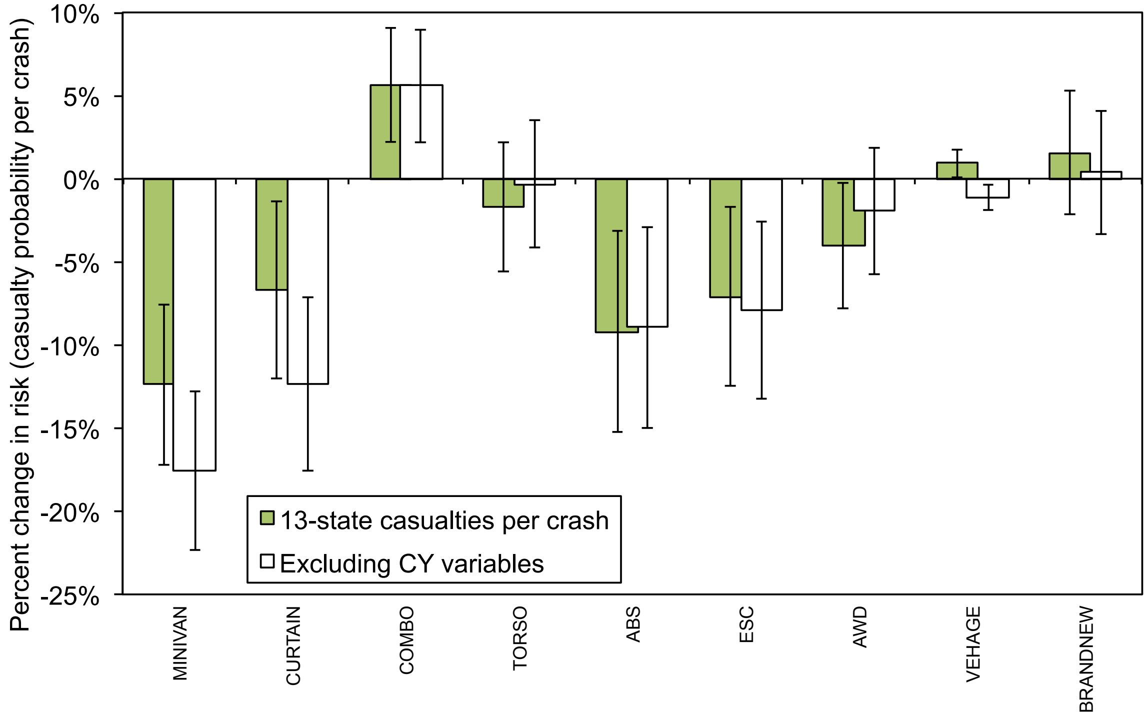


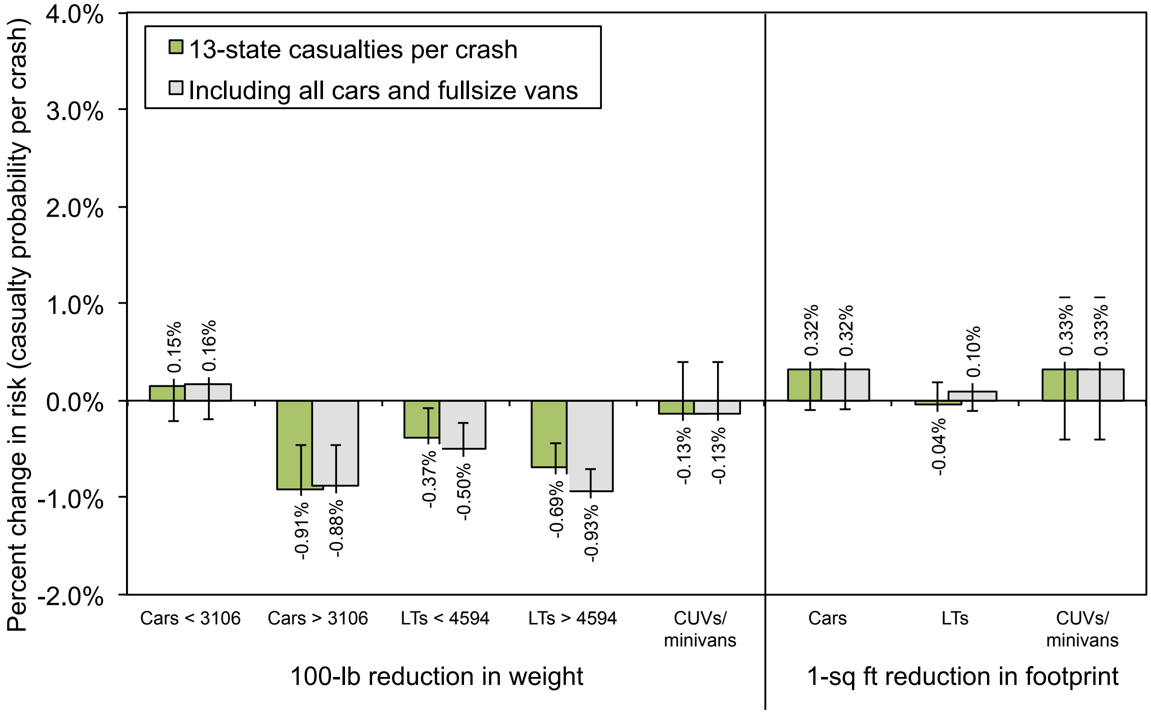
Figure 5.10. Effect of selected control variables on CUV/minivan risk, including and excluding calendar year variables



5.5. Effect of including sports, police, and all-wheel drive cars, and fullsize vans

In its analysis of US fatality risk per VMT, NHTSA excluded three types of cars, model sused as sports cars, police cars, and models with all-wheel drive, as well as fullsize vans. Including these vehicles in our analysis of 13-state casualty risk per crash slightly increases the effect of mass reduction, and has no change on the effect of footprint reduction, on casualty risk for cars, as shown in Figure 5.11. Including fullsize vans has the opposite effect on the results for light trucks: the effect of mass reduction is slightly reduced, while the effect of footprint reduction is slightly increased.

Figure 5.11. Effect of mass and footprint reduction on 13-state casualty risk per crash by vehicle type, after including sports, police, and all-wheel drive cars, and fullsize vans



5.6. Effect of adding additional data

As mentioned above, we excluded certain data that NHTSA did not include in their regression analyses:

- vehicles from 2000 to 2007 for three states (Georgia, Illinois, and New Mexico) that NHTSA did not include in its analysis because those states did not report the posted speed limit at the crash site (Georgia data are available only through 2006, while New Mexico data are available through 2008). NHTSA included IL in its 2003 and 2010 analyses, using the fraction of FARS crashes occurring on roads with a posted limit 55 mph or over, by roadway classification; we used this same method to assign posted speed limits to these three states in this analysis;
- vehicles whose model year was not reported in the state crash data (except all crash records from Washington, which were included in the above analysis);
- vehicles involved in police-reported crashes in 2008 (from six states), and in 2000 and 2001 (from all states but Michigan, New Jersey, and Washington);
- vehicles that had apparent VIN transcription errors that we corrected so that the model year reported in the state crash data matched the VIN model year. The method to make these corrections for VIN errors is described in LBNL 2011a.

We added these data sequentially and analyzed the effect of each on the regression coefficients on vehicle mass and footprint; we also ran regression models using all of the additional data. Figure 5.12 shows that including all of the additional data increases the number of vehicle records by nearly 40%. Figure 5.13 indicates that adding the data, either sequentially or all at once, results in little change in the effect of mass or footprint reduction on casualty risk per crash, for all vehicle types. The results in Figure 5.13 are from single regression analyses across all crash types, for each vehicle type, and are not adjusted for the effect of full adoption of ESC by 2017. Figure 5.14 compares the first and last cases in Figure 5.13, after reweighting the coefficients for each type of crash by the anticipated distribution of casualties in 2017, after full adoption of ESC. Note in Figure 5.14 that the last column (in light orange), which represents the effect from increasing the sample size by about 40%, reduces the uncertainty of the estimates of the effect of mass or footprint on risk by only a small amount. This suggests that the uncertainty is a function of the variability in the effect of mass or footprint reduction on risk by vehicle, and not a function of relatively small sample sizes.

Figure 5.12. Number of vehicles involved in casualty crashes by vehicle type, using additional state crash data

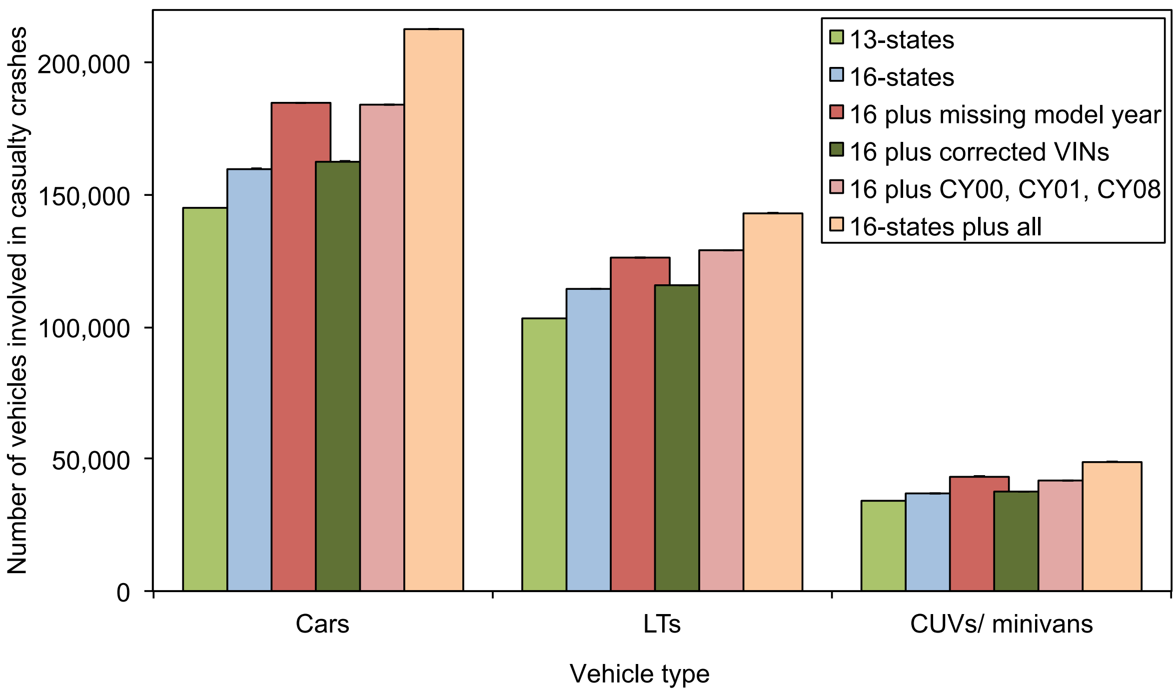


Figure 5.13. Effect of mass and footprint reduction on casualty risk per crash by vehicle type, using additional state crash data

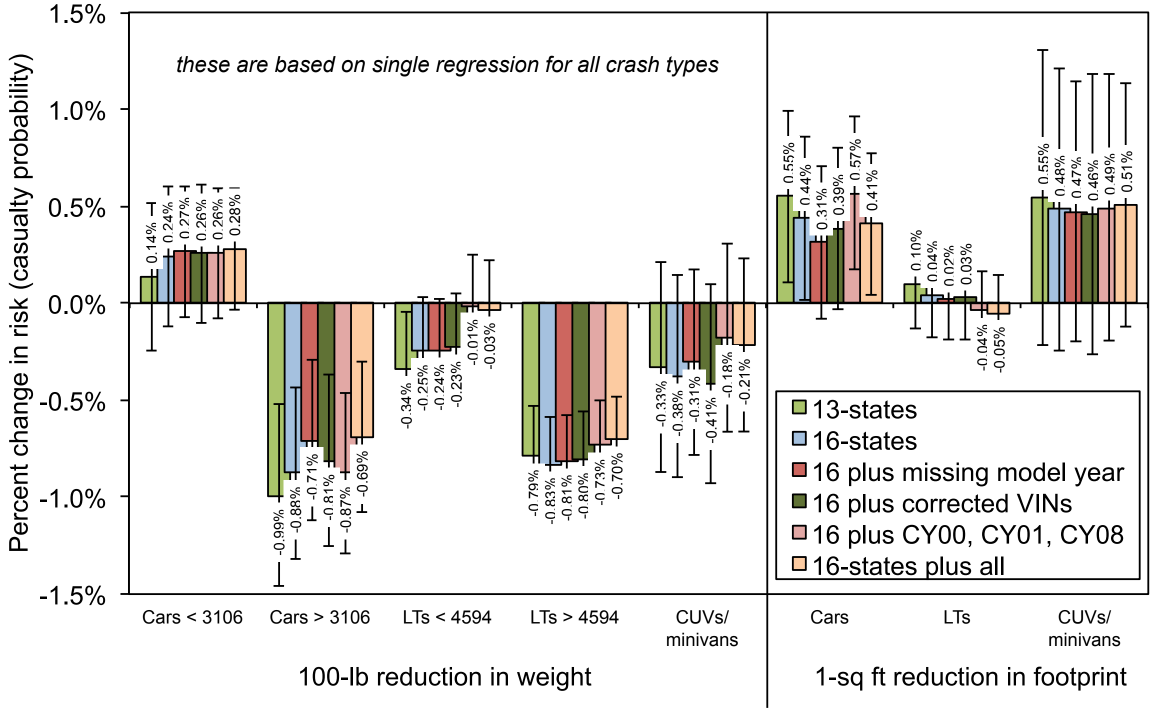
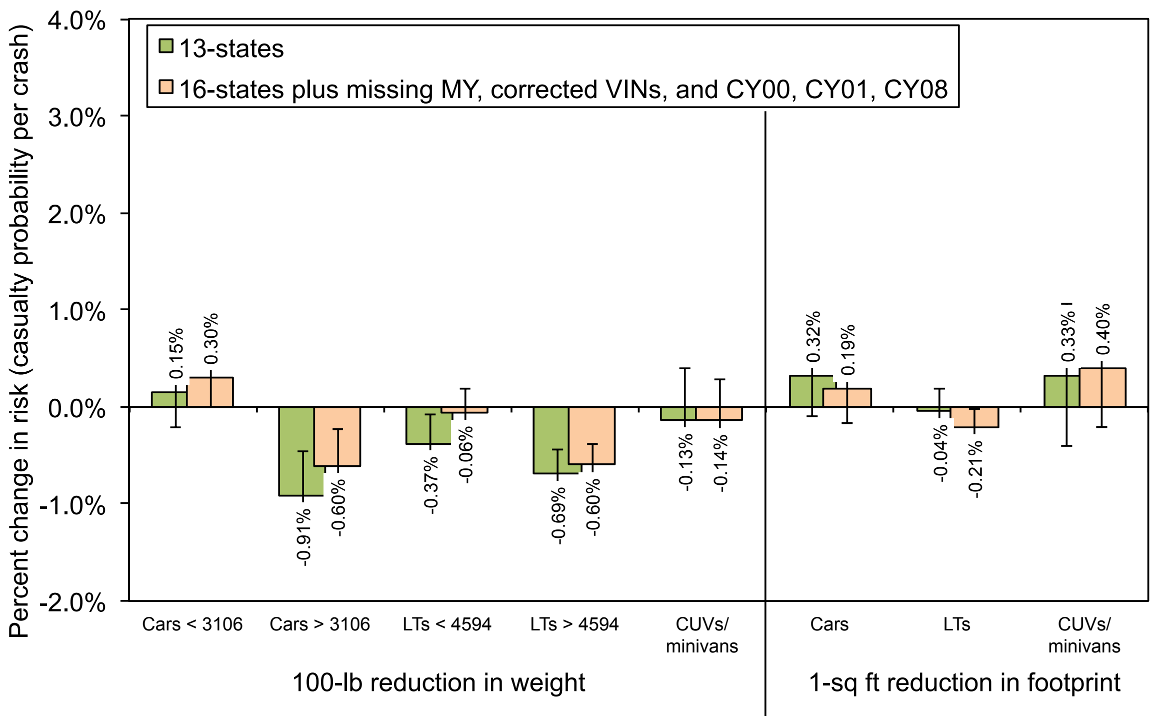


Figure 5.14. Effect of mass and footprint reduction on casualty risk per crash by vehicle type, using additional state crash data, after accounting for full adoption of ESC



6. Conclusions

NHTSA recently completed a logistic regression analysis (Kahane, 2011) updating its 2003 and 2010 studies of the relationship between vehicle mass and US fatality risk per vehicle mile traveled (VMT). The new study updates the previous analyses in several ways: updated FARS data for 2002 to 2008 involving MY00 to MY07 vehicles are used; induced exposure data from police reported crashes in several additional states are added; a new vehicle category for car-based crossover utility vehicles (CUVs) and minivans is created; crashes with other light-duty vehicles are divided into two groups based on the crash partner vehicle's weight, and a category for all other fatal crashes is added; and new control variables for new safety technologies and designs, such as electronic stability controls (ESC), side airbags, and methods to meet voluntary agreement to improve light truck compatibility with cars, are included.

In a companion report (Wenzel, 2011b), we use the updated databases NHTSA has created to replicate their findings on the relationship between vehicle weight, size (actually footprint, or vehicle wheelbase times track width), and US fatality risk per vehicle miles traveled (VMT), for model year 2000 to 2007 light-duty vehicles involved in fatal crashes between 2002 and 2008. The data are examined in slightly different ways, to get a deeper understanding of the relationship between reductions in vehicle mass and footprint, and overall safety.

This report compares the logistic regression results of the NHTSA analysis of US fatality risk per VMT with an analysis of 13-state fatality risk and casualty risk per crash. This analysis differs from the NHTSA analysis in two respects: first, it analyzes risk per crash, using data on all police-reported crashes from thirteen states, rather than risk per estimated VMT; and second, it analyzes casualty (fatality plus serious injury) risk, as opposed to just fatality risk. There are several good reasons to investigate the effect of mass and footprint reduction on casualty risk per crash. First, risk per VMT, accounts for two effects that influence whether a person is killed or seriously injured in a crash: how well a vehicle can be driven (based on its handling, acceleration, and braking capabilities) to avoid being involved in a serious crash (crash avoidance), and, once a serious crash has occurred, how well a vehicle protects its occupants from fatality or serious injury (crashworthiness). By encompassing both of these aspects of vehicle design, risk per VMT gives a complete picture of how vehicle design can promote, or reduce, road user safety. On the other hand, risk per crash isolates the second of these two safety effects, crashworthiness, by examining the effect of mass and footprint reduction on how well a vehicle protects its occupants once a crash occurs.

Second, estimating risk on a per crash basis requires using data on police-reported crashes from states. Because only sixteen states currently record the vehicle identification number of vehicles involved in police-reported crashes, which is necessary to determine vehicle characteristics, and only thirteen states also report the posted speed limit of the roadway on which the crash occurred, extending the analysis to casualties (fatalities plus serious/incapacitating injuries) reduces the statistical uncertainty of analyzing just fatalities per crash. Finally, a serious incapacitating injury can be just as traumatic to the victim and her family, and costly from an economic perspective, as a fatality. Limiting the analysis to the risk of fatality, which is an extremely rare event, ignores the effect vehicle design may have on reducing the large number of incapacitating injuries that occur each year on the nation's roadways. All risks in this report are societal risk, including fatalities and serious injuries in the case vehicle and any crash partners, and include not only driver casualties but passenger and non-occupant casualties as well.

Table 6.1 summarizes the results of our analysis of the effect of vehicle mass or footprint reduction on the two components of risk per VMT, crash frequency (number of crashes per VMT) and crashworthiness (risk per crash), for both fatality and casualty risk, using data from 13 states. We convert the percent change in the log-odds of casualty or fatality per crash output from the SAS LOGIST procedure to the percent change in the probability of casualty or fatality per crash. This conversion has no effect on the output regression coefficients when the change in the log-odds of casualty is small, but substantially increases the percent change for explanatory variables that have a large effect on the log-odds of casualty. Effects that are statistically significant are shown in red in the table; significance is based on the 95% confidence interval derived from the standard error of the output of the SAS LOGIST procedure, converted to a percent probability interval.

Table 6.1 indicates that for cars and light trucks, the effects from the two components, crash frequency and crashworthiness, roughly add together to result in the overall effect on fatality risk per VMT. For example, a 100-lb reduction in the mass of lighter cars leads to a 1.84% increase in crash frequency (columns B), while mass reduction leads to a 0.76% decrease in the number of fatalities per crash (column C); the net effect is only a 1.08% increase in the risk of fatality per VMT (column D). For CUVs/minivans, the relationship is different; mass reduction leads to a 0.71% increase in crash frequency, as well as a 0.87% increase in the number of fatalities per crash; however, the net result, a 1.29% increase in the number of fatalities per VMT, is less than the sum of the two components.

Table 6.1 indicates that mass reduction increases crash frequency (columns B and E) in all five vehicle types, with larger increases in lighter-than-average cars and light-duty trucks. As a result, mass reduction has a more beneficial effect on crashworthiness, or casualty risk per crash (column F), than on casualty risk per VMT (column G), and on fatality risk per crash (column C) than on fatality risk per VMT (column D). Mass reduction actually decreases casualty risk per crash (column F) in all vehicles except light cars, and in three of the four cases these reductions are statistically significant, albeit small. Footprint reduction increases crash frequency (columns B and E) in cars and light trucks, but slightly reduces crash frequency in CUVs/minivans; footprint reduction does not have a statistically-significant effect on casualty risk per crash (column F), and only for fatality risk per crash (column C) for light trucks. In general mass or footprint reduction has a smaller effect on casualty risk per crash (column F) than on fatality risk per crash (column C).

The effect of mass reduction on 13-state casualty risk per VMT (column G) is quite consistent with that NHTSA estimated for US fatality risk per VMT (column A), although the effect is estimated to be slightly larger for lighter cars and lighter light trucks, and slightly smaller for heavier cars, heavier light trucks, and CUVs/minivans.

In contrast with NHTSA's findings on US fatality risk per VMT (column A), mass reduction reduces casualty risk per crash (column F) for four of the five vehicle types, and three of these four reductions are statistically significant. Mass reduction results in a small but insignificant increase in casualty risk per crash for lighter cars. And footprint reduction results in much smaller, and not statistically significant, effects on casualty risk per crash (column F) than on US fatality risk per VMT (column A).

Many of the control variables included in the logistic regressions are statistically significant, and have a large effect on fatality or casualty risk per crash, although not as large an effect as on fatality risk per VMT. For example, a car's mass could be reduced by 2,300 lbs while adding ABS without increasing its casualty risk per crash. While the effect of mass reduction may result in a statistically-significant increase in risk in certain cases, the increase is small and is overwhelmed by other known vehicle, driver, and crash factors.

Control variables for ABS and ESC in cars, AWD in light trucks and CUVs/minivans, and drivers aged 14 to 30 have a larger effect on crash frequency than fatality risk per crash. On the other hand, whether a vehicle is a two-door car, SUV, or heavy-duty pickup, side airbag variables in cars, and middle-aged drivers have a larger effect on fatality risk per crash than on crash frequency. Whether a driver is male has essentially no effect on crash frequency, but surprisingly causes a statistically significant increase in fatality risk once a crash occurs. Driving at night on high-speed rural roads, also has a surprisingly much lower effect on crash frequency than on fatality risk given a crash.

In contrast with NHTSA's results for US fatalities per VMT, allowing footprint to vary along with weight results in little change in the effect of mass reduction on casualty risk per crash than when footprint is held constant; however, the detrimental effect of mass reduction on casualty risk per crash in lighter cars is increased just enough to make it statistically significant. When mass is allowed to vary along with footprint, footprint reduction slightly reduces the already small detrimental effect on casualty risk per crash (Alternative 1 in Table 6.2). As with NHTSA's analysis of fatality risk per VMT, mass reduction does not consistently increase casualty risk per crash across all footprint deciles for any combination of vehicle type and crash type. Mass reduction increases casualty risk per crash in a majority of footprint deciles for 10 of the 27 crash and vehicle combinations, but few of these increases are statistically significant. On the other hand, mass reduction decreases risk in a majority of footprint deciles for 14 of the 27 crash and vehicle combinations.

Similar to our findings on US fatality risk per VMT, after accounting for all of the control variables in the logistic regression model, except for vehicle mass and footprint, we find that the correlation between mass and the casualty risk per crash by vehicle model is very low. There also is no significant correlation between the residual, unexplained risk and vehicle weight. These results corroborate our earlier finding that, even after accounting for many vehicle, driver, and crash factors, the variance in risk by vehicle model is quite large and unrelated to vehicle weight.

Other changes in the data and variables used in the regression models result in only slight changes in the effect of mass or footprint reductions on casualty risk per crash, as summarized in Table 6.2. For example:

- Regression analyses using police-reported crash data from states must use control variables to account for differences in definitions of "serious" or "incapacitating" injuries, and reporting requirements, across states. Removing the 12 state control variables results in a large reduction in casualty risk per crash from mass reduction in all five vehicle types, a large increase in risk from footprint reduction in cars and CUVs/minivans, and a small reduction in risk from footprint reduction in light trucks (Alternative 2 in Table 6.2). Including only two variables to control for states with high and low casualty risk per crash substantially reduces the effect of mass and footprint reduction on casualty risk (Alternative 3 in Table 6.2), while including the 12 control variables for individual states reduces the effect a little bit more. These results indicate that excluding control variables for the state in which a crash occurred from a regression model using state police-reported crash data can give inaccurate estimates of the effect of mass or footprint reduction on casualty risk per crash.

- Calculating risk as casualty crashes, rather than total casualties, per crash results in little change in the effect of mass reduction on risk, but does increase the small detrimental effect of footprint reduction in cars on risk, and makes it statistically significant (Alternative 4 in Table 6.2).

- Adding control variables for vehicle manufacturer results in mass reduction increasing casualty risk per crash in cars, but increases the small <u>beneficial</u> effect of mass reduction in light trucks and CUVs/minivans. Accounting for vehicle manufacturer causes a reduction in footprint to reduce casualty risk per crash in cars, but increase casualty risk per crash in light trucks and CUVs/minivans (Alternative 5 in Table 6.2).

- As we found in our assessment of NHTSA's analysis of US fatality risk per VMT, including calendar year variables in the regression models appears to weaken the benefit of side air bags in cars and CUVs/minivans, and compatibility measures and ESC in light trucks. These variables also appear to minimize the increased risk of SUVs and heavy-duty pickup trucks. Excluding the calendar year variables from the regression models slightly reduces the beneficial effect of mass reduction on casualty risk per crash in light trucks and CUVs/minivans, and slightly increases the detrimental effect of footprint reduction on casualty risk per crash in cars (Alternative 6 in Table 6.2).

- Including all-wheel-drive, sports, and police cars, and fullsize vans results in virtually no change in the effect of mass or footprint reduction on casualty risk per crash for cars or light trucks (Alternative 7 in Table 6.2).

- Adding data from three additional states, including vehicles with unreported model year, correcting VIN transcription errors, and expanding the analysis to calendar years 2000, 2001, and 2008, increases the number of state crash records by about 40 percent. Including these data in the regression analyses results in the effect of mass reduction in lighter cars being slightly more detrimental, and the effect of mass reduction in heavier cars, all light trucks, and CUVs/minivans being slightly less beneficial. Including these data slightly reduces the small detrimental effect of footprint reduction on casualty risk per crash for cars, increases the beneficial effect for light trucks, and increases the detrimental effect for

CUVs/minivans. However, increasing the sample size included in the regression analysis by 40% does not noticeably reduce the confidence intervals around the point estimates (Alternative 8 in Table 6.2).

In conclusion, casualty risk per crash is not necessarily a better metric than fatality risk per VMT for evaluating the effect of mass or footprint reduction on risk; rather, it provides a different perspective in assessing the benefits or drawbacks of mass and footprint reduction on safety in vehicles. However, it does allow the separation of risk per VMT to be separated into its two components, crash frequency and risk per crash. Our analysis indicates that much of the detrimental effect of mass or footprint reduction on risk can be attributed to the tendency for mass or footprint reduction to increase crash frequency, rather than to reduce vehicle crashworthiness (risk once a crash has occurred).

As with our analysis of US fatalities per VMT, this report concludes that the effect of mass reduction on casualty risk per crash is small, and tends to be overwhelmed by other control variables, such as vehicle type, specific safety technologies, and crash conditions such as whether the crash occurred at night, in a rural county, or on a high-speed road. This report indicates that the effects are only slightly sensitive to what variables and data are included in the regression analysis. Finally, as in our analysis of US fatality risk per VMT, this report shows that after accounting for many vehicle, driver, and crash variables there remains a wide variation in casualty risk per crash by vehicle make and model, and this variation is unrelated to vehicle mass.

It is important to recognize that the results of this study are based on the relationship of vehicle mass and footprint on risk for recent vehicle designs (model year 2000 to 2007). These relationships may or may not continue into the future as manufacturers utilize new vehicle designs and incorporate new technologies, such as more extensive use of strong lightweight materials and specific safety technologies.

Table 6.1. Effect of mass and footprint reduction on two components of fatality and casualty risk per VMT, crash frequency (crashes per VMT) and crashworthiness (risk per crash); effects in red are statistically significant (see text)

Variable	Case vehicle type	A. NHTSA US fatalities per VMT	B. 13-state crashes per VMT	C. 13-state fatalities per crash	D. 13-state fatalities per VMT	E. 13-state crashes per VMT	F. 13-state casualties per crash	G. 13-state casualties per VMT
Mass reduction	Cars < 3106 lbs	1.43%*	1.84%	-0.76%	1.08%	1.84%	0.15%	1.76%
	Cars > 3106 lbs	0.48%	1.23%	-2.44%	-1.42%	1.23%	-0.91%	0.32%
	LTs < 4594 lbs	0.52%	1.42%	-1.98%	-0.43%	1.42%	-0.37%	1.41%
	LTs > 4594 lbs	-0.40%	0.93%	-1.22%	-0.46%	0.93%	-0.69%	-0.22%
	CUV/ minivan	-0.47%	0.71%	0.87%	1.29%	0.71%	-0.13%	-0.02%
Footprint reduction	Cars	1.89%	1.05%	1.24%	2.80%	1.05%	0.32%	2.00%
	LTs	-0.02%	1.15%	0.73%	1.92%	1.15%	-0.04%	1.13%
	CUV/ minivan	1.73%	-0.37%	-2.25%	-1.54%	-0.37%	0.33%	1.52%

* Based on NHTSA's estimation of uncertainty using a jack-knife method, only mass reduction in cars less than 3,106 lbs has a statistically significant effect on US fatality risk.

Table 6.2. Effect of mass and footprint reduction on 13-state casualty risk, under alternative regression model specifications and using additional data; effects in red are statistically significant (see text)

Variable	Case vehicle type	13-state casualties per police-reported crash	1. Excluding, mass or footprint variable	2. Excluding state control variables	3. Including only two state control variables	4. Casualty crashes per crash	5.Including vehicle make variables	6. Excluding CY variables	7. Including sports, squad, AWD cars and fullsize vans	8. Including all additional data
Mass reduction	Cars < 3106 lbs	0.15%	0.36%	-0.78%	-0.06%	0.24%	1.13%	0.12%	0.16%	0.30%
	Cars > 3106 lbs	-0.91%	-0.67%	-1.91%	-1.32%	-0.85%	0.55%	-1.07%	-0.88%	-0.60%
	LTs < 4594 lbs	-0.37%	-0.41%	-0.46%	-0.44%	-0.32%	-0.54%	0.07%	-0.50%	-0.06%
	LTs > 4594 lbs	-0.69%	-0.72%	-1.85%	-0.79%	-0.67%	-0.76%	-0.34%	-0.93%	-0.60%
	CUV/ minivan	-0.13%	0.02%	-1.95%	-0.43%	-0.25%	-0.58%	0.29%	-0.13%	-0.14%
Footprint reduction	Cars	0.32%	-0.05%	1.78%	0.55%	0.55%	-0.37%	0.68%	0.32%	0.19%
	LTs	-0.04%	-0.44%	-0.84%	-0.09%	0.19%	0.22%	-0.24%	0.10%	-0.21%
	CUV/ minivan	0.33%	0.20%	3.58%	0.46%	0.74%	1.35%	0.26%	0.33%	0.40%

7. References

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