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Assessment of NHTSA's Report "Relationships Between Fatality Risk, Mass, and Footprint in Model Year 2000-2007 Passenger Cars and LTVs"

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Executive Summary

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). The new study updates the previous analyses in several ways: updated FARS data from 2002 to 2008 for 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.

Using the updated databases, NHTSA estimates that reducing vehicle mass by 100 lbs while holding footprint fixed would increase fatality risk per VMT by 1.55% for lighter-than-average cars, 0.51% for heavier-than-average cars, and 0.52% for lighter-than-average light-duty trucks, but reduce risk by 0.34% for heavier-than-average light-duty trucks and by 0.38% for CUVs/minivans. NHTSA found that only the estimated effect of mass reduction on lighter than average cars is statistically significant. NHTSA concludes that, when footprint is held fixed, "no judicious combination of mass reductions in the various classes of vehicles results in a statistically significant fatality increase and many potential combinations are safety-neutral as point estimates".

The effect of mass reduction on risk that NHTSA estimated in 2012 is much smaller than in its 2003 and 2010 studies, particularly for cars. NHTSA attributes this reduction in the importance of mass reduction on safety to the phase-out of relatively light cars that had unusually high fatality risk, an observed improvement in how light, small cars are driven which reduces their tendency to be involved in serious crashes, and voluntary improvements made to light trucks to improve their compatibility with other vehicles. The 2012 NHTSA analysis estimates that reducing vehicle footprint by one square foot while holding mass fixed would increase fatality risk per VMT by 1.87% in cars and 1.72% in CUVs and minivans (the effect on risk in light trucks is small and not statistically significant).

This report replicates the 2012 NHTSA analysis, and reproduces their main results. This report uses the confidence intervals output by the logistic regression models, which are smaller than the intervals NHTSA estimated using a jack-knife technique that accounts for the sampling error in the FARS fatality and state crash data. As a result, in its report NHTSA finds that only the 1.55% estimated increase in risk from mass reduction in lighter-than-average cars is statistically significant. In addition to reproducing the NHTSA results, this report also examines the NHTSA data in slightly different ways to get a deeper understanding of the relationship between vehicle weight, footprint, and safety. This final report incorporates revisions from the preliminary report released in November 2011, including revised estimates of national weights for vehicle miles traveled, inclusion of 2008 police-reported crash data from eight additional states, and responses to reviewers' comments.

The results of these alternative analyses are summarized in Tables ES.1 and ES.2; statistically significant estimates, based on the confidence intervals output by the logistic regression models, are shown in red in the tables. In particular, we found that:

- NHTSA's (reasonable) assumption that all vehicles will have ESC installed by 2017 slightly increases the estimated detrimental effect of mass reduction, but slightly decreases the estimated detrimental effect of footprint reduction, on risk in cars, CUVs and minivans (Alternative 1 in Table ES.1; explained in more detail in Section 2.1 of this report). This is because NHTSA projects ESC to substantially reduce the number of fatalities in rollovers and crashes with stationary objects, and mass reduction appears to reduce risk, while footprint reduction appears to increase risk, in these types of crashes, particularly in cars and CUVs/minivans. A single regression model including all crash types results in slightly different estimates of the relationship between decreasing mass and risk, as shown in Alternative 2 in Table ES.1.

- Many of the control variables NHTSA includes in its logistic regressions are statistically significant, and have a much larger estimated effect on fatality risk than vehicle mass. For example, installing torso side airbags, electronic stability control, or an automated braking system in a car is estimated to reduce fatality risk by about 10%; cars driven by men are estimated to have a 40% higher fatality risk than cars driven by women; and cars driven at night, on rural roads, or on roads with a speed limit higher than 55 mph are estimated to have a fatality risk over 100 times higher than cars driven during the daytime on low-speed non-rural roads. While the estimated 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.

Table ES.1. Estimated effect of mass or footprint reduction on US fatality risk per VMT, under alternative regression model specifications

Variable	Case vehicle type	NHTSA preferred model (fatalities per VMT)	1. Weighted by current distribution of fatalities	2. Single regression model for all crash types	3. Excluding footprint or weight	4. Fatal crashes per VMT	5. Fatalities per induced exposure crash	6. Fatalities per registered vehicle-year
Mass reduction	Cars < 3106 lbs	1.55%*	1.27%	1.26%	2.74%	1.95%	-0.22%	0.93%
	Cars > 3106 lbs	0.51%	0.37%	0.35%	1.95%	0.89%	-1.45%	2.40%
	LTs < 4594 lbs	0.52%	0.42%	0.41%	0.47%	0.54%	-1.13%	-0.09%
	LTs > 4594 lbs	-0.34%	-0.36%	-0.42%	-0.39%	-0.42%	-0.76%	-0.76%
	CUV/ minivan	-0.38%	-0.70%	-0.74%	0.60%	-0.47%	-0.84%	-0.40%
Footprint reduction	Cars	1.87%	2.16%	2.28%	2.98%	1.83%	2.28%	0.32%
	LTs	-0.07%	0.14%	0.22%	0.07%	0.14%	-1.30%	-0.08%
	CUV/ minivan	1.72%	2.25%	2.26%	1.33%	1.79%	2.18%	0.03%

* 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.
Estimates that are statistically significant at the 95% level are shown in red.

- Vehicle mass and footprint are correlated, but only strongly for passenger cars. NHTSA includes both variables in their regression models, introducing the possibility that multi-collinearity may create biased results. When footprint is allowed to vary along with weight (i.e. the regression model accounts for weight but not footprint), mass reduction results in a larger estimated increase in risk for cars and CUVs/minivans than when footprint is held constant. Similarly, when mass is allowed to vary along with footprint, footprint reduction results in a larger estimated increases in risk for cars, but a smaller estimated increase in risk for CUVs and minivans (Alternative 3 in Table ES.1, further addressed in Section 3 of this report). To isolate the effect of mass reduction from footprint reduction on risk, NHTSA estimates the effect of mass reduction on risk for deciles of vehicles with similar footprint. Mass reduction does not consistently increase risk across all footprint deciles for any combination of vehicle type and crash type. Risk increases with decreasing mass in a majority of footprint deciles for 12 of the 27 crash and vehicle combinations, but few of these increases are statistically significant. On the other hand, risk decreases with decreasing mass in a majority of footprint deciles for 5 of the 27 crash and vehicle combinations; in some cases these risk reductions are large and statistically significant.

  • Logistic regression methods do not have a statistic, such as the model R^2 in a linear regression model, to measure how much variability in risk by vehicle model is explained by the control variables included in the model. Analysis of pseudo-R^2 and R^2 from a linear regression model suggests that much of the variation in risk remains unexplained, even after accounting for many important vehicle, driver, and crash variables. After accounting for all of the variables in NHTSA's logistic regression model, except for vehicle mass and footprint, we find that the correlation between estimated fatality risk by vehicle model and mass is very low. There also is no significant correlation between the residual, unexplained risk and vehicle weight. These results indicate that, even after accounting for many vehicle, driver, and crash factors, the variation in risk by vehicle model is quite large and unrelated to vehicle weight (addressed in more detail in Section 4). The large remaining unexplained variation in risk by vehicle model could be attributable to other differences in vehicle design, or how drivers who select certain vehicles drive them. It is possible that including variables that account for these factors in the regression models would change the estimated relationship between mass or footprint and risk.

- NHTSA's estimates are sensitive to the definition of risk used in its regression models. Calculating risk as fatal crashes, rather than total fatalities, per vehicle mile traveled, as suggested by one of the independent reviewers of the previous NHTSA reports, increases the estimated detrimental effect of mass reduction on risk in cars, but has no effect on mass reduction in light trucks or CUVs/minivans, or on footprint reduction in any vehicle type (Alternative 4 in Table ES.1). Calculating risk as total fatalities per induced exposure crash, rather than per vehicle mile traveled, reverses the sign of the estimated effect of mass reductions on risk in cars and the lighter light trucks, with mass reduction leading to an estimated reduction in risk in all vehicle types. Footprint reduction continues to result in large estimated increases in risk per induced exposure crash for cars and CUVs/minivans, but leads to a large estimated reduction in fatality risk per induced exposure crash for light trucks (Alternative 5 in Table ES.1). Calculating risk per registered vehicle-year, rather than per mile driven, substantially reduces the estimated effect of mass reduction on risk for lighter cars and lighter light trucks, but substantially increases the estimated effect on risk for heaver cars (Alternative 6 in Table ES.1; further addressed in Section 5.1).

- NHTSA's estimates are sensitive to changes in the data and variables used in its regression models, as shown in Table ES.2. Adding control variables for vehicle manufacturer tends to increase the estimated effect of mass reduction, but decrease the estimated effect of footprint reduction, on risk for cars and light trucks, and estimates that mass reduction becomes substantially detrimental, and footprint reduction beneficial, for CUVs/minivans (Alternative 7 in Table ES.2; further addressed in Section 5.2). Adding control variables for five luxury brands (Cadillac, Lincoln, Acura, Infiniti and Lexus) magnifies these changes in the estimated effects for cars (Alternative 8 in Table ES.2).

- An alternative to control variables for vehicle manufacturers is a single continuous variable for the vehicle's initial purchase price; purchase price may better account for other differences in vehicle design that may influence traffic safety. Adding this single variable to NHTSA's regression models substantially increases the estimated increase in risk from mass reduction of heavier-than-average cars, slightly lowers the estimated increase in risk in lighter cars and lighter trucks; and substantially increases the estimated beneficial effect from mass reduction in heavier light trucks and CUVs/minivans. Accounting for vehicle purchase price increases the estimated beneficial effect of footprint reduction in light trucks, but has little impact on the estimated detrimental effects of footprint reduction in cars or CUVs/minivans (Alternative 9 in Table ES.2; further addressed in Section 5.2).

- NHTSA included control variables for the calendar year in which the crash occurred, to reflect reducing risk from changes to vehicles, driver behavior and driving conditions over time. However, including these calendar year variables in the regression models appear to weaken the estimated benefit of curtain side air bags in cars, CUVs, and minivans, and compatibility measures and ESC in light trucks. These variables also appear to minimize the estimated increased risk of SUVs and heavy-duty pickup trucks. Excluding these calendar year variables from the regression models increases the estimated detrimental effect of mass reduction on risk in light trucks (Alternative 10 in Table ES.2, addressed in Section 5.3).

- Because details on the driver's condition or behavior are not consistently reported in the state crash data used to develop the induced exposure cases and VMT weights, it is not possible to control for individual drivers' behavior in the regression model. However, excluding crashes involving alcohol or drugs, or drivers with poor driving records, increases the estimated detrimental effect of mass reduction on risk, but reduces the estimated detrimental effect of footprint reduction on risk (Alternatives 11 and 12 in Table ES.2, Section 5.4). One possible surrogate for the behavior of drivers who tend to select certain vehicle models is driver household income. Including a measure of household income by vehicle model reduces the estimated detrimental effect of mass reduction on risk in cars, but has little effect on the association of mass with risk in trucks or CUVs/minivans (Alternative 13 in Table ES.2). Including all-wheel-drive, sports, and police cars increases the estimated effect of mass reduction, but reduces the estimated effect of footprint reduction, on risk for cars; while including fullsize vans reduces the estimated effect of mass reduction, and increases the estimated effect of footprint reduction, on risk for light trucks (Alternative 14 in Table ES.2, Section 5.5).

- As mentioned above, for its baseline fatalities NHTSA assumes that all new vehicles will have ESC installed by 2017, which will reduce the fraction of fatalities in rollovers and crashes with stationary objects, and thus will increase the estimated detrimental overall effect of mass reduction, but decrease the estimated detrimental overall effect of footprint reduction, on risk. However, other recent trends that are likely to continue through 2017 may also affect the distribution of crashes in that year. For example, side airbags in cars will likely reduce the fraction of fatalities in side-impact crashes (Section 6.1), and better alignment of light truck bumpers with those of other vehicles appears to reduce the risk imposed on car occupants, at least in side impact crashes (Section 6.2). However, it appears that mass reduction has less of an estimated detrimental effect on risk when cars are struck in the side than when they are involved in frontal or rear-end crashes, so any future reduction in fatalities in car side impact crashes will not necessarily influence the relationship between mass and risk. And it is not clear whether full adoption of side airbags or compatibility measures for light trucks will reduce fatality risk when light-duty trucks, CUVs or minivans are struck in the side.

Table ES.2. Estimated effect of mass or footprint reduction on US fatality risk per VMT, excluding certain data or using different control variables

Variable	Case vehicle type	NHTSA preferred model (fatalities per VMT)	7. Accounting for vehicle manufacturer	8.Accounting for vehicle manufacturer plus five luxury brands	9. Accounting for initial vehicle purchase price	10. Excluding CY variables	11. Excluding crashes with alcohol/drugs	12. Excluding. bad drivers	13. Accounting for median household income	14. Including sports, squad, AWD cars and fullsize vans
Mass reduction	Cars < 3106 lbs	1.55%*	1.90%	2.04%	1.42%	1.52%	1.88%	2.32%	1.20%	1.79%
	Cars > 3106 lbs	0.51%	0.75%	1.80%	0.84%	0.43%	0.88%	1.19%	0.16%	0.49%
	LTs < 4594 lbs	0.52%	0.59%	0.57%	0.45%	1.20%	0.78%	1.01%	0.68%	0.49%
	LTs > 4594 lbs	-0.34%	-0.11%	-0.11%	-0.52%	0.30%	-0.35%	-0.11%	-0.30%	-0.77%
	CUV/ minivan	-0.38%	1.62%	1.28%	-0.92%	0.03%	-0.16%	-0.01%	-0.44%	-0.38%
Footprint reduction	Cars	1.87%	1.71%	1.20%	1.99%	2.11%	1.65%	1.32%	2.30%	1.64%
	LTs	-0.07%	-0.29%	-0.28%	-0.36%	-0.42%	-0.26%	-0.39%	-0.19%	-0.02%
	CUV/ minivan	1.72%	-0.77%	-0.28%	1.57%	1.61%	1.36%	1.12%	1.82%	1.72%

* 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.
Estimates that are statistically significant at the 95% level are shown in red.

- Finally, in part because of high gas prices and the poor economy, households have been purchasing smaller and lighter vehicles in the last decade. For example, the explosion of CUVs appears to have led to a reduction in the market share of minivans, cars, and in recent years (MY05 to MY07) SUVs and pickups. It is likely that these trends would continue, even in the absence of stronger CAFE and GHG emission standards. Any future market shifts from SUVs or pickups to cars or car-based CUVs and minivans will result in much larger reductions in fatality risk than the relatively small increases in risk expected from mass or footprint reduction. For example, we estimate that a large-scale shift in the market share of pickups and SUVs to CUVs, minivans, and cars will reduce overall fatalities by over 3% (Section 6.3).

Table ES.3 shows the results of additional sensitivity tests NHTSA conducted in response to comments from the peer reviewers of its preliminary 2012 report. Alternative 15 in Table ES.3 indicates that using only stopped vehicles, and not all vehicles judged to be not-at-fault in two-vehicle crashes, substantially reduces the estimated detrimental effect of mass reduction on risk in all types of vehicles, while substantially increasing the estimated detrimental effect of footprint reduction on risk in cars. Replacing vehicle footprint with its two components, track width and wheelbase, similarly reduces the estimated detrimental effect of mass reduction, as shown in Alternative 16; an increase in risk is associated with decreasing track width in cars and light trucks, but with decreasing wheelbase in CUVs/minivans. Alternative 17 indicates that combining these two sensitivities, i.e. using stopped vehicles as the measure of exposure and replacing footprint with track width and wheelbase, further reduces the estimated detrimental effect of mass reduction, such that fatality risk is estimated to increase in light cars by a statistically non-significant 0.26%. Weighting the distribution of fatalities in CUVs and minivans by their respective shares of sales in 2010 (which reflects more CUVs and fewer minivans) causes the estimated effects to change signs, with decreasing mass now associated with an estimated increase in risk, and decreasing footprint with an estimated reduction in risk,

Table ES.3. Estimated effect of mass or footprint reduction on US fatality risk per VMT, under alternative regression model specifications suggested by NHTSA peer reviewers

Variable	Case vehicle type	NHTSA preferred model (fatalities per VMT)	15. Using stopped instead of non-culpable vehicles for induced exposure	16. Including track width and wheelbase instead of footprint	17. Using stopped vehicles and track width/wheelbase	18. Reweighting CUVs and minivans by 2010 sales	19. Excluding non-significant control variables
Mass reduction	Cars < 3106 lbs	1.55%*	0.97%	0.95%	0.26%	1.55%	1.63%
	Cars > 3106 lbs	0.51%	-0.63%	0.24%	-0.90%	0.51%	0.69%
	LTs < 4594 lbs	0.52%	0.35%	-0.07%	-0.10%	0.52%	0.35%
	LTs > 4594 lbs	-0.34%	-0.80%	-0.58%	-0.97%	-0.34%	-0.54%
	CUV/ minivan	-0.38%	-0.33%	-0.25%	-0.14%	0.55%	-0.46%
Footprint reduction	Cars	1.87%	3.43%	—	—	1.87%	1.73%
	LTs	-0.07%	-0.03%	—	—	-0.07%	0.11%
	CUV/ minivan	1.72%	1.81%	—	—	-0.61%	1.97%
Track width reduction	Cars	—	—	4.36%	6.03%	—	—
	LTs	—	—	1.07%	0.90%	—	—
	CUV/ minivan	—	—	0.08%	-0.55%	—	—
Wheel base reduction	Cars	—	—	-0.09%	0.38%	—	—
	LTs	—	—	-0.09%	-0.09%	—	—
	CUV/ minivan	—	—	1.16%	1.45%	—	—

* 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.

for CUVs and minivans (Alternative 18). Alternative 19 removes non-significant control variables from each of the regression models; the result is slightly larger estimated detrimental effects of reduced mass in cars, and slightly smaller estimated effects in light trucks.

Table ES.4 compares the results from NHTSA's 2003, 2010, and 2012 analyses with the alternative model specifications examined in this report (again, results that are statistically significant are shown in red in the table). The first two columns of the table indicate that NHTSA's 2012 analysis of a simultaneous reduction in mass and footprint (i.e. excluding a control variable for footprint in the regression model) results in a smaller estimated increase in fatalities than in NHTSA's 2003 analysis, particularly for lighter cars (a 2.74% increase rather than a 4.39% increase) and light trucks (a 0.47% increase rather than a 2.90% increase). The third and fourth columns of the table indicate a similar reduction in estimated additional fatalities for cars when footprint is held constant (i.e. when a control variable for footprint is included in the regression model). However, holding footprint constant increases the estimated effect of mass reduction slightly in light trucks (a 0.52% increase rather than a 0.17% increase in fatalities for lighter light trucks, and a 0.34% reduction rather than a 1.90% reduction in fatalities for the heavier light trucks). This small estimated increase in light truck risk may be due to NHTSA analyzing crossover utility vehicles and minivans as a separate vehicle class, rather than as light trucks, in the 2012 analysis.

The last column in Table ES.4 shows that the results of the alternative model specifications examined in this report are, in nearly all cases, lower than the results of the 2003 NHTSA report, and often lower than the results of the 2010 and 2012 analyses.

Table ES.4. Previous NHTSA results of the estimated effect of mass and footprint reduction on US fatality risk per VMT, compared with different scenarios analyzed in this report

Variable	Case vehicle type	NHTSA (2003) excluding footprint	NHTSA (2012) excluding footprint	NHTSA (2010) including footprint	NHTSA (2012) including footprint	Range of different scenarios analyzed in this report
Mass reduction	Cars < 3106 lbs	4.39%	2.74%	2.21%	1.55%	-0.22% to 2.74%
	Cars > 3106 lbs	1.98%	1.95%	0.89%	0.51%	-1.45% to 2.40%
	LTs < 4594 lbs	2.90%	0.47%	0.17%	0.52%	-1.13% to 1.20%
	LTs > 4594 lbs	0.48%	-0.39%	-1.90%	-0.34%	-0.97% to 0.30%
	CUV/ minivan	—	0.60%	—	-0.38%	-0.92% to 1.62%
Footprint reduction	Cars	—	—	—	1.87%	-0.09% to 3.43%
	LTs	—	—	—	-0.07%	-1.30% to 0.22%
	CUV/ minivan	—	—	—	1.72%	-0.77% to 2.26%

The 2012 NHTSA study, and this report, conclude that the estimated effect of mass reduction while maintaining footprint on societal US fatality risk is small, and statistically non-significant for all but the lightest cars. This report indicates that although the estimated effects are sensitive to what variables and data are included in the regression analysis, in nearly all cases the effects are less, in some cases dramatically less, than reported in the 2003 NHTSA study. This report also finds that the estimated effects of 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, on risk are much larger, in some cases two orders of magnitude larger, than the estimated effect of mass or footprint reduction on risk. Finally, this report shows that after accounting for the many vehicle, driver, and crash variables NHTSA used in its regression analyses, there remains a wide variation in risk by vehicle make and model, and this variation is unrelated to vehicle mass.

Although the purpose of the NHTSA and LBNL reports is to estimate the effect of vehicle mass reduction on societal risk, this is not exactly what the regression models are estimating. Rather, they are estimating the recent historical relationship between mass and risk, after accounting for most measurable differences between vehicles, drivers, and crash times and locations. In essence, the regression models are comparing the risk of a 2600-lb Dodge Neon with that of a 2500-lb Honda Civic, after attempting to account for all other differences between the two vehicles. The models are not estimating the effect of literally removing 100 lbs from the Neon, leaving everything else unchanged.

In addition, the analyses 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. Therefore, throughout this report we use the phrase “the estimated effect of mass (or footprint) reduction on risk” as shorthand for “the estimated change in risk as a function of its relationship to mass (or footprint) for vehicle models of recent design.”

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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 2012). 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.

This report uses 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. In addition, we examine the data in slightly different ways, to get a deeper understanding of the relationship between reductions in vehicle mass and footprint, and overall safety. This final report incorporates revisions from the preliminary report released in November 2011, including revised estimates of national weights for vehicle miles traveled, inclusion of 2008 police-reported crash data from eight additional states, and responses to reviewers' comments.

The section below summarizes the expected relationships between vehicle mass, size and fatality risk. In Section 2 we reproduce NHTSA's results, and analyze the control variables NHTSA includes in their preferred regression models. Section 3 examines in more detail the multi-collinearity between vehicle mass and footprint, and the methods NHTSA took to address that multi-collinearity. In Section 4 we examine the relationship between vehicle mass and risk by vehicle model, before and after accounting for differences in driver characteristics, crash locations, and other vehicle attributes by vehicle model. In Section 5 we test alternative specifications of the regression models developed by NHTSA, in order to examine the sensitivity of their results to the assumptions they used and different model specifications. Finally in Section 6 we examine the influence of recent trends in vehicle market share on the expected effect of mass reduction on risk in 2017 to 2025.

1.1. Expected relationships between vehicle mass, size and fatality risk

In Section 1.5 of its 2012 report, NHTSA describes the hypothetical physical factors of vehicle design that could explain the historical relationship between vehicle mass and societal fatality risk. One would expect lighter vehicles to have higher fatality rates for their own occupants, all else being equal, for several reasons:

- in frontal or rear crashes, light vehicles tend to be smaller than heavy vehicles, and therefore do not have the crush space which protects occupants;

- in two-vehicle crashes, as the mass differential between the two vehicles increases, the delta V (change in velocity) for the lighter vehicle, and therefore the risk to its occupants, increases relative to that of the heavier vehicle.
- in crashes with a stationary object additional mass may be sufficient to knock the object, such as a tree or pole, down, allowing the vehicle to continue moving and reducing its delta V than if it was completely stopped by the object. In a previous study NHTSA estimated that the object is knocked down in about 25% of frontal collisions with stationary objects (Partyka, 1995).
- in crashes with a medium- or heavy-duty truck, additional mass in the light-duty vehicle would transfer more of its momentum to the truck, reducing the delta V of, and fatality risk in, the light vehicle without increasing the risk in the heavier vehicle.

NHTSA notes that accounting for vehicle size in the regression analysis may reduce or eliminate the estimated benefit of additional vehicle mass correlated with additional crush space. And that accounting for societal risks, that is risk of fatality both to the occupants of the subject vehicle and its crash partner, may reduce or eliminate the effect of mass differential in two-vehicle crashes, as increased fatalities in the lighter vehicle may be offset by reduced fatalities in the heavier vehicle.

On the other hand, there are situations where lower mass is expected to <u>reduce</u> fatality risk:

- in crashes with an immovable stationary object, reducing the mass of a vehicle while maintaining its crush space and structural strength would lower the kinetic energy of the crash, reducing the amount of energy for the vehicle's structure to absorb, and likely reducing occupant fatality risk;
- in rollovers, reducing mass without changing the vehicle's roof structure would reduce the force applied on the roof once a vehicle turns over.
- lower-mass vehicles should respond more quickly to steering, braking, or acceleration, thereby reducing their crash frequency.

Changing the size of a vehicle is expected to reduce risk in several ways. Increasing wheelbase or track width, or better yet frontal or side overhang, can increase crush space and reduce risk in all types of crashes. Adding to a vehicle's track width also increases a vehicle's static stability, and reduces its propensity to rollover.

Changing other vehicle dimensions also can reduce risk. Lowering bumpers or the "average height of force" in larger, heavier vehicles such as pickups and SUVs can make them more compatible with cars, and reduce risk to occupants in crash partner vehicles. Similarly, raising the door sill of a car provides more structure to engage with a bumper of a taller vehicle, such as a pickup or SUV, striking the car in the side. And lowering the center of gravity also is important in increasing stability and preventing rollovers. Finally, strengthening a vehicle's frontal or side structure can increase the amount of energy it can absorb in all types of crashes; however, increasing frontal stiffness will likely have negative impacts on the occupants of a crash partner in a frontal collision.

All of these hypothetical effects of the changes in vehicle mass, footprint, or other dimensions assume no other changes to the vehicle. However, this is rarely the case, as often the source of the additional mass is the installation of a particular safety feature (such as 4-wheel drive or ESC), and manufacturers often make other changes to a vehicle design at the same time they change its mass or footprint. In short, it is possible that other changes in vehicle design, as well as introduction of safety technologies, can mitigate the increase in risk from reducing vehicle mass or footprint.

In Section 1.6 NHTSA discusses the issue that, despite their theoretical advantage in terms of handling, braking, and accelerating, small and light vehicles historically have had higher crash and insurance claim frequency per vehicle mile traveled. This discrepancy suggests that small and light vehicles have not been driven as well as larger, heavier ones. NHTSA provides two hypotheses for why this would be the case: that less capable drivers tend to chose smaller and lighter vehicles; and that drivers of more maneuverable smaller and lighter vehicles tend to drive them more recklessly. As an example of the latter, NHTSA cites the high crash rates in vehicles with large engines, which in theory should reduce crash frequency because they allow a vehicle to accelerate out of dangerous situations.

In summary, the complexity of the factors in vehicle design and operation makes it extremely difficult to isolate their effect on occupant and societal risk. As NHTSA concludes, "although [the 2010 NHTSA] report and this one both concentrate on the effects of mass and footprint, because that is their purpose, these effects are indeed small relative to design and engineering, which shape a vehicle's intrinsic safety and also bear indirectly on its fatality rates by influencing what types of drivers choose the vehicle."

2. NHTSA results

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 13 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 Sections 2.3 through 2.6 of the 2012 NHTSA report (Kahane 2012).

In this section we replicate the logistic regression results NHTSA obtained using the database they constructed. We also test the effect certain changes in the regression model specifications have on the coefficients for the independent variables of interest, vehicle mass and footprint.

2.1. Data and methods

For this new analysis NHTSA used FARS data on fatal crashes, and police-reported crash data from 13 states, for MY00 to MY07 light-duty vehicles between 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). As in its previous analyses, NHTSA excluded three types of cars, models used as sports cars, police cars, and models with all-wheel drive, as well as fullsize passenger and cargo vans, from its initial regression analyses; in addition, NHTSA excluded all Ford Crown Victorias, which tend to be high-mileage vehicles, on the basis that the sparse odometer data available for this large car model are not representative. We followed NHTSA's convention of excluding these vehicles from our analyses; we test the sensitivity of the estimates to excluding these vehicles in Section 5.5.

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 2012 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

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	D	D	D
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

C #: for some models the VIN does not indicate whether a particular vehicle is equipped with that option or not. In these cases the fraction of that model that is equipped with the particular feature is used.

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.

regression models for all other crashes involving cars or CUVs/minivans. No airbag variables were included in the regression models for light trucks.

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.[1] 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.

Table 2.2. Baseline fatal crash involvements, by case vehicle type and crash type

	Baseline fatal crash involvements: MY04-07 vehicles in CY04-08			Adjusted for full penetration of ESC			Percent difference		
Crash type	Cars	LTVs	CUVs/ minivans	Cars	LTVs	CUVs/ minivans	Cars	LTVs	CUVs/ minivans
1: Rollovers	938	1,627	277	454	508	100	-52%	-69%	-64%
2: w/object	3,496	2,090	571	2,076	1,253	373	-41%	-40%	-35%
3: Ped etc.	2,259	2,192	812	2,259	2,192	812	0%	0%	0%
4: w/HDT	1,248	838	316	1,158	779	297	-7%	-7%	-6%
5: w/lgt car	1,500	1,922	534	1,399	1,791	503	-7%	-7%	-6%
6: w/hvy car	1,984	1,758	604	1,846	1,640	569	-7%	-7%	-6%
7: w/lgt LT	963	893	259	894	830	244	-7%	-7%	-6%
8: w/hvy LT	1,328	837	311	1,232	779	294	-7%	-7%	-5%
9: Other	4,375	3,621	1,459	4,082	3,388	1,380	-7%	-6%	-5%
Total	18,091	15,778	5,143	15,400	13,160	4,572	-15%	-17%	-11%

All of the regression coefficients presented in the NHTSA 2012 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 decrease in vehicle mass or footprint; we use the same convention throughout this report). The output from the SAS LOGIST procedure reflect the percent change in the log-odds of fatality per billion VMT for a one-unit increase in the explanatory variable. In order to obtain the percent change in the probability of fatality, the SAS outputs need to be

[1] 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.

converted from log-space to linear space, and from odds to probabilities. We use the conversion factor $e^x - 1$, 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 fatality is small; however it substantially increases the percent change for explanatory variables that have a large effect on the log-odds of fatality (such as the crash location variables). For example, the fatality risk from a rollover crash involving a car is estimated to have a 2.20 times higher log-odds of fatality if it occurs in a rural county; after conversion, this crash is estimated to have a 802 percent higher probability of fatality if it occurs in a rural county (EXP(2.20) - 1 = 8.02). Unless noted otherwise, the 95% confidence intervals shown in this report are calculated the same way, using the standard error of the log-odds output by the SAS LOGIST procedure.

Figure 2.1 presents the regression coefficients from the NHTSA report (in light blue); the coefficients for each of the 9 crash types are weighted by the distribution of 2016 baseline fatal crash involvements, after adjustment for full ESC penetration, from Table 2.2. (The coefficients are slightly different from those provided in the 2012 NHTSA report, perhaps because of rounding errors and our reporting of percent changes in risk as probabilities rather than as log-odds.) The figure indicates that lower mass is associated with an increase in societal[2] fatality risk of about one percent for cars and lighter-than-average light trucks, while lower mass is associated with 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 2012 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. As a result, NHTSA's 2012 report indicates that only the estimated 1.55% increase in risk from mass reduction for the lighter cars is statistically significant.

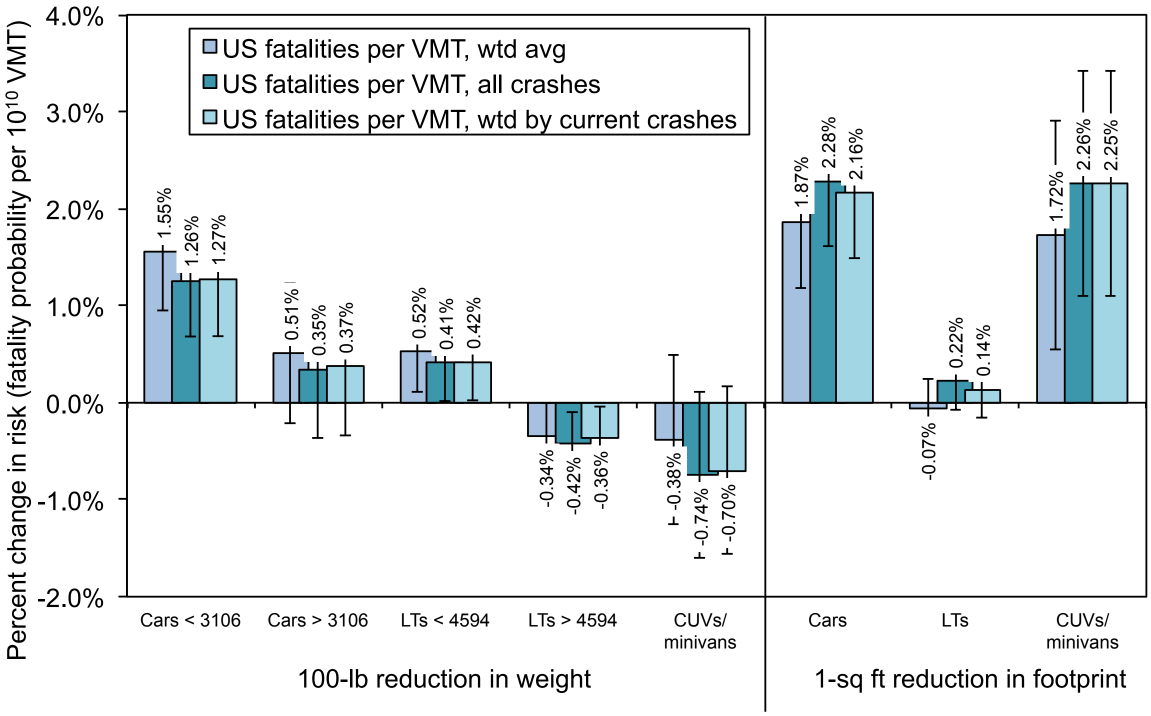
Figure 2.1 also shows that lower footprint is associated with increased risk for all three types of vehicles, and has a larger estimated effect on risk than lower mass for cars and CUVs/minivans. A 1-square foot reduction in footprint is estimated to increase fatality risk in cars and CUVs/minivans by close to 2 percent, but has no estimated effect on risk in light trucks.

Results from a single regression analysis across all crash types are also shown in Figure 2.1 (in dark turquoise), as are the results of the nine regression models by crash type weighted by the current distribution of fatalities (light turquoise), not the distribution NHTSA assumes for 2017-2025 based on full ESC penetration. Full penetration of ESC in the on-road fleet slightly increases the estimated safety penalty from mass reduction, as the NHTSA weighted values (in light blue) are all higher than the unweighted values (in light turquoise). On the other hand, full

[2] All of the fatality risks reported in the 2012 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.

ESC penetration reduces the estimated safety penalty from a reduction in footprint, for all vehicle types.

Figure 2.1. Estimated effect of mass or footprint reduction on US fatality risk per VMT, across all crash types and weighted average effect in each type of crash, by vehicle type



Figures 2.2 through 2.4, and Table 2.3, show the estimated effect of changes in mass or footprint on risk, by type of crash. For cars, mass reduction is estimated to increase risk in all crash types except rollovers and crashes with stationary objects, as shown in Figure 2.2. As described in Section 1.1, 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; and mass reduction is expected to reduce risk in crashes with immovable stationary objects. Because NHTSA assumes that by 2017 ESC will have eliminated many of the fatalities in rollovers and crashes with stationary objects, and these are the only types of crashes in which mass reduction is estimated to reduce risk, NHTSA's weighted regression results for 2017-2025 show a larger increase in overall risk than the results based on recent crashes (in Figure 2.1). On the other hand, lower footprint is associated with the largest increases in risk in rollovers and crashes with stationary objects (Figure 2.2), so removing fatalities in these types of crashes by 2017 will reduce the estimated detrimental effects of footprint reduction (as shown in the light blue columns in Figure 2.1).

Mass reduction in the lighter cars is associated with the biggest increase in risk (5.80%) in crashes with a heavy light truck. For heavier cars, mass reduction is associated with generally smaller increases in risk for most types of crashes. A reduction in car footprint is estimated to increase risk in all types of crashes, including rollovers and crashes with stationary objects. In fact, lower footprint is associated with the largest increases in risk in these two crash types

(7.76% and 3.93%), followed by crashes with a lighter light-duty truck (3.88%) and with a heavy-duty truck (2.92%).

Figure 2.3 shows the estimated effect of mass and footprint reductions on risk in light trucks. In general, the estimated effects on risk are smaller for light trucks than for cars, and there are more cases in which lower mass is associated with reduced risk, although the effects are often small and not statistically-significant. Mass reduction is associated with a statistically-significant reduction in risk in lighter truck crashes with objects, and heavier truck rollovers; but (statistically-insignificant) increases in risk in lighter truck rollovers and heaver truck crashes with objects. As with light cars, the biggest estimated effect of weight reduction in lighter trucks is in crashes with a heavier light truck, with an estimated 4.36% increase in risk. A reduction in light truck footprint is estimated to increase risk, although the increases are small and often not statistically-significant. However, contrary to cars, lower footprint in light trucks is associated with a statistically significant reduction in fatality risk in crashes with pedestrians and cyclists, and with heavier light trucks.

Figure 2.2. Estimated effect of mass or footprint reduction on risk in cars, by type of crash

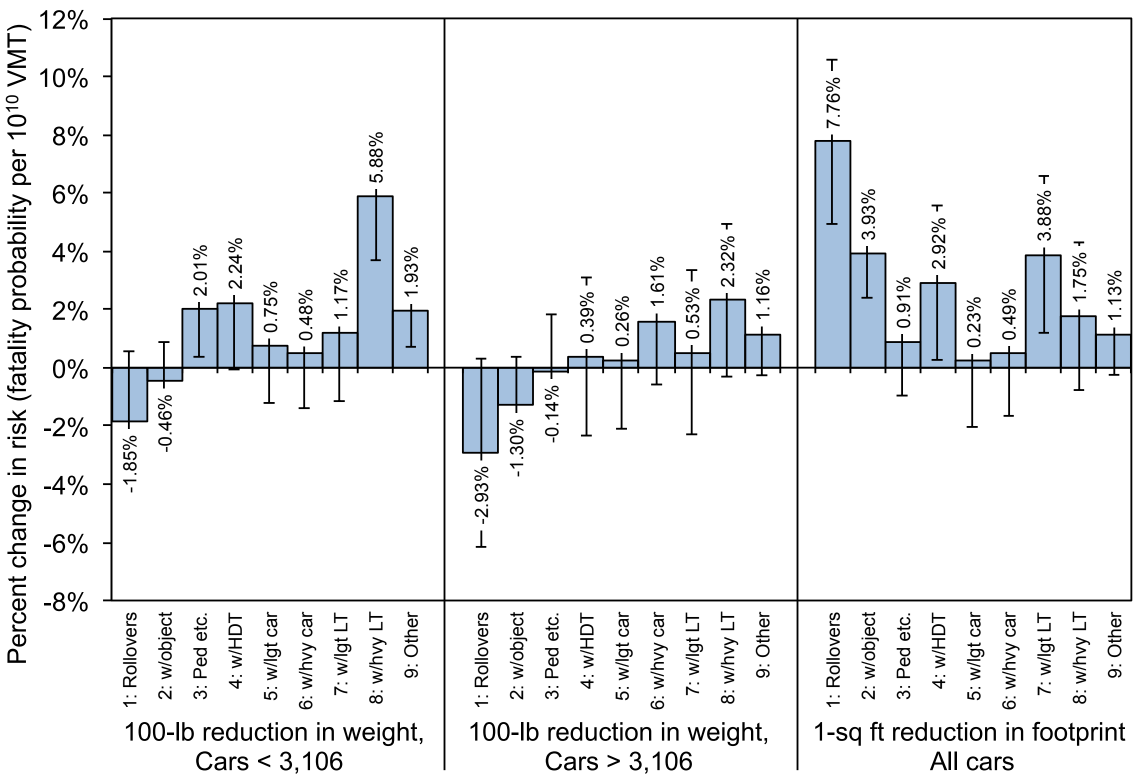
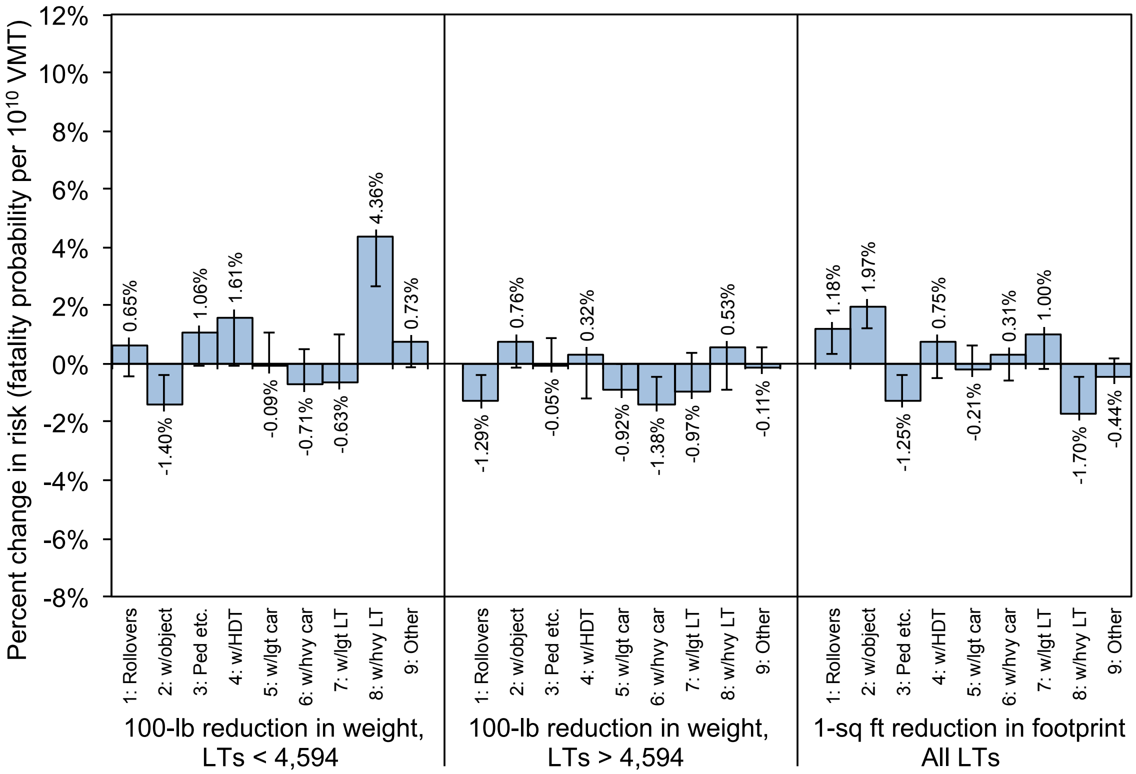


Figure 2.3. Estimated effect of mass or footprint reduction on risk in light trucks, by type of crash



The estimated effect of reductions in mass and footprint on risk in crashes involving CUVs and minivans are shown in Figure 2.4. The estimated effects from mass reduction tend to be larger in CUVs and minivans than in cars or light trucks, with a greater than 7% estimated reduction in risk in rollovers and an estimated 3.68% reduction in risk in crashes with objects. Mass reduction in CUVs/minivans is estimated to have the most detrimental effect on risk in crashes with a light light-duty truck, a 3.75% increase. The estimated effect of reductions in footprint in CUVs and minivans is similar to that for cars, with a larger, statistically-significant estimated increase in risk in rollovers (10.94%) and crashes with objects (7.39%). As with cars, NHTSA's assumption of fewer fatalities in rollovers and crashes with stationary objects due to full adoption of ESC by 2017 results in an increase in the estimated effect of mass reduction, but a decrease in the estimated effect of footprint reduction, on risk in CUVs and minivans (light blue columns in Figure 2.1).

Figure 2.4. Estimated effect of mass or footprint reduction on risk in CUVs/minivans, by type of crash

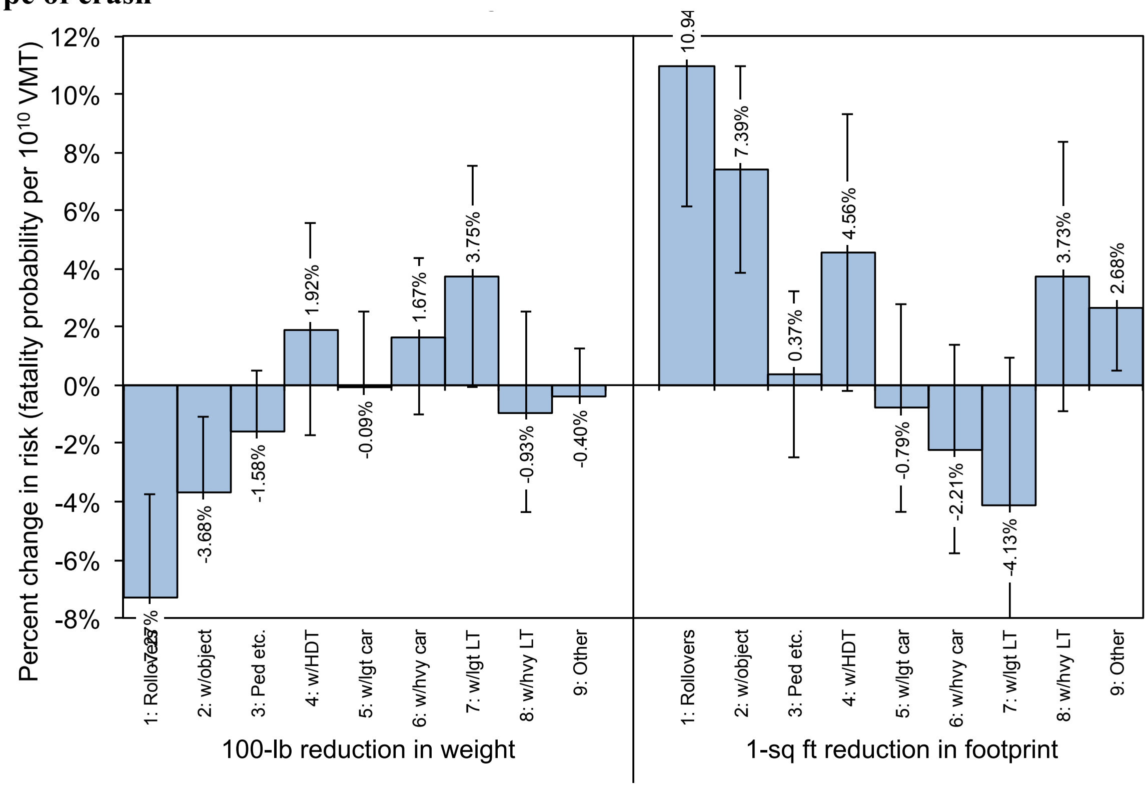


Table 2.3. Estimated effect of mass or footprint reduction on US fatality risk per VMT, by type of crash

	Mass reduction					Footprint reduction		
Type of crash	Cars < 3106 lbs	Cars > 3106 lbs	LTs < 4594 lbs	LTs > 4594 lbs	CUVs/ minivans	Cars	LTs	CUVs/ minivans
1: Rollovers	-1.85%	-2.93%	0.65%	-1.29%	-7.27%	7.76%	1.18%	10.94%
2: w/object	-0.46%	-1.30%	-1.40%	0.76%	-3.68%	3.93%	1.97%	7.39%
3: Ped etc.	2.01%	-0.14%	1.06%	-0.05%	-1.58%	0.91%	-1.25%	0.37%
4: w/HDT	2.24%	0.39%	1.61%	0.32%	1.92%	2.92%	0.75%	4.56%
5: w/lgt car	0.75%	0.26%	-0.09%	-0.92%	-0.09%	0.23%	-0.21%	-0.79%
6: w/hvy car	0.48%	1.61%	-0.71%	-1.38%	1.67%	0.49%	0.31%	-2.21%
7: w/lgt LT	1.17%	0.53%	-0.63%	-0.97%	3.75%	3.88%	1.00%	-4.13%
8: w/hvy LT	5.88%	2.32%	4.36%	0.53%	-0.93%	1.75%	-1.70%	3.73%
9: Other	1.93%	1.16%	0.73%	-0.11%	-0.40%	1.13%	-0.44%	2.68%
All	1.55%	0.51%	0.52%	-0.34%	-0.38%	1.87%	-0.07%	1.72%

Estimates that are statistically significant at the 95% level are shown in red.

Figures 2.5 through 2.10, and Table 2.4, compare the estimated effect of mass and footprint reduction on risk with that of the other control variables, by vehicle type. In terms of other car characteristics, Figure 2.5 indicates that two-door cars are estimated to increase US fatality risk per VMT by 8%, while TORSO side airbags, automated braking systems (ABS), and electronic stability control (ESC), are estimated to reduce risk by about 10%. The driver age variables tend to increase risk, with young male and elderly drivers (male and female) increasing US fatality risk per VMT from 5% to 8%. Car age causes a small estimated increase in risk, while a brand new car is estimated to increase risk by 10%, presumably because the driver is unfamiliar with a new car's controls, handling, and/or braking capabilities. The calendar year variables are estimated to have a decreasing effect on risk over time, declining from an estimated 6% increase in risk in 2002 to an estimated 13% reduction in risk in 2008. The calendar year variables are examined in more detail in Section 5.3.

Note that the three vehicle variables of interest, UNDRWT, OVERWT, and FOOTPRINT, all have a much lower estimated effect on risk than almost all of the control variables in Figure 2.5. For instance, a 100-lb reduction in curb weight for an underweight car is estimated to increase risk by 1.55%, while installing ESC would reduce risk by 11.9%; the models estimate that the beneficial effect of adding ESC is nearly ten times that of reducing mass by 100 lbs.

The control variables in Figure 2.6 have a much bigger estimated effect on risk than the mass or footprint reduction variables, or the control variables presented in Figure 2.5. Male drivers are estimated to increase US fatality risk per VMT by nearly 40%, while the three control variables for crash environment, NITE, RURAL, and SPDLIM55, are estimated to more than triple fatality risk per VMT. A crash occurring in a high-fatality state carries an estimated 30% higher fatality risk per VMT than a crash in other states. Since driving on a roadway with a posted speed limit greater than 55 miles per hour is estimated to increase risk by over 400%, the regression models suggest that a 0.39% increase in driving on high-speed roads would result in the same increase in fatalities as estimated for a 100-lb reduction in mass for every car (1.6% / 414% = 0.39%).

Figure 2.5. Estimated effect of selected control variables on risk, passenger cars

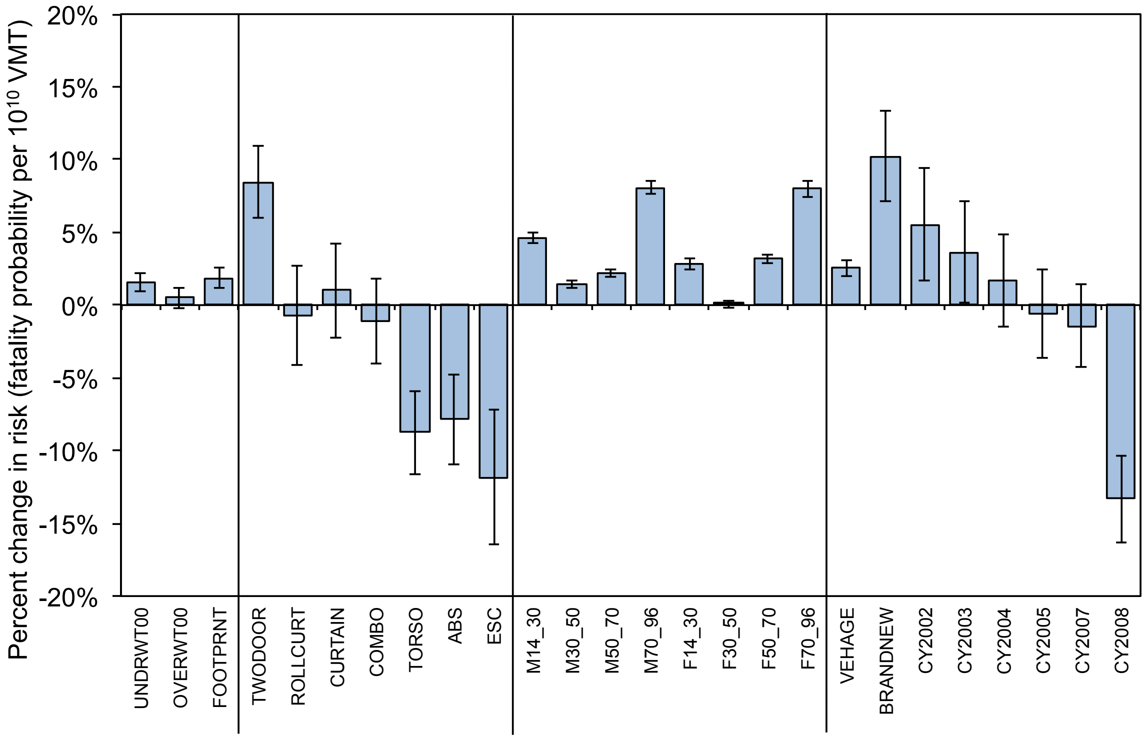


Figure 2.6. Estimated effect of selected control variables on risk, passenger cars

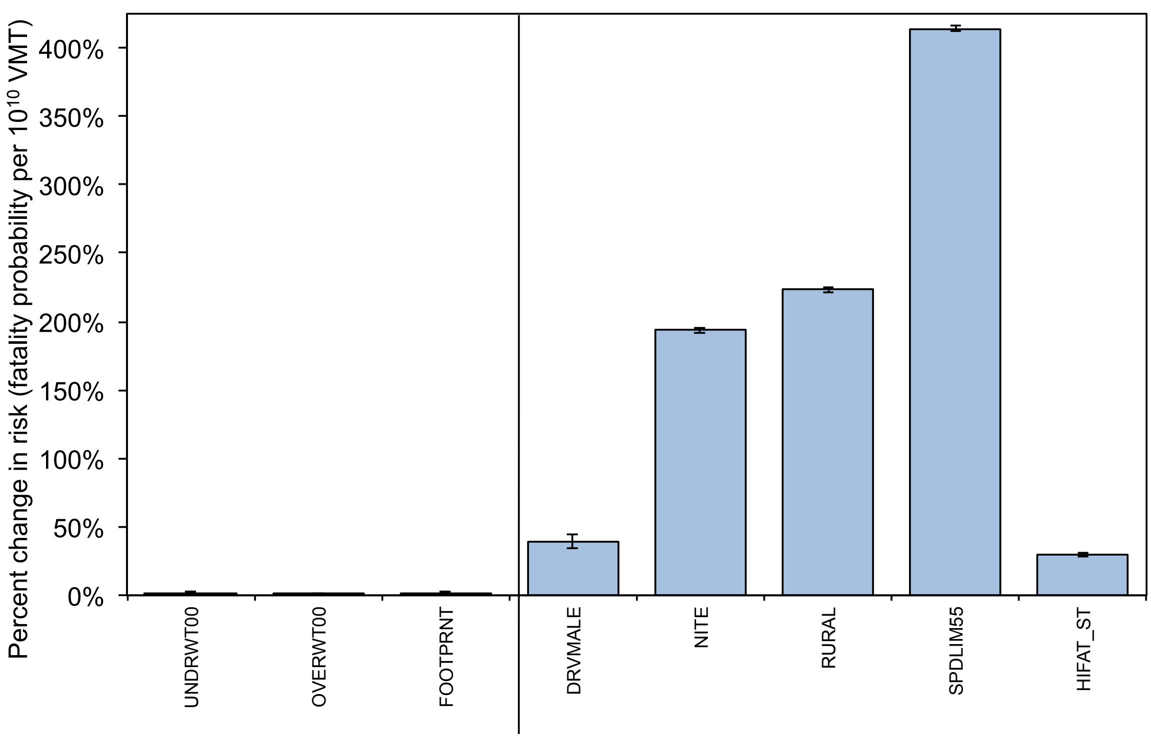


Table 2.4. Estimated effect on US fatality risk per VMT, by vehicle type

Type	Control variable	Cars Estimate	Cars 95% CI	Light-duty trucks Estimate	Light-duty trucks 95% CI	CUVs/ minivans Estimate	CUVs/ minivans 95% CI
Vehicle variables	UNDRWT00	1.55%	0.60%	0.52%	0.41%	—	—
	OVERWT00	0.51%	0.72%	-0.34%	0.34%	—	—
	LBS100	—	—	—	—	-0.38%	0.87%
	FOOTPRINT	1.87%	0.69%	-0.07%	0.30%	1.72%	1.18%
	TWODOOR	8.45%	2.50%	—	—	—	—
	SUV	—	—	8.94%	3.94%	—	—
	HD_PKP	—	—	1.73%	4.04%	—	—
	BLOCKER1	—	—	-1.41%	2.11%	—	—
	BLOCKER2	—	—	-2.32%	3.08%	—	—
	MINIVAN	—	—	—	—	-0.94%	7.43%
	ROLLCURT	-0.73%	3.38%	—	—	-1.67%	1.16%
	CURTAIN	1.00%	3.24%	—	—	-2.85%	7.22%
	COMBO	-1.10%	2.95%	—	—	-6.43%	4.94%
	TORSO	-8.77%	2.91%	—	—	0.86%	5.39%
	ABS	-7.87%	3.08%	—	—	-16.5%	9.69%
	ESC	-11.9%	4.62%	-18.8%	4.40%	-3.89%	7.83%
	AWD	—	—	-14.5%	2.31%	-14.0%	5.74%
	VEHAGE	2.54%	0.55%	3.57%	0.62%	5.50%	1.23%
	BRANDNEW	10.22%	3.12%	3.62%	3.32%	8.76%	6.03%
Driver variables	DRVMALE	39.2%	4.74%	19.3%	4.87%	37.1%	8.06%
	M14_30	4.63%	0.37%	3.54%	0.35%	3.92%	0.97%
	M30_50	1.40%	0.24%	1.25%	0.19%	0.84%	0.48%
	M50_70	2.20%	0.29%	1.24%	0.26%	1.82%	0.51%
	M70_96	8.08%	0.44%	7.65%	0.70%	7.10%	1.03%
	F14_30	2.81%	0.42%	3.64%	0.58%	4.77%	0.99%
	F30_50	0.09%	0.27%	0.22%	0.32%	-0.47%	0.48%
	F50_70	3.21%	0.32%	3.10%	0.52%	3.22%	0.60%
	F70_96	8.00%	0.57%	6.36%	1.86%	7.69%	1.61%
Crash variables	NITE	194%	1.8%	192%	1.9%	160%	4.0%
	RURAL	223%	1.8%	207%	1.9%	215%	3.7%
	SPDLIM55	414%	1.8%	409%	1.9%	405%	3.7%
	HIFAT_ST	29.5%	1.73%	24.6%	1.95%	33.8%	3.65%
	CY2002	5.56%	3.89%	22.4%	4.09%	7.59%	8.80%
	CY2003	3.60%	3.48%	18.2%	3.67%	4.97%	7.67%
	CY2004	1.69%	3.21%	14.1%	3.36%	-3.28%	6.97%
	CY2005	-0.60%	3.03%	7.86%	3.16%	0.02%	6.22%
	CY2007	-1.42%	2.83%	-1.19%	3.03%	-4.99%	5.64%
	CY2008	-13.3%	3.00%	-15.0%	3.28%	-19.7%	6.08%

Estimates that are statistically significant at the 95% level are shown in red.

Figures 2.7 and 2.8 present the estimated effect of the control variables on fatality risk in crashes involving light-duty trucks. SUVs (8.9%), and to a lesser extent heavy-duty pickups (1.7%), have a higher estimated fatality risk than regular pickups. NHTSA includes two variables identifying approaches to comply with voluntary measures to reduce light truck aggressivity towards cars: BLOCKER1, vertical alignment of bumpers, and BLOCKER2, employment of an additional blocker beam behind the bumper. Each of these two approaches are estimated to reduce fatalities by about 1%. As with cars, risk is estimated to be higher with young male (19%) and elderly (7%) drivers. Brand new light trucks (3.6%) have a lower estimated risk than brand new cars (10%), which is surprising as one would think unfamiliarity with the handling of a light truck would increase the chance of it rolling over. As with cars, the calendar year variables have a decreasing effect on risk over time, but the decline is much greater, from an estimated 22% increase in risk in 2002 to an estimated 15% decrease in risk in 2008. The calendar year variables are discussed in more depth in Section 5.3.

ESC is estimated to reduce risk by 19% in light trucks (Figure 2.8) as opposed to only 12% in cars (Figure 2.5), while male drivers are estimated to increase risk in trucks only 19% but 39% in cars (Figure 2.6). All-wheel drive (AWD) is estimated to reduce risk in pickups by nearly 15%. As in cars, driving at night, in rural areas, and on roadways with high speed limits are estimated to more than triple the risk in trucks, while driving in high fatality states has a similar increase in risk as in cars (25%).

Figure 2.9 indicates that minivans are estimated to have a slightly (1%) lower fatality risk than CUVs. For CUVs and minivans, combination airbags are estimated to have a larger reduction in risk than side curtain airbags (6.4% vs. 2.9%), while torso airbags are associated with a slight, non-significant (0.9%) increase in risk. As there is no logical explanation of why torso air bags could increase risk, this result indicates the lack of precision in the regression coefficients for some of the safety technologies, especially in regressions limited to relatively small subsets of the data. ABS is associated with a bigger reduction in risk (17%) than ESC (4%) for CUVs and minivans, opposite to the results seen for cars (8% and 12%, respectively) in Figure 2.5. In terms of driver characteristics, young and elderly drivers are associated with the highest increase in risk. The coefficients on the calendar year control variables are smaller than those for light trucks (with the exception of CY2008); these are discussed in more detail in Section 5.3.

The control variables for CUVs and minivans presented in Figure 2.10 are similar to those for cars (Figure 2.6) and light trucks (Figure 2.8). For all vehicle types, many of the control variables shown in Figures 2.5 through 2.10 and Table 2.4 have a much greater estimated effect on fatality risk than reductions in vehicle mass or footprint.

Figure 2.7. Estimated effect of selected control variables on risk, light trucks

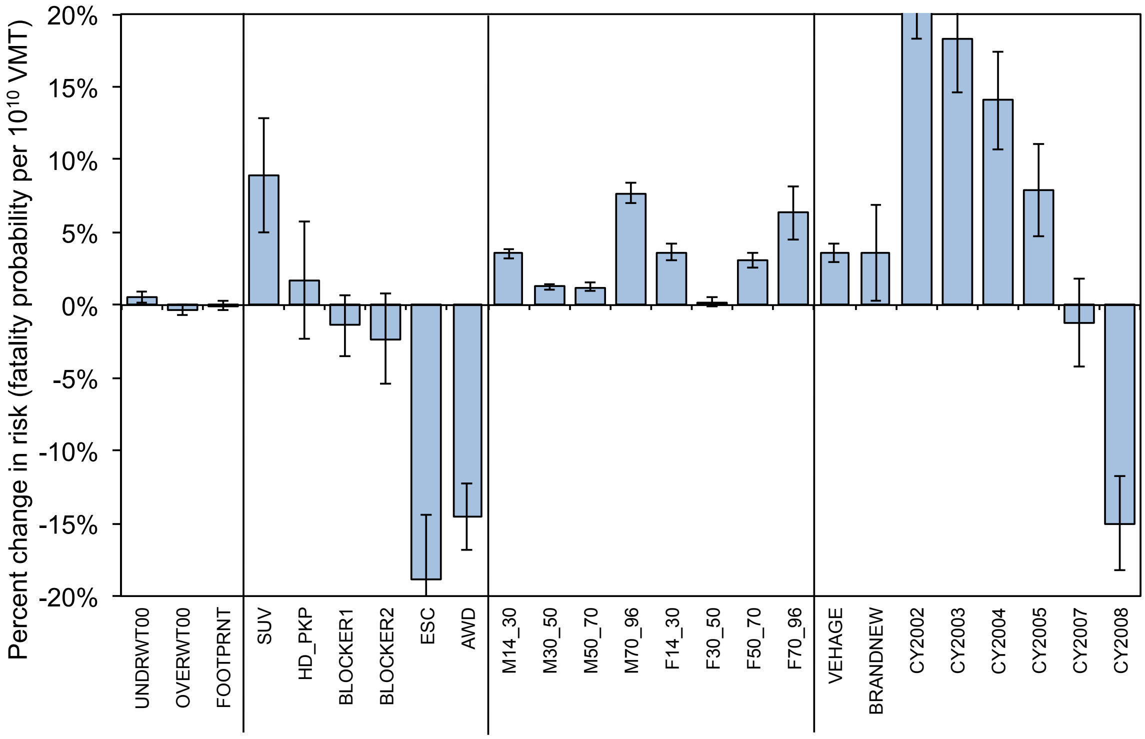


Figure 2.8. Estimated effect of selected control variables on risk, light trucks

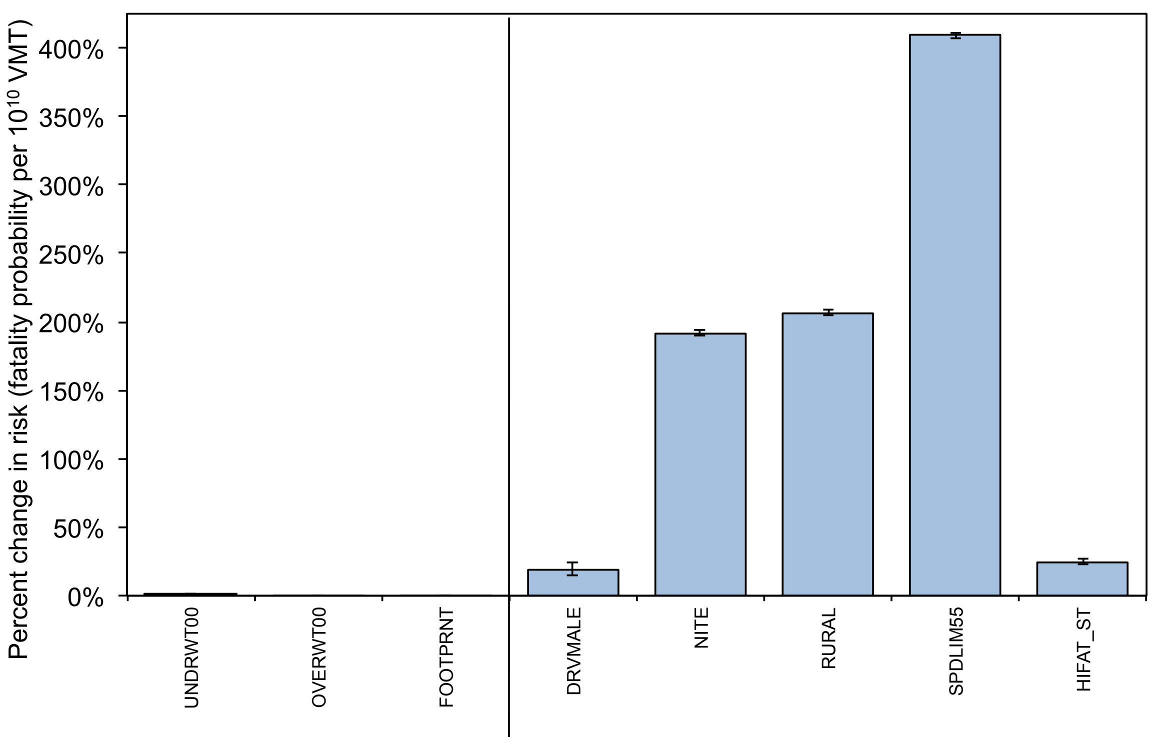


Figure 2.9. Estimated effect of selected control variables on risk, CUVs and minivans

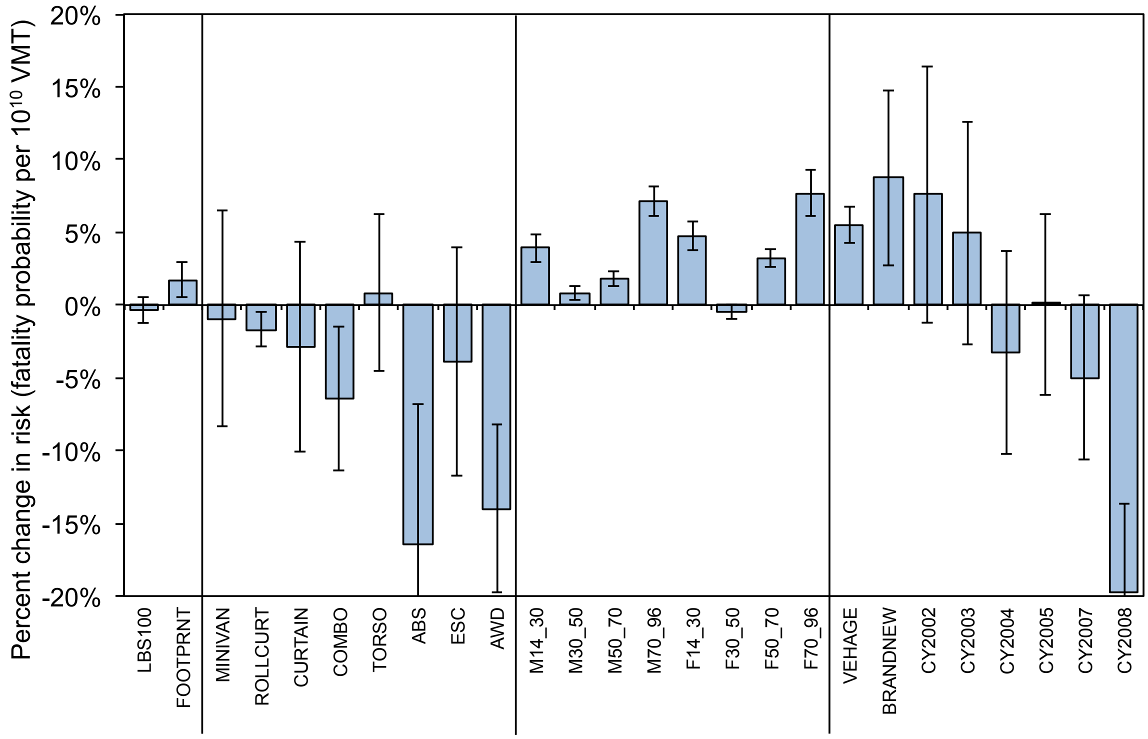
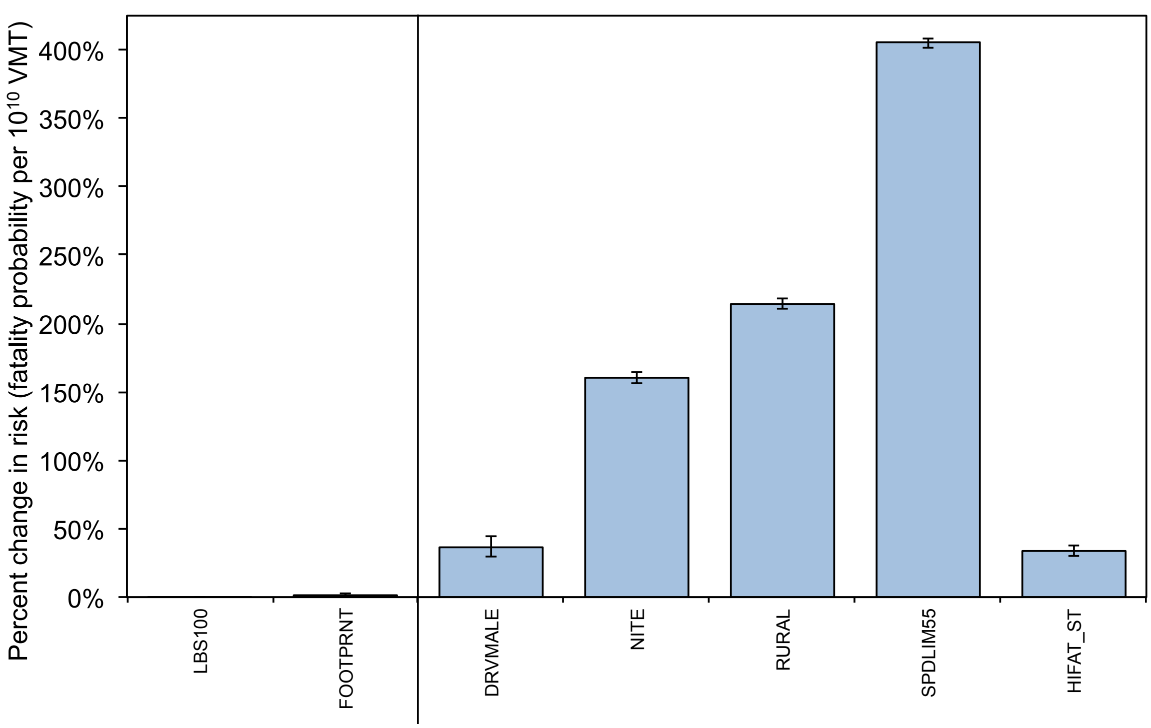


Figure 2.10. Estimated effect of selected control variables on risk, CUVs and minivans



3. Multi-collinearity between vehicle mass and footprint

In its 2003 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. Using two or more variables that are strongly correlated in the same regression model (referred to as multi-collinearity) can lead to biased results. The variance inflation factor, or VIF, is a measure of the degree of multi-collinearity in a regression model. Allison[3] "begins to get concerned" with VIF values greater than 2.5, while Menard[4] suggests that a VIF greater than 5 is a "cause for concern", while a VIF greater than 10 "almost certainly indicates a serious collinearity problem"; however, O'Brien[5] suggests that "values of VIF of 10, 20, 40 or even higher do not, by themselves, discount the results of regression analyses." .

DRI showed that regression analyses that included both mass and size (i.e. wheelbase and track width) in the same regression model (i.e. that estimated the effect of mass while holding size constant, and vice versa) estimated smaller effects for changes in mass or size on US fatality risk per VMT (Van Auken and Zellner 2002, 2003, 2004, 2005a, 2005b). In its 2010 and 2012 analyses, NHTSA included both mass and size (i.e. footprint, or wheelbase times track width) in the same regression model, in part because the model year 2012 to 2016 light truck standards adopted in 2010, and the proposed 2017 to 2025 standards for all light-duty vehicles, assign a target fuel economy/greenhouse gas emission level based on a vehicle's footprint (Kahane 2010 and 2012).

Figure 3.1 shows the correlation between curb weight and footprint by vehicle model in the NHTSA database; only the most popular 275 models, with at least 10 billion VMT or 100 fatalities, 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 (Pearson correlation coefficient, or r, of 0.90) than for light trucks (r of 0.75) or CUVs/minivans (r of 0.78). Figure 3.2 shows the same data as Figure 3.1, but uses seven vehicle types. Here the correlation ranges from over 0.80 for 4-door cars, SUVs, small pickups, and CUVs to less than 0.80 for large pickups and 2-door cars, to only 0.49 for minivans. The correlation of 0.75 for all light trucks (pickups and SUVs) combined in Figure 3.1 is improved when the types of trucks are analyzed separately in Figure 3.2: 0.90 for SUVs and 0.86 for small pickups, but only 0.67 for large pickups. On the other hand, separating CUVs from minivans improves the correlation between curb weight and footprint for CUVs (0.86) but not for minivans (0.49). 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 0.63.

[3] Allison, P.D.. *Logistic Regression Using SAS, Theory and Application*. SAS Institute Inc., Cary NC, 1999.
[4] Menard, S. *Applied Logistic Regression Analysis, Second Edition*. Sage Publications, Thousand Oaks CA, 2002.
[5] O'Brien, R.M. "A Caution Regarding Rules of Thumb for Variance Inflation Factors," Quality and Quantitiy, (41) 673-690, 2007.

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

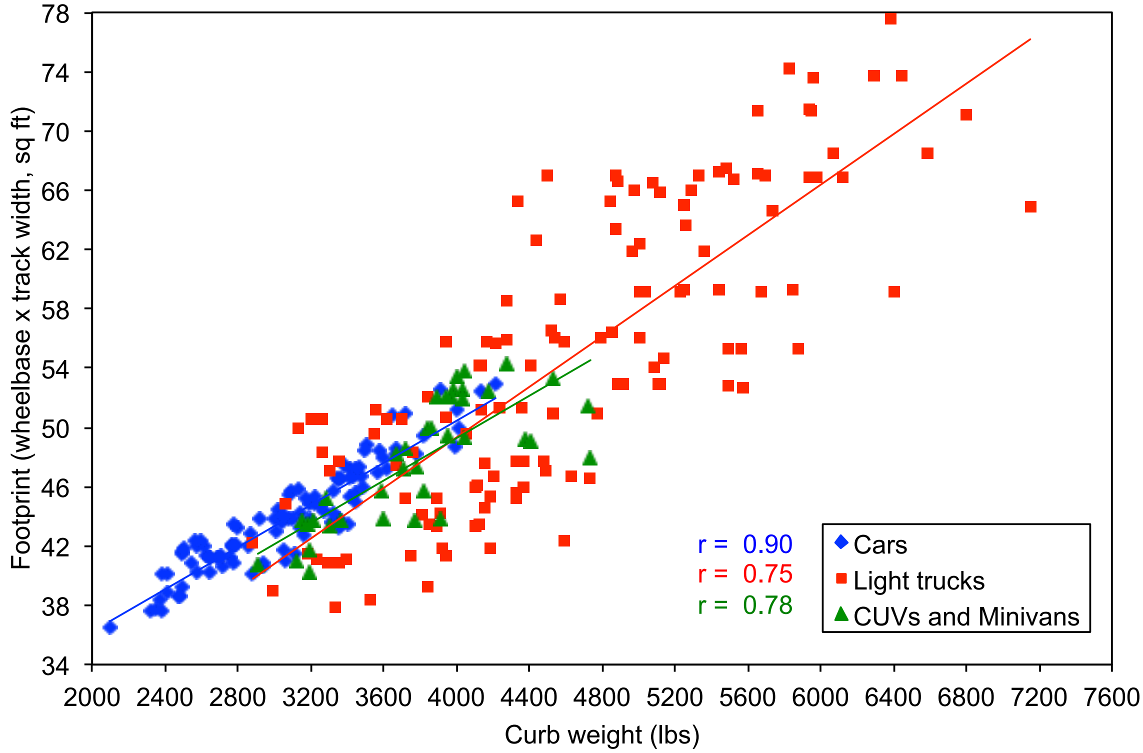


Figure 3.2. Correlation between vehicle curb weight and footprint, by vehicle model and seven vehicle types

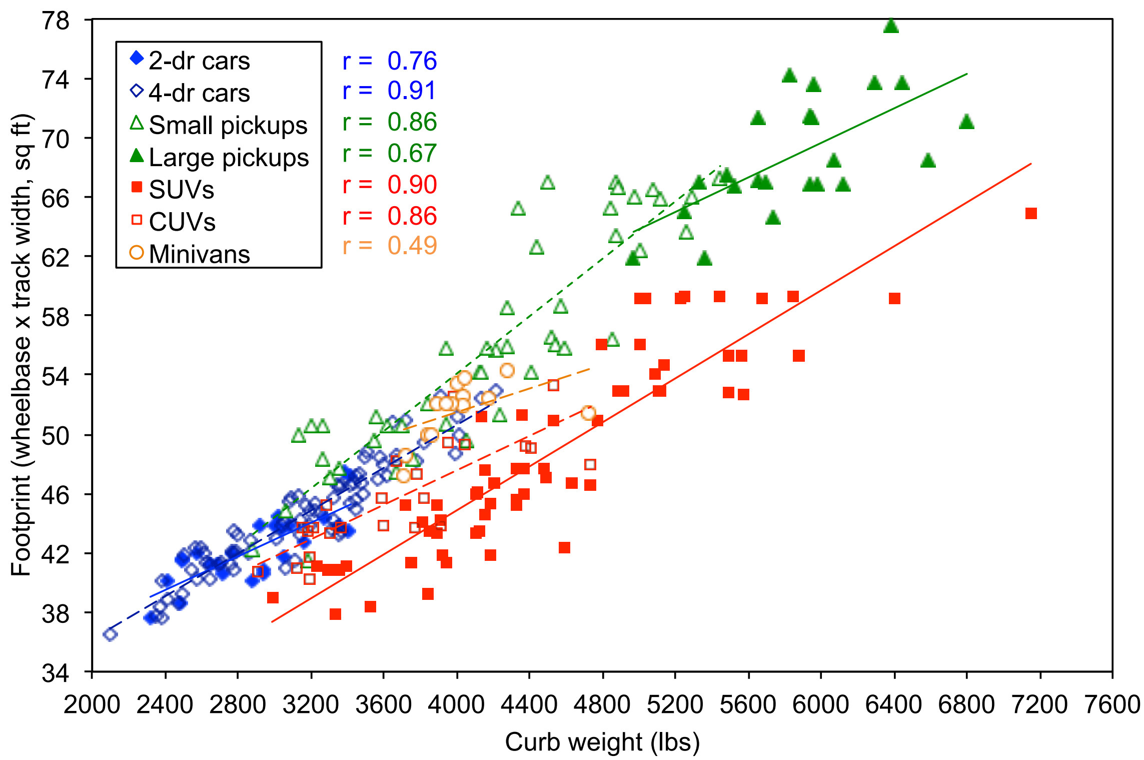


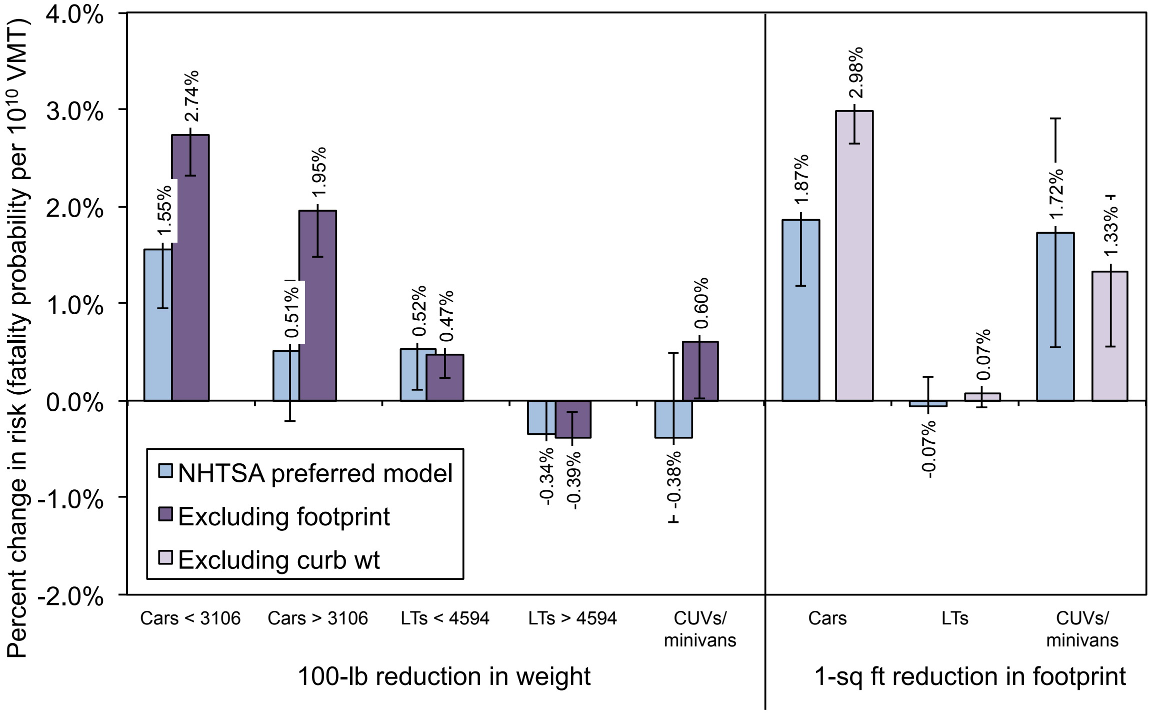
Table 3.1 shows the correlation coefficients of curb weight with footprint, and variance inflation factors, by vehicle type. The values in the table are weighted by the VMT weights for individual makes and models. The table indicates that curb weight is most highly correlated with footprint for 4-door cars and SUVs (r over 0.90), followed by small pickups and CUVs (r of 0.80) and 2-door cars (0.76). The correlation between weight and footprint is lowest for large pickups (0.67) and minivans (0.49); the low correlation between weight and footprint for minivans is strongly influenced by one model, the Kia Sedona, which is unusually heavy for its size. Removing this model from the analysis increases the correlation to 0.63. Table 3.1 also indicates that six of the seven vehicle types (all except minivans) have a VIF associated with curb weight greater than 2.5, the point at which multi-collinearity becomes a concern.

Table 3.1. Correlation coefficients and variance inflation factors of curb weight with footprint, by vehicle type

		Variance inflation factor (VIF)			
	Correlation coefficient	Accounting for vehicle and type variables		Accounting for all variables	
Vehicle type	(r)	CURBWT	FOOTPRNT	CURBWT	FOOTPRNT
Cars	0.896	6.2	5.6	7.3	6.0
Light trucks	0.748	6.5	8.6	8.1	9.8
CUVs/minivans	0.781	3.8	6.7	4.7	8.7
2-dr cars	0.758	3.3	2.7	3.8	3.0
4-dr cars	0.910	6.8	6.2	8.6	6.8
Sm pickups	0.862	4.1	4.0	6.5	4.8
Lg pickups	0.673	2.0	1.9	3.6	2.3
SUVs	0.904	6.0	5.8	7.8	1.0
CUVs	0.863	5.1	4.4	7.9	6.4
Minivans	0.488	1.5	1.4	2.1	1.8

Figure 3.3 compares NHTSA's preferred model, in light blue from Figure 2.1, with two alternative model specifications to test the sensitivity of the results from the preferred model. The first sensitivity, in dark purple, includes the weight variables in the regression model but excludes the footprint variable; this model tests the estimated effect of mass reduction while allowing footprint to vary with vehicle mass. This sensitivity increases the risk from a 100-lb mass reduction in cars (from an estimated 1.55% to 2.74% for lighter cars, and from an estimated 0.51% to 1.95% for heavier cars) and CUVs/minivans (from an estimated 0.38% decrease in risk to an estimated 0.60% increase in risk); however, there is no change in fatality risk in light-duty trucks. These results are quite similar to those reported by NHTSA in Section 3.7 of the 2012 report; the slight differences are likely due to rounding errors, as well as our reporting of percent changes in risk as probabilities rather than as log-odds, as described above.

Figure 3.3. Estimated effect of mass or footprint reduction on risk, by vehicle type: mass only, footprint only, and both



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 along with footprint increases the estimated effect of a reduction in footprint on car risk, from an estimated 1.87% increase to an estimated 2.98% increase, but decreases the effect of footprint reduction on CUV/minivan risk, from an estimated 1.72% increase to an estimated 1.33% increase. Allowing light truck mass to be reduced along with footprint does not change the estimated effect of a reduction in footprint on risk in light trucks. Figure 3.3 suggests that including both mass and footprint reductions in the same regression model somewhat reduces the estimated effect of both variables in cars and CUVs/minivans, but has no effect on the variables for light trucks.

Figures 3.4 through 3.6 show the effect of these two sensitivities by crash type; in contrast to Figures 2.2 through 2.4, the figures indicate that including only mass or footprint in the regression models reduces or eliminates any estimated reduction in risk in a particular crash type, particularly for mass reductions in car rollover and object crashes, and for mass or footprint reductions in CUV/minivan crashes.

Figure 3.4. Estimated effect of reduction in car mass or footprint on US fatality risk per VMT, by crash type

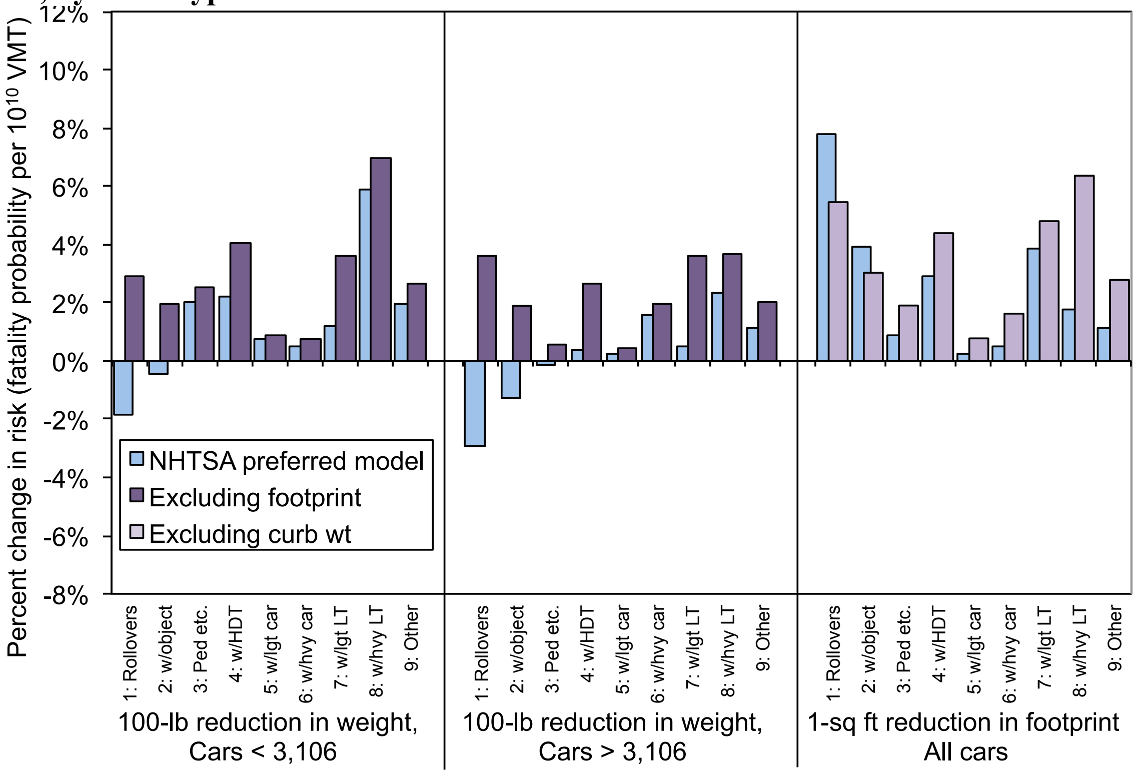


Figure 3.5. Estimated effect of reduction in light-duty truck mass or footprint on US fatality risk per VMT, by crash type

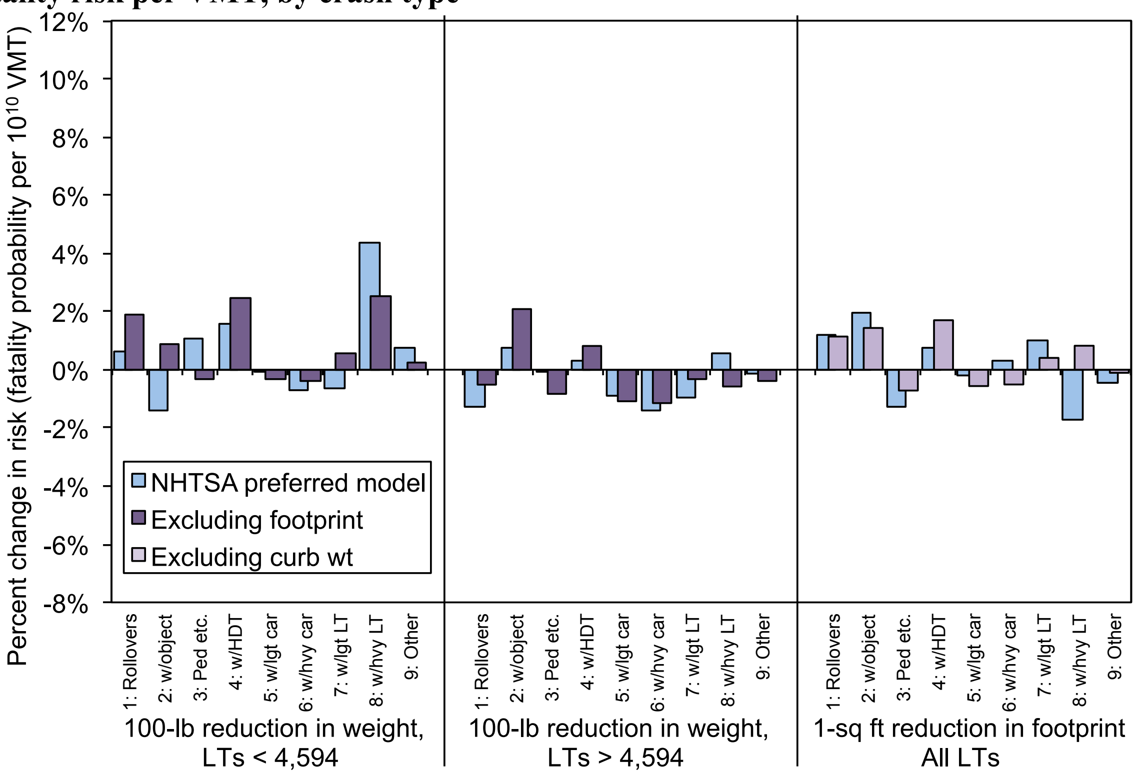
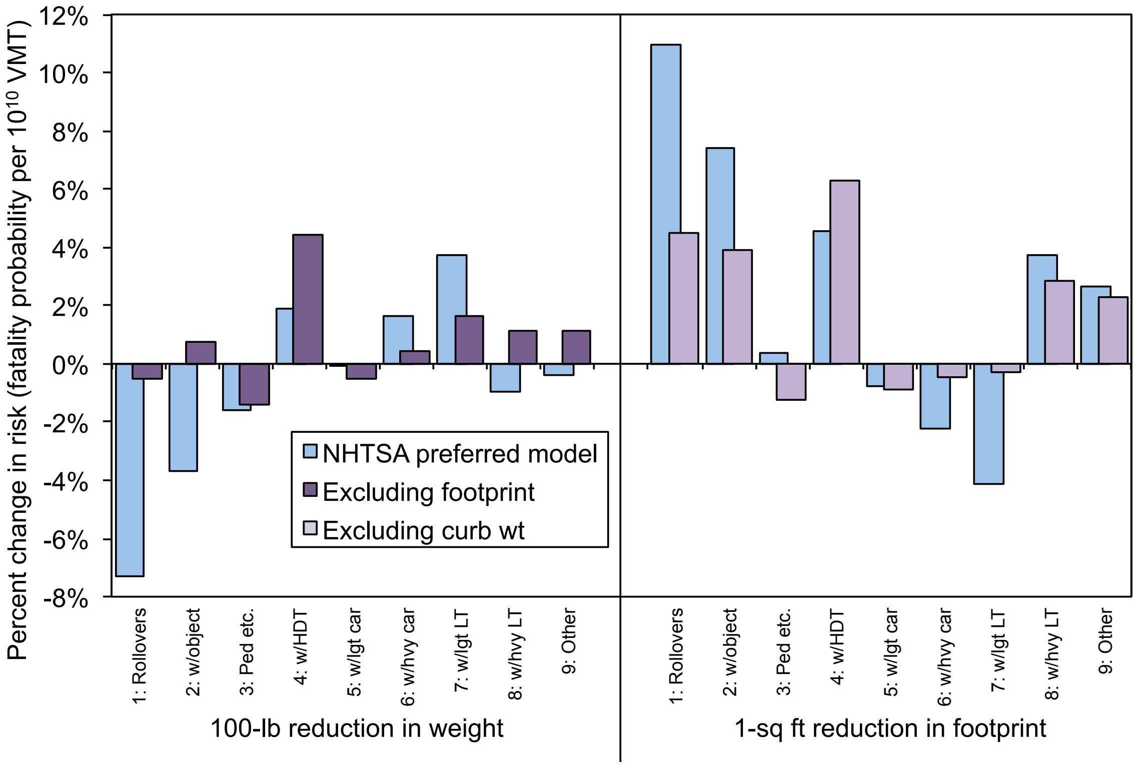


Figure 3.6. Estimated effect of reduction in CUV/minivan mass or footprint on US fatality risk per VMT, by crash type



In its 2012 analysis NHTSA examined the relationship between curb weight and fatality risk for deciles of vehicles with roughly the same footprint. Figure 3.7 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 lower mass reduction is associated with an increase in fatality risk.

Figure 3.7. Range in curb weight for the footprint deciles, by vehicle type

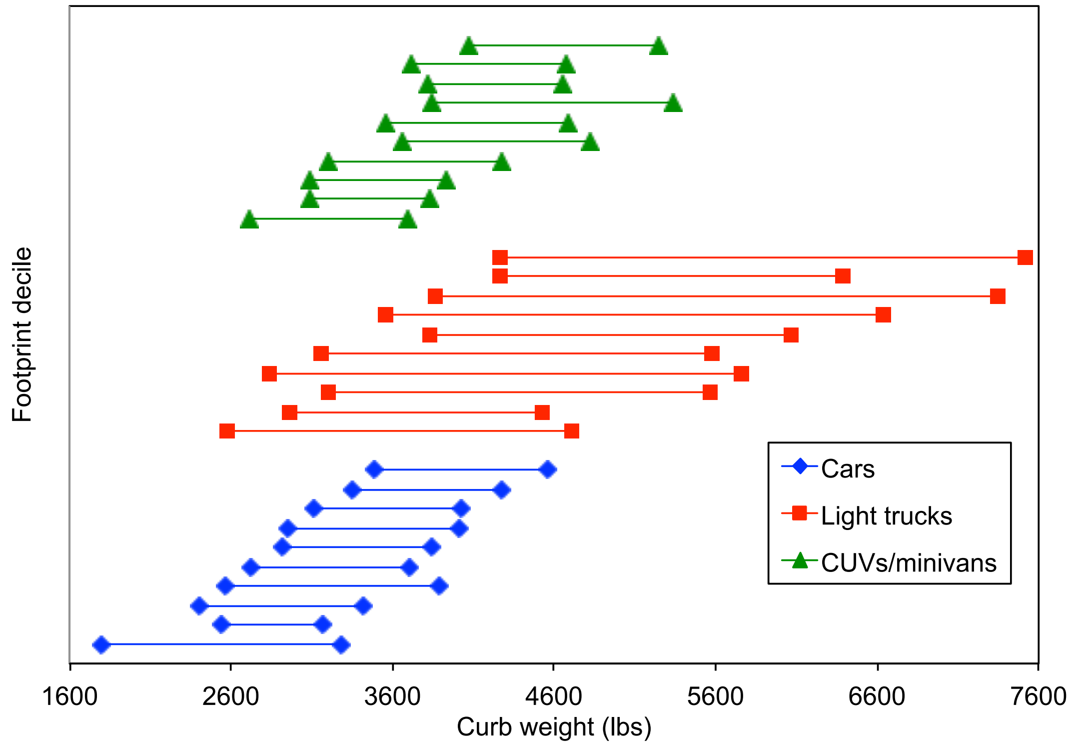


Table 3.2 replicates this analysis and results, and includes the number of footprint deciles in which the coefficient on vehicle mass is statistically significant, for each combination of vehicle and crash type. There are four columns for each vehicle type in Table 3.2; the first two indicate the number of footprint deciles in which lower vehicle mass is associated with increased risk, 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 lower vehicle mass is associated with reduced risk, and the number that are statistically significant. For example, in car rollover crashes, lower mass is associated with increased risk in five footprint deciles; however, none of those increases is statistically significant. On the other hand, lower mass is associated with decreased risk in five footprint deciles in car rollover crashes, and four of those five are statistically significant. Table 3.2 indicates that lower car mass is associated with increased risk in a majority of footprint deciles in only four crash types: with a pedestrian/cyclist, a heavy-duty truck, a heavy light-duty truck, or other crashes; however, very few of these relationships are statistically significant. On the other hand, lower car mass is associated with reduced risk in rollover crashes for five of the footprint deciles, and four of these reductions. Lower light truck mass is associated with increased risk for six deciles in rollover crashes; three of these increases are statistically significant. Lower light truck mass is associated with decreased risk for seven deciles in crashes with light or heavy cars, and several of these decreases are statistically significant. For CUVs and minivan crashes with heavy cars, lower mass is associated with increased risk in eight deciles, with three of those increases being statistically significant.

Table 3.2. Number of footprint deciles in which lower vehicle mass is associated with an increase or decrease in US fatality risk by VMT, 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	5	0	5	4	6	3	4	2	4	0	6	2
2: w/object	4	0	6	2	5	0	5	0	5	0	5	1
3: w/ped etc.	7	2	3	2	5	1	5	1	3	0	7	0
4: w/HDT	7	0	3	0	7	2	3	0	6	1	4	0
5: w/lgt car	5	0	5	0	3	1	7	4	5	1	5	0
6: w/hvy car	5	1	5	0	3	0	7	3	8	3	2	1
7: w/lgt LT	5	1	5	1	6	0	4	0	7	0	3	0
8: w/hvy LT	7	2	3	0	9	2	1	0	5	0	5	2
9: Other	6	1	4	1	5	1	5	1	6	1	4	1

The data in Table 3.2 give no information on the size of the estimated effect of mass reduction on risk in the footprint deciles. Figures 3.8 through 3.10 show the estimated percent change in 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 3.8 indicates that lower mass is associated with reduced risk in car rollover crashes (shown as blue diamonds) in five deciles, by over 10% in footprint deciles six and seven, and by 20% in footprint decile eight. Figure 3.10 indicates that mass reduction in CUVs/minivans is estimated to reduce risk in crashes with a heavy light-duty truck (shown as purple circles) in five of the footprint deciles, and that these reductions are quite large (over 45%), and statistically significant, for the largest two deciles of CUVs/minivans. Figures 3.8 through 3.10 suggest that there are no consistent trends in the estimated effect of mass reduction on risk when vehicles are grouped by footprint decile.

Figure 3.8. Estimated effect of car mass reduction on fatality risk, by footprint decile and crash type

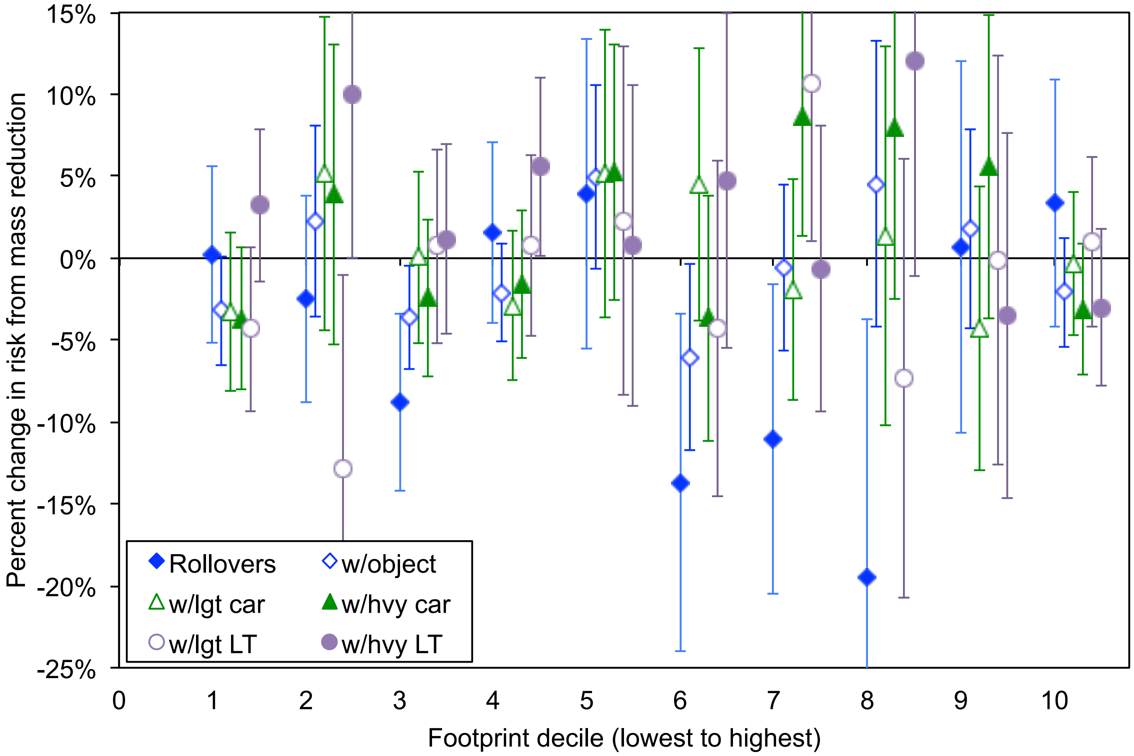


Figure 3.9. Estimated effect of light truck mass reduction on fatality risk, by footprint decile and crash type

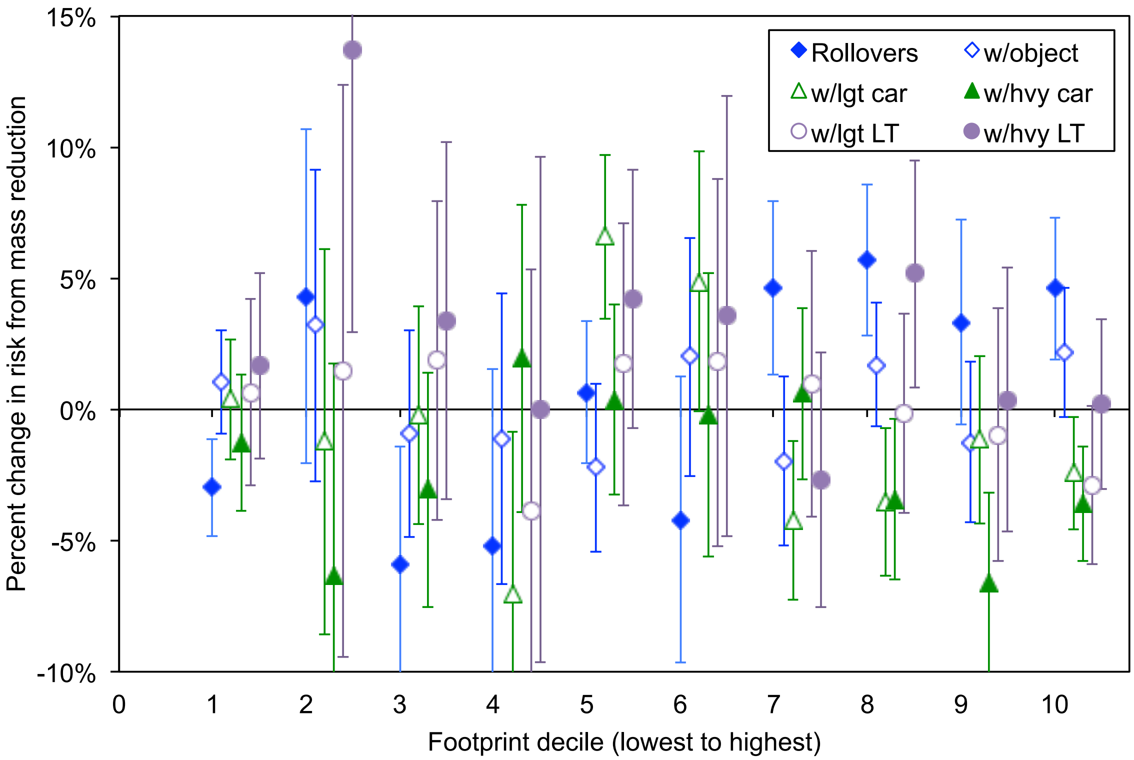
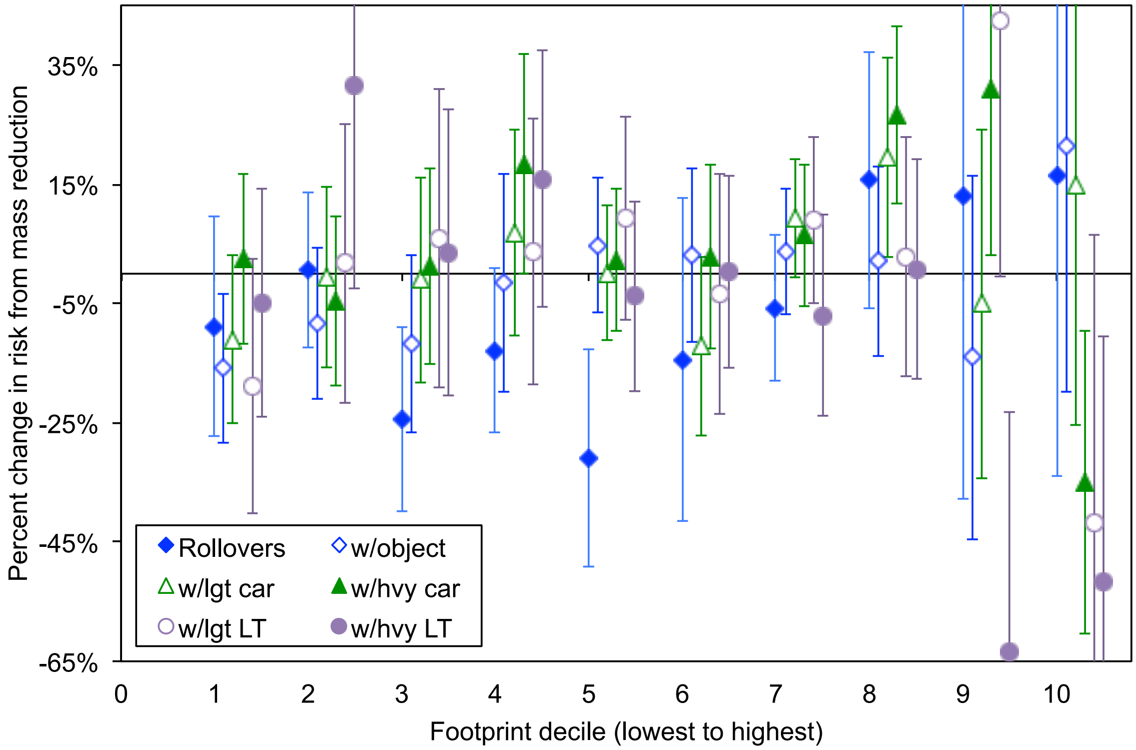


Figure 3.10. Estimated effect of CUV/minivan mass reduction on fatality risk, by footprint decile and crash type



4. Fatality risk by vehicle model

Unless noted otherwise, all fatality risks in this report are societal risk, including fatalities in the case vehicle and any crash partners, and include not only driver fatalities but passenger fatalities as well. In this section we examine the variation in societal fatality risk by vehicle model, both before and after accounting for the vehicle, driver and crash variables NHTSA includes in its regression models. Figure 4.1 plots unadjusted US fatality risk per VMT against average curb weight, with vehicles grouped into 100-lb increments of vehicle curb weight. Figure 4.1 indicates that, although risk does tend to decrease linearly as curb weight increases for cars and CUVs/minivans, there remains a fair degree of variability, as indicated by the Pearson correlation coefficient (r) values below 0.70. On the other hand, societal risk increases slightly as light truck mass increases, and the correlation is quite low (r of -0.13).

Figures 4.2 through 4.4 show the relationship between unadjusted risk and mass by more detailed vehicle type. Figure 4.2 indicates that the relationship between curb weight and fatality risk is weaker for 4-door cars than for 2-door cars. Figure 4.3 suggests that for large pickups risk increases as curb weight increases. And Figure 4.4 indicates that the relationship between risk and curb weight is strongest for minivans.

Figure 4.1. Relationship between US fatality risk and curb weight, with vehicles grouped into 100-lb increments of curb weight, by vehicle type

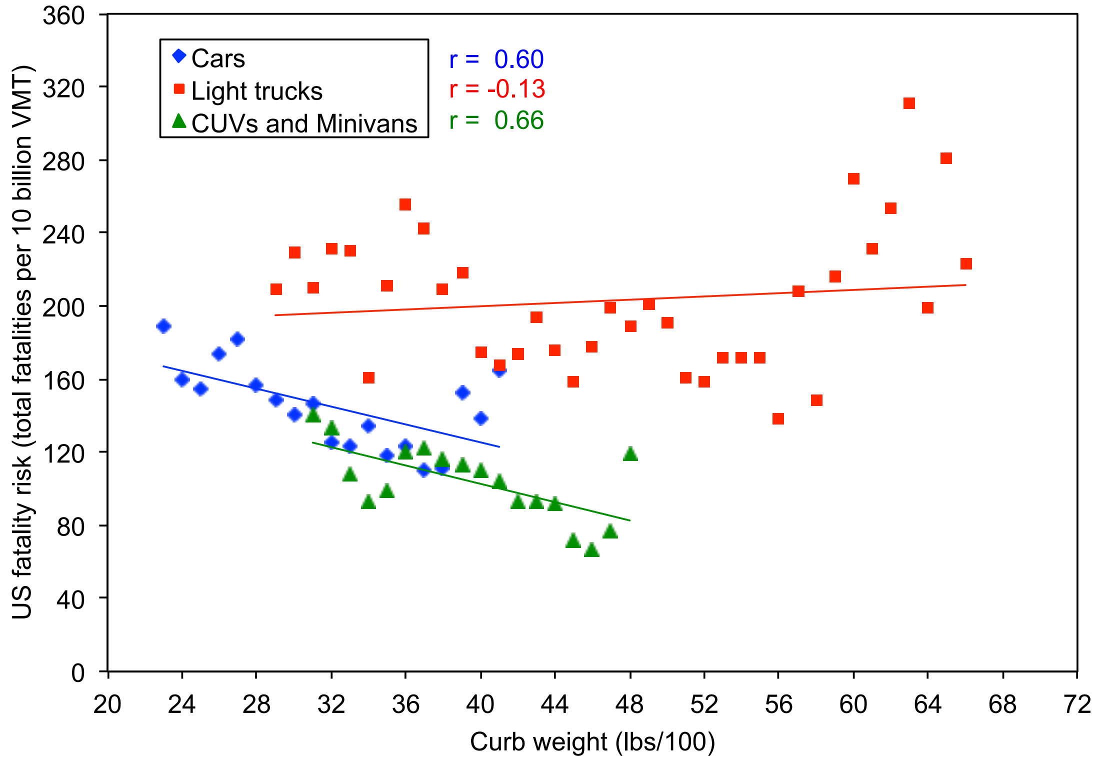


Figure 4.2. Relationship between US fatality risk and curb weight, with vehicles grouped into 100-lb increments of curb weight, passenger cars

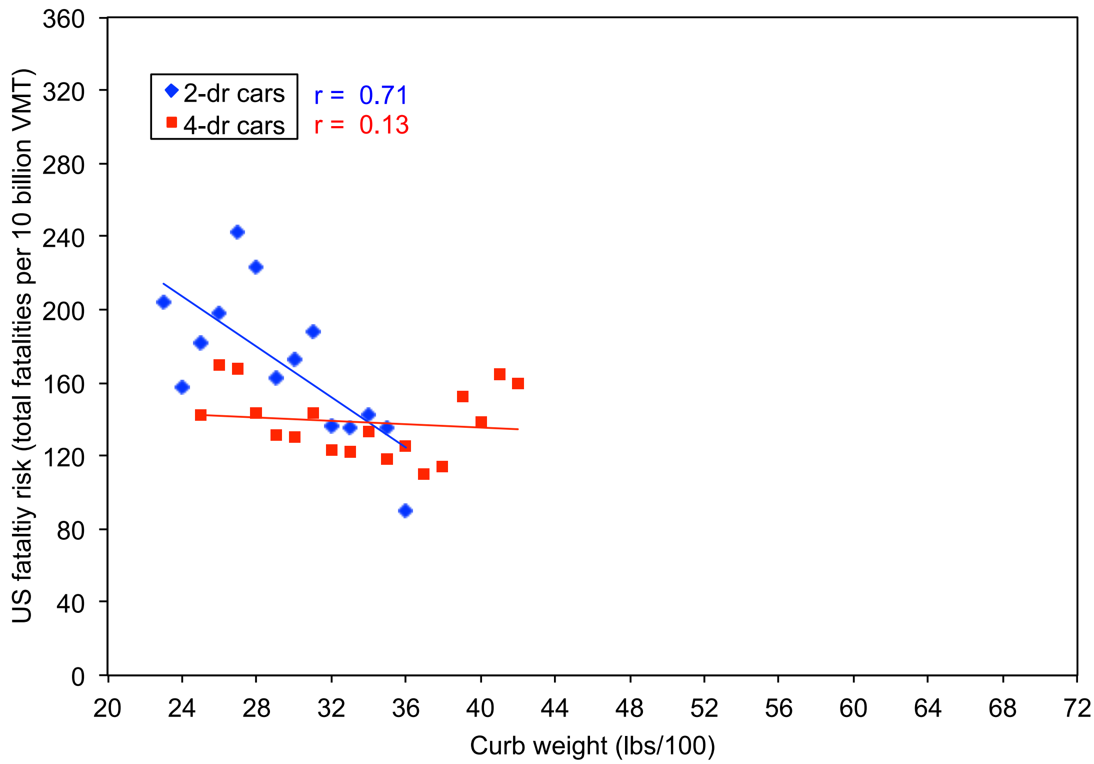


Figure 4.3. Relationship between US fatality risk and curb weight, with vehicles grouped into 100-lb increments of curb weight, light trucks

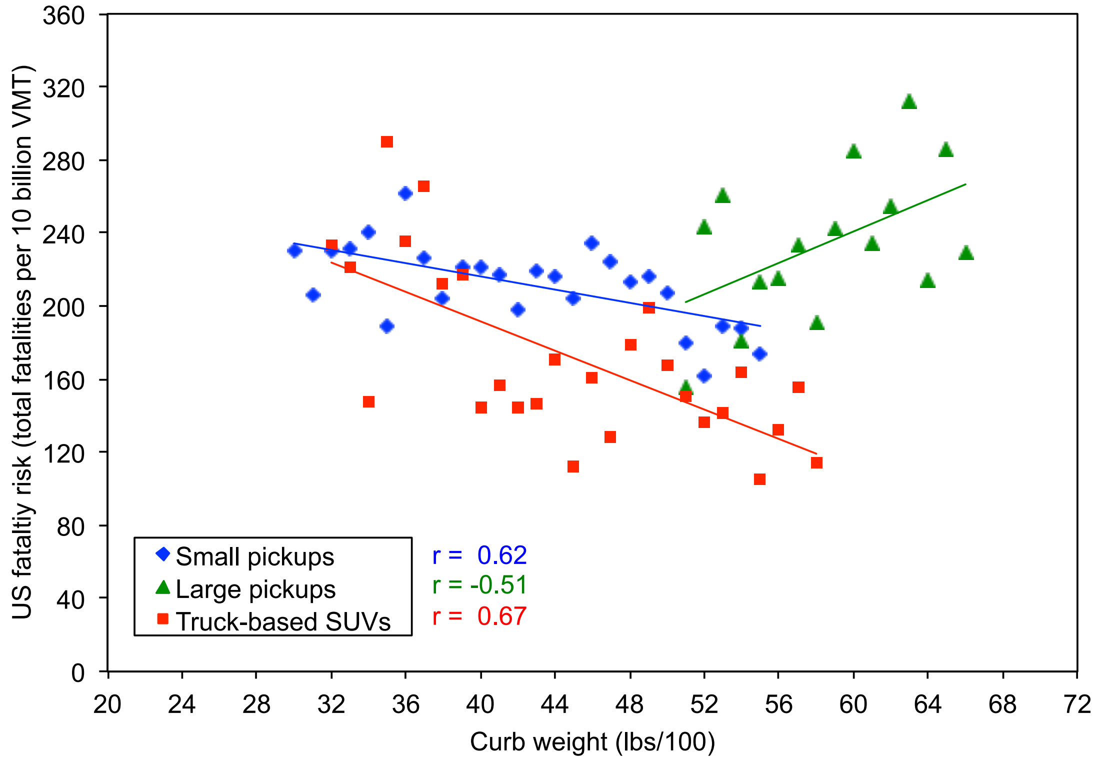
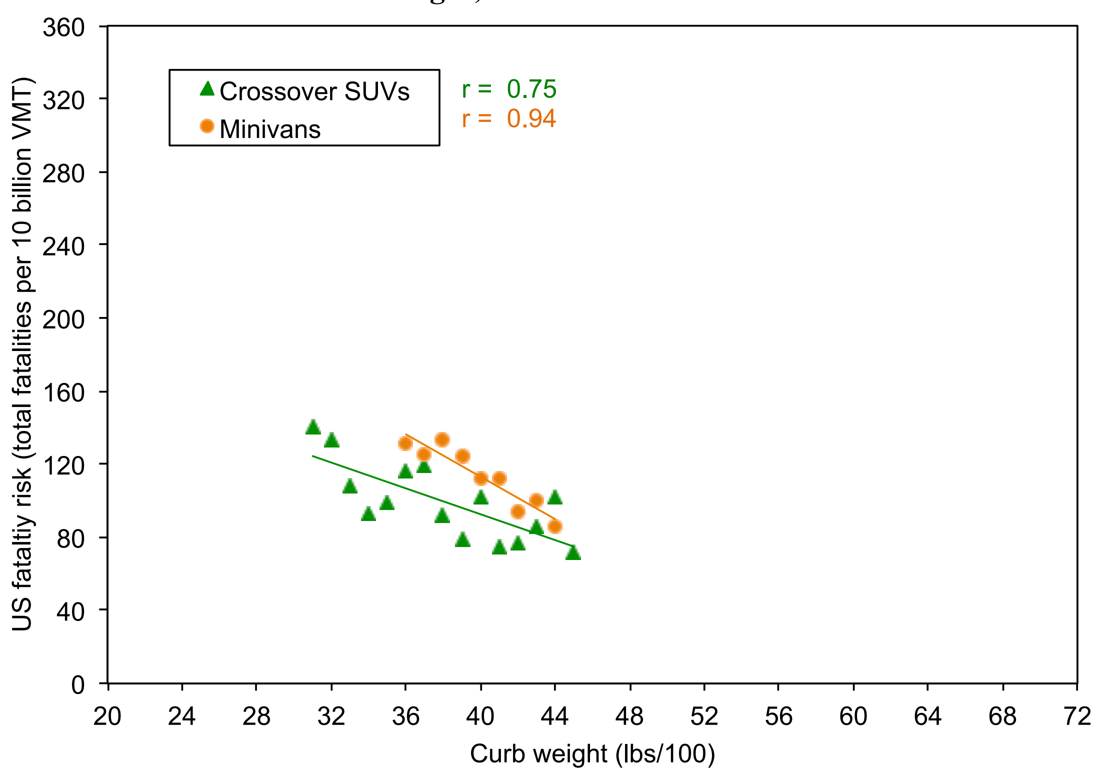


Figure 4.4. Relationship between US fatality risk and curb weight, with vehicles grouped into 100-lb increments of curb weight, CUVs and minivans



It is possible that the relationship between vehicle mass and fatality risk is greater in certain types of crashes. Figure 4.5 presents the relationship by vehicle type for fatality 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. The relationship between light truck mass and risk in crashes with stationary objects improves dramatically over that for all crashes (0.55 vs. -0.13); however, the relationship for cars and CUVs/minivans is slightly lower in crashes with stationary objects than in all types of crashes.

Note that, for a given vehicle weight, light trucks have a higher fatality risk in crashes with stationary objects than cars, and an even higher rate than CUVs and minivans. Since there are no crash partner fatalities in crashes with stationary objects, we suspect that light trucks have a higher risk than cars in Figure 4.5 because of their tendency to roll over, their increased use on more dangerous rural roads, and perhaps more passenger fatalities in light trucks than in cars.

Figure 4.5. Relationship between US fatality risk in crashes with stationary objects and curb weight, by vehicle type

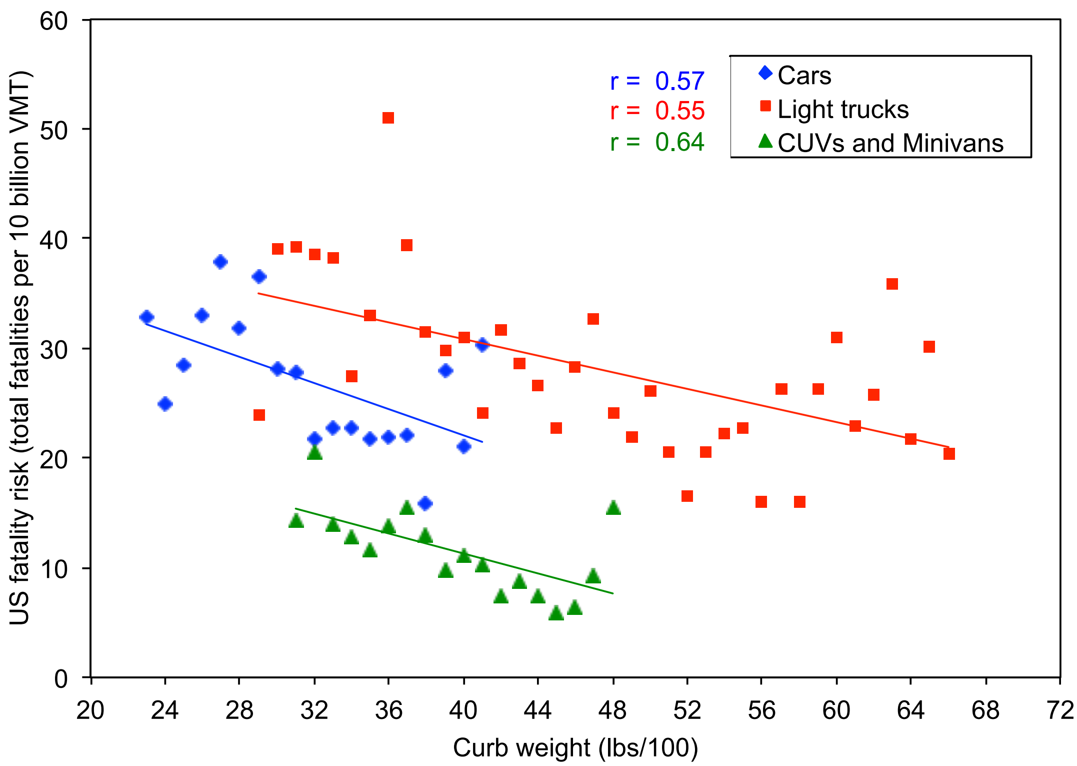


Table 4.1 summarizes the correlations between risk and a decrease in curb weight by 100-lb weight bins, by vehicle type, presented in Figures 4.1 through 4.5.

Table 4.1. Correlation between risk and a decrease in curb weight, for vehicles grouped in 100-lb curb weight bins

Vehicle type	US fatality risk, all crashes			US fatality risk, crashes with stationary objects		
	Estimate	r	R^2	Estimate	r	R^2
Cars	2.4% *	0.60	0.36	0.60% *	0.57	0.32
Light trucks	-0.4%	-0.13	0.02	0.38% *	0.55	0.31
CUVs/minivans	2.5% *	0.66	0.43	0.45% *	0.64	0.41
2-dr cars	6.9% *	0.71	0.50	1.07%	0.36	0.13
4-dr cars	0.5%	0.13	0.02	-0.70%	-0.27	0.07
Sm pickups	1.8% *	0.62	0.38	0.66% *	0.62	0.39
Lg pickups	-4.3% *	-0.51	0.26	-0.37%	-0.24	0.06
SUVs	4.0% *	0.67	0.45	0.92% *	0.80	0.64
CUVs	3.5% *	0.75	0.56	0.71% *	0.77	0.60
Minivans	5.8% *	0.94	0.89	1.25% *	0.89	0.80

Figures 4.1 through 4.5 and Table 4.1 show that grouping vehicles into 100-lb mass increments suggests that fatality risk decreases as mass increases, for most vehicle types (the exception is large pickups). Figure 4.6 shows the relationship between vehicle mass and unadjusted fatality risk by vehicle model. Only 275 models with at least 12 billion VMT, or at least 100 fatalities, are included (106 car models, 131 light truck models, and 38 CUV/minivan models); these models represent about 90% of all fatalities, vehicle registration-years, and VMT. Here we see that fatality risk declines with increasing mass for cars, and at a smaller rate for CUVs and minivans, while risk increases as mass increases for light trucks. However, although risk declines with increasing car weight, the relatively low R^2 (0.17) indicates that this is not a very strong relationship; there is a large range in risk for individual vehicle models at a given weight. For example, the model labeled as A in the figure, which weighs 2,881 lbs, has a fatality risk of 278 per 10 billion VMT, while model B, which weighs essentially the same (2,871 lbs) has a fatality risk of only 82.

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-fatality states) by vehicle model may explain some of the large range in risk by vehicle weight. To account for these various variables, we reran NHTSA's 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 risk for each induced exposure vehicle from the 13 state crash databases.[6] We first 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 log odds of fatality per vehicle. We then multiplied these odds by the VMT weighting each induced exposure vehicle represents, to obtain the number of predicted fatalities in each induced exposure vehicle, and summed across vehicle make and model. Finally we divided the total number of predicted

[6] Because all of the induced exposure vehicles are the non-culpable vehicle in a two-vehicle crash, we could not account for type of crash in the three new logistic regression models we ran for the three vehicle types.

fatalities in each make and model by their total VMT, to obtain predicted risk, the number of predicted fatalities per ten billion VMT. We exclude footprint as well as mass in the predicted risks we calculate from the NHTSA regressions, as the two vehicle attributes are moderately correlated.

Figure 4.7 shows the risks predicted by the regression model coefficients for all control variables except vehicle mass and footprint. Figure 4.7 indicates that, even after controlling for the all of the driver, crash, and vehicle variables NHTSA used in their logistic regression model, except vehicle mass and footprint, there still is a large range in fatality risk across vehicle models of similar weight, for all three vehicle types.

Figures 4.8 shows the remaining residual, or unexplained, risks after accounting for all variables except vehicle mass and footprint. In essence Figure 4.8 shows that there is no relationship between vehicle mass and risk, after accounting for driver, crash and all other vehicle attributes.

Figure 4.6. US fatality risk per VMT and curb weight, by vehicle model

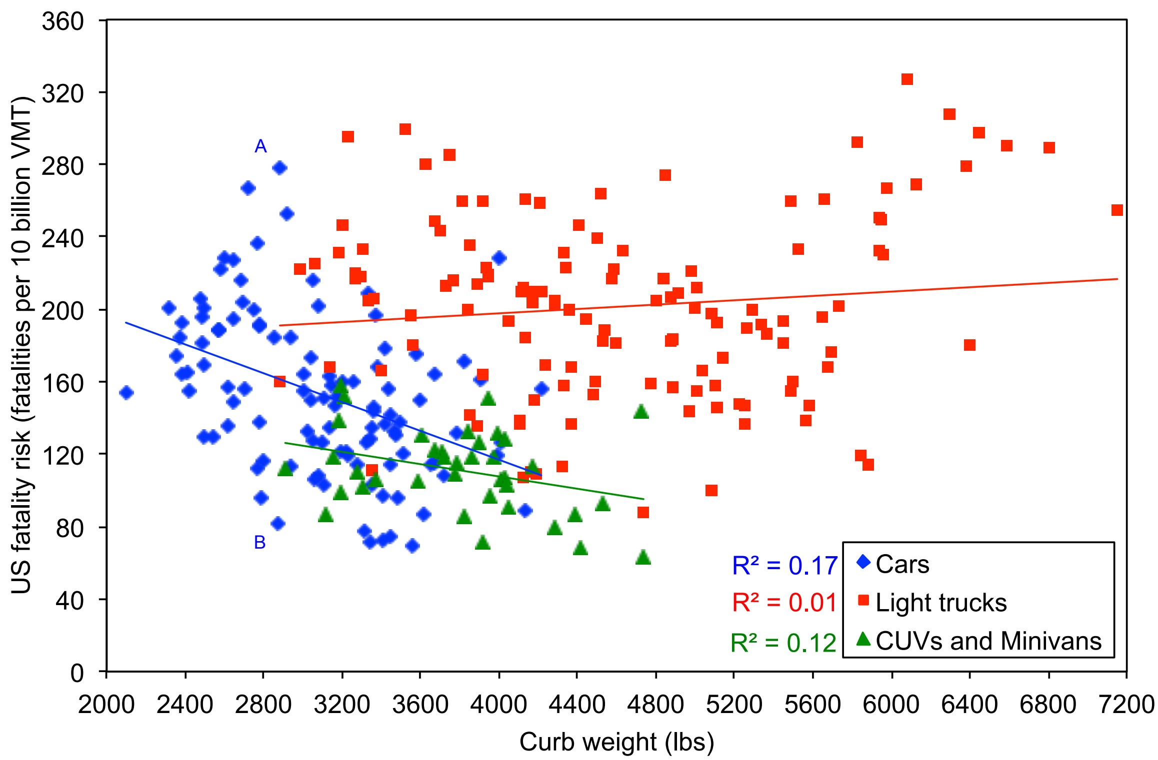


Figure 4.7. Predicted US fatality risk per VMT after accounting for all driver, crash, and vehicle variables except mass and footprint, vs. curb weight

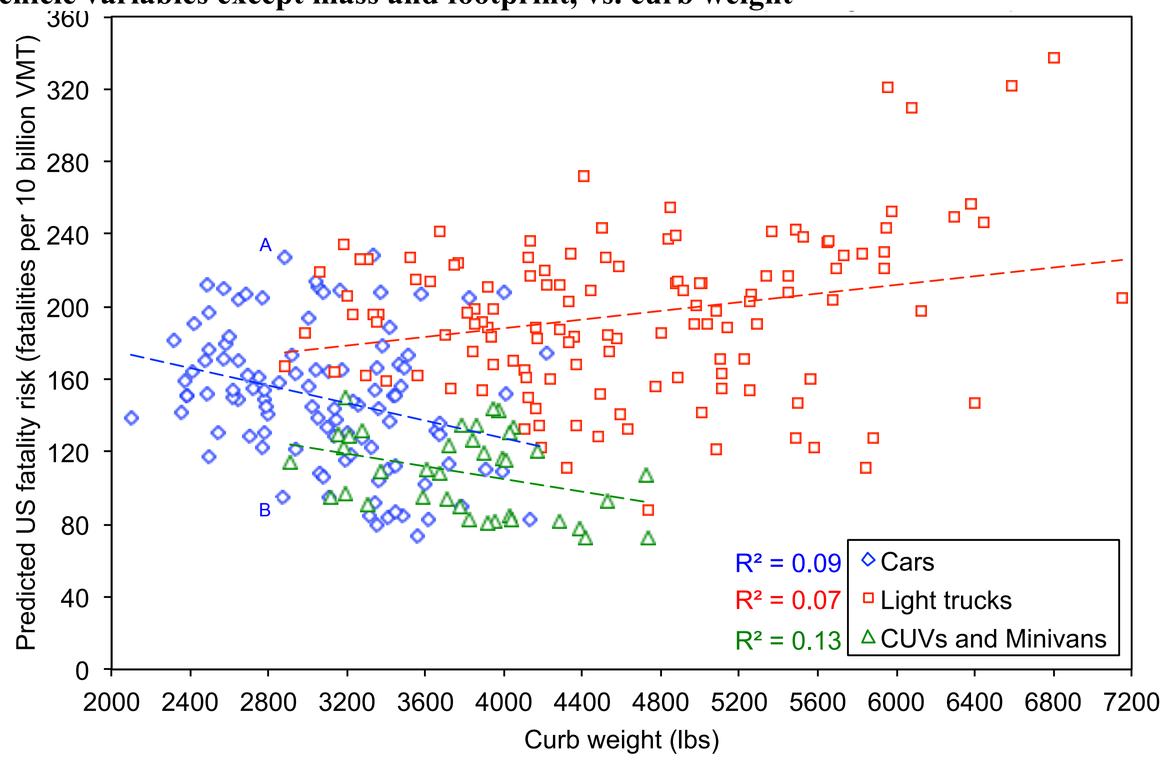
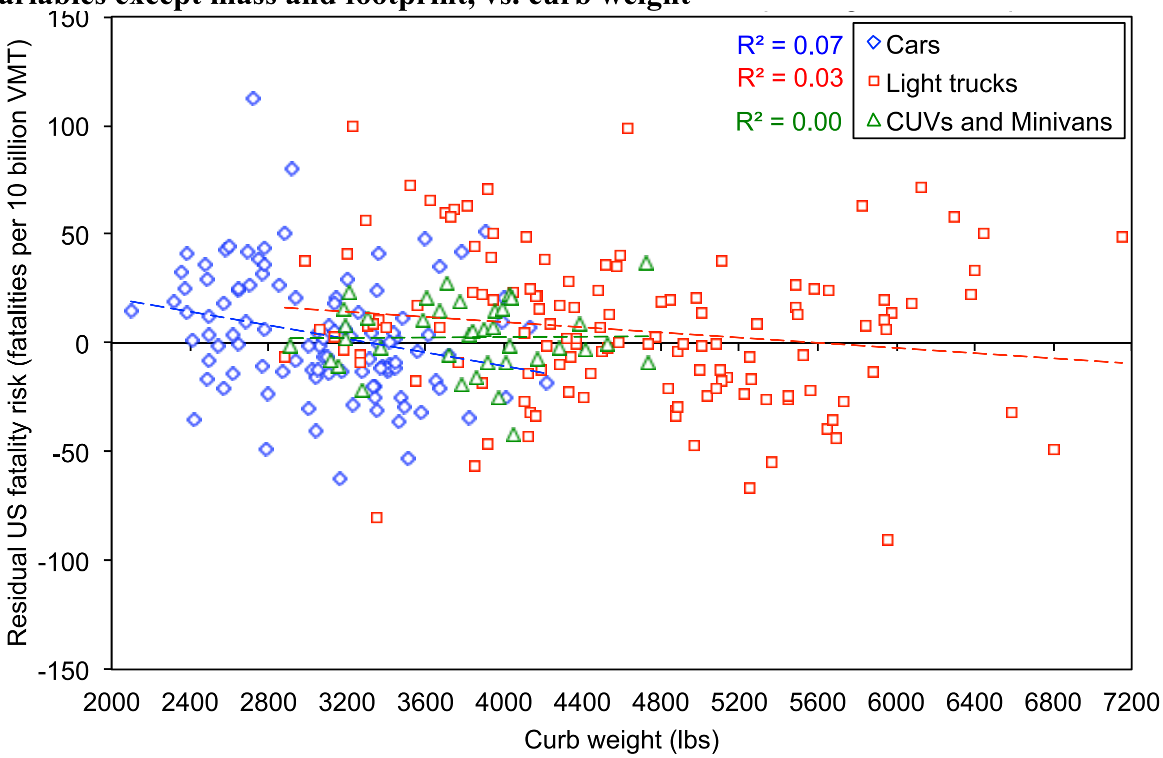


Figure 4.8. Residual US fatality risk after accounting for all driver, crash, and vehicle variables except mass and footprint, vs. curb weight



Figures 4.9 through 4.11 show similar plots for 106 car models, with 2- and 4-door cars shown separately. The figures indicate that two-door car models tend to have higher risk than 4-door models. The model labeled C provides an example of the values shown in Figures 4.9 through 4.11. This model has an actual risk of 228 fatalities per ten billion VMT, while the NHTSA regression model predicts that a vehicle with the same driver, crash location, and vehicle attributes (except mass and footprint) would have a risk of only 207 fatalities per ten billion VMT. In other words, after accounting for all of the variables except vehicle mass and footprint, this vehicle model has a higher actual risk than predicted by the NHTSA regression model. This remaining residual risk, 21 fatalities per ten billion VMT, can be attributed to the model's mass and footprint relative to other car models, as well as other, unexplained differences among vehicles.

Figure 4.10 indicates that some vehicles on the road today have the same, or lower, risk than models that weigh substantially more, and are substantially larger in terms of footprint. For example, after accounting for differences in driver age and gender, safety features installed, and crash times and locations, model D, which weighs 3,367 lbs and has a footprint of 46.6 square feet, has an expected fatality risk over twice that of model E, which weighs 3,346 lbs and has a footprint of 43.8 square feet (208 vs. 91 fatalities per ten billion VMT). Similarly, model F (3,107 lbs, 43.9 sq ft, 164 fatalities per VMT) has a predicted fatality risk nearly twice that of model G (3,111 lbs, 41.4 sq ft, 95 fatalities per VMT), while model H (2,647 lbs, 42.3 sq ft, 170 fatalities per VMT) has a predicted risk 50% higher than that that of model I (2,501 lbs 41.8 sq ft, 117 fatalities per VMT). Models E, G, and I all have risk similar to or lower than that of

Figure 4.9. US fatality risk per VMT vs. curb weight, car models

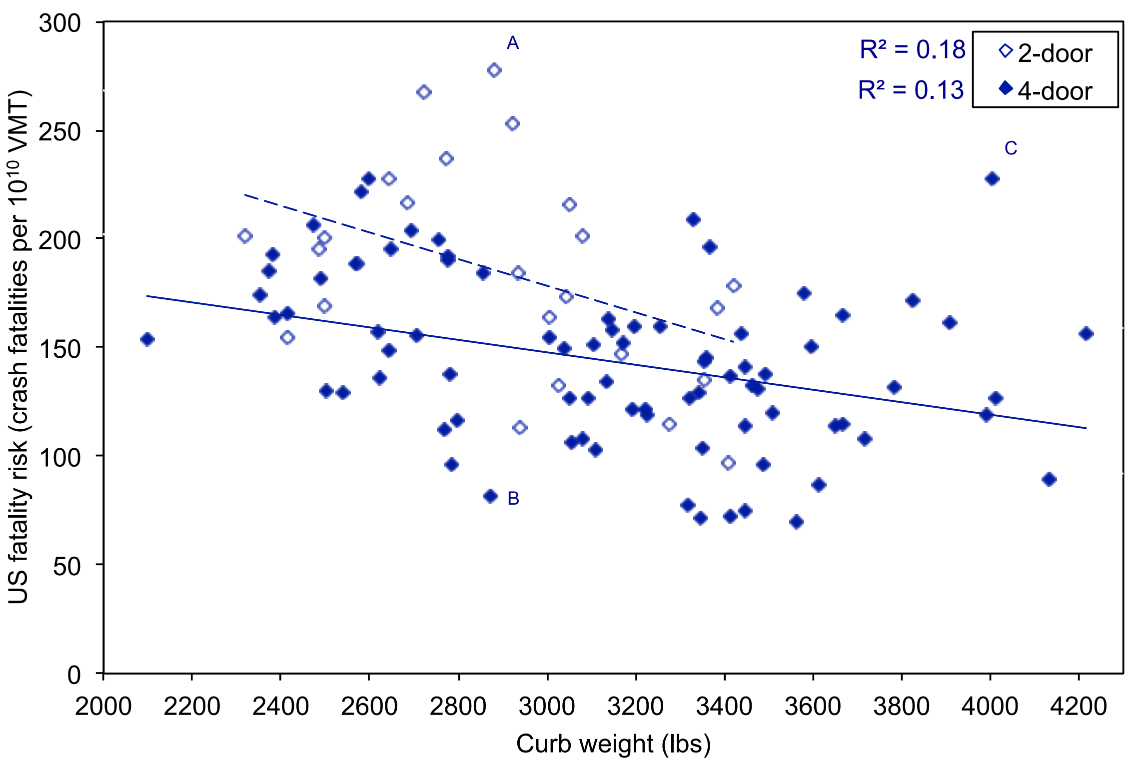


Figure 4.10. Predicted US fatality risk per VMT after accounting for all driver, crash, and vehicle variables except mass and footprint vs. curb weight, car models

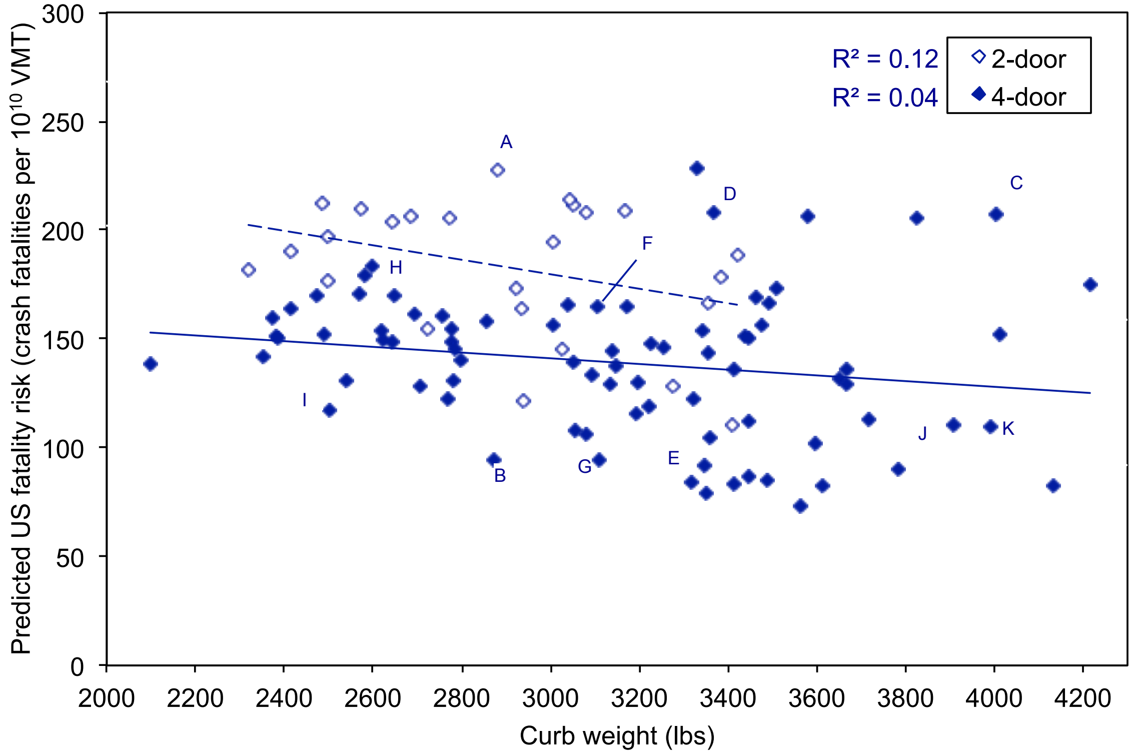
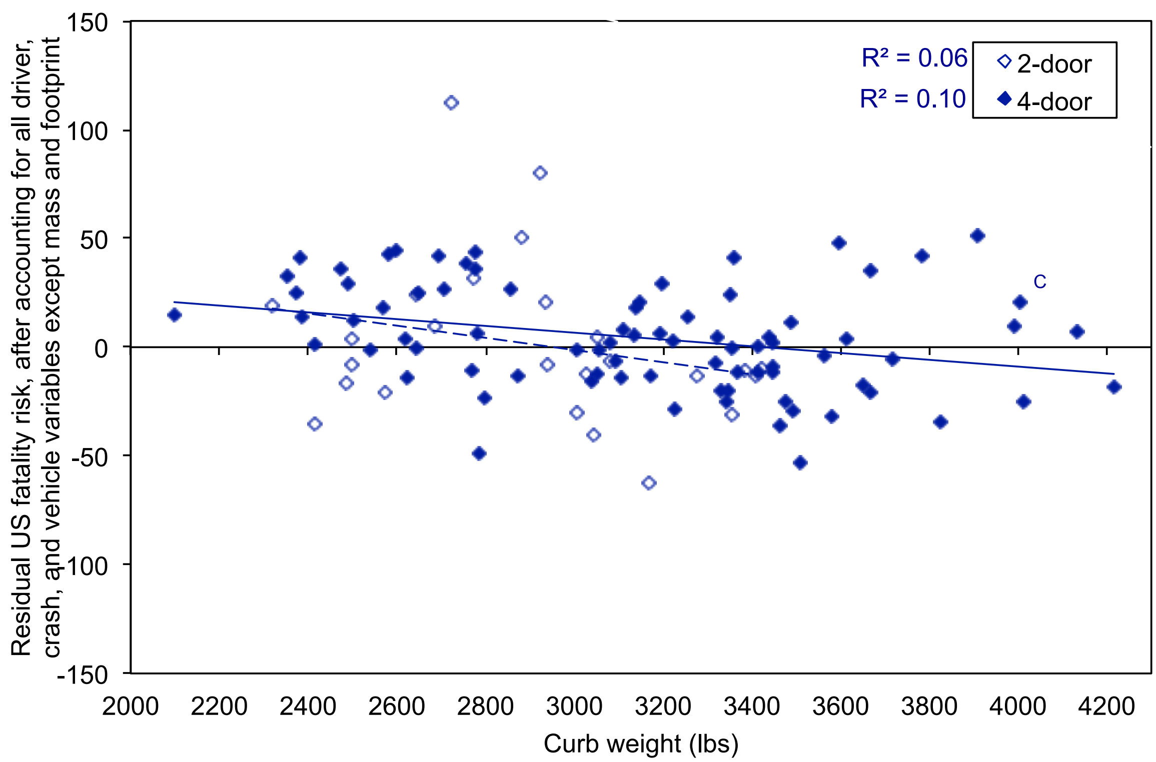


Figure 4.11. Residual US fatality risk per VMT after accounting for all driver, crash, and vehicle variables except mass and footprint vs. curb weight, car models



models J and K, which are both substantially larger and heavier (J: 3,908 lbs, 52.5 sq ft, 110 fatalities per ten billion VMT; K: 3,990 lbs, 48.7 sq ft, 109 fatalities per ten billion VMT). Clearly differences in vehicle design can, and already do, mitigate any safety penalty from reduced mass. The fact that NHTSA attributes the change in its regression results between the 2003 study and the 2012 study in part to the redesign or removal of certain smaller and lighter models of poor design confirms that vehicle design can overcome the safety penalty in lightweight or small vehicles. Figure 4.10 suggests that manufacturers can continue to design vehicles that overcome the safety penalty from reducing mass in order to improve fuel economy and reduce greenhouse gas emissions; and Figure 4.11 indicates that, after accounting for all variables except mass and footprint, there is no correlation between the remaining residual risk and curb weight.

Figures 4.12 and 4.13 show the actual and predicted risks vs. curb weight for pickup trucks and truck-based SUV models. Risk declines with increasing curb weight for SUVs, but increases with increasing weight for pickups. However, the correlations between fatality risk and curb weight are weak, even after accounting for all of the driver, crash, and other vehicle variables in the NHTSA logistic regression model. Figure 4.14 indicates that there is no correlation between the residual risk and weight, after accounting for all variables except for mass and footprint.

Risk, predicted risk, and residual risk for CUV and minivan models are shown in Figures 4.15 through 4.17. There is a reasonable correlation between risk and mass for CUVs (Figure 4.15); however, the correlation decreases after accounting for all variables except mass and footprint (Figure 4.16). After accounting for all variables except vehicle mass and footprint, there is no correlation between residual risk and CUV curb weight, while residual risk increases with increasing minivan weight, as shown in Figure 4.17.

Figure 4.12. US fatality risk per VMT vs. curb weight, light truck models

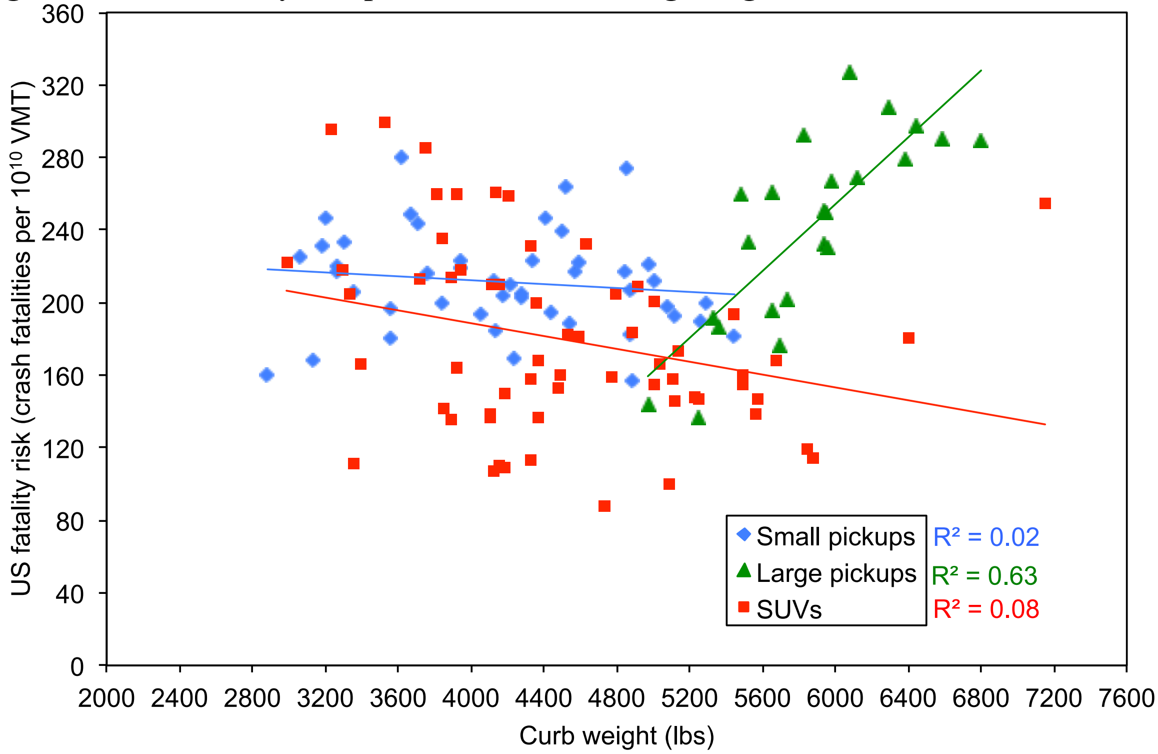


Figure 4.13. Predicted US fatality risk per VMT after accounting for all driver, crash, and vehicle variables except mass and footprint vs. curb weight, light truck models

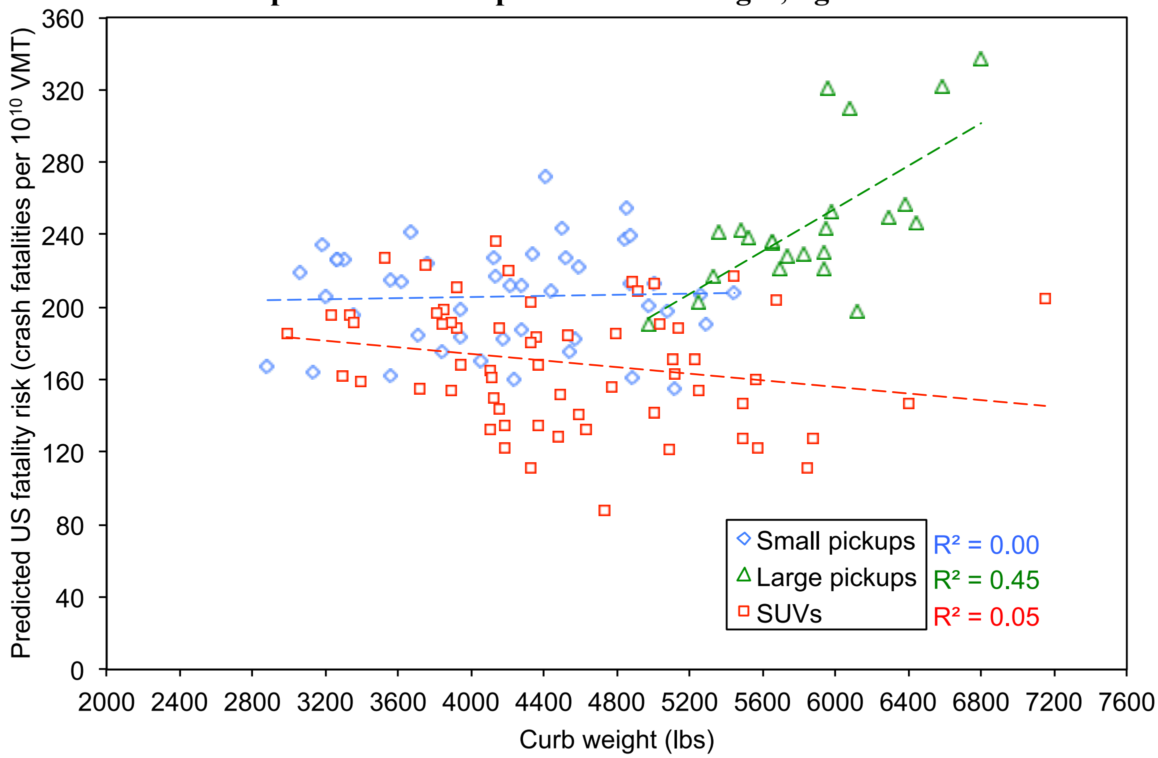


Figure 4.14. Residual US fatality risk per VMT after accounting for all driver, crash, and vehicle variables except mass and footprint vs. curb weight, light truck models

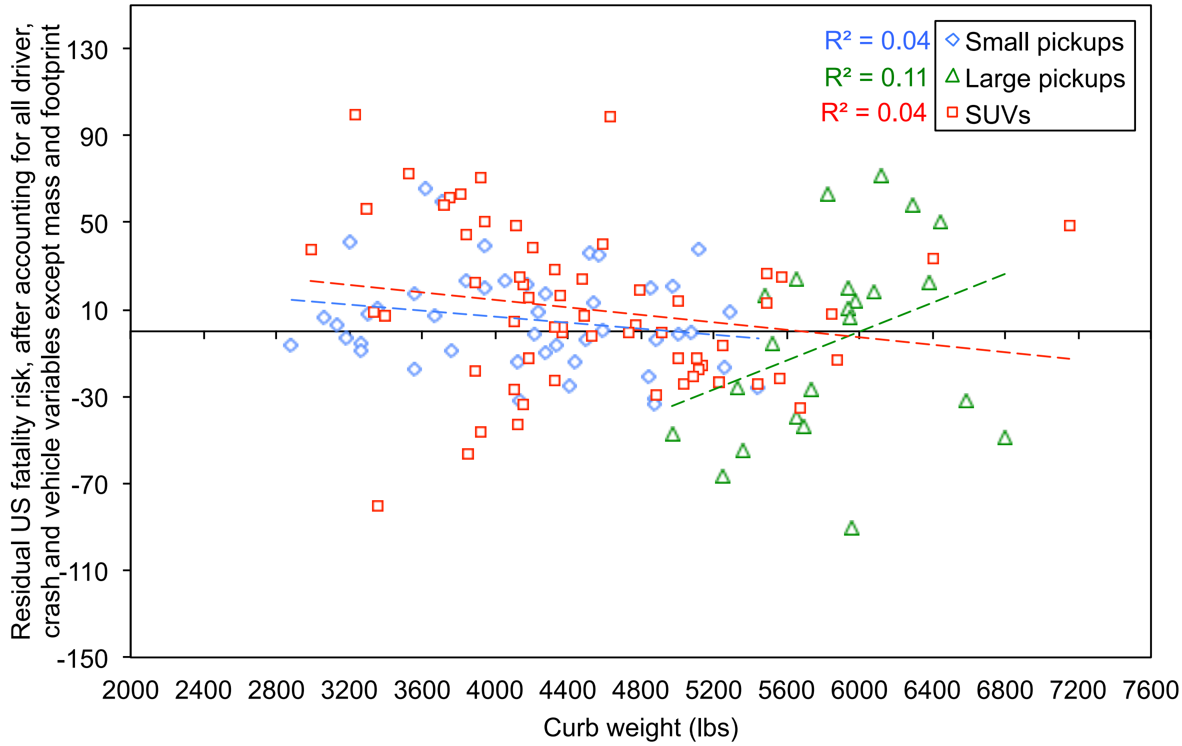


Figure 4.15. US fatality risk per VMT vs. curb weight, CUV/Minivan models

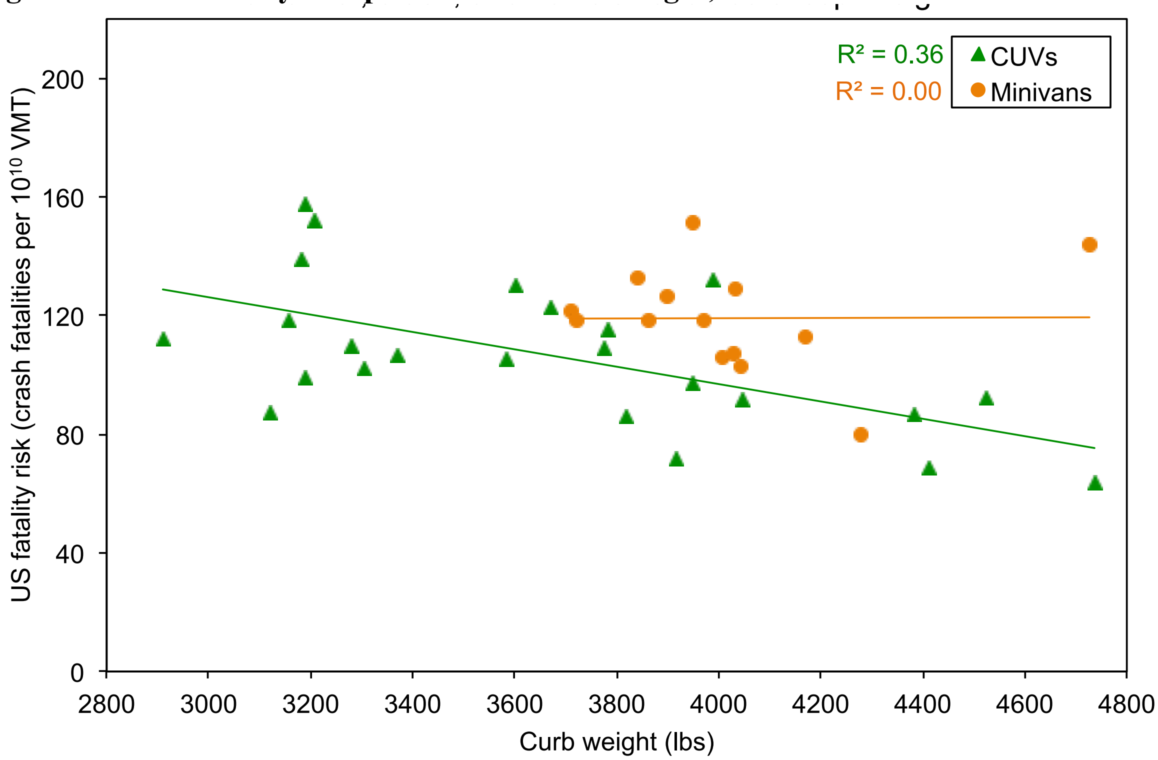


Figure 4.16. Predicted US fatality risk per VMT after accounting for all driver, crash and vehicle variables except mass and footprint vs. curb weight, CUV/Minivan models

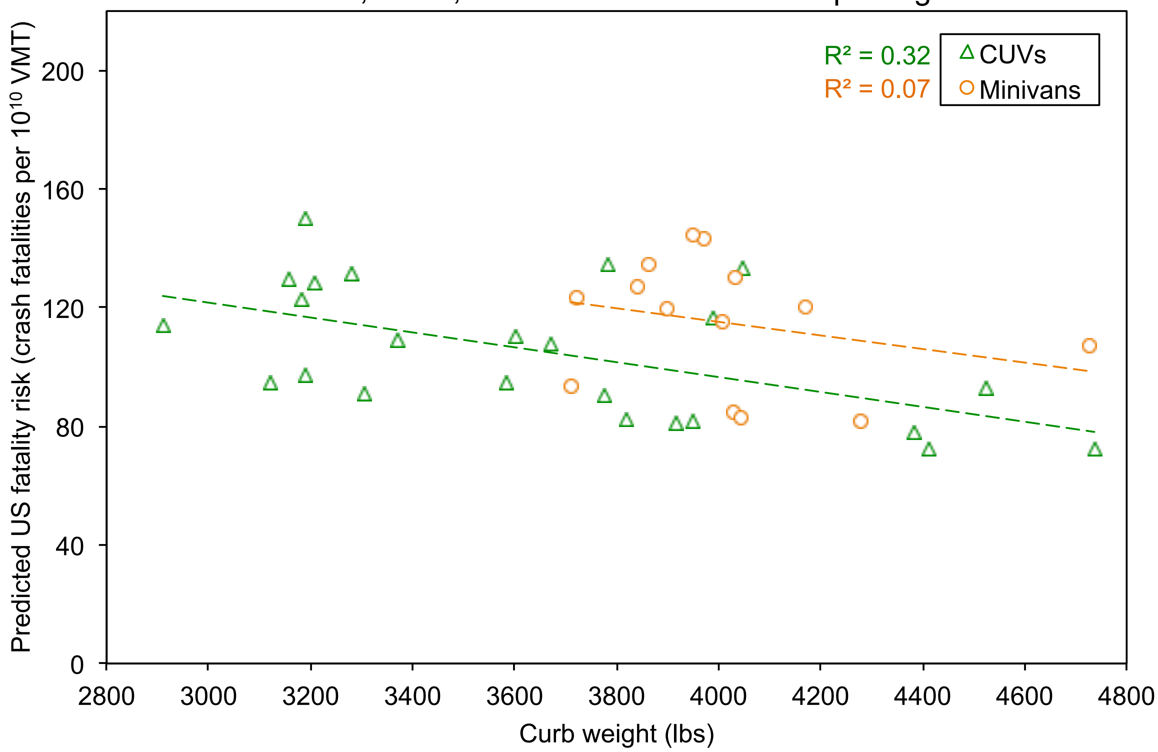


Figure 4.17. Residual US fatality risk per VMT after accounting for all driver, crash and vehicle variables except mass and footprint vs. curb weight, CUV/Minivan models

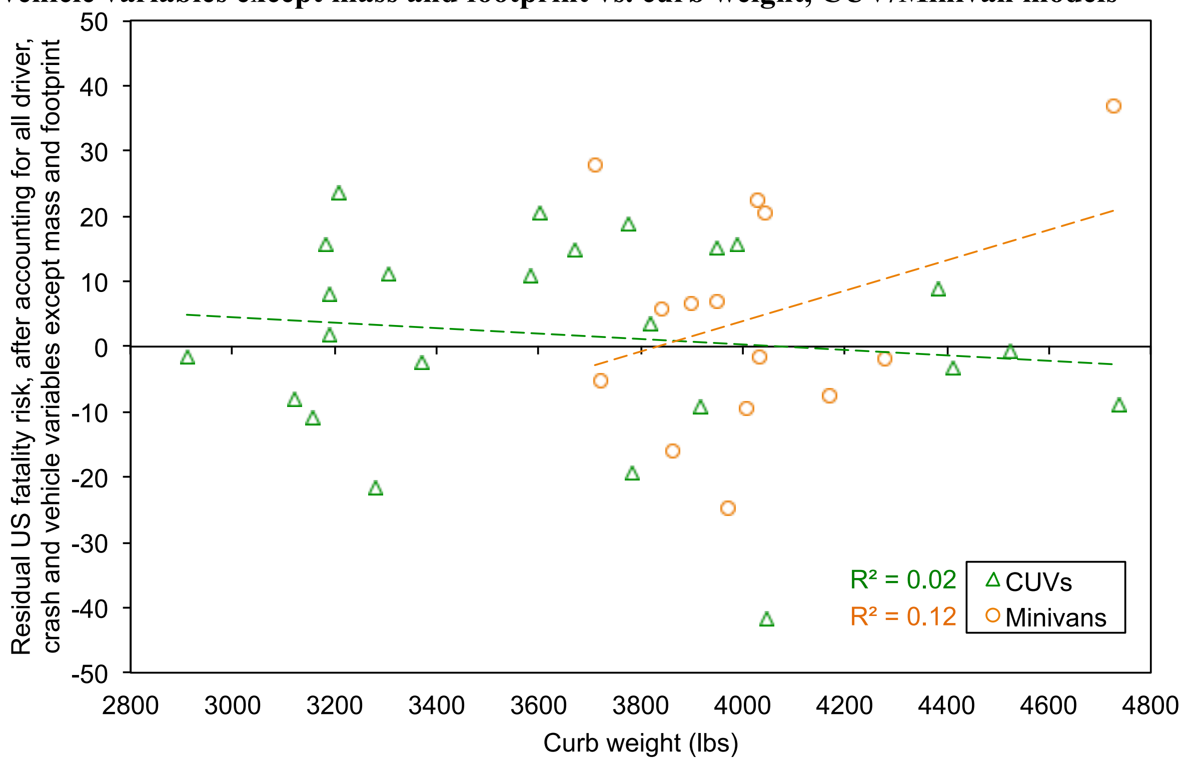


Table 4.2 summarizes the relationships between predicted and residual fatality risk and vehicle curb weight that are presented in Figures 4.6 through 4.17. The table shows the estimated percent change in actual, predicted, and residual fatality risk per 100-pound decrease in mass, as well as the correlation between risks and curb weight. 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 estimated relationship between fatality risk and decreasing vehicle weight, i.e. where risk is estimated to decrease as weight decreases, are shown in red in the table, and cases where the correlation between risk and decreasing weight by vehicle model exceeds 0.30 are shown in blue. Table 4.2 indicates that fatality risk increases as weight decreases for cars, on average; however, while the increases are statistically significant for both two-door and four-door cars in terms of actual risk, the increases are smaller, and not statistically significant, after accounting for all variables included in NHTSA's regression models except vehicle mass and footprint. In addition, there is a wide range in risk for cars of similar mass, as evidenced by the rather low R^2 values. On the other hand, fatality risk <u>decreases</u> as weight decreases for heavy-duty pickups, and that the estimated effect is large, 11% for actual fatality risk, and 7% for predicted risk after accounting for all variables except vehicle mass and footprint. In these two cases the correlation between risk and weight is also rather high (R^2 of 0.62 and 0.43). For CUVs, the correlation between actual and predicted fatality risk and mass is moderate, with an R^2 of over 0.30, with estimated risk increasing about 3% for every 100-lb reduction in mass.

Table 4.2. Relationship between actual, predicted, and residual fatality risk, and decreasing vehicle <u>mass</u>, after accounting for all driver, crash, and vehicle variables <u>except mass and footprint</u>, by vehicle type and model

	Actual US fatality risk			Predicted risk			Residual risk		
Vehicle type	Estimate		R^2	Estimate		R^2	Estimate		R^2
Cars	4.0%	*	0.17	2.4%	*	0.09	1.6%	*	0.07
Light trucks	-0.6%		0.01	-1.2%	*	0.07	0.6%		0.03
CUVs/minivans	1.7%	*	0.12	1.7%	*	0.13	0.0%		0.00
2-dr cars	6.1%	*	0.18	3.3%		0.12	2.8%		0.06
4-dr cars	2.9%	*	0.13	1.3%		0.04	1.6%	*	0.10
Small pickups	0.5%		0.02	-0.2%		0.00	0.7%		0.04
Heavy-duty pickups	-9.2%	*	0.63	-5.9%	*	0.45	-3.3%		0.11
SUVs	1.8%	*	0.08	0.9%		0.05	0.9%		0.04
CUVs	2.9%	*	0.36	2.5%	*	0.32	0.4%		0.02
Minivans	0.0%		0.00	2.3%		0.07	-2.3%		0.12
Cars < 3106	3.3%		0.03	0.8%		0.00	2.5%		0.04
Cars > 3106	-0.5%		0.00	0.3%		0.00	-0.8%		0.01
LTs < 4594	2.1%		0.04	1.2%		0.03	0.9%		0.02
LTs > 4594	-5.2%	*	0.28	-4.1%	*	0.20	-1.0%		0.03
CUVs/ minivans	1.7%	*	0.12	1.7%	*	0.13	0.0%		0.00

* statistically significant at the 95% confidence level

In his peer review of the LBNL draft Phase 1 report, Mike Van Auken (DRI) commented that the predicted risk should be estimated after accounting for all variables NHTSA used in its regression models except vehicle weight; that is, after also accounting for vehicle footprint (SRA 2012). Table 4.3 shows this analysis, the predicted (and residual) risks after accounting for all variables in the regression models except vehicle weight. Table 4.3 indicates that, after also accounting for footprint, the estimated effect of mass reduction on predicted risk is generally more detrimental for six of the seven vehicle types (in the middle section of the table), particularly for cars, and slightly reduces the estimated detrimental effect of mass reduction in heavy-duty pickups. The correlation between predicted risk and mass also is higher in Table 4.3 than in Table 4.2, again particularly for cars (from 0.09 to 0.27). However, the correlations are still rather weak, with none greater than 0.40 except CUVs. And the estimated residual risks after accounting for footprint in Table 4.3 are of smaller magnitude, and even less correlated with mass, than those shown in Table 4.2.

Table 4.3. Relationship between actual, predicted, and residual fatality risk, and decreasing vehicle <u>mass</u>, after accounting for all driver, crash, and vehicle variables <u>except mass</u>, by vehicle type and model

	Actual US fatality risk			Predicted risk			Residual risk		
Vehicle type	Estimate		R^2	Estimate		R^2	Estimate		R^2
Cars	4.0%	*	0.17	4.3%	*	0.27	-0.3%		0.00
Light trucks	-0.6%		0.01	-0.9%	*	0.04	0.3%		0.01
CUVs/minivans	1.7%	*	0.12	2.2%	*	0.20	-0.5%		0.02
2-dr cars	6.1%	*	0.18	5.3%	*	0.30	0.9%		0.01
4-dr cars	2.9%	*	0.13	3.4%	*	0.22	-0.5%		0.01
Small pickups	0.5%		0.02	0.4%		0.01	0.1%		0.00
Heavy-duty pickups	-9.2%	*	0.63	-5.6%	*	0.42	-3.6%		0.13
SUVs	1.8%	*	0.08	1.3%	*	0.09	0.5%		0.01
CUVs	2.9%	*	0.36	3.1%	*	0.48	-0.2%		0.00
Minivans	0.0%		0.00	3.0%		0.13	-3.0%		0.21
Cars < 3106	3.3%		0.03	3.4%	*	0.08	-0.1%		0.00
Cars > 3106	-0.5%		0.00	2.2%		0.03	-2.7%	*	0.10
LTs < 4594	2.1%		0.04	1.7%		0.05	0.4%		0.00
LTs > 4594	-5.2%	*	0.28	-4.1%	*	0.20	-1.1%		0.03
CUVs/ minivans	1.7%	*	0.12	2.2%	*	0.20	-0.5%		0.02

* statistically significant at the 95% confidence level

Table 4.4 presents the same information as Table 4.2, but for the relationship between risks and vehicle footprint. As in Table 4.2, fatality risks for heavy-duty pickups consistently decrease as footprint decreases, between 4% and 9%. However, the correlation between actual risk and footprint by heavy-duty pickup model (0.46) is not as high as with mass (0.63 in Table 4.2). And the correlations between actual and predicted risk and CUV footprint (0.07 and 0.05, respectively) are much lower than the correlations with CUV mass (0.36 and 0.32 in Table 4.2). This is somewhat surprising, as Figure 2.1 indicates that footprint reduction has a relatively large estimated (detrimental) effect on CUV and minivan fatality risk, while mass reduction has a smaller, estimated beneficial effect. However, there is essentially no correlation between decreasing footprint and risk for CUVs and minivans combined, as shown in Table 4.4.

Table 4.4. Relationship between actual, predicted, and residual fatality risk, and decreasing vehicle footprint, after accounting for all driver, crash, and vehicle variables except mass and footprint, by vehicle type and model

Vehicle type	Actual US fatality risk			Predicted risk			Residual risk		
	Estimate		R^2	Estimate		R^2	Estimate		R^2
Cars	4.5%	*	0.13	2.2%	*	0.04	2.2%	*	0.08
Light trucks	-1.5%	*	0.09	-2.2%	*	0.26	0.7%	*	0.04
CUVs/minivans	0.1%		0.00	0.0%		0.00	0.1%		0.00
2-dr cars	6.8%		0.11	2.5%		0.04	4.2%		0.07
4-dr cars	3.0%	*	0.08	0.7%		0.01	2.3%	*	0.12
Small pickups	0.6%		0.03	-0.1%		0.00	0.7%		0.05
Heavy-duty pickups	-8.8%	*	0.46	-3.9%	*	0.16	-4.9%	*	0.19
SUVs	1.7%		0.05	0.2%		0.00	1.5%	*	0.08
CUVs	1.8%		0.07	1.4%		0.05	0.4%		0.01
Minivans	3.5%		0.16	2.1%		0.04	1.4%		0.03
Cars < 3106	5.6%		0.07	1.3%		0.01	4.3%	*	0.09
Cars > 3106	-2.3%		0.03	-2.1%		0.02	-0.2%		0.00
LTs < 4594	-1.0%		0.02	-1.8%	*	0.12	0.8%		0.03
LTs > 4594	-5.2%	*	0.47	-5.2%	*	0.53	0.0%		0.00
CUVs/ minivans	0.1%		0.00	0.0%		0.00	0.1%		0.00

* statistically significant at the 95% confidence level

Table 4.5. Relationship between actual, predicted, and residual fatality risk, and decreasing vehicle footprint, after accounting for all driver, crash, and vehicle variables except footprint, by vehicle type and model

Vehicle type	Actual US fatality risk			Predicted risk			Residual risk		
	Estimate		R^2	Estimate		R^2	Estimate		R^2
Cars	4.5%	*	0.13	4.5%	*	0.18	0.0%		0.00
Light trucks	-1.5%	*	0.09	-1.7%	*	0.16	0.1%		0.00
CUVs/minivans	0.1%		0.00	0.1%		0.00	0.0%		0.00
2-dr cars	6.8%		0.11	5.3%	*	0.15	1.5%		0.01
4-dr cars	3.0%	*	0.08	3.2%	*	0.12	-0.2%		0.00
Small pickups	0.6%		0.03	0.6%		0.03	0.0%		0.00
Heavy-duty pickups	-8.8%	*	0.46	-3.7%		0.13	-5.1%	*	0.19
SUVs	1.7%		0.05	0.7%		0.02	1.0%		0.03
CUVs	1.8%		0.07	1.7%		0.09	0.1%		0.00
Minivans	3.5%		0.16	2.7%		0.06	0.8%		0.01
Cars < 3106	5.6%		0.07	4.0%	*	0.08	1.6%		0.01
Cars > 3106	-2.3%		0.03	-1.2%		0.01	-1.1%		0.02
LTs < 4594	-1.0%		0.02	-1.5%	*	0.08	0.5%		0.01
LTs > 4594	-5.2%	*	0.47	-4.7%	*	0.49	-0.4%		0.01
CUVs/ minivans	0.1%		0.00	0.1%		0.00	0.0%		0.00

* statistically significant at the 95% confidence level

Table 4.5 shows the relationships between risks and decreasing vehicle footprint, after accounting for all other vehicle attributes as well as mass. Accounting for vehicle mass in the estimates of predicted risk has little effect on the relationship between predicted risk and decreasing footprint.

It is possible that other differences in vehicle models, particularly other aspects of vehicle design or subtle differences in driver behavior, explain some of the remaining variation in risk for vehicles of similar weight. We examined the relationship between fatality risk, vehicle mass, and two other variables: the initial vehicle purchase price and the driver's income. The initial purchase price of a vehicle may be a proxy for the quality of design of a particular vehicle model. We obtained initial purchase price based on the estimates provided by R.L. Polk's VIN decoding software. Some researchers have speculated that low-income drivers tend to drive poorly, or in environments that are more dangerous than higher income drivers. Neither FARS nor the state crash databases report driver income (FARS reports the zip code on the driver's license, but the states do not). We used a database of California vehicle registrations from 2010 to estimate the average income of the household owning the vehicle, based on the zip code of its registered owner. We used the median household income for each zip code in California from the 2000 US Census. Although this income variable likely does not reflect the actual income of the households included in the FARS or state crash databases, it does capture the range in the average income of the drivers of different vehicle models.

Figure 4.18 plots predicted US fatality risk per VMT by vehicle initial purchase price, by vehicle type and model, while Figure 4.19 plots vehicle purchase price by curb weight. Figure 4.18 indicates that fatality risk tends to decrease as vehicle purchase price increases, although the correlation between fatality risk and vehicle price is fairly weak for all vehicle types except two-door cars (R^2 of 0.40) and CUVs (R^2 of 0.53). However, Figure 4.19 indicates that the correlation between vehicle weight and purchase price is strong for all vehicle types except minivans, with price increasing as weight increases.[7]

Figures 4.20 and 4.21 show the relationships between average median household income and predicted US fatality risk (Figure 4.20) and vehicle curb weight (Figure 4.21). Predicted fatality risk is estimated using the procedure used in Figures 4.7, 4.10, 4.13, 4.16 and the middle column of Table 4.2; that is, after accounting for all driver and crash characteristics, and all vehicle variables except mass and footprint. Figure 4.20 indicates that fatality risk decreases as household income increases, and that the correlation between fatality risk and household income is fairly strong for all vehicle types except full-size pickups, with R^2 ranging from 0.42 for small pickups to 0.65 for CUVs, and essentially zero for fullsize pickups. However, Figure 4.21 indicates that, while vehicle weight tends to increase as household income increases, there is relatively low correlation between household income and vehicle weight; the trend of increasing fatality risk as income declines does not appear to be explained by low income households driving lighter vehicles.

[7] The extremely low correlation between minivan weight and price is caused by a single model, the Kia Sedona, with a high weight relative to its size; removing the Kia Sedona improves the correlation between minivan weight and price to 0.39. Similarly the correlation between two-door car weight and price improves to 0.68 after removing the outlier Mercedes S.

Figure 4.18. Relationship between vehicle initial purchase price and predicted US fatality risk per VMT, by vehicle model

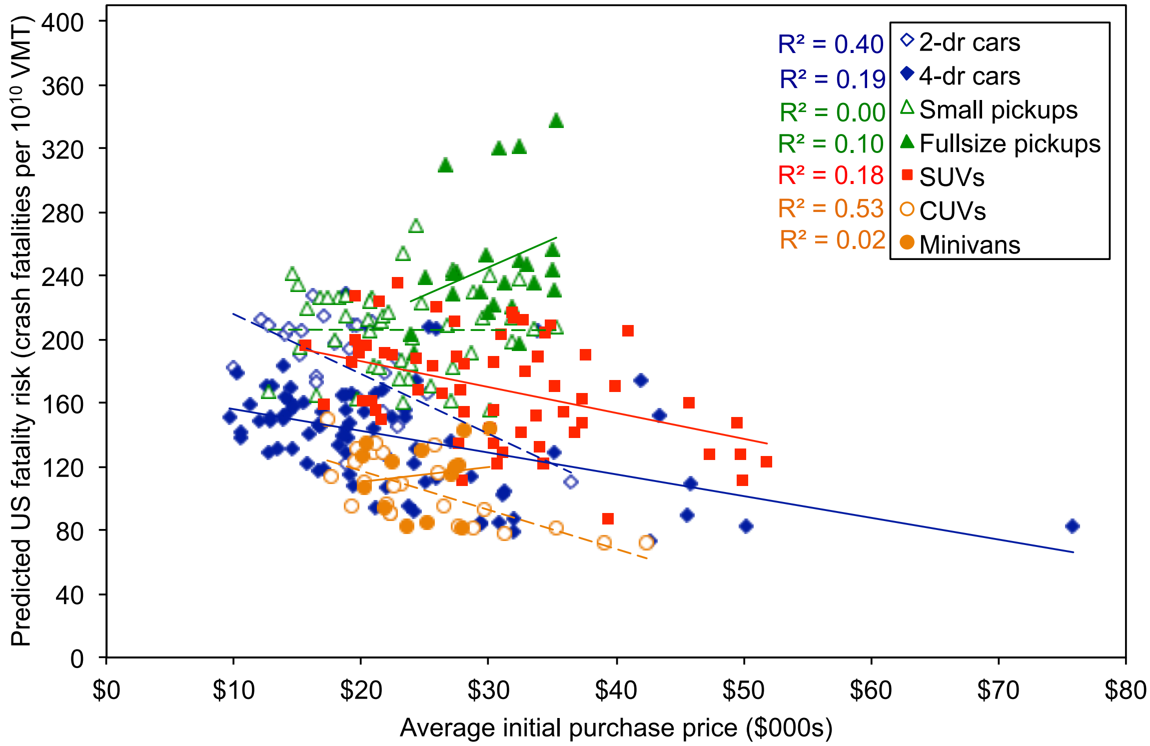


Figure 4.19. Relationship between vehicle mass and initial purchase price, by vehicle model

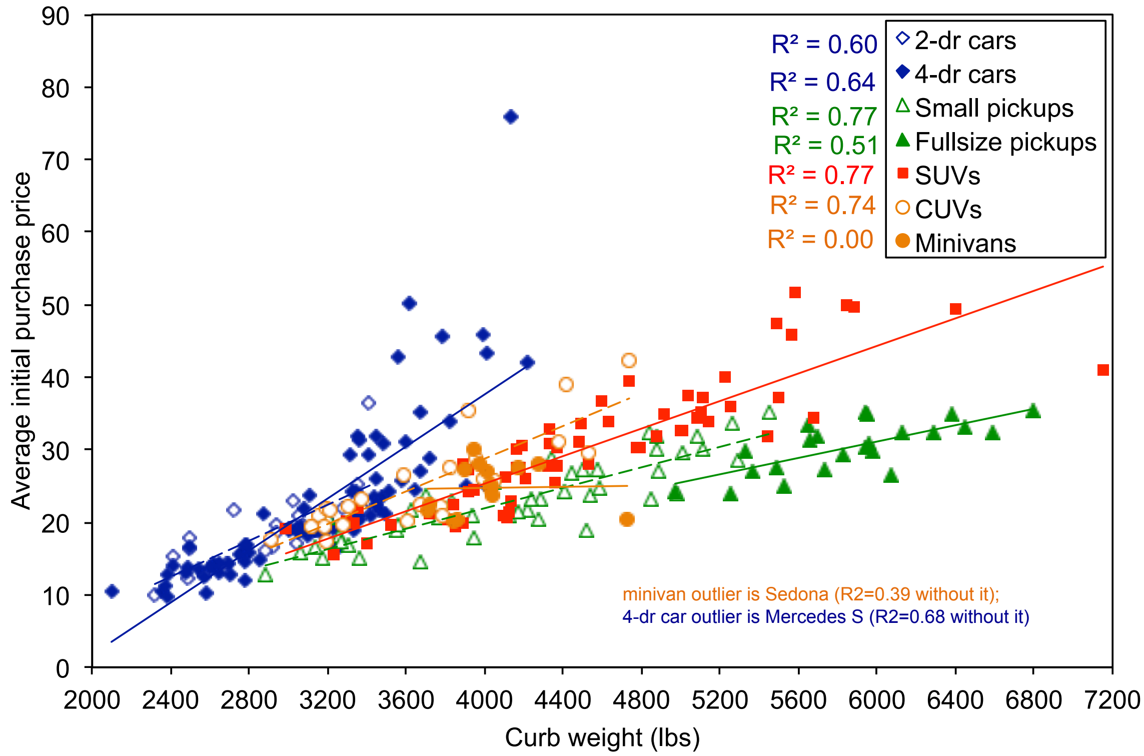


Figure 4.20. Relationship between household income and predicted US fatality risk per VMT, by vehicle model

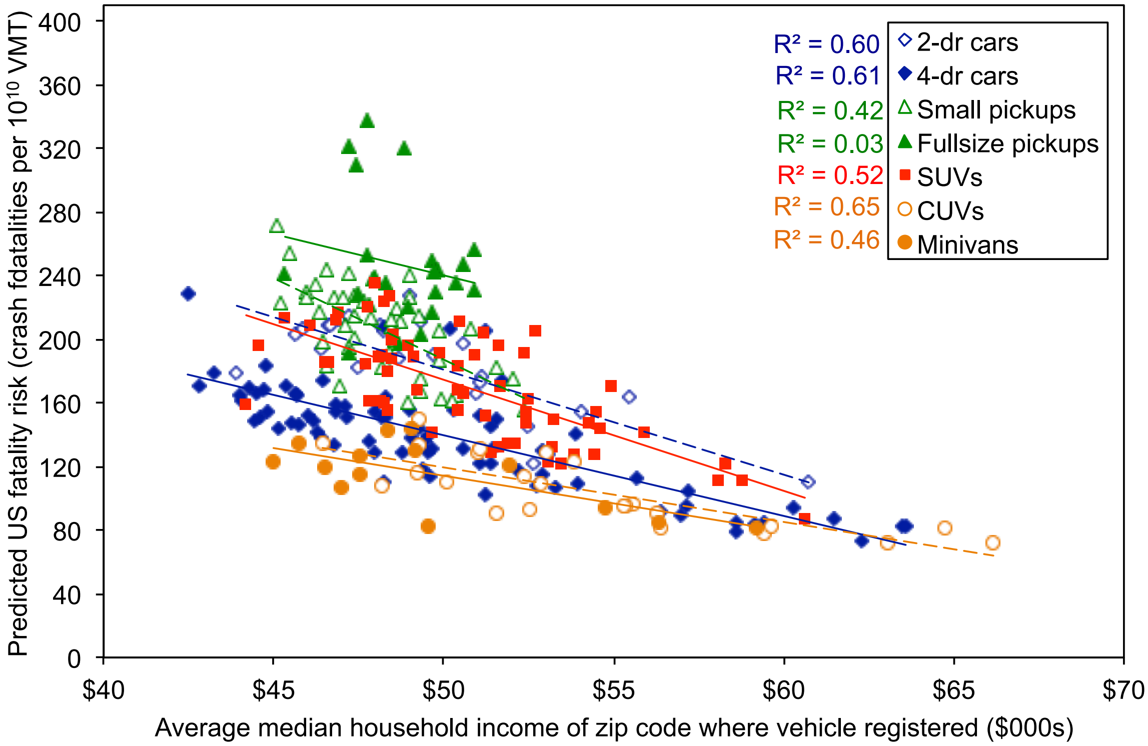


Figure 4.21. Relationship between vehicle mass and household income, by vehicle model

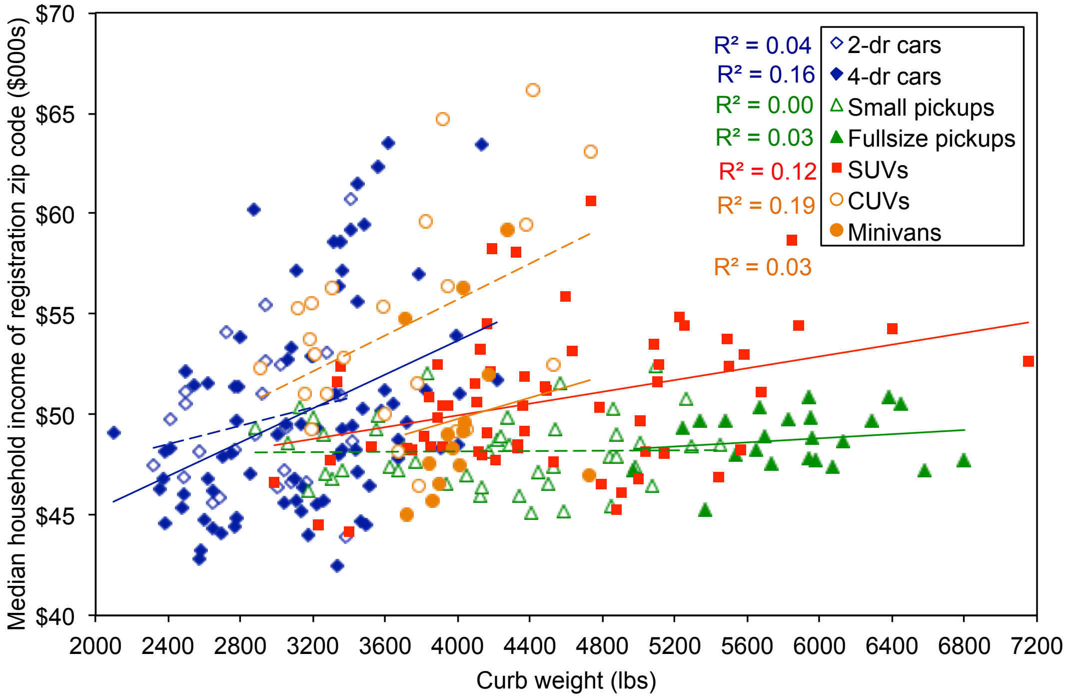
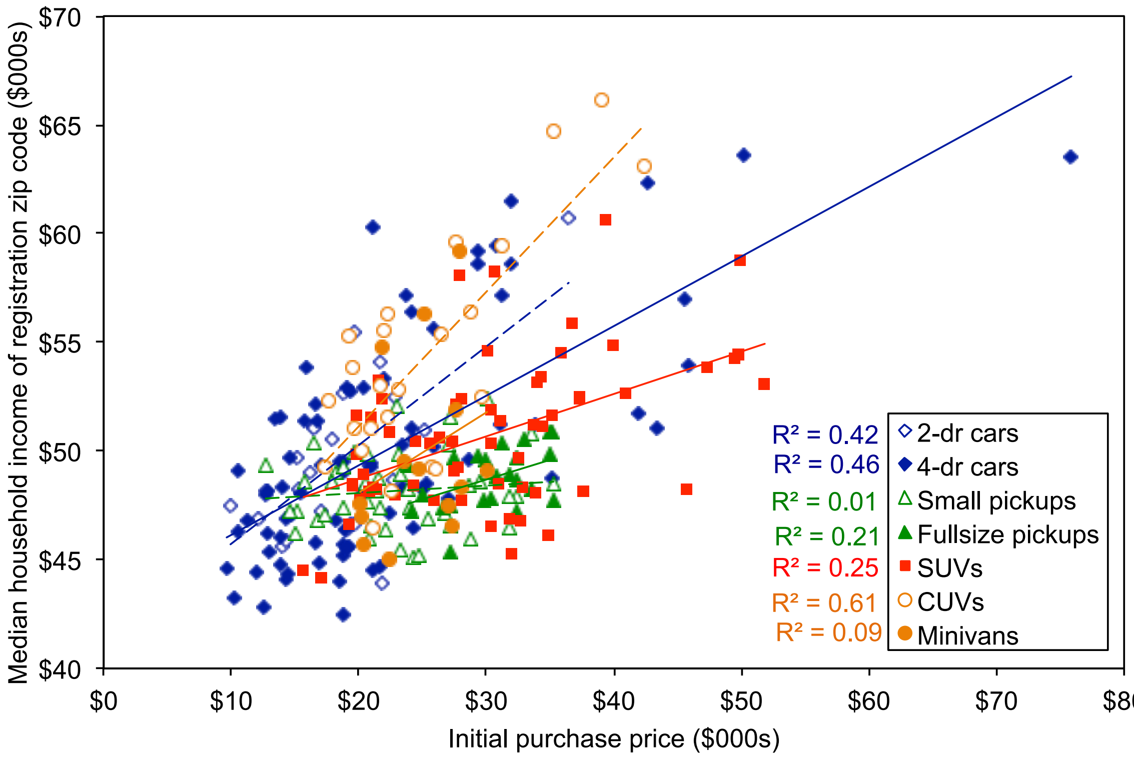


Figure 4.22 indicates that initial vehicle purchase price is correlated with median household income for CUVs and cars, and to a lesser extent for SUVs, while pickup and minivan price is not correlated with household income.

Figure 4.22. Relationship between vehicle initial purchase price and median household income, by vehicle model



Tables 4.6 and 4.7 show the relationships between predicted fatality risk, mass, initial vehicle purchase price, and household income, for the seven vehicle types in Figures 4.18 through 4.22, as well as for the three general vehicle types (cars, light-duty trucks, CUVs/minivans) and the five vehicle types and mass groups NHTSA used in their regression models.

How a particular individual drives their vehicle, how closely they obey traffic regulations and how quickly or well they adapt to dangerous situations, could account for much of the remaining risk unexplained by our regression models. As described above, while this information is available in FARS, it is not consistently recorded in state crash data. However, it may be possible to more directly estimate the effect of driver behavior in particular states that record this information.

We examine the estimated effect of mass or footprint reductions on US fatality risk after accounting for initial vehicle purchase price and average median household income in Sections 5.2 and 5.4.

Table 4.6. Relationship between predicted fatality risk, mass, and initial vehicle purchase price, by vehicle type and model

Vehicle type	Predicted risk and initial purchase price (Figure 4.18)			Initial purchase price and mass (Figure 4.19)		
	Estimate		R^2	Estimate		R^2
Cars	-1.8%	*	0.22	1.7%	*	0.64
Light trucks	-1.3%	*	0.05	0.6%	*	0.58
CUVs/minivans	-2.0%	*	0.26	0.8%	*	0.47
2-dr cars	-3.8%	*	0.40	1.2%	*	0.60
4-dr cars	-1.4%	*	0.19	1.8%	*	0.64
Small pickups	0.0%		0.00	0.7%	*	0.77
Heavy-duty pickups	3.5%		0.10	0.6%	*	0.51
SUVs	-1.6%	*	0.18	0.9%	*	0.77
CUVs	-2.5%	*	0.53	1.1%	*	0.74
Minivans	0.9%		0.02	0.0%		0.00
Cars < 3106	-1.4%		0.02	1.1%	*	0.62
Cars > 3106	-1.6%	*	0.19	2.8%	*	0.51
LTs < 4594	-2.6%	*	0.16	0.8%	*	0.57
LTs > 4594	-4.2%	*	0.27	0.3%	*	0.07
CUVs/ minivans	-2.0%	*	0.26	0.8%	*	0.47

* statistically significant at the 95% confidence level

Table 4.7. Relationship between predicted fatality risk, mass, and median household income, by vehicle type and model

Vehicle type	Predicted risk and household income (Figure 4.20)			Household income and mass (Figure 4.21)			Household income and initial purchase price (Figure 4.22)		
	Estimate		R^2	Estimate		R^2	Estimate		R^2
Cars	-5.4%	*	0.48	0.4%	*	0.14	0.3%	*	0.44
Light trucks	-9.3%	*	0.39	0.1%	*	0.03	0.2%	*	0.24
CUVs/minivans	-3.2%	*	0.59	0.2%		0.03	0.6%	*	0.40
2-dr cars	-6.6%	*	0.60	0.2%		0.04	0.5%	*	0.42
4-dr cars	-5.1%	*	0.61	0.4%	*	0.16	0.3%	*	0.46
Small pickups	-10.2%	*	0.42	0.0%		0.00	0.0%		0.01
Heavy-duty pickups	-5.2%		0.03	0.1%		0.03	0.2%	*	0.21
SUVs	-7.0%	*	0.52	0.1%	*	0.12	0.2%	*	0.25
CUVs	-3.4%	*	0.65	0.4%	*	0.19	0.6%	*	0.61
Minivans	-3.5%	*	0.46	0.3%		0.03	0.4%		0.09
Cars < 3106	-4.0%	*	0.20	0.4%	*	0.07	0.6%	*	0.35
Cars > 3106	-5.5%	*	0.58	0.5%		0.05	0.4%	*	0.46
LTs < 4594	-8.4%	*	0.47	0.1%		0.04	0.3%	*	0.22
LTs > 4594	-11.0%	*	0.43	0.0%		0.01	0.3%	*	0.41
CUVs/ minivans	-3.2%	*	0.59	0.2%		0.03	0.6%	*	0.40

* statistically significant at the 95% confidence level

5. Sensitivity of NHTSA results to data used and model specification

In this section we examine the sensitivity of the NHTSA results on the estimated effect of mass or footprint reduction on US fatality risk per VMT. We examine the effect of calculating risk of a fatal crash (as opposed to risk of fatality), and risk of fatality per non-culpable vehicle; and how the estimated effect of mass or footprint reduction changes after accounting for vehicle manufacturer, after excluding the calendar year control variables, and after excluding crashes involving alcohol or drug use, or otherwise bad driving behavior.

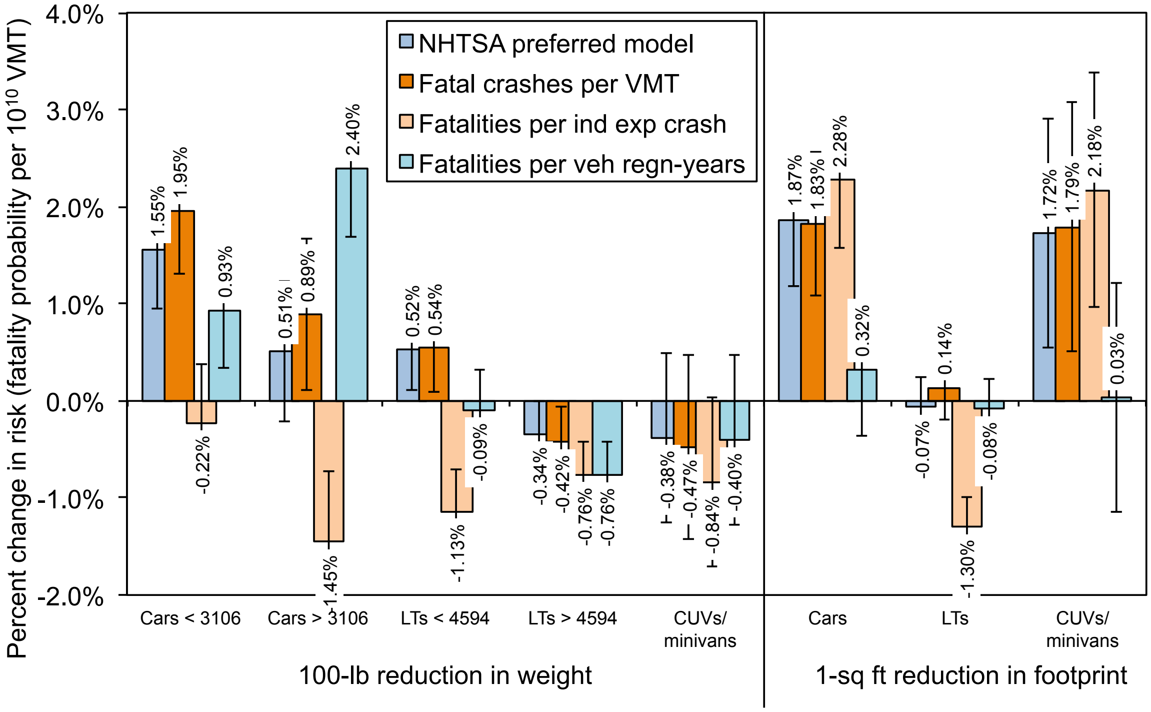
5.1. Alternative measures of risk

Figure 5.1 compares the estimates for US fatality risk per VMT using NHTSA's preferred regression model specification (in light blue) with two other measures of US fatality risk. The first measure is the risk of a fatal crash, rather than the risk of all fatalities that occurred in the crash. In other words, the fatal crash cases are not weighted by the total number of fatalities, either in the case vehicle or in its crash partner, as they are in NHTSA's preferred model. 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 (Green et al 2011). As shown in Figure 5.1, this alternative measure of risk, the risk of a fatal crash per ten billion VMT (shown in dark orange) increases the estimated detrimental effect of mass reduction on risk in cars, from 1.55% to 1.95% for lighter than average cars, and from 0.51% to 0.89% for heavier cars. On the other hand, analyzing risk of fatal crash per VMT has essentially no impact on the estimated effect of mass reduction in light trucks or CUVs/minivans.

The statistical uncertainties around the point estimates of the effect of mass reduction on risk per fatal crash in Figure 5.1 are only slightly higher than the uncertainties around the risk per fatality point estimates, in part because on average there are only 1.16 fatalities per fatal crash (123,324 fatalities in 106,613 fatal crashes).

We also investigate the effect NHTSA's weighting of the induced exposure crashes has on its regression estimates. NHTSA uses the non-culpable vehicle in two-vehicle crashes from the 13 states as its measure of induced exposure. It then creates weights so that the crashes from the 13 states can first be scaled up to represent national vehicle registration-years, and then multiplied by average annual VMT by vehicle age and type to arrive at national VMT. In the light orange columns in Figure 5.1 we exclude these two calculations, and examine US fatality risk per induced exposure crash from the 13 states (rather than VMT). Using induced exposure crashes as the measure of exposure changes the sign of the estimated effect of car mass reduction, and light truck mass and footprint reduction, on risk; for all vehicle types, mass reduction is now associated with a reduction in fatality risk given that a crash occurs. Footprint reduction in light trucks is similarly associated with a reduction in fatality risk per crash, while it is associated with increased risk per crash in cars and CUVs/minivans.

Figure 5.1. Estimated effect of mass or footprint reduction on US fatalities, using three different measures of exposure (VMT, induced exposure crashes, vehicle registration-years) and fatal crashes per VMT



The effect of analyzing fatality risk per crash shown in Figure 5.1 is approximate, as total U.S. fatalities are combined with induced exposure crashes for only 13 states. A more exact analysis would utilize both fatalities and crashes from the same states. We will perform just such an analysis in the near future, using fatality, serious injury, and crash data from the same source, the police-reported crashes from 13 states.

In his review of the draft LBNL Phase 1 report, Mike Van Auken (DRI) suggested using vehicle registration-years, rather than vehicle miles traveled, as the measure of exposure. VMT is preferable to registration-years as the measure of exposure, as a vehicle that is not driven has zero risk (SRA 2012). Registration years have been used as the measure of exposure when accurate estimates of annual vehicle miles traveled have not been available by vehicle model and year. The estimates NHTSA obtained from Polk appear to be accurate, although they do not reflect the decline in driving in 2008 when gas prices rose and the economy stumbled.

Nonetheless, LBNL conducted a sensitivity using vehicle registration years rather than VMT as the measure of exposure. This alternative estimates lower effects of mass reduction on risk in lighter cars and light trucks, no change in CUVs/minivans, but a substantially higher effect of mass reduction in heavier cars (from an estimated 0.51 % increase in risk to an estimated 2.40% increase in risk), as shown in Figure 5.1.

5.2. Vehicle manufacturer

The analysis by vehicle model in Section 4 indicates that the variables included in the NHTSA preferred model only account for 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 14 dummy variables based on the vehicle nameplate manufacturer.[8] 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, both in fatalities and VMT. The five Chrysler brands (Jeep, Chrysler, Dodge, Plymouth, and Sprinter) were combined in a single Chrysler category, while the three Ford brands (Ford, Lincoln, Mercury) were combined in a single Ford category. Ten low-volume manufacturers were grouped into a separate Other manufacturer category.[9]

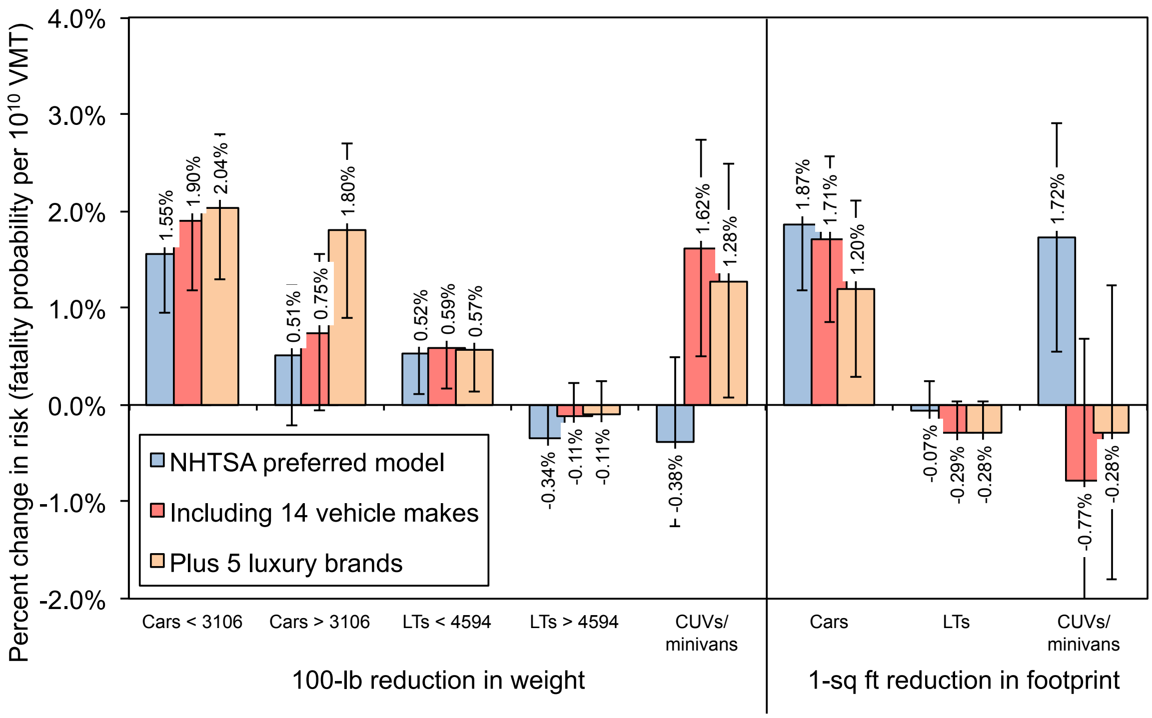
Figure 5.2 compares the estimated effect of adding variables for each of the 14 manufacturers (shown in red) to NHTSA's preferred regression model specification (shown in light blue). For cars and light trucks, accounting for vehicle manufacturer increases the estimated effect of mass reduction, but decreases the estimated effect of footprint reduction, on risk. Accounting for vehicle manufacturer in the CUV/minivan regression models makes the estimated effect of mass reduction detrimental and statistically-significant, while the estimated effect of footprint reduction becomes beneficial but no longer statistically-significant.

Figure 5.2 also shows a second case in which five additional control variables are included for five luxury brands (Cadillac, Lincoln, Acura, Infiniti, and Lexus). The effect of including the five luxury brands in the regression models is that the estimated detrimental effect of mass reduction on risk in the heavier cars is much higher, comparable to that of the lighter cars, and is statistically significant. It also substantially reduces the estimated detrimental effect of footprint reduction on cars. Including the five luxury models somewhat mitigates the large change in the estimated effect of mass or footprint reduction in CUVs/minivans when accounting for vehicle manufacturer.

[8] The 14 manufacturers are: Chrysler, Ford, BMW, Honda, Hyundai, Kia, Mazda, Mercedes-Benz, Mitsubishi, Nissan, Subaru, Toyota, Volkswagen, and Volvo.

[9] The manufacturers included in the Other category are: AM General, Audi, Daewoo, Isuzu, Jaguar, Land Rover, Mini, Porsche, Saab, and Suzuki.

Figure 5.2. Estimated effect of mass or footprint reduction on US fatalities per VMT, after controlling for vehicle manufacturer, by vehicle type



Initial vehicle purchase price, rather than manufacturer nameplate, is another proxy for the general quality of vehicle design. We obtained the initial purchase price from the Polk VIN decoder, using 2010 California registration data from the state Department of Motor Vehicles. Every $1,000 increase in initial purchase price is estimated to increase risk in cars by 0.21% (+/- 0.12%), but decrease risk in light trucks by 0.56% (+/- 0.11%) in light trucks and by 0.80% (+/- 0.27%) in CUVs/minivans. Figure 5.3 shows how accounting for vehicle purchase price changes the estimated effect of mass or footprint reduction on risk, compared to the other measures of quality of vehicle design. Including initial purchase price in the regression models substantially increases the estimated effect of mass reduction in heavier-than-average cars (from an estimated 0.51% to 0.84% increase in risk), and substantially increases the estimated beneficial effect of mass reduction in heavier-than-average light-duty trucks and CUVs/minivans. Accounting for initial vehicle purchase price increases the estimated beneficial effect of footprint reduction in light trucks, but results in little change in the estimated effect of footprint reduction on risk for cars and CUVs/minivans. Accounting for vehicle purchase price has a smaller effect on the estimated effect of mass reduction on risk than accounting for vehicle manufacturer, except for heavier-than-average light trucks; accounting for price has a larger effect on the estimated effect of footprint reduction on risk than accounting for manufacturer.

Figure 5.3. Estimated effect of mass or footprint reduction on US fatalities per VMT, after controlling for vehicle manufacturer or for initial vehicle purchase price, by vehicle type

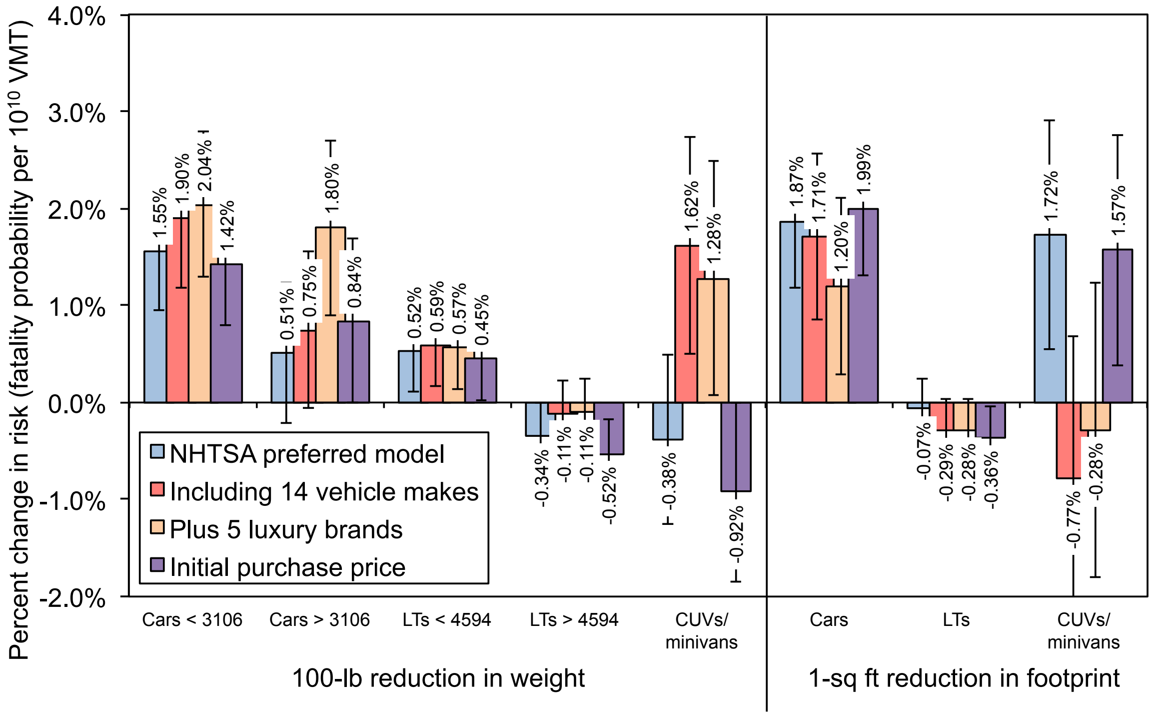


Table 5.1 shows the correlation and VIF between curb weight and initial purchase price, by vehicle type. The table indicates that vehicle mass is correlated fairly strongly with initial purchase price for all vehicle types, with r greater than 0.65 and VIF greater than 2.5 for all vehicle types except minivans (0.273, 1.3) and large pickups (0.561, 1.6).

Table 5.1. Correlation coefficients and variance inflation factors of curb weight with initial purchase price, by vehicle type

Vehicle type	Correlation coefficient (r)	Variance inflation factor (VIF) accounting for vehicle variables	
		CURBWT	PRICE000
Cars	0.760	7.8	3.6
Light trucks	0.677	4.4	2.5
CUVs/minivans	0.663	4.8	2.4
2-dr cars	0.714	4.7	3.2
4-dr cars	0.778	8.3	3.8
Sm pickups	0.785	4.4	3.2
Lg pickups	0.561	2.1	1.6
SUVs	0.761	9.1	2.8
CUVs	0.833	8.8	4.1
Minivans	0.273	1.5	1.3

The control variables for vehicle manufacturer and initial purchase price attempt to account for differences in vehicle models not controlled for in the NHTSA regression models. Other vehicle attributes which could explain the remaining unexplained risk include:

- relatively low bumper height, which increases the extent to which a vehicle's front bumper overlaps the bumper or door sill of a crash partner, may reduce risk in two-vehicle crashes;
- lower center of gravity, or static stability factor, may reduce the tendency of a vehicle to roll over;
- high engine power-to-weight ratio may increase crash frequency, and
- measures of braking distance and handling capabilities which may affect the ability of vehicles to avoid crashes;

LBNL may estimate the effect of accounting for these vehicle attributes in future analyses.

5.3. Calendar year variables

One interesting effect is the reduction in risk over time, as indicated in the calendar year control variables. This is consistent for each vehicle type, but largest for light trucks, 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. 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 indicates that the effect of the calendar year variables on light truck risk is strongest 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 (although not as large) decreases over time in light truck risk in rollovers, crashes with heavy-duty trucks and heavy cars, and other (mostly multi-vehicle) crashes. NHTSA believes that the decline in light truck rollover risk over time may be the result of manufacturers increasing static stability factor or other aspects of light truck design to reduce their likelihood to rollover. However, cars and CUVs/minivans show a similar trend in reduced rollover risk over time (cars and CUVs/minivans also show similarly large reductions in risk over time in crashes with light cars and light LTVs). NHTSA suspects that the risk associated with light trucks involved in crashes with heavy-duty trucks decreases over time because heavy-duty truck activity decreases as the economy falters. 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 risk, by vehicle type

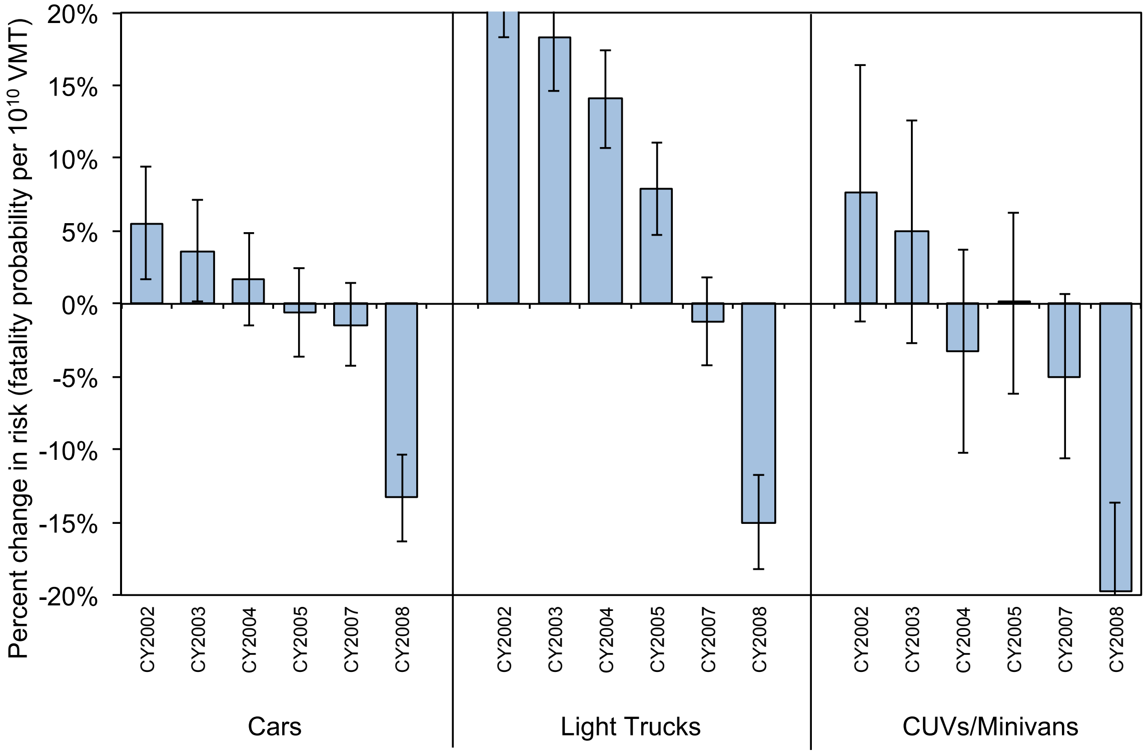
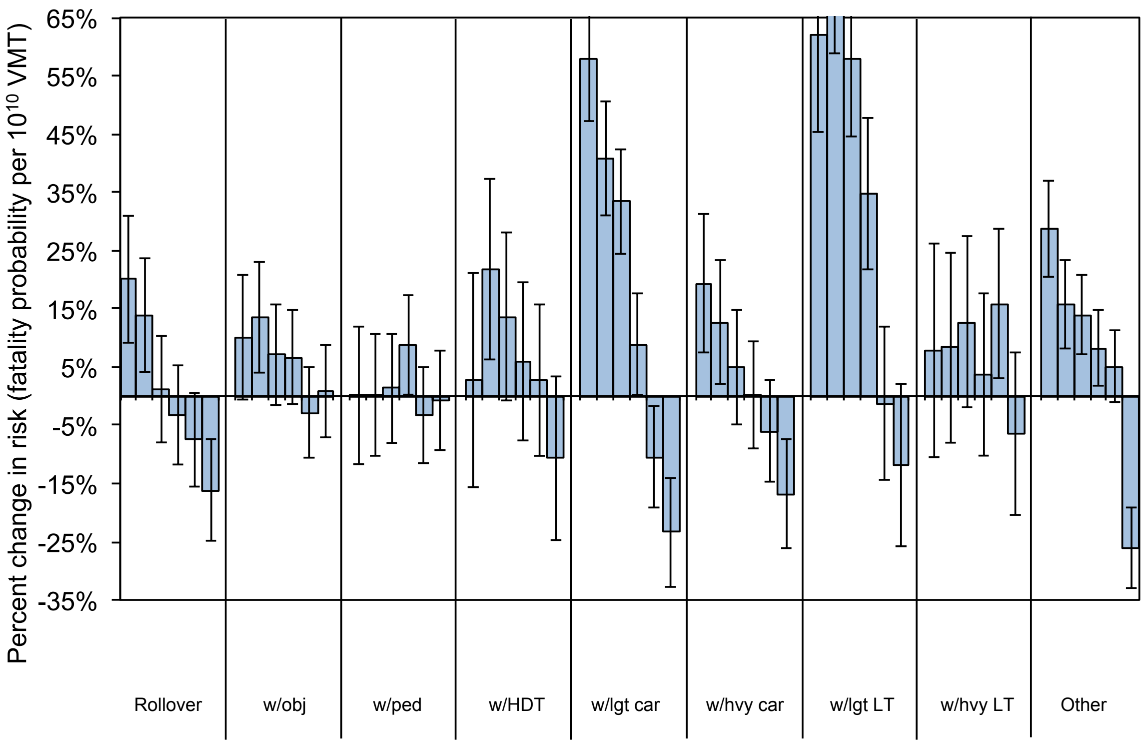
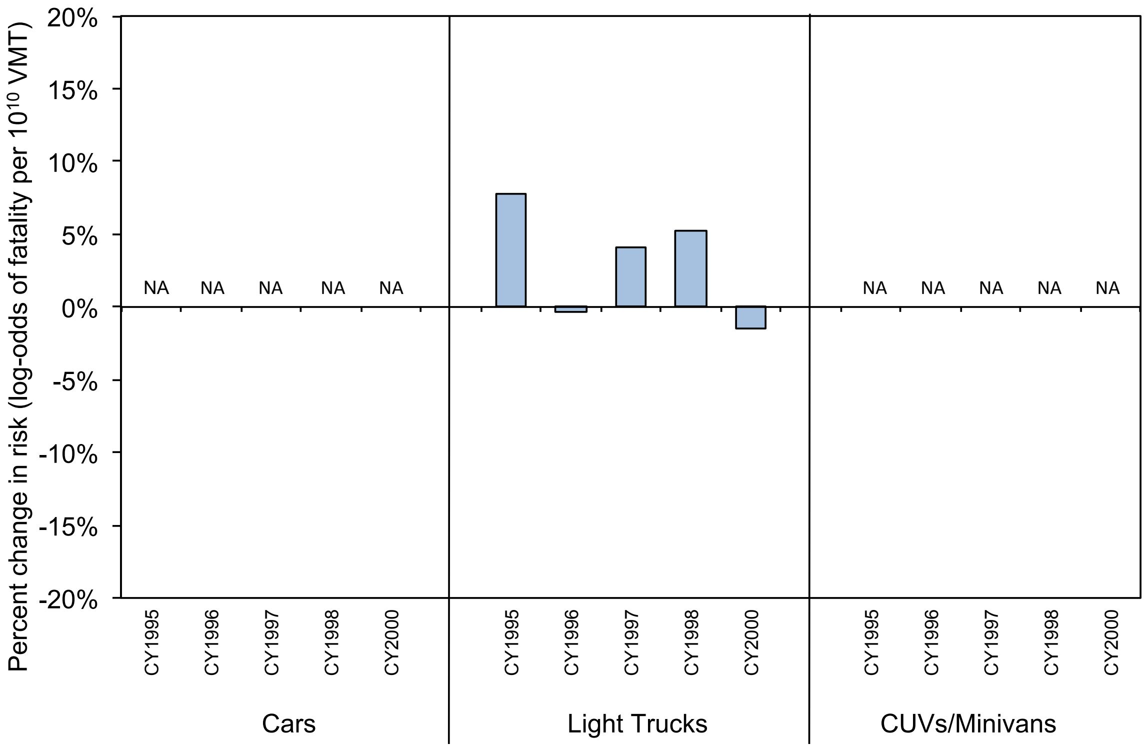


Figure 5.5. Effect of calendar year variables on light truck risk, by crash type



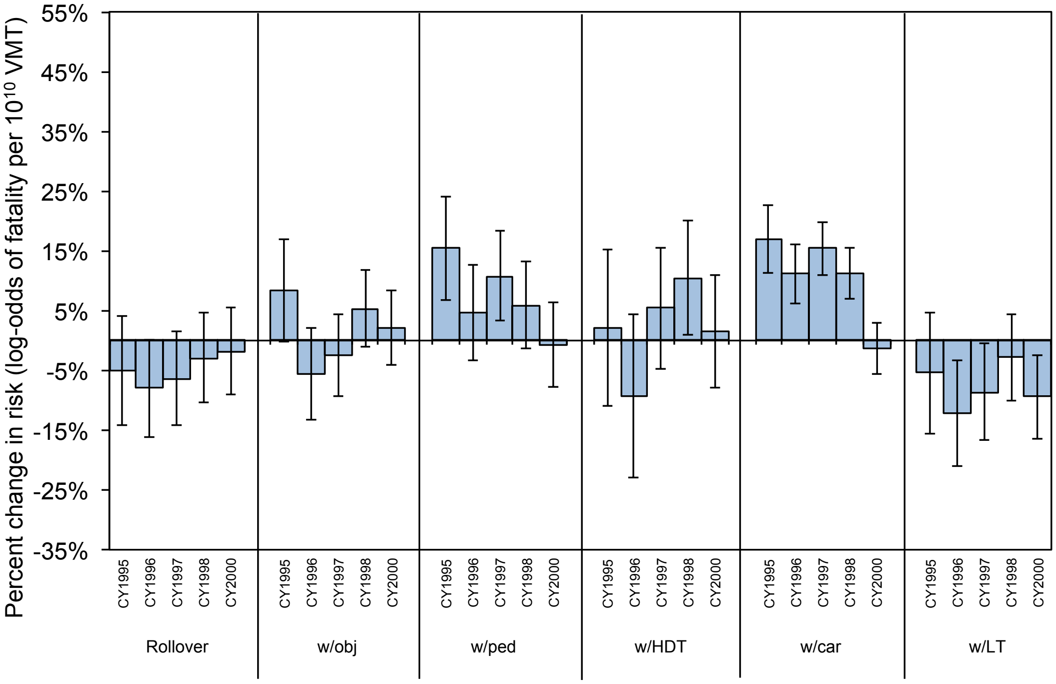
In its 2003 report, NHTSA included calendar year variables for light trucks, but not for cars, because "light trucks grew in weight throughout the 1990's but cars did not" (NHTSA did not analyze CUVs/minivans as a separate vehicle class in the 2003 study). Figure 5.6 shows the weighted average coefficients on the calendar year variables from the 2003 analysis (taken from the tables in Section 4.3 of that report). Note that the effect of the calendar year variables on risk is much smaller than in the 2012 analysis, and there is not the consistent decrease of the effect of calendar year on risk in later years as in the 2012 analysis.

Figure 5.6. NHTSA 2003 effect of calendar year variables on risk, by vehicle type



The calendar year effect for light trucks is strongest on crashes with cars and other light trucks in the 2003 NHTSA analysis, as shown in Figure 5.7. However, calendar year increases the risk in crashes with cars, but decreases the risk in crashes with another light truck. In addition, there is no consistent trend in the variables over time.

Figure 5.7. NHTSA 2003 effect of calendar year variables on light truck risk, by crash type



In its current analysis, NHTSA attributes the large reduction in risk in 2008 to the sharp drop in fatalities in that year; however, it is not clear the extent to which fatalities declined in 2008 because of real safety changes, or because of reduced driving because of high gas prices and the economic recession. Figure 5.8 shows that, for most vehicle types, fatality risk per VMT was fairly constant between 2002 and 2007, with a consistent decline in 2008; pickups were the only vehicle type that showed reduction in risk in any years other than 2008. Figure 5.9 shows that the NHTSA assumptions regarding vehicle miles traveled do not account for any additional reduction in VMT for model year 2002 vehicles in 2008, in response to higher gas prices or the economic recession, other than the linear reduction in annual VMT as vehicles age. (Note that the US VMT for 4-dr cars is much higher than for all other vehicle types, and is plotted along the right vertical axis.) So it is possible that the calendar year trends in risk shown in Figure 5.8 explain the large negative coefficient on the CY2008 variable, but not the decreasing reduction in risk for the other calendar year variables (particularly for cars and CUVs/minivans).

Figures 5.10 through 5.13 show the effect of removing the calendar year variables from NHTSA's preferred regression model (shown in light blue). Figure 5.10 indicates that excluding the calendar year variables has little effect on the estimated coefficients for mass or footprint reduction in cars, or for footprint reduction in CUVs/minivans. However, removing the calendar year variables increases the estimated effect of mass reduction in trucks and CUVs/minivans; reducing by 100 lbs the weight of lighter trucks now is estimated to increase risk by 1.20% (as opposed to 0.52%), is associated with an estimated 0.30% increase rather than an estimated 0.34% decrease in risk in the heavier trucks, and lowers the estimated decrease in risk in CUVs/minivans from a 0.38% decrease to essentially a slight estimated increase in risk.

Figure 5.8. US fatality risk per VMT, by vehicle type and calendar year

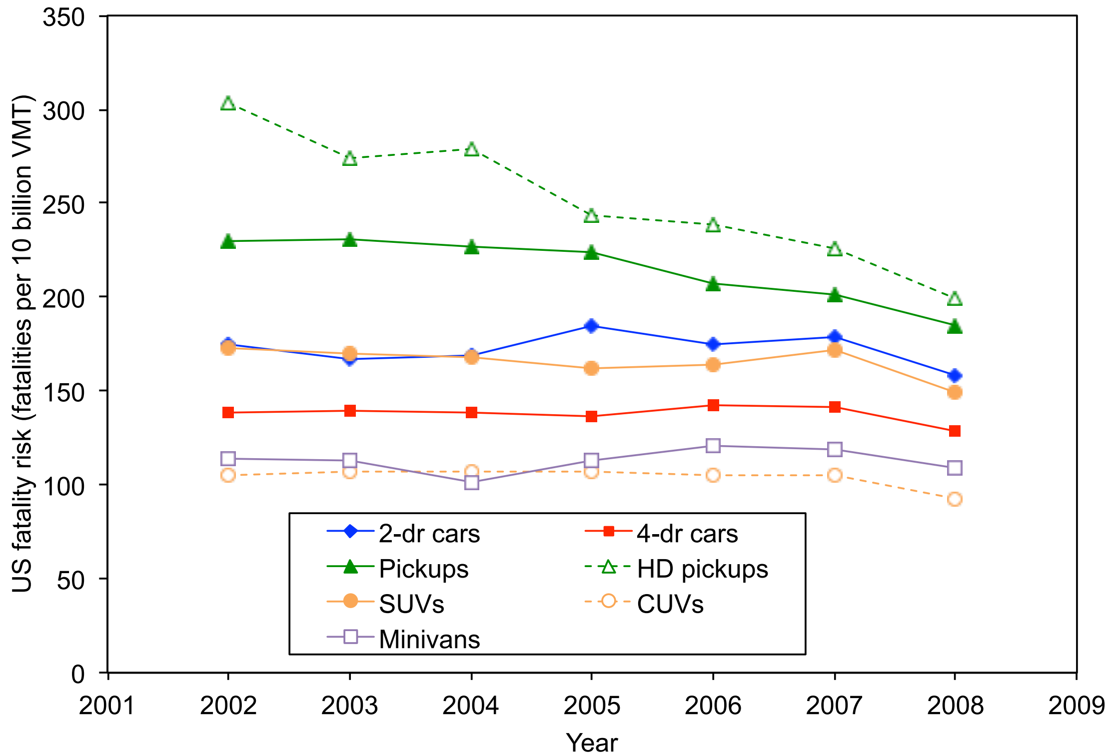


Figure 5.9. Total US VMT for MY2002 vehicles, by vehicle type and calendar year

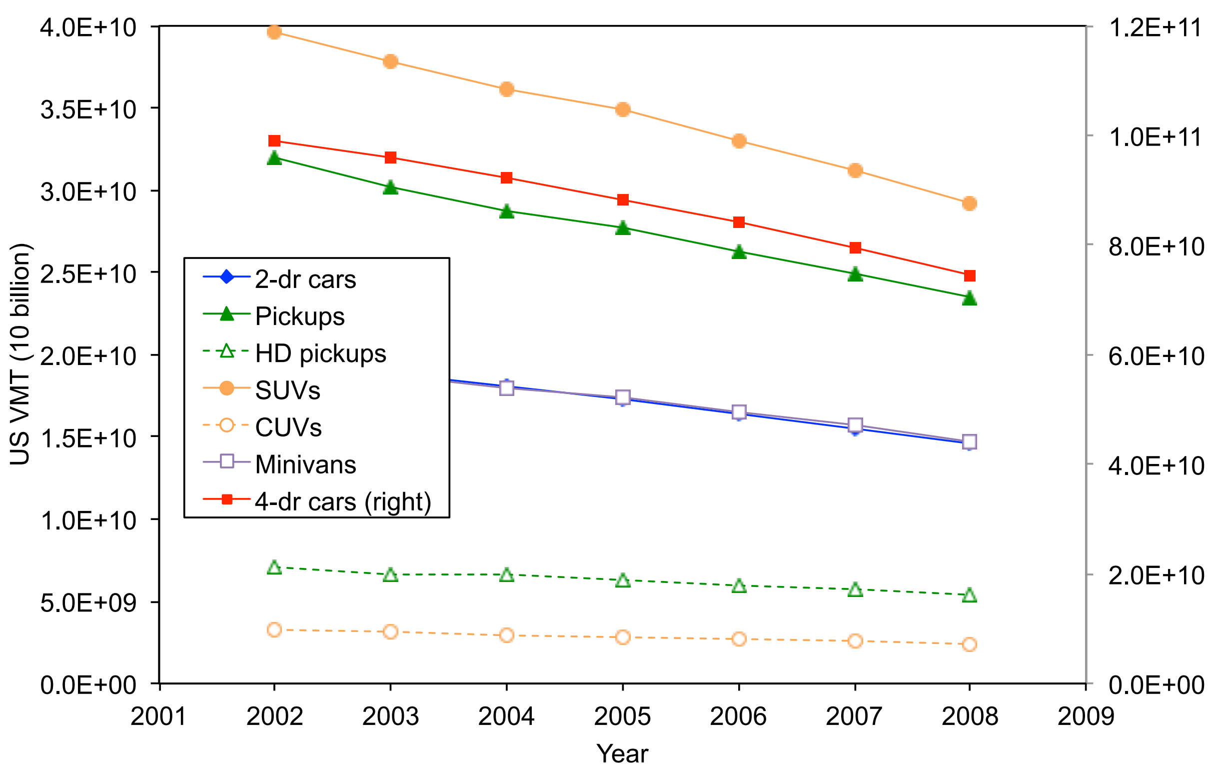
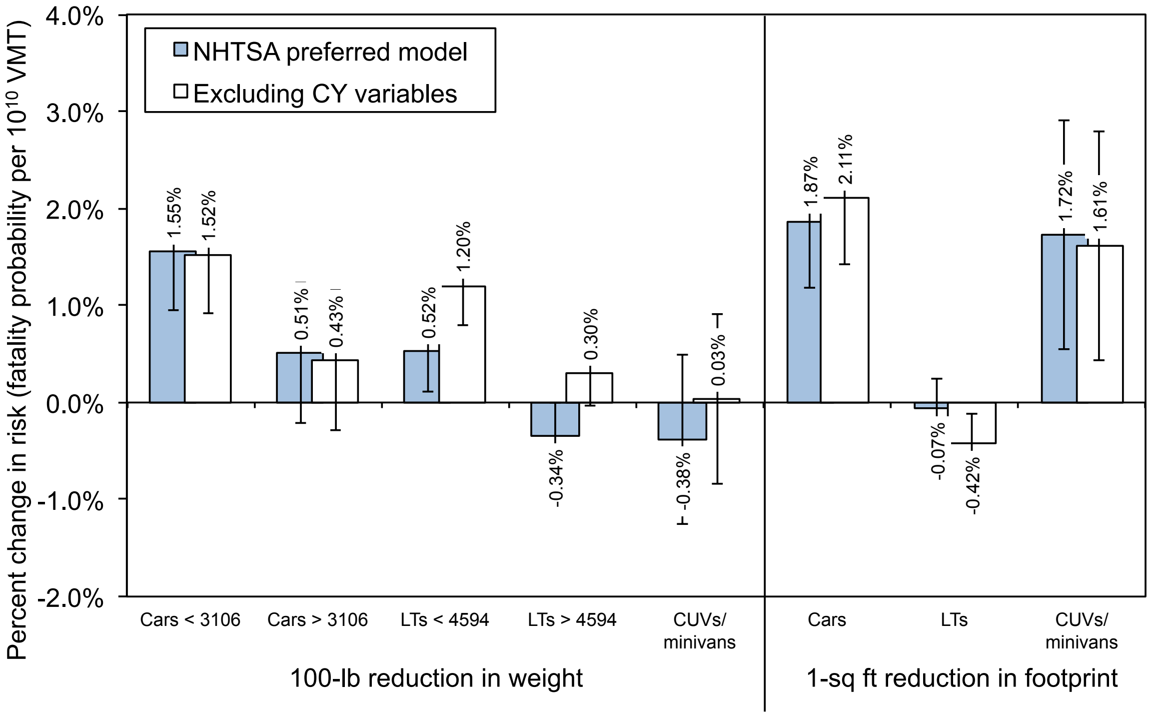


Figure 5.10. Effect of increasing weight or size on risk, including and excluding calendar year variables



We next examined what effect removing the calendar year variables had on the control variables NHTSA used in their preferred model. Figures 5.11 through 5.13 show the effect on the vehicle control variables; there is little to no effect on the driver or crash control variables (not shown). Figures 5.11 through 5.13 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 estimated effect of vehicle age on risk in all three vehicle types. Figures 5.10 through 5.13 suggest that NHTSA's inclusion of the calendar year variables in their preferred model dilutes the estimated effect of airbag technologies in cars and CUVs and minivans, the estimated added risk in SUVs and heavy-duty pickups, and the estimated beneficial effect of ESC in light trucks in general, while over-stating the estimated effect of vehicle age in all three vehicle types.

Figure 5.11. Estimated effect of selected control variables on car risk, including and excluding calendar year variables

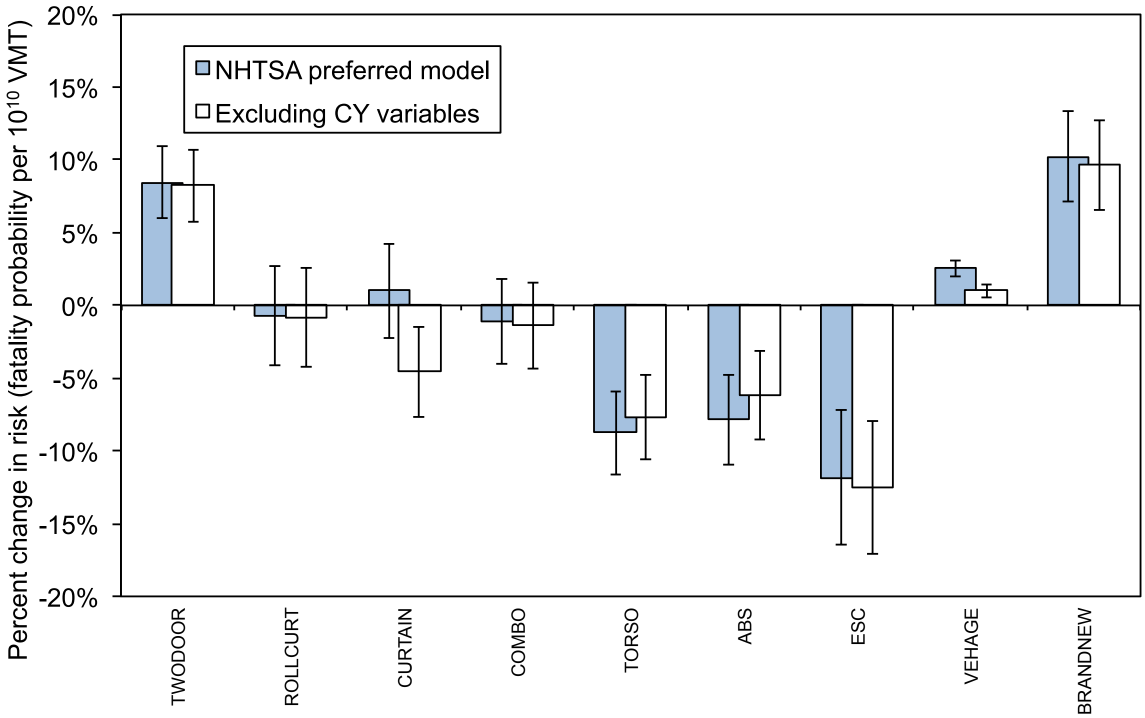


Figure 5.12. Estimated effect of selected control variables on light truck risk, including and excluding calendar year variables

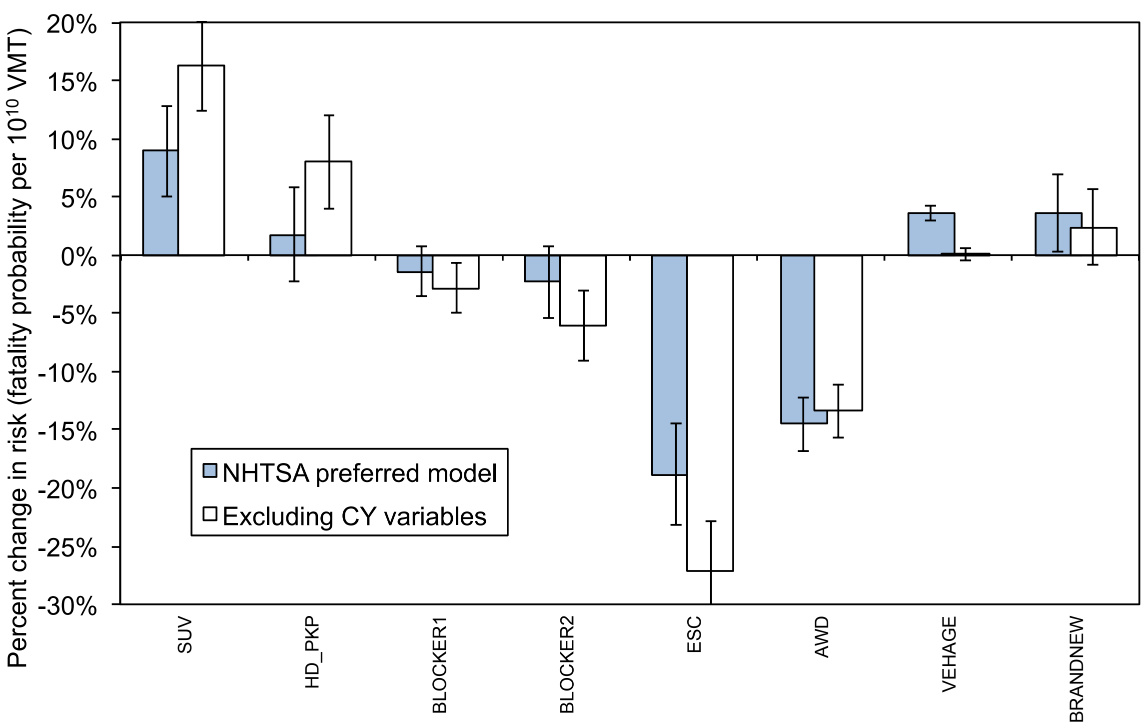
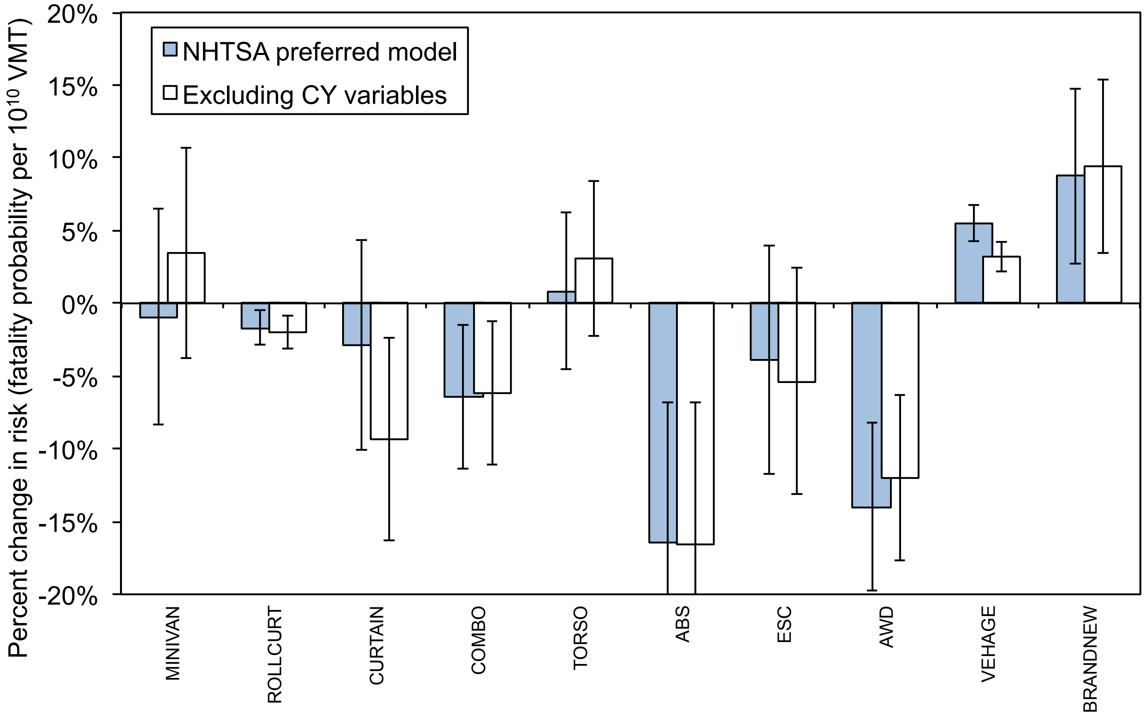


Figure 5.13. Estimated effect of selected control variables on CUV/minivan risk, including and excluding calendar year variables



5.4. Effect of alcohol/drug use and driving behavior

FARS indicates about 10% of car and light truck drivers, and 6% of CUV/minivan drivers, in fatal crashes were reported to have been drinking or engaged in drug use. We examined the effect of excluding case vehicles where the driver was reported to have been drinking or using drugs from our regression analysis; we also excluded these cases when calculating the weighted average effect across all crash types after full penetration of ESC by 2017. Although we excluded fatal crashes involving case vehicles whose drivers were reported to have been drinking or using drugs, we did not make any adjustments to the induced exposure cases from the 13 states.[10] The dark green columns in Figure 5.14 indicate that removing from the analysis the FARS cases where alcohol or drug used was involved slightly increases the estimated effect of mass reduction on risk, but slightly reduces the estimated effect of footprint reduction on risk, as compared with NHTSA's preferred regression model.

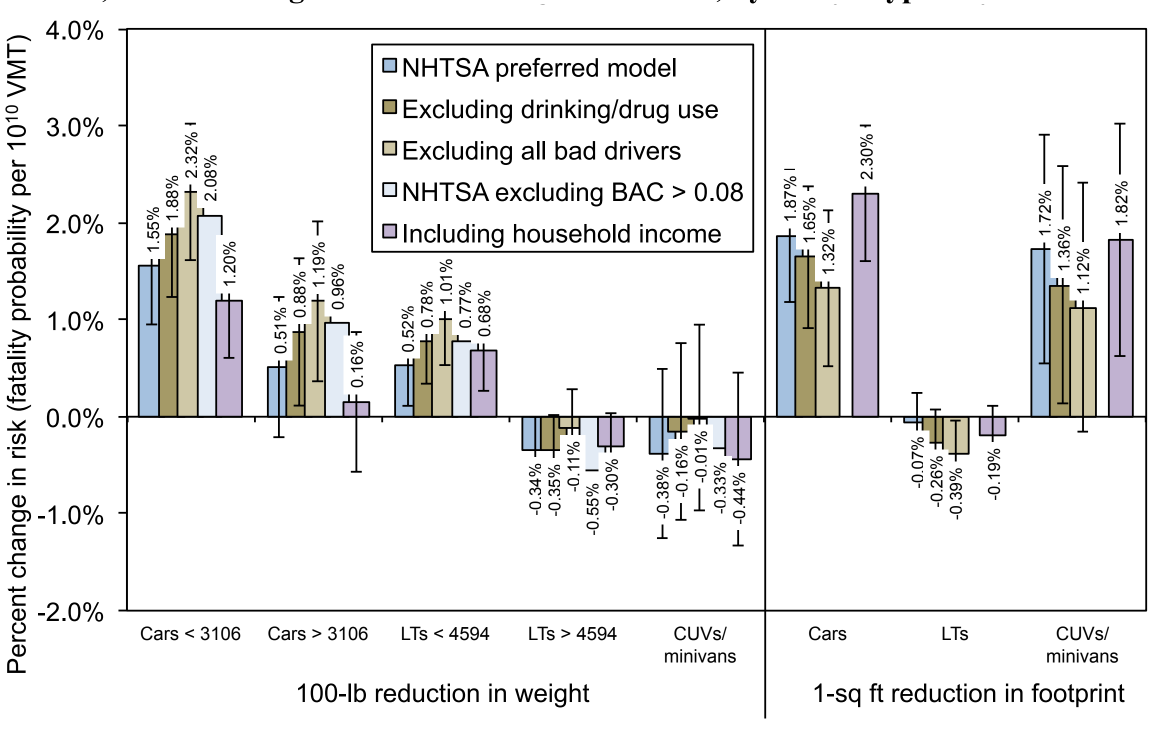
In its 2003 report NHTSA created a "bad driver rating" variable based on whether alcohol or drugs were involved in the current crash, as well as driving without a valid license or reckless driving in the current crash, and the driver's driving record in the last three years. These additional "bad" drivers account for another 11% of car and light truck drivers, and another 8% of CUV/minivan drivers, in the FARS cases. The light green columns in Figure 5.14 indicate that also excluding these bad drivers from the analysis further increases the estimated effect of mass reduction on risk. For example, excluding all bad drivers increases the estimated increase

[10] Most states report suspected driver alcohol or drug use, so we could exclude these induced exposure cases and recalculate the vehicle registration annual VMT weights used in calculating vehicle exposure.

in risk from mass reduction from 1.55% to 2.32% in lighter cars, from 0.51% to 1.19% in heavier cars, and from 0.52% to 1.01% in lighter trucks. On the other hand, excluding all bad drivers from the analysis further reduces the estimated effect of footprint reduction on risk. The fraction of drivers who are drunk, drugged, or bad drivers is two to three times higher in rollovers and fixed object crashes than in all other crash types. Because mass reduction is most beneficial, and footprint reduction most harmful, in these two types of crashes (as shown in Figures 2.2 through 2.4 above), removing crashes involving these drivers from the analysis makes overall mass reduction more harmful, and footprint reduction less harmful.

The pale blue column in Figure 5.14 shows the effect calculated by NHTSA from excluding drivers of case vehicles whose measured or imputed blood alcohol content (BAC) level exceeded 0.08, rather than whether alcohol or drug use was reported. NHTSA's analysis indicates that excluding cases where drivers had high measured or imputed BAC levels has a larger estimated effect on risk than excluding cases where alcohol or drug use was reported, for cars, but a similar estimated effect on risk for trucks and CUVs/minivans. This is likely because NHTSA excludes drivers who were imputed to have been drinking, based on other characteristics of the driver and crash. Excluding the additional drivers who were imputed to have been drinking, but were not reported as such, would likely increase the estimated effects shown in green in Figure 5.14.

Figure 5.14. Estimated effect of mass or footprint reduction on US fatalities per VMT, after excluding case vehicles whose driver was drinking, using drugs or exhibited bad driving behavior, or controlling for median household income, by vehicle type



Household income can also act as a proxy for driver behavior; as shown in Figure 4.18 above, there is a fairly strong correlation between household income and predicted fatality risk, with risk decreasing as income increases. And Figure 4.20 above indicates that crash frequency increases as household income increases, particularly for cars. Every $1,000 increase in household income is estimated to reduce US fatality risk per VMT 0.72% (+/- 0.26%) for cars, and 0.24% (+/- 0.16%) for light trucks, while increasing risk 0.04% (+/- 0.24%) for CUVs/minivans. The last columns in Figure 5.14 (shown in violet) show the estimated effect of mass or footprint reduction on risk after accounting for household income. Accounting for household income has a bigger influence on the estimated effect of mass or footprint reduction in cars than in light trucks or CUVs/minivans: accounting for household income substantially reduces the estimated effect of mass reduction in cars, and substantially increases the estimated effect of footprint reduction in cars. This is in contrast to excluding the alcohol/drug use and bad driving behavior cases, which substantially increased the estimated effect of mass reduction in cars on risk (and reduced the estimated effect of footprint reduction).

Table 5.2 shows the Pearson correlation coefficient r and VIF between curb weight and average median household income, by vehicle type. Table 5.2 indicates that vehicle mass is not correlated with initial purchase price, with a correlation coefficient greater than 0.50 only for CUVs (0.539) and VIF less than 2.5 for all vehicle types (the high VIFs for CURBWT in Table 5.2 are the results of the correlation between curb weight and footprint, as shown in Table 3.1 above).

Table 5.2. Correlation coefficients and variance inflation factors of curb weight with average median household income, by vehicle type

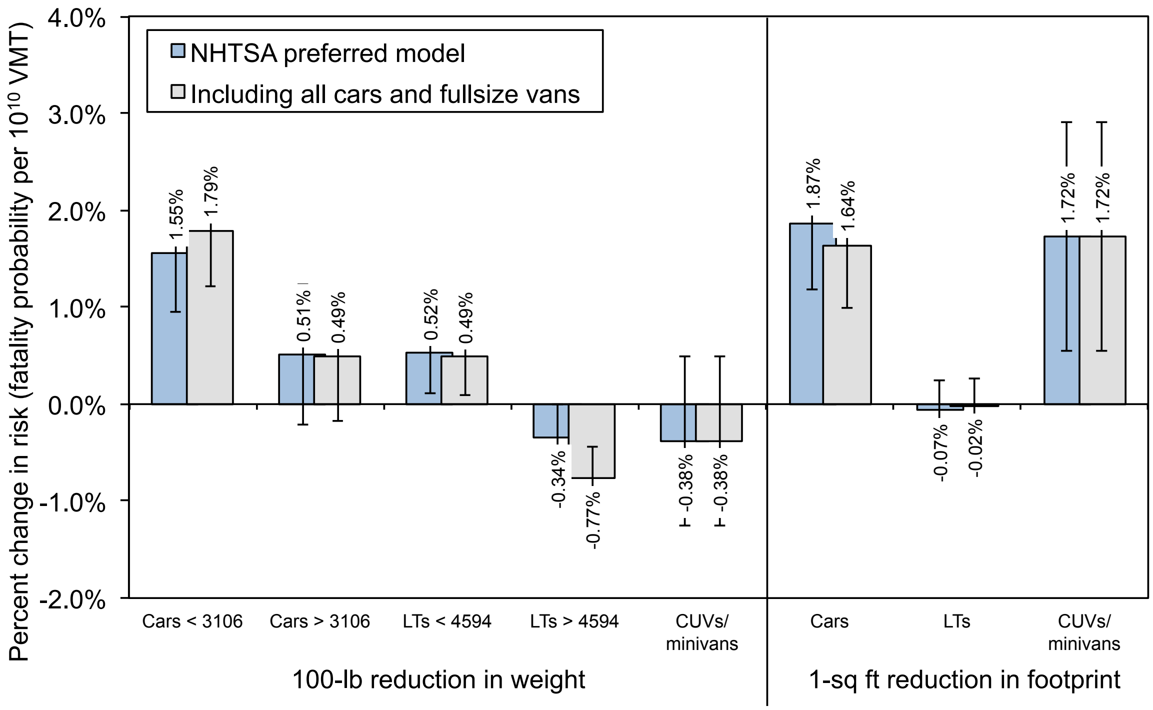
Vehicle type	Correlation coefficient (r)	Variance inflation factor (VIF) accounting for vehicle variables	
		CURBWT	INC000
Cars	0.278	6.5	1.7
Light trucks	0.132	3.0	1.5
CUVs/minivans	0.264	4.0	1.7
2-dr cars	0.343	3.7	2.1
4-dr cars	0.286	7.2	1.6
Sm pickups	0.123	4.2	1.1
Lg pickups	0.228	2.0	1.2
SUVs	0.214	6.8	1.5
CUVs	0.539	6.9	2.1
Minivans	0.418	1.6	1.4

LBNL believes that the information in FARS on driver behavior in the current crash, as well as their recent driving history, is the best available to account for how a particular individual drives their vehicle, how closely they obey traffic regulations and how quickly or well they adapt to dangerous situations. While this information is not consistently recorded in state crash data, it may be possible to more accurately control for the effect of driver behavior in the relationship between mass or footprint and fatality risk, using data from particular states that record this information.

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

As mentioned above, NHTSA excluded three types of cars, models used as sports cars, police cars, and models with all-wheel drive, all Ford Crown Victorias, and fullsize passenger and cargo vans, from its preferred regression model. Including these vehicles in the analysis, and adding five control variables for the additional vehicle types, increases the estimated effect of mass reduction in lighter-than-average cars, has little change in heavier cars and lighter light trucks, and increases the estimated beneficial effect of mass reduction in heavier light trucks, as shown in Figure 5.15. Including these vehicles has little effect on the estimated effect of footprint reduction on risk in light trucks, but reduces the estimated increase in risk from footprint reduction in cars.

Figure 5.15. Estimated effect of mass and footprint reduction on US fatality risk per VMT, after including sports, police, and all-wheel drive cars, and fullsize passenger and cargo vans, by vehicle type



5.6. Effect of changes suggested by NHTSA peer reviewers

In its review of the preliminary NHTSA 2012 study, DRI commented that some drivers may be better able to avoid a crash, due to skill, level of alertness, or reaction time, than others, even in crashes in which they were not determined to be at fault (Van Auken and Zellner 2012a and 2012b). Using all vehicles deemed not-at-fault in two-vehicle crashes, rather than only those that were stopped at the time of the crash, as the measure of exposure might over-represent the effect of poor driving behavior in the regression results. DRI suggested that NHTSA use only stopped vehicles, rather than all non-culpable vehicles, in developing the weights for vehicle registration-years and miles-driven to be used as the measure of crash exposure. In addition, DRI suggested that NHTSA account for the two components of vehicle footprint, wheelbase and track width, separately in the regression models. DRI has found that these two changes to the regression models tended to reduce the estimated detrimental effect of mass reduction on risk (Van Auken and Zellner 2005b and 2012b).

Table 5.3 shows the results of the additional sensitivity tests NHTSA conducted in response to the DRI comments. Table 5.3 indicates that using only stopped vehicles, and not all vehicles judged to be not-at-fault, in two-vehicle crashes substantially reduces the estimated detrimental effect of mass reduction on risk in cars and trucks, while substantially increasing the estimated detrimental effect of footprint reduction on risk in cars. Replacing vehicle footprint with its two components, track width and wheelbase, similarly reduces the estimated detrimental effect of mass reduction; an increase in risk is associated with decreasing track width in cars and light trucks, but with decreasing wheelbase in CUVs/minivans. The last column of Table 5.3 indicates that combining these two sensitivities, i.e. using stopped vehicles as the measure of exposure and replacing footprint with track width and wheelbase, further reduces the estimated detrimental effect of mass reduction, such that fatality risk is estimated to increase in light cars by a statistically non-significant 0.26%.

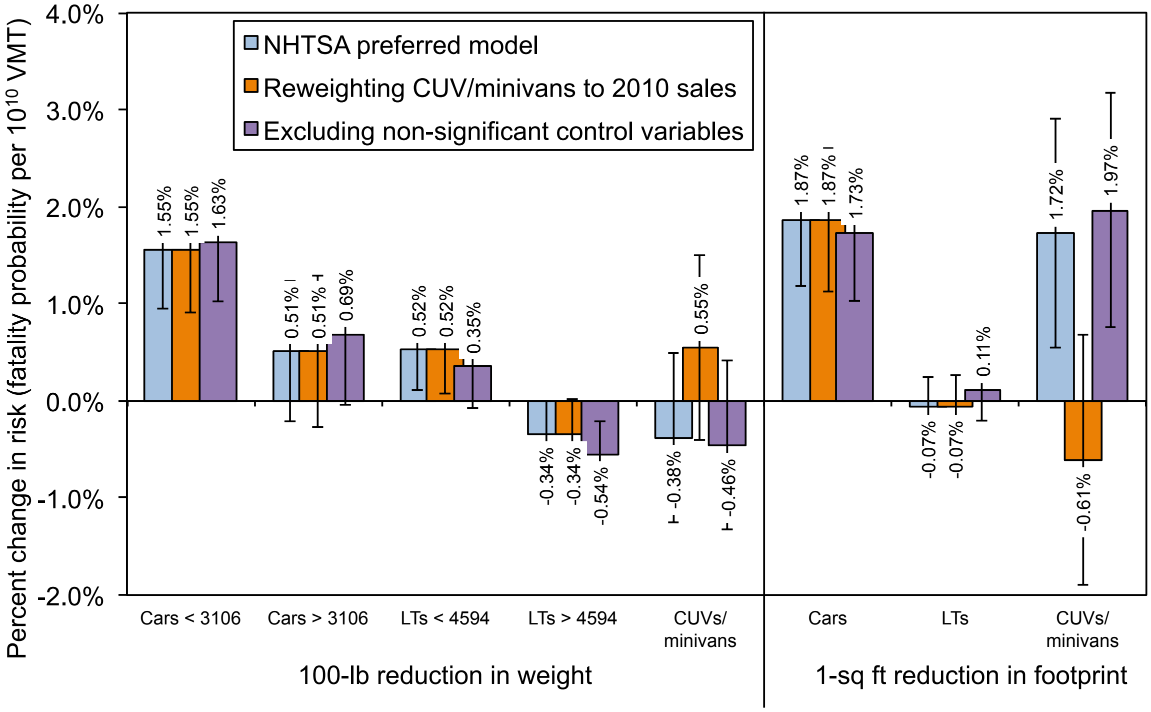
Table 5.3. Estimated effect of mass or footprint reduction on US fatality risk per VMT, under alternative regression model specifications suggested by NHTSA peer reviewers

Variable	Case vehicle type	NHTSA preferred model (fatalities per VMT)	Using stopped vehicles	Replace footprint with track width and wheelbase	Using stopped vehicles and track width/ wheelbase
Mass reduction	Cars < 3106 lbs	1.55%	0.97%	0.95%	0.26%
	Cars > 3106 lbs	0.51%	-0.63%	0.24%	-0.90%
	LTs < 4594 lbs	0.52%	0.35%	-0.07%	-0.10%
	LTs > 4594 lbs	-0.34%	-0.80%	-0.58%	-0.97%
	CUV/ minivan	-0.38%	-0.33%	-0.25%	-0.14%
Footprint reduction	Cars	1.87%	3.43%	—	—
	LTs	-0.07%	-0.03%	—	—
	CUV/ minivan	1.72%	1.81%	—	—
Track width reduction	Cars	—	—	4.36%	6.03%
	LTs	—	—	1.07%	0.90%
	CUV/ minivan	—	—	0.08%	-0.55%
Wheel base reduction	Cars	—	—	-0.09%	0.38%
	LTs	—	—	-0.09%	-0.09%
	CUV/ minivan	—	—	1.16%	1.45%

Estimates that are statistically significant at the 95% level are shown in red.

Other reviewers suggested that NHTSA conduct two additional sensitivities: reweighting the fatalities of CUVs and minivans by their market shares in 2010 (Paul Green); and removing the non-significant control variables from the 27 regression models for the three vehicle types and nine crash types (Farmer). Figure 5.16 shows the sensitivity of NHTSA's main results to these changes. Weighting the distribution of fatalities in CUVs and minivans by their respective shares of sales in 2010 (which reflects more CUVs and fewer minivans) causes the estimated effects to change signs, with decreasing mass now associated with an estimated increase in risk, and decreasing footprint with an estimated reduction in risk, for CUVs and minivans (shown in orange). Removing non-significant control variables from each of the regression models results in slightly larger estimated detrimental effects of reduced mass in cars, and slightly smaller estimated effects in light trucks.

Figure 5.16. Estimated effect of mass and footprint reduction on US fatality risk per VMT, after reweighting CUV/minivan fatalities to 2010 sales and excluding non-significant control variables, by vehicle type



6. Influence of recent trends on the expected effect of mass reduction on risk in 2017-2025

As discussed in Section 2, NHTSA estimated the change in fatalities in 2017-2025 after assuming full market penetration of electronic stability control (ESC) in new vehicles. There are other trends in vehicle technologies, in addition to ESC, that may affect baseline fatalities in 2017 through 2025. Side airbags are becoming standard equipment on most vehicles, and manufacturers are taking measures to improve light truck compatibility with other vehicles in frontal crashes. And in recent years there has been a market shift from truck-based SUVs to car-based CUVs. In this section we analyze what influence these trends, if they continue, may have on the effect of mass reduction on risk in the 2017-2025 timeframe. Note that new safety technologies, such as ESC and side airbags, often are first introduced in more expensive vehicles, and bundled with other features that enhance occupant safety; as a result, the initially observed safety benefit on a per vehicle basis may be reduced as the technology is more widely adopted. And while a vehicle with ESC or side airbags will most likely have a lower risk than a vehicle without these technologies, the effectiveness of the technologies could well vary across vehicle models.

6.1 Effect of electronic stability control (ESC)

Figure 6.1 indicates that manufacturers began installing ESC as a standard feature in MY05, with about half of MY07 CUVs and minivans, and a third of MY07 light trucks, having ESC. As NHTSA has required ESC on all light-duty vehicles by MY12, there likely has been a quick increase in the market penetration of ESC in new vehicles, including cars, between MY07 and MY12.

A recent NHTSA study estimates 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.[11] (These estimates treat crossover SUVs and minivans as light trucks rather than cars.) Figure 6.2 compares these recent results, shown in red, with the estimated effect of ESC installation on fatality risk from NHTSA's regression models in the current analysis, by vehicle and crash type. The figure indicates that the current analysis gives comparable estimates for ESC effectiveness for cars in rollovers, light trucks in rollovers and crashes with objects, and CUVs/minivans in crashes with objects. However, the current analysis estimates a lower ESC effectiveness for car crashes with objects, and CUV/minivan rollovers, than the Sivinski study. On the other hand, the current study estimates substantially higher ESC effectiveness in reducing risk in crashes with other vehicles in many cases.

[11] 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.

Figure 6.1. Market penetration of ESC, by vehicle type and model year

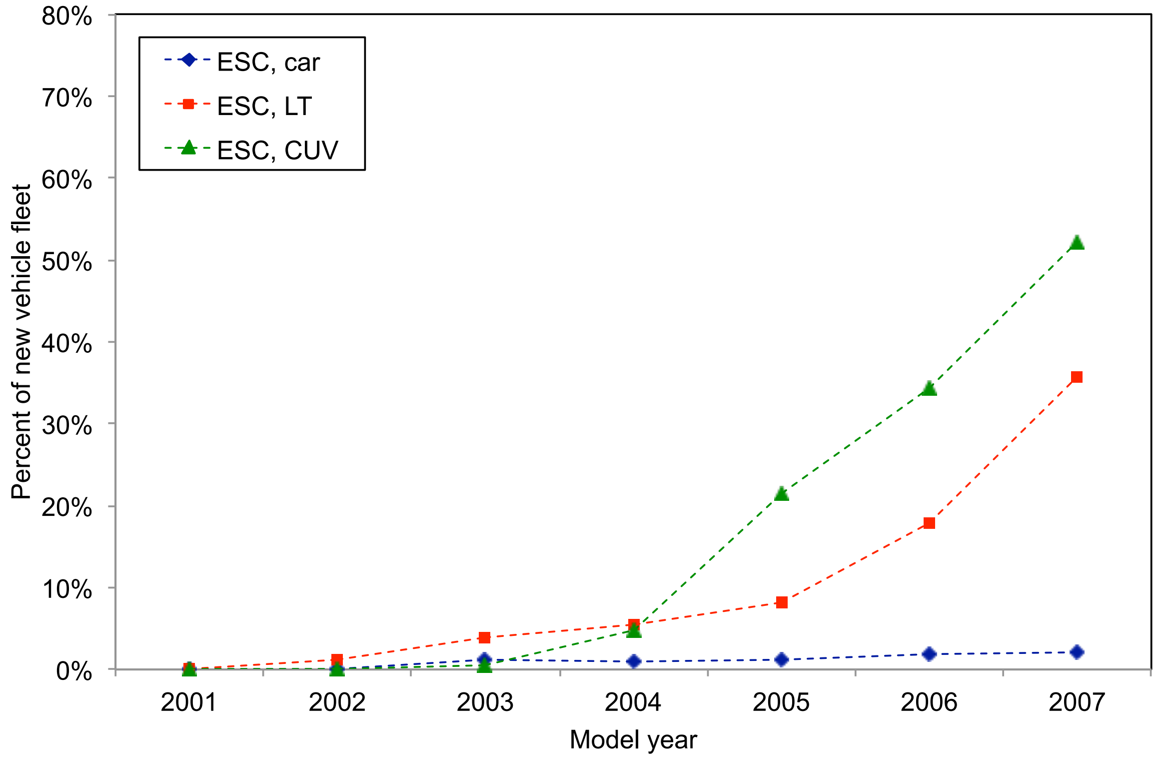
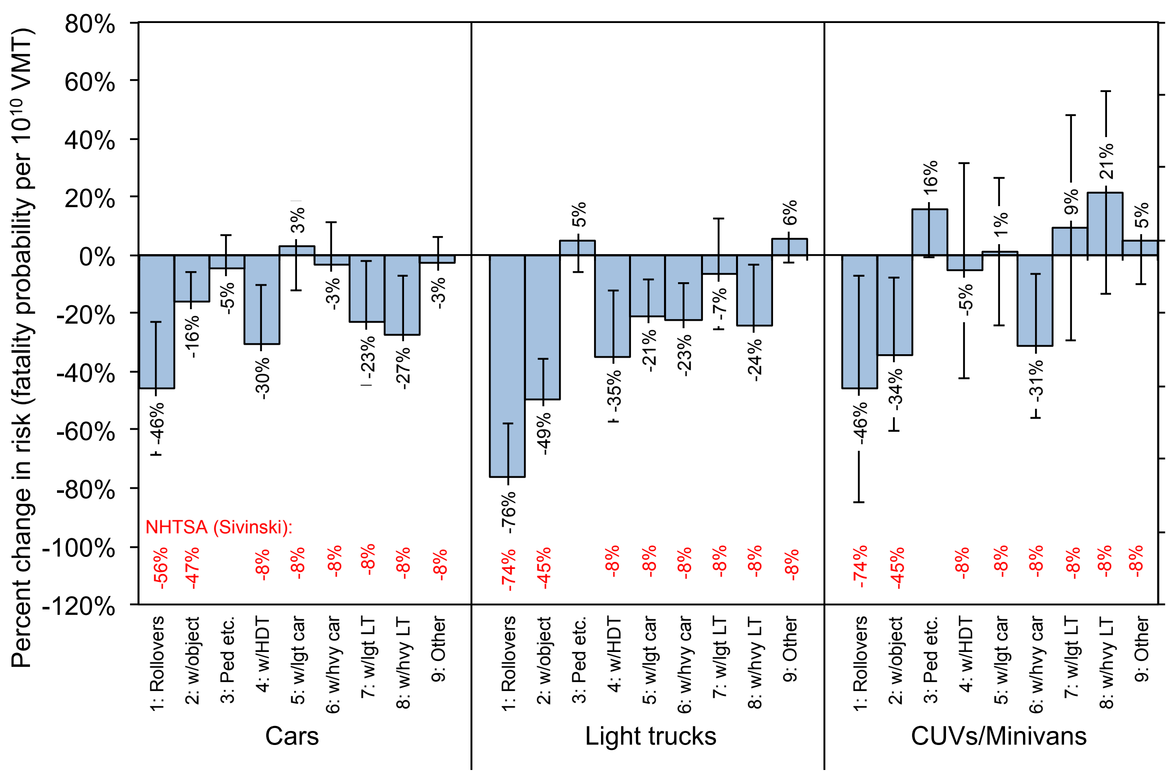


Figure 6.2. Estimated effect of ESC on fatality risk, by vehicle type and crash type

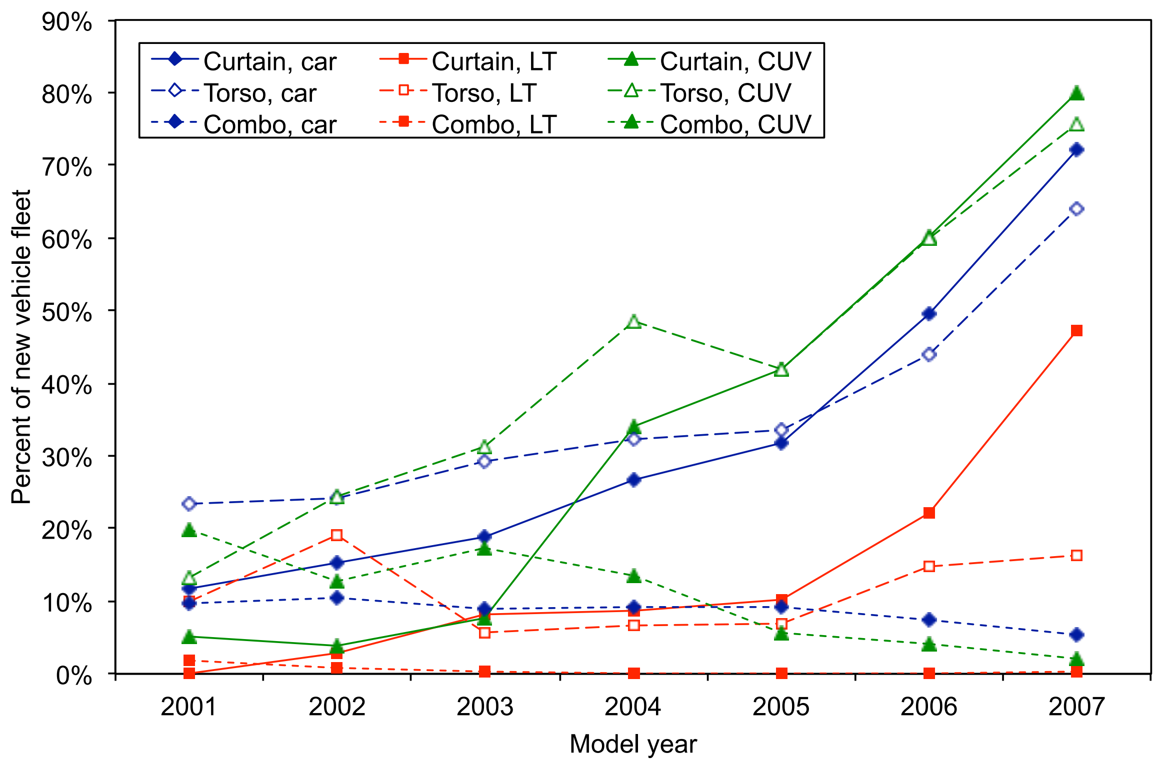


6.2 Effect of side airbags

Figure 6.3 shows the recent trend in the market penetration of side airbag technologies in new vehicles. The data in Figure 6.3 are only for vehicles coded in the NHTSA database as having zero or 100% of a particular airbag technology; because side airbag technologies are optional equipment on many models, particularly light trucks, NHTSA used the fraction of vehicles of these models that had the technology installed. The data in Figure 6.3 account for 80% to 90% of all cars, 60% to 100% of all light trucks, and 77% to 86% of all CUVs/minivans, depending on the model year. Because many models are coded as having both side curtain and side torso airbags, the data for each vehicle type are not additive; by MY07, 63% of cars, 16% of light trucks, and 76% of CUVs/minivans had both side curtain and side torso airbags installed.

Figure 6.3 indicates that side airbags have been available for a longer period than ESC (shown in Figure 6.1 above); in MY01 23% of cars, 10% of light trucks, and 13% of CUVs and minivans came with side torso airbags. Side curtain airbags have become more prevalent than side torso airbags, particularly for light trucks; by MY07, 72% of cars, 80% of CUVs/minivans, and 47% of light trucks came with side curtain airbags.

Figure 6.3. Market penetration of side impact airbags, by vehicle type and model year



Side airbags should reduce fatality risk in crashes when another vehicle strikes the case vehicle in the side (although curtain airbags are designed to also deploy in rollovers and severe frontal crashes). Figures 6.4 through 6.6 show the effect the three side airbag technologies have on the risk of fatality <u>to the occupants in the case vehicle only</u>, by case vehicle type. The effect of side airbags is shown for crashes where the case vehicle is struck in its side (either driver or passenger side) by its crash partner; the vehicle type of the crash partner is shown along the x-axis (light and heavy cars, light and heavy light-duty trucks).

Figure 6.4 indicates that, for example, combo side airbags in a car struck in the side by a light car reduce the fatality risk in the case car by 53%. The figure suggests that combo and torso side airbags have a large, and for the most part statistically-significant, reduction on fatality risk: 17% to 53% for side combo airbags and 29% to 42% for side torso airbags, depending on the striking vehicle type. Curiously, side curtain airbags have a much smaller reduction in fatality risk than side torso or side combo airbags, and actually increase fatality risk in cars struck by another lighter car (however, none of the effects of side curtain airbags are statistically significant). The rightmost panel in Figure 6.4 (darker blue) shows the result of a separate regression model that combines the side airbag variables into a single SIDEAB variable, as many vehicles have both the curtain and the torso side airbag. The inclusion of any type of side airbag results in slightly lower benefits than estimated for torso side airbags only, and reduces the sampling error somewhat. Note that any side airbag technology is slightly more beneficial to car occupants when struck by another car than when struck by a light truck. The benefits do not appear to be affected by the mass of the striking vehicle; in other words, when a car is struck in the side by another car, the protective effect of side airbags is unaffected by the mass of the striking car.

Figure 6.4. Estimated effect of side airbags on risk to car occupants only, when struck in the side by another light-duty vehicle, by crash partner vehicle type

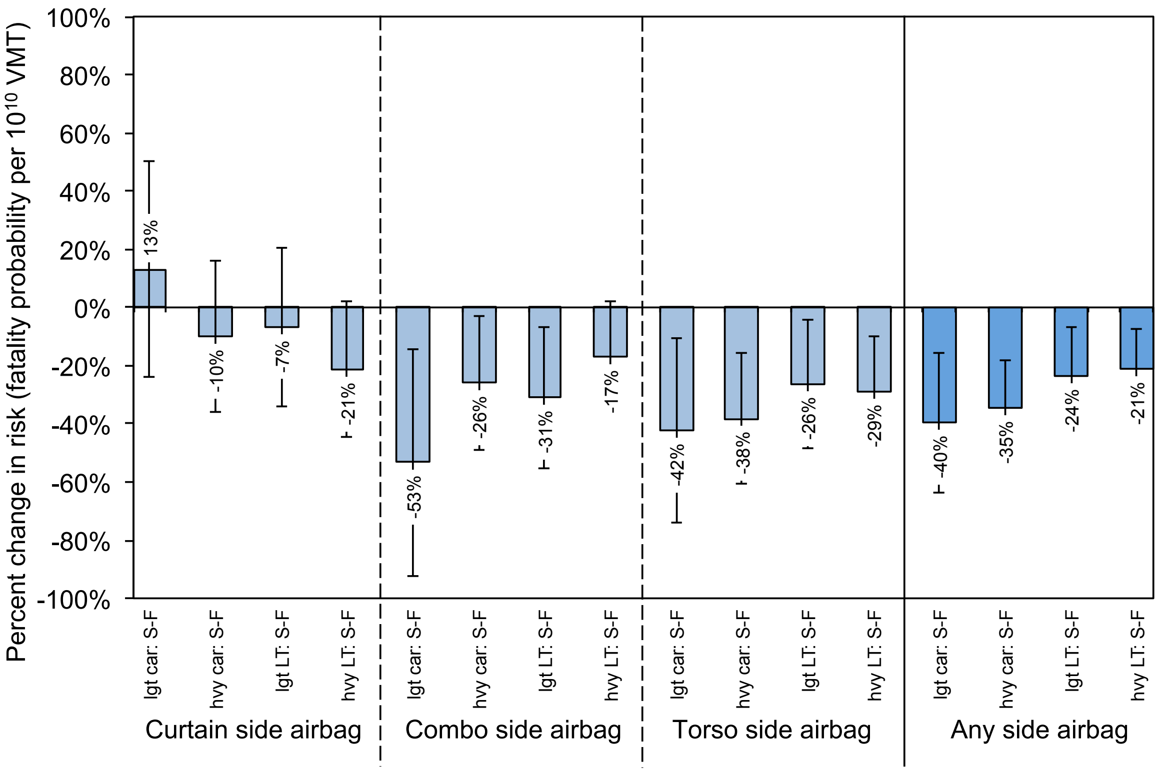
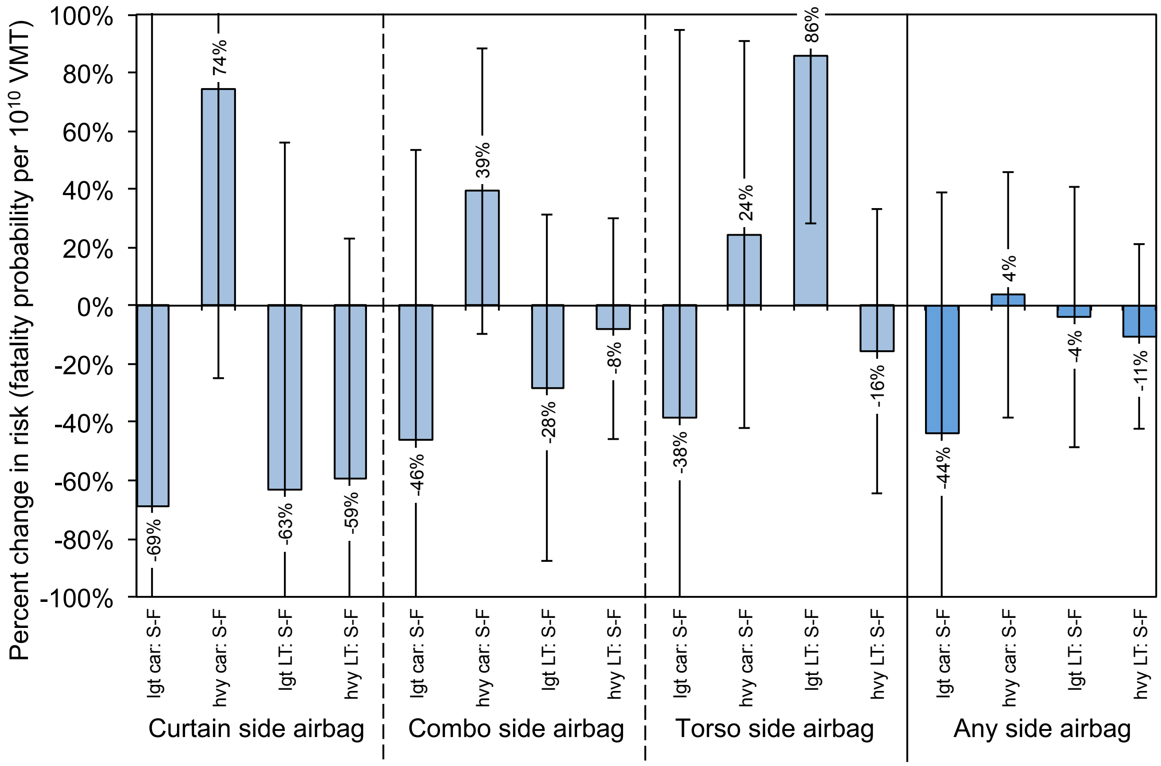


Figure 6.5. Estimated effect of side airbags on risk to <u>CUV/minivan occupants only</u>, when struck in the side by another light-duty vehicle, by crash partner vehicle type



And when a car is struck in the side by a light truck, the protective effect of side airbags is unaffected by the mass of the striking light truck.

Figure 6.5 indicates that the relationship is less clear for CUVs and minivans struck in the side by another vehicle; side airbags appear to increase fatality risk in cars struck in the side by certain vehicle types, although none of the effects of the three individual airbag technologies are statistically significant in any of the side impact crashes with CUVs/minivans (except side torso airbags in CUVs/minivans struck in the side by a light light-duty truck, which has a statistically significant 86% increase in fatality risk). Modeling the effect of any type of side airbag (rightmost panel, in darker blue) results in a large, but statistically insignificant, reduction in risk in CUVs and minivans struck in the side by a light car; the results for the other striking vehicle types are smaller and also not statistically significant.

Figure 6.6 shows the effect of the three side airbag technologies on risk to light-duty truck occupants; as with CUVs/minivans, there is no consistent or statistically-significant protective effect of side airbags in light-duty trucks. (Recall that NHTSA did not include the side airbag variables in its regression equations for light-duty trucks; Figure 6.6 represents a new regression model that does include these variables). The inclusion of any type of side airbag improves the relationship somewhat, with reduced risk when struck by three of the four vehicle types, but the effect is statistically insignificant in all cases.

Figure 6.6. Estimated effect of side airbags on risk to <u>light truck occupants only</u>, when struck in the side by another light-duty vehicle, by crash partner vehicle type

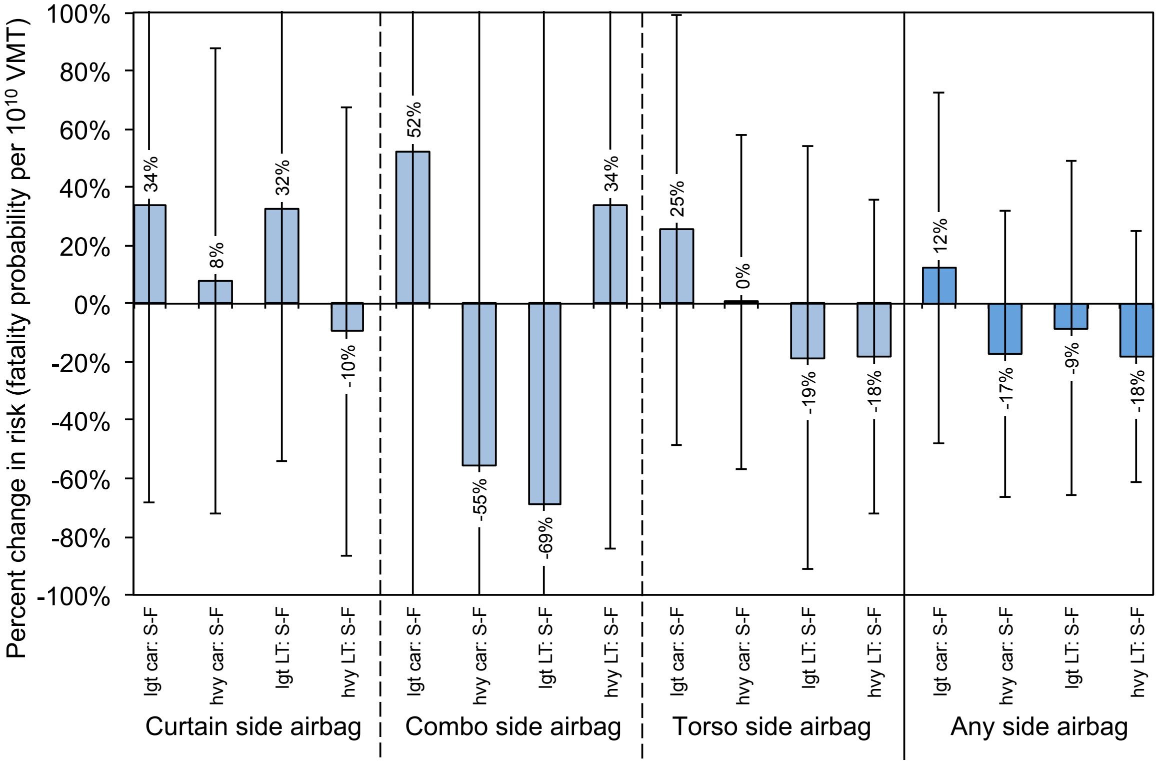


Figure 6.7 through 6.9 show the effect of mass reduction in crashes between two light-duty vehicles, by crash partner vehicle type, for three crash configurations: front-to-front crashes (F-F), crashes where the case vehicle is struck in the driver or passenger side (S-F), and all other crash configurations (mostly rear impact crashes). Figure 6.7 indicates that mass reduction has a larger effect on risk in side impact crashes (shown in dark blue) than in other crash configurations in only one case: when a underweight car is struck by a light light-duty truck. In all other cases, the detrimental effect of mass reduction on risk is greater in either frontal crashes or other crashes with another light-duty vehicle, than when the case vehicle is struck in the side. Full adoption of side airbags, which Figure 6.4 above suggests will reduce the number of fatalities in cars struck in the side, will only reduce the influence of mass reduction on risk in this one type of side impact crash; in crashes with other crash partners, the reduction of side impact fatalities will tend to increase the overall effect of mass reduction on risk in cars.

Figure 6.8 shows that the effect of mass reduction on risk in CUVs and minivans when struck in the side by another car is slightly higher than in other crash configurations when the striking vehicle is a heavy car or a light light-duty truck. The effect of mass reduction is much larger than in other crash configurations when the striking vehicle is a heavy light-duty truck. Therefore it appears that a reduction in the number fatalities in crashes where a CUV/minivan is struck in the side would slightly reduce the detrimental effect of mass reduction in CUVs and minivans. However, as shown in Figure 6.5 above, it is not clear the extent to which side airbags will reduce fatalities when CUVs/minivans are struck in the side.

Interestingly, Figure 6.9 indicates that the detrimental effect of mass reduction on risk to light-duty truck occupants is for the most part greater when a light truck is struck in the side, than in a frontal or rear impact crash. In other words, increased mass appears to have a larger beneficial safety effect for light trucks hit in the side than for cars, CUVs, or minivans hit in the side. This is likely because the relatively high door sills of light trucks provide some protection from intrusion of the target vehicle into the occupant compartment; casualties in side impact crashes in light trucks are therefore mostly the effect of changes in momentum, which can be mitigated by increasing the mass of the struck light truck. Door sills of cars and CUVs/minivans are relatively low, and do not provide as much protection from intrusion of the striking vehicle; therefore, increasing the mass of cars and CUVs/minivans has little safety benefit in crashes where they are struck in the side, regardless of the striking vehicle type. Although mass reduction is detrimental to light trucks when they are struck in the side, recall that Figure 6.6 above suggests that there is no statistically significant benefit of side airbags in preventing fatalities in light-duty trucks when struck in the side.

Overall, it appears that full adoption of side airbags will reduce fatality risk in cars struck in the side by another light-duty vehicle; however, if anything, reduction of this type of fatality will increase the detrimental effect of mass reduction in cars. It is not clear whether full adoption of side airbags will reduce fatality risk when light-duty trucks, CUVs and minivans are struck in the side.

Figure 6.7. Estimated effect of mass reduction on risk to <u>car occupants only</u> in two-vehicle crashes, by crash partner vehicle type and crash configuration

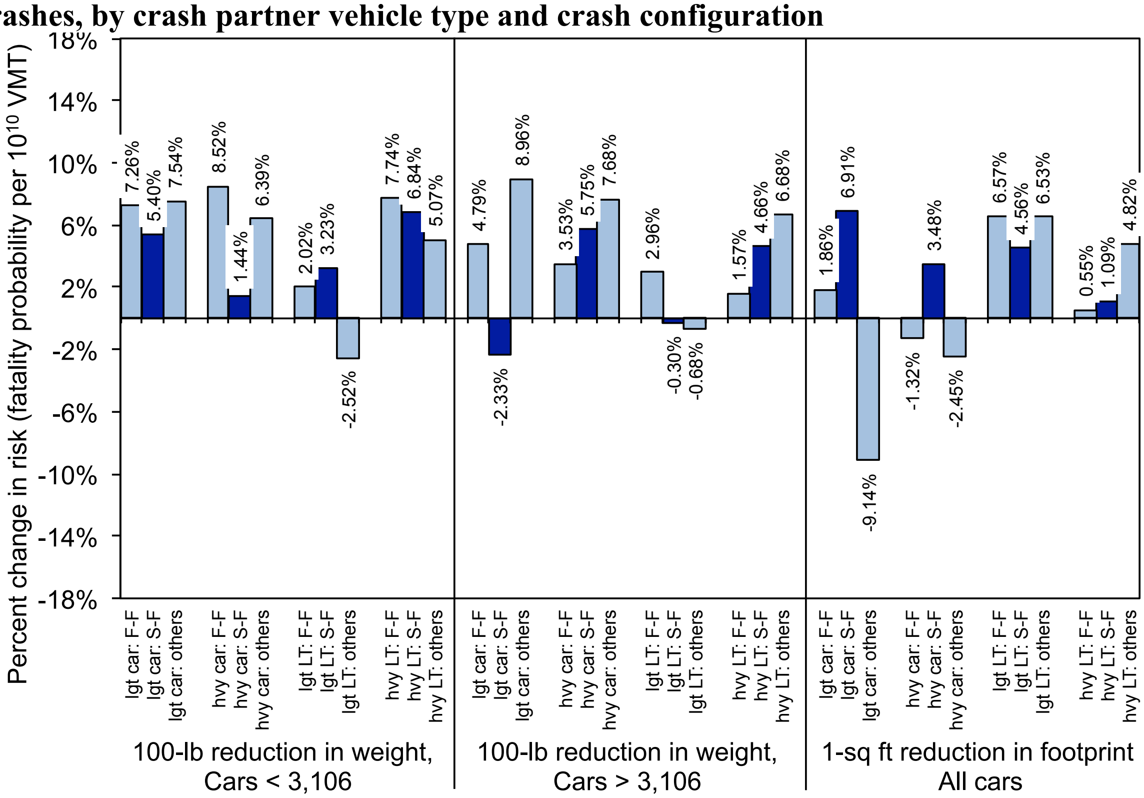


Figure 6.8. Estimated effect of mass reduction on risk to CUV/minivan occupants only in two-vehicle crashes, by crash partner vehicle type and crash configuration

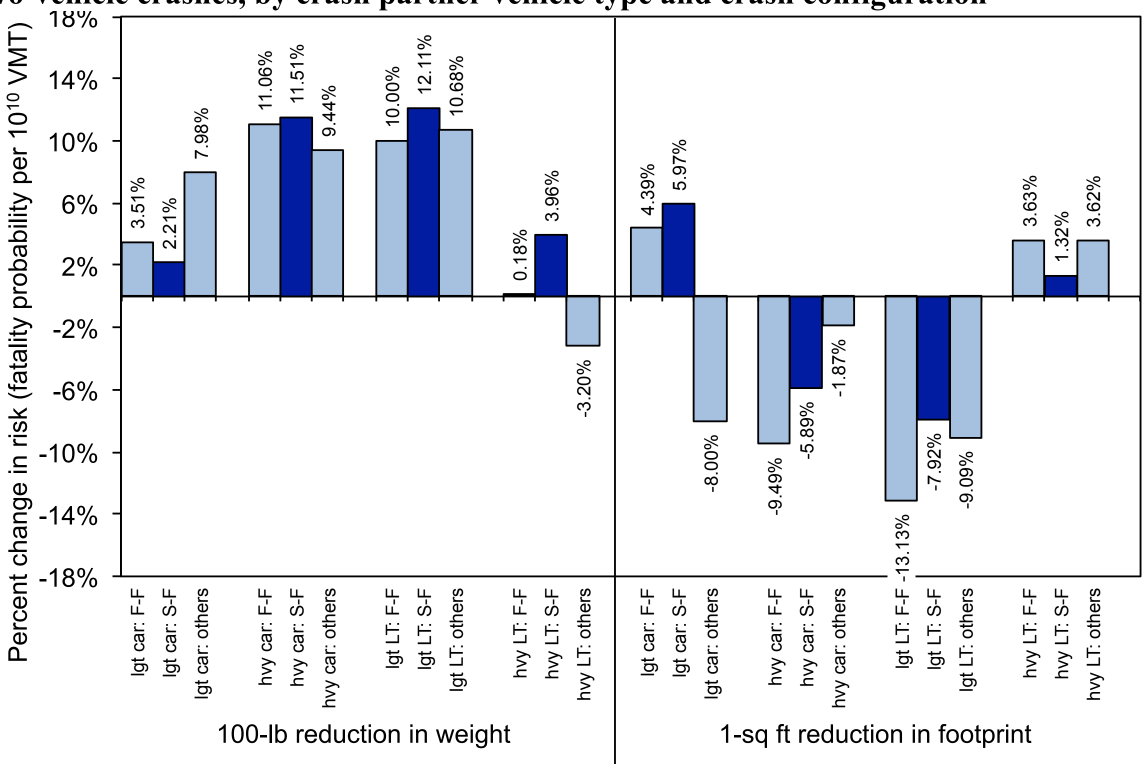
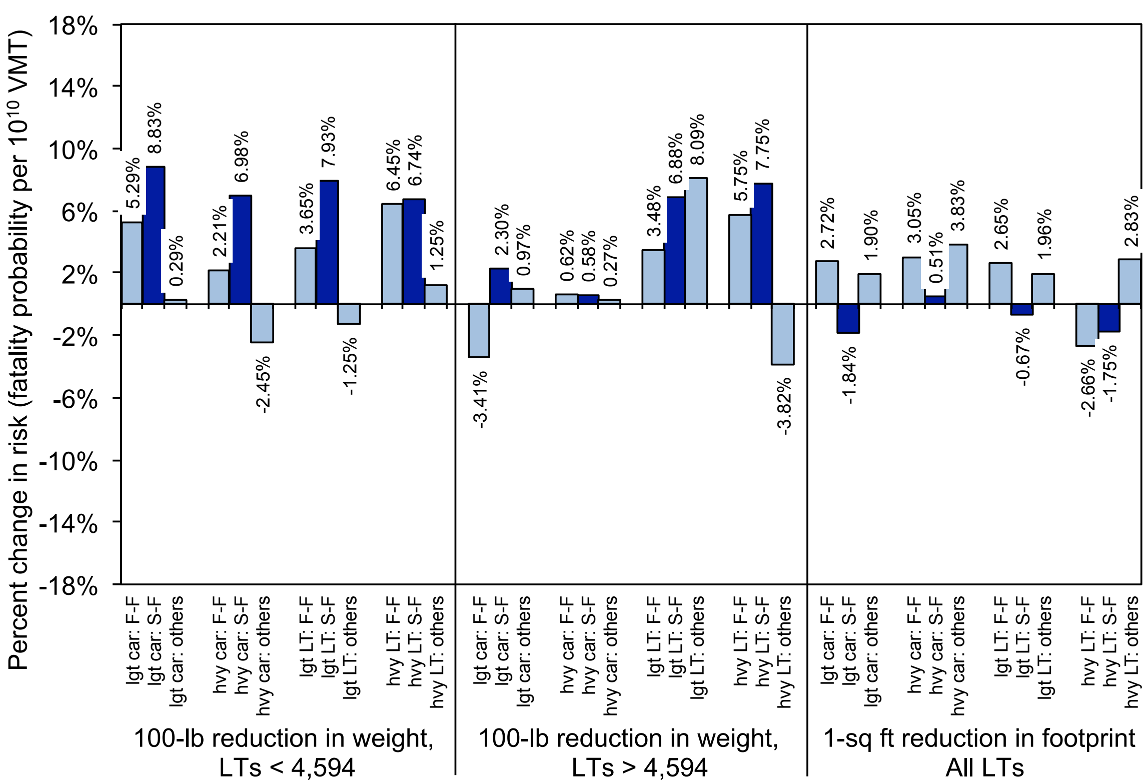


Figure 6.9. Estimated effect of mass reduction on risk to light truck occupants only in two-vehicle crashes, by crash partner vehicle type and crash configuration



6.3 Effect of measures to increase light truck compatibility

In 2003 manufacturers made a voluntary commitment to reduce the aggressivity of light trucks in crashes with other vehicles, by incorporating one of two designs in their new vehicles by MY10. The first is improving the overlap of light truck bumpers with those of other vehicles. The second is adding a secondary energy-absorbing structure (known as a "blocker beam") behind and below the bumper, so that it engages the bumper of the other vehicle.

Figure 6.10 indicates that about 30% to 50% of MY01 light trucks already met the increased bumper overlap guidelines; this percent has held fairly constant, but increased substantially in MY07. Fewer small pickups and SUVs used the blocker beam technology than bumper overlap in MY01, but use of the blocker beam has increased in the last few years, particularly in smaller pickup trucks.

Figure 6.11 shows the estimated effect of the two measures to improve light truck compatibility on risk to occupants of the crash partner vehicle, by crash partner vehicle type and crash configuration. The figure indicates that greater bumper overlap reduces fatality risk in the crash partner vehicle by 1% to 11% in frontal crashes, depending on the crash partner vehicle type; however, none of these reductions are statistically significant. On the other hand, greater bumper overlap reduces fatalities in cars struck in the side by a light truck, by a statistically-significant 15% (and has only a small reduction in fatalities when a light truck strikes another light truck in

Figure 6.10. Market penetration of compatibility measures in light trucks, by light truck type and model year

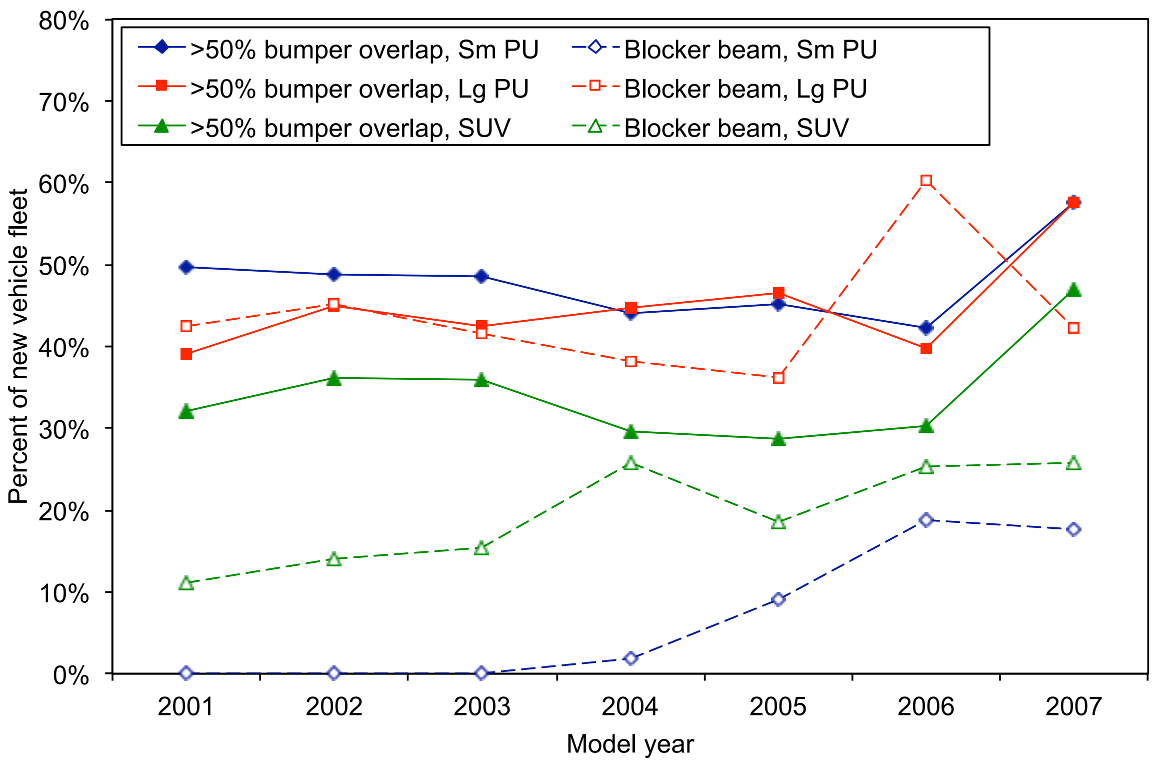
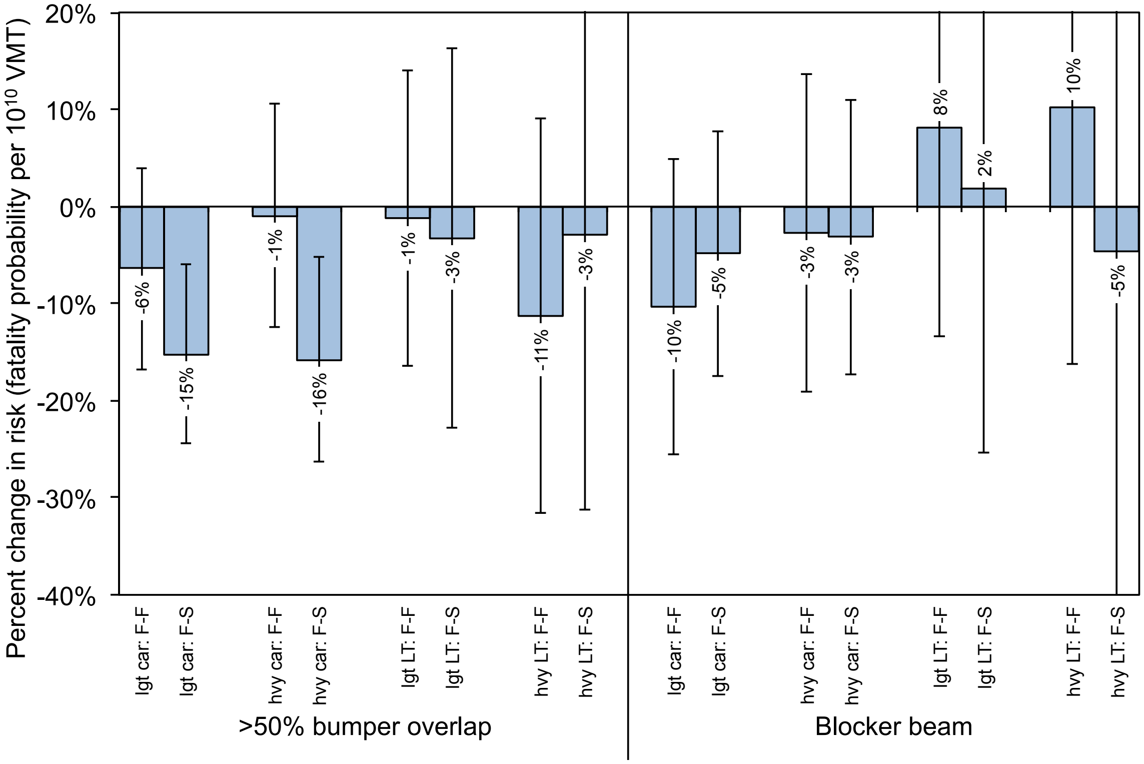


Figure 6.11. Effect of compatibility measures on risk imposed by light trucks on other light-duty vehicles, by crash partner vehicle type and crash configuration



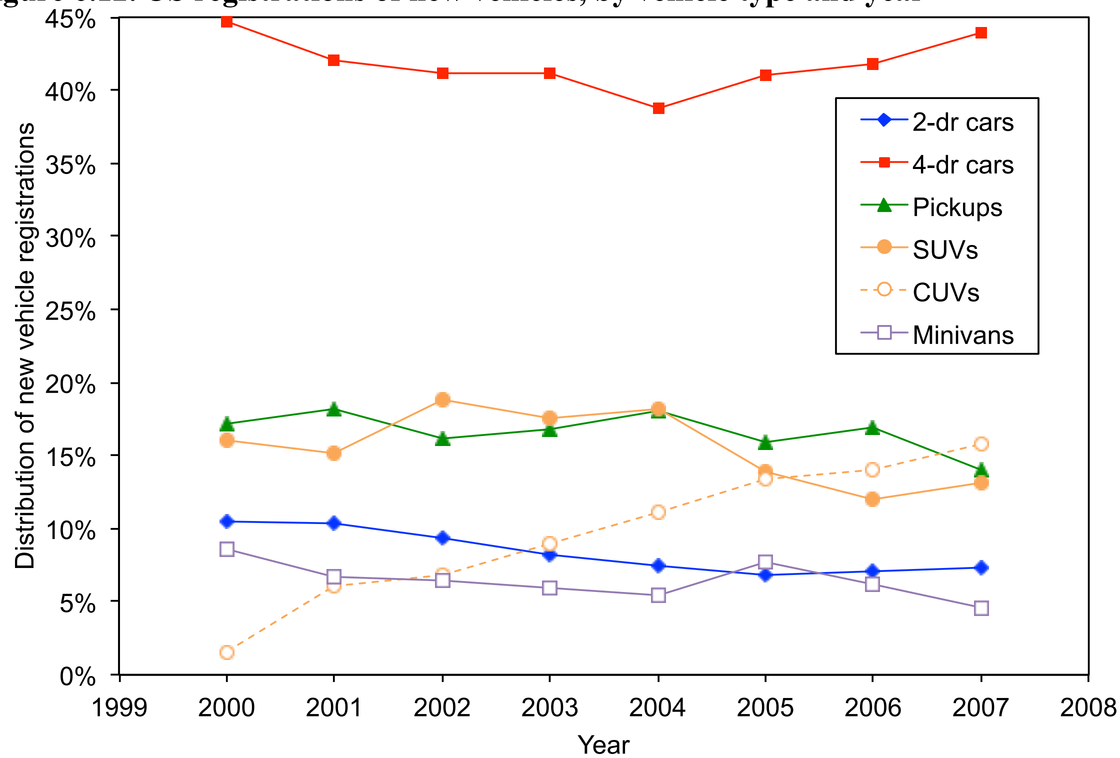
the side). The blocker beam technology tends to reduce fatality risk in cars struck in either the front or the side by a light truck, but none of the reductions are statistically significant.

Although better alignment of light truck bumpers with those of other vehicles appears to result in a statistically significant reduction in risk imposed on car occupants, the effect of mass reduction on risk to car occupants when struck in the side by light trucks is not consistently higher than in other types of two vehicle crashes, as shown in Figure 6.7 above. Therefore, by reducing the number of fatalities in crashes where light trucks strike cars in the side, full penetration of measures to improve light truck compatibility will likely have little impact on the effect of mass reduction on risk.

6.4 Effect of sales shift from SUVs and other light trucks to CUVs and other car-based vehicles

Figure 6.12 shows the rapid growth in market share of CUVs, from nearly zero in MY00 to over 15% of all new MY07 vehicle registrations (from Table 1-3 in the NHTSA 2012 report). At the same time the share of minivans decreased from 9% to 5%, and 2-door cars from 11% to 5%. Between MY01 and MY04 the advent of CUVs appears to have taken market share from 4-door cars (from 45% to 39%), while after MY04 the market share of SUVs and pickups declined (from a combined 36% to 26%). It is likely that the share of SUVs, and perhaps pickups, will decline further if gas prices remain high, as consumers continue to switch to more fuel-efficient CUVs and cars.

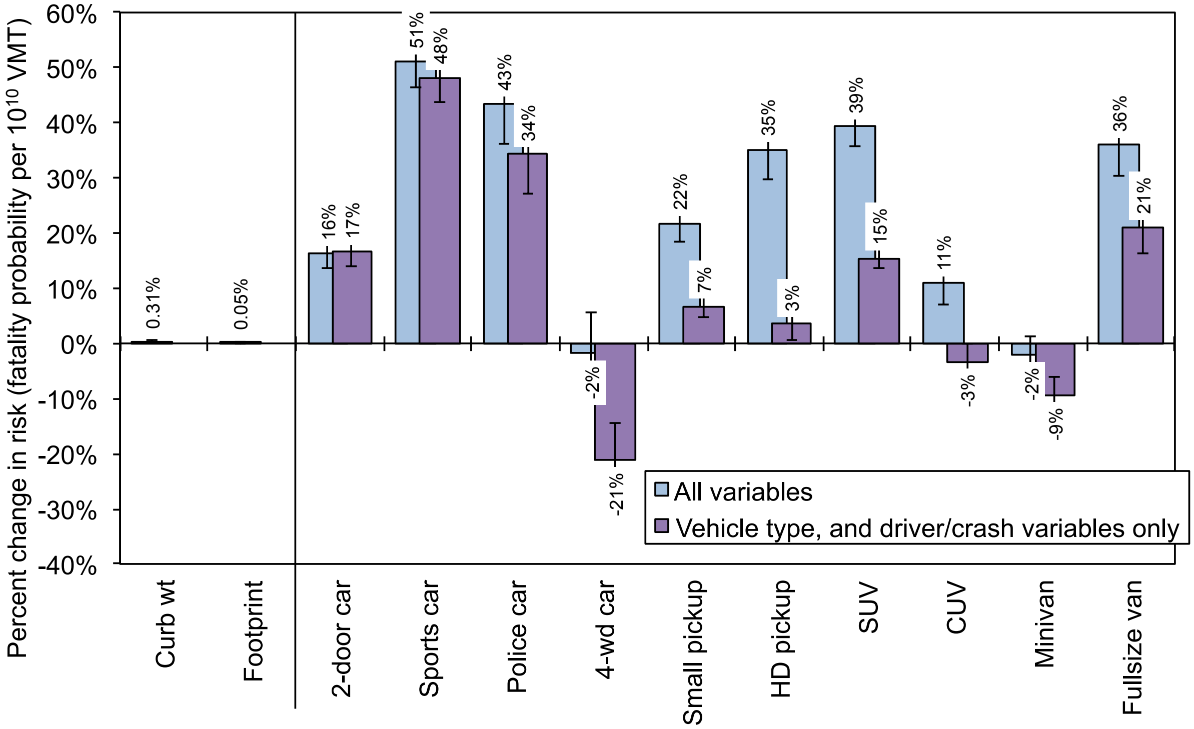
Figure 6.12. US registrations of new vehicles, by vehicle type and year



The effect of long-term shifts in the market shares among vehicle types can be estimated by examining the effect of the vehicle type control variables on fatality risk. Alternative regression models were run for the nine crash types, where all vehicle types, including sports, police, and all-wheel drive cars, and fullsize vans, were included in the same regression model for each crash type. The single variable LBS100 was used to account for vehicle curb weight, while all vehicle type variables and the four side airbag variables were included. To avoid double-counting, each fatal crash is weighted by the number of total fatalities in each crash divided by the number of case vehicles involved in each crash, so that the total number of fatalities in a given crash are evenly allocated to each of the case vehicles involved in the crash. The regression coefficients on mass, footprint, and vehicle type were then reweighted by the expected distribution of fatalities in 2017-2025, to reflect full adoption of ESC.

Using the results by crash type over all vehicle types, a 100-lb reduction in vehicle mass is associated with a statistically significant 0.31% increase in fatality risk, while a 1-square foot reduction in footprint is associated with a non-significant 0.05% increase in risk. Figure 6.13 compares these estimated effects of mass and footprint reduction on risk with those by vehicle type relative to risk in a four-door sedan. Compared to four-door sedans of the same mass and footprint, for a driver of the same age and gender, and for equal values on the other control variables such as urbanization and time of day, sports cars (51%), police cars (43%), SUVs (39%), fullsize vans (36%), heavy-duty pickups (36%), and other pickup trucks (22%) have much higher risk than four-door sedans (shown in light blue in Figure 6.13). Two-door sedans (16%) and CUVs (11%) have higher risk, while all-wheel drive cars and minivans have about the same risk as four-door sedans, after accounting for all differences in vehicles, drivers, and crash times and locations.

Figure 6.13. Effect of mass and footprint reductions across all vehicle types, and a comparison of fatality risk by vehicle type compared to four-door sedans



However, much of the additional risk in pickups relative to four-door sedans is due to who drives these vehicles and where they are driven. Table 6.1 shows the average driver (percent male, under age 30, and over age 70) and crash (at night, on rural roads, on high-speed roads, and in high fatality states) characteristics by vehicle type, for the induced-exposure cases weighted by national vehicle registration-year and miles traveled weights. Pickups have the highest fractions of male drivers, and are driven the most on rural, high-speed roads in high-fatality states. Therefore fatality risks by vehicle type need to account for driver and crash variables before estimating the effect of shifting the distribution from light trucks to other vehicle types. Figure 6.13 also shows the risk by vehicle type relative to that of a four-door sedan, after accounting for the driver and crash variables (in purple). Accounting for how and where vehicles are driven reduces the risk of light trucks relative to that of four-door sedans, so that the heavy-duty pickups have essentially the same risk as four-door sedans.

To simulate the effect of drivers switching from a relatively high-risk vehicle such as a light truck, to a lower risk vehicle such as a four-door sedan, we need to estimate the risk per ten billion VMT of light truck drivers in a four-door sedan. Table 6.2 shows estimated risks for each vehicle type, after accounting for all vehicle, driver, and crash time/location control variables used in NHTSA's preferred regression model (first column), and after moving the average driver of the case vehicle into one of four types of safer vehicles (last four columns). For example, heavy-duty pickups have a risk of 166 fatalities per ten billion VMT; if all the heavy-duty pickup drivers, who are overwhelmingly male and mostly drive on high-speed roads in rural counties in high-risk states, were to instead drive four-door sedans, their risk would be 161 fatalities per ten billion VMT (much higher than that of the typical car driver, 96). The incremental effect of heavy-duty pickup owners driving at the same times in the same locations, but in a car instead of a heavy-duty pickup, is only 5 fatalities per ten billion VMT (166 - 161), and not the difference between the risk of the average driver of a heavy-duty pickup and that of the average driver of a four-door sedan (70 fatalities per ten billion VMT, or 166 - 96). The initial risks of light truck drivers are shown in green in Table 6.2; the risks if those drivers instead drove a four-door sedan, all-wheel drive car, CUV, or minivan are shown in red in the table. We use the difference between the risks in green and the risks in red in Table 6.2 to simulate the effect of a fraction of drivers replacing their light trucks with safer cars, CUVs, and minivans.

Table 6.1. Average driver characteristics and crash times and locations, by vehicle type

	Driver characteristics			Crash times and locations			
Vehicle type	DRVMALE	AGE14_30	AGE70_96	NITE	RURAL	SPDLIM55	HIFAT_ST
2-dr cars	41%	55%	1.9%	22%	18%	15%	38%
4-dr sedans	42%	34%	7.2%	18%	19%	15%	39%
Sports cars	57%	46%	1.4%	23%	19%	16%	49%
Police cars	90%	31%	0.3%	38%	21%	13%	41%
AWD cars	48%	25%	4.6%	16%	14%	16%	20%
Small pickups	83%	26%	3.7%	16%	31%	20%	51%
Heavy-duty pickups	91%	20%	1.9%	13%	39%	26%	49%
SUVs	47%	26%	1.8%	18%	21%	17%	43%
CUVs	37%	21%	3.2%	16%	16%	17%	35%
Minivans	39%	13%	5.8%	14%	22%	16%	34%
Fullsize vans	85%	21%	2.0%	11%	16%	19%	35%
All	51%	30%	4.7%	17%	21%	17%	41%

In its 2003 report, NHTSA estimated the effect of a change in the mix of vehicle types on the number of fatalities (Section 5.7, page 220). We conduct a similar estimate here, based on the updated data on US fatalities and estimated vehicle miles traveled. Table 6.3 shows the number of fatalities in crashes involving case light-duty vehicles from model years 2000 through 2007, for the last five years of data available (between 2004 and 2008); the number of fatalities has been adjusted to account for full use of ESC by 2017. To avoid double-counting, the number of total fatalities in each crash is divided by the number of case vehicles involved in each crash, so that the total number of fatalities in a given crash are evenly allocated to each of the case vehicles involved in the crash.

Table 6.2. Actual risk per billion VMT, and risk adjusted to the average driver and crash time/location in a four-door sedan, all-wheel-drive car, CUV, and minivan, by vehicle type

Case vehicle type	Actual risk (per 10 billion VMT)	Adjusted risk after moving the average driver and crash location/time of the case vehicle into a: 4-door sedan	AWD car	CUV	Minivan
2-dr cars	117	101	79	97	91
4-dr sedans	96	96	76	93	87
Sports cars	168	114	90	110	103
Police cars	174	129	102	125	117
AWD cars	62	78	62	76	71
Small pickups	142	133	105	129	121
Heavy-duty pickups	166	161	127	156	146
SUVs	109	95	75	92	86
CUVs	72	74	59	72	67
Minivans	79	87	69	84	79
Fullsize vans	108	89	70	86	81

Tables 6.2 and 6.3 can be used to estimate how the number of fatalities involving model year 2000 to 2007 vehicles would be changed by shifting VMT among the vehicle types, while maintaining the average driver and crash time/location characteristics of the original vehicle types. For example, moving SUV drivers into CUVs, while maintaining the driver characteristics and driving times and locations of the SUVs, would reduce the fatality risk from 109 to 92 fatalities per ten billion VMT. Table 6.4 shows the results from three scenarios of shifting market share: replacing 10% of SUVs with CUVs, replacing 10% of small pickups with CUVs, and replacing 10% of large SUVs with SUVs. The last scenario shown in Table 6.4 simulates an aggressive shift in vehicle market share: replacing 80% of SUVs (50% with CUVs, 20% with minivans, and 10% with AWD cars); replacing 80% of small pickups (60% with CUVs, and 20% with four-door cars); and replacing 50% of large pickups (25% with CUVs and 25% with minivans). This aggressive shift in market share would reduce fatalities of model year 2000 to 2007 vehicles by 2,411, resulting in a 3.3% reduction in fatalities.

Although the reductions in fatalities from shifting light truck drivers into safer, car-based vehicles are small in percentage terms, they are larger than the mass reduction scenarios NHTSA simulated in its 2012 report (Section 3.6, Table 3-8). The four mass reduction scenarios NHTSA simulated, including the effect of reducing mass of all vehicles by 100 lbs, all result in less than a 0.5% change in fatalities. Even an aggressive mass reduction scenario, in which the mass of lighter and heavier light trucks are reduced 1,351 and 1,872 lbs, respectively, to the average mass of lighter and heavier cars, would reduce fatalities by only 0.5%. Therefore, shifts in market share from more dangerous vehicles such as light trucks to safer car-based vehicles would result in much larger reductions in fatalities than the small changes in fatalities expected from even substantial reductions in vehicle mass.

Table 6.3. Total fatalities and VMT in model year 2000 to 2007 light-duty vehicles between 2004 and 2008, by vehicle type

Vehicle type	Fatalities	VMT (billion)
2-dr cars	5,195	446
4-dr sedans	26,001	2,749
Sports cars	1,528	93
Police cars	644	39
AWD cars	737	120
Small pickups	12,326	897
Heavy-duty pickups	4,344	276
SUVs	12,439	1,159
CUVs	4,111	578
Minivans	3,583	462
Fullsize vans	1,421	141
Total	72,329	6,961

Table 6.4. Estimated change in annual fatalities from four scenarios of shifts among vehicle types

Scenario	Decrease in fatalities	Percent change in fatalities
1. Replace 10% of SUVs with CUVs	-183	-0.3%
2. Replace 10% of small pickups with CUVs	-75	-0.1%
3. Replace 10% of large pickups with minivans	-32	0.0%
4. Replace 80% of SUVs and small pickups, and 50% of heavy-duty pickups	-2,411	-3.3%

7. Conclusions

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). The new study updates the previous analyses in several ways: updated FARS data from 2002 to 2008 for 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.

Using the updated databases, NHTSA estimates that reducing vehicle mass by 100 lbs while holding footprint fixed would increase fatality risk per VMT by 1.55% for lighter-than-average cars, 0.51% for heavier-than-average cars, and 0.52% for lighter-than-average light-duty trucks, but reduce risk by 0.34% for heavier-than-average light-duty trucks and by 0.38% for CUVs/minivans. NHTSA found that only the estimated effect of mass reduction on lighter than average cars is statistically significant. NHTSA concludes that, when footprint is held fixed, "no judicious combination of mass reductions in the various classes of vehicles results in a statistically significant fatality increase and many potential combinations are safety-neutral as point estimates".

The effect of mass reduction on risk that NHTSA estimated in 2012 is much smaller than in its 2003 and 2010 studies, particularly for cars. NHTSA attributes this reduction in the importance of mass reduction on safety to the phase-out of relatively light cars that had unusually high fatality risk, an observed improvement in how light, small cars are driven which reduces their tendency to be involved in serious crashes, and voluntary improvements made to light trucks to improve their compatibility with other vehicles. The 2012 NHTSA analysis estimates that reducing vehicle footprint by one square foot while holding mass fixed would increase fatality risk per VMT by 1.87% in cars and 1.72% in CUVs and minivans (the effect on risk in light trucks is small and not statistically significant).

This report replicates the 2012 NHTSA analysis, and reproduces their main results. This report uses the confidence intervals output by the logistic regression models, which are smaller than the intervals NHTSA estimated using a jack-knife technique that accounts for the sampling error in the FARS fatality and state crash data. As a result, in its report NHTSA finds that only the 1.55% estimated increase in risk from mass reduction in lighter-than-average cars is statistically significant. In addition to reproducing the NHTSA results, this report also examines the NHTSA data in slightly different ways to get a deeper understanding of the relationship between vehicle weight, footprint, and safety. This final report incorporates revisions from the preliminary report released in November 2011, including revised estimates of national weights for vehicle miles traveled, inclusion of 2008 police-reported crash data from eight additional states, and responses to reviewers' comments.

The results of these alternative analyses are summarized in Tables 7.1 and 7.2; statistically significant estimates, based on the confidence intervals output by the logistic regression models, are shown in red in the tables. In particular, we found that:

- NHTSA's (reasonable) assumption that all vehicles will have ESC installed by 2017 slightly increases the estimated detrimental effect of mass reduction, but slightly decreases the estimated detrimental effect of footprint reduction, on risk in cars, CUVs and minivans (Alternative 1 in Table 7.1; explained in more detail in Section 2.1 of this report). This is because NHTSA projects ESC to substantially reduce the number of fatalities in rollovers and crashes with stationary objects, and mass reduction appears to reduce risk, while footprint reduction appears to increase risk, in these types of crashes, particularly in cars and CUVs/minivans. A single regression model including all crash types results in slightly different estimates of the relationship between decreasing mass and risk, as shown in Alternative 2 in Table 7.1.

- Many of the control variables NHTSA includes in its logistic regressions are statistically significant, and have a much larger estimated effect on fatality risk than vehicle mass. For example, installing torso side airbags, electronic stability control, or an automated braking system in a car is estimated to reduce fatality risk by about 10%; cars driven by men are estimated to have a 40% higher fatality risk than cars driven by women; and cars driven at night, on rural roads, or on roads with a speed limit higher than 55 mph are estimated to have a fatality risk over 100 times higher than cars driven during the daytime on low-speed non-rural roads. While the estimated 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.

Table 7.1. Estimated effect of mass or footprint reduction on US fatality risk per VMT, under alternative regression model specifications

Variable	Case vehicle type	NHTSA preferred model (fatalities per VMT)	1. Weighted by current distribution of fatalities	2. Single regression model for all crash types	3. Excluding footprint or weight	4. Fatal crashes per VMT	5. Fatalities per induced exposure crash	6. Fatalities per registered vehicle-year
Mass reduction	Cars < 3106 lbs	1.55%*	1.27%	1.26%	2.74%	1.95%	-0.22%	0.93%
	Cars > 3106 lbs	0.51%	0.37%	0.35%	1.95%	0.89%	-1.45%	2.40%
	LTs < 4594 lbs	0.52%	0.42%	0.41%	0.47%	0.54%	-1.13%	-0.09%
	LTs > 4594 lbs	-0.34%	-0.36%	-0.42%	-0.39%	-0.42%	-0.76%	-0.76%
	CUV/ minivan	-0.38%	-0.70%	-0.74%	0.60%	-0.47%	-0.84%	-0.40%
Footprint reduction	Cars	1.87%	2.16%	2.28%	2.98%	1.83%	2.28%	0.32%
	LTs	-0.07%	0.14%	0.22%	0.07%	0.14%	-1.30%	-0.08%
	CUV/ minivan	1.72%	2.25%	2.26%	1.33%	1.79%	2.18%	0.03%

* 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.
Estimates that are statistically significant at the 95% level are shown in red.

• Vehicle mass and footprint are correlated, but only strongly for passenger cars. NHTSA includes both variables in their regression models, introducing the possibility that multi-collinearity may create biased results. When footprint is allowed to vary along with weight (i.e. the regression model accounts for weight but not footprint), mass reduction results in a larger estimated increase in risk for cars and CUVs/minivans than when footprint is held constant. Similarly, when mass is allowed to vary along with footprint, footprint reduction results in a larger estimated increases in risk for cars, but a smaller estimated increase in risk for CUVs and minivans (Alternative 3 in Table 7.1, further addressed in Section 3 of this report). To isolate the effect of mass reduction from footprint reduction on risk, NHTSA estimates the effect of mass reduction on risk for deciles of vehicles with similar footprint. Mass reduction does not consistently increase risk across all footprint deciles for any combination of vehicle type and crash type. Risk increases with decreasing mass in a majority of footprint deciles for 12 of the 27 crash and vehicle combinations, but few of these increases are statistically significant. On the other hand, risk decreases with decreasing mass in a majority of footprint deciles for 5 of the 27 crash and vehicle combinations; in some cases these risk reductions are large and statistically significant.

• Logistic regression methods do not have a statistic, such as the model R^2 in a linear regression model, to measure how much variability in risk by vehicle model is explained by the control variables included in the model. Analysis of pseudo-R^2 and R^2 from a linear regression model suggests that much of the variation in risk remains unexplained, even after accounting for many important vehicle, driver, and crash variables. After accounting for all of the variables in NHTSA's logistic regression model, except for vehicle mass and footprint, we find that the correlation between estimated fatality risk by vehicle model and mass is very low. There also is no significant correlation between the residual, unexplained risk and vehicle weight. These results indicate that, even after accounting for many vehicle, driver, and crash factors, the variation in risk by vehicle model is quite large and unrelated to vehicle weight (addressed in more detail in Section 4). The large remaining unexplained variation in risk by vehicle model could be attributable to other differences in vehicle design, or how drivers who select certain vehicles drive them. It is possible that including variables that account for these factors in the regression models would change the estimated relationship between mass or footprint and risk.

• NHTSA's estimates are sensitive to the definition of risk used in its regression models. Calculating risk as fatal crashes, rather than total fatalities, per vehicle mile traveled, as suggested by one of the independent reviewers of the previous NHTSA reports, increases the estimated detrimental effect of mass reduction on risk in cars, but has no effect on mass reduction in light trucks or CUVs/minivans, or on footprint reduction in any vehicle type (Alternative 4 in Table 7.1). Calculating risk as total fatalities per induced exposure crash, rather than per vehicle mile traveled, reverses the sign of the estimated effect of mass reductions on risk in cars and the lighter light trucks, with mass reduction leading to an estimated reduction in risk in all vehicle types. Footprint reduction continues to result in large estimated increases in risk per induced exposure crash for cars and CUVs/minivans, but leads to a large estimated reduction in fatality risk per induced exposure crash for light trucks (Alternative 5 in Table 7.1). Calculating risk per registered vehicle-year, rather than per mile driven, substantially reduces the estimated effect of mass reduction on risk for lighter cars and lighter light trucks, but substantially increases the estimated effect on risk for heaver cars (Alternative 6 in Table 7.1; further addressed in Section 5.1).

- NHTSA's estimates are sensitive to changes in the data and variables used in its regression models, as shown in Table 7.2. Adding control variables for vehicle manufacturer tends to increase the estimated effect of mass reduction, but decrease the estimated effect of footprint reduction, on risk for cars and light trucks, and estimates that mass reduction becomes substantially detrimental, and footprint reduction beneficial, for CUVs/minivans (Alternative 7 in Table 7.2; further addressed in Section 5.2). Adding control variables for five luxury brands (Cadillac, Lincoln, Acura, Infiniti and Lexus) magnifies these changes in the estimated effects for cars (Alternative 8 in Table 7.2).

- An alternative to control variables for vehicle manufacturers is a single continuous variable for the vehicle's initial purchase price; purchase price may better account for other differences in vehicle design that may influence traffic safety. Adding this single variable to NHTSA's regression models substantially increases the estimated increase in risk from mass reduction of heavier-than-average cars, slightly lowers the estimated increase in risk in lighter cars and lighter trucks; and substantially increases the estimated beneficial effect from mass reduction in heavier light trucks and CUVs/minivans. Accounting for vehicle purchase price increases the estimated beneficial effect of footprint reduction in light trucks, but has little impact on the estimated detrimental effects of footprint reduction in cars or CUVs/minivans (Alternative 9 in Table 7.2; further addressed in Section 5.2).

- NHTSA included control variables for the calendar year in which the crash occurred, to reflect reducing risk from changes to vehicles, driver behavior and driving conditions over time. However, including these calendar year variables in the regression models appear to weaken the estimated benefit of curtain side air bags in cars, CUVs, and minivans, and compatibility measures and ESC in light trucks. These variables also appear to minimize the estimated increased risk of SUVs and heavy-duty pickup trucks. Excluding these calendar year variables from the regression models increases the estimated detrimental effect of mass reduction on risk in light trucks (Alternative 10 in Table 7.2, addressed in Section 5.3).

- Because details on the driver's condition or behavior are not consistently reported in the state crash data used to develop the induced exposure cases and VMT weights, it is not possible to control for individual drivers' behavior in the regression model. However, excluding crashes involving alcohol or drugs, or drivers with poor driving records, increases the estimated detrimental effect of mass reduction on risk, but reduces the estimated detrimental effect of footprint reduction on risk (Alternatives 11 and 12 in Table 7.2, Section 5.4). One possible surrogate for the behavior of drivers who tend to select certain vehicle models is driver household income. Including a measure of household income by vehicle model reduces the estimated detrimental effect of mass reduction on risk in cars, but has little effect on the association of mass with risk in trucks or CUVs/minivans (Alternative 13 in Table 7.2). Including all-wheel-drive, sports, and police cars increases the estimated effect of mass reduction, but reduces the estimated effect of footprint reduction, on risk for cars; while including fullsize vans reduces the estimated effect of mass reduction, and increases the estimated effect of footprint reduction, on risk for light trucks (Alternative 14 in Table 7.2, Section 5.5).

- As mentioned above, for its baseline fatalities NHTSA assumes that all new vehicles will have ESC installed by 2017, which will reduce the fraction of fatalities in rollovers and crashes with stationary objects, and thus will increase the estimated detrimental overall effect of mass reduction, but decrease the estimated detrimental overall effect of footprint reduction, on risk. However, other recent trends that are likely to continue through 2017 may also affect the distribution of crashes in that year. For example, side airbags in cars will likely reduce the fraction of fatalities in side-impact crashes (Section 6.1), and better alignment of light truck bumpers with those of other vehicles appears to reduce the risk imposed on car occupants, at least in side impact crashes (Section 6.2). However, it appears that mass reduction has less of an estimated detrimental effect on risk when cars are struck in the side than when they are involved in frontal or rear-end crashes, so any future reduction in fatalities in car side impact crashes will not necessarily influence the relationship between mass and risk. And it is not clear whether full adoption of side airbags or compatibility measures for light trucks will reduce fatality risk when light-duty trucks, CUVs or minivans are struck in the side.

Table 7.2. Estimated effect of mass or footprint reduction on US fatality risk per VMT, excluding certain data or using different control variables

Variable	Case vehicle type	NHTSA preferred model (fatalities per VMT)	7. Accounting for vehicle manufacturer	8.Accounting for vehicle manufacturer plus five luxury brands	9. Accounting for initial vehicle purchase price	10. Excluding CY variables	11. Excluding crashes with alcohol/drugs	12. Excluding. bad drivers	13. Accounting for median household income	14. Including sports, squad, AWD cars and fullsize vans
Mass reduction	Cars < 3106 lbs	1.55%*	1.90%	2.04%	1.42%	1.52%	1.88%	2.32%	1.20%	1.79%
	Cars > 3106 lbs	0.51%	0.75%	1.80%	0.84%	0.43%	0.88%	1.19%	0.16%	0.49%
	LTs < 4594 lbs	0.52%	0.59%	0.57%	0.45%	1.20%	0.78%	1.01%	0.68%	0.49%
	LTs > 4594 lbs	-0.34%	-0.11%	-0.11%	-0.52%	0.30%	-0.35%	-0.11%	-0.30%	-0.77%
	CUV/ minivan	-0.38%	1.62%	1.28%	-0.92%	0.03%	-0.16%	-0.01%	-0.44%	-0.38%
Footprint reduction	Cars	1.87%	1.71%	1.20%	1.99%	2.11%	1.65%	1.32%	2.30%	1.64%
	LTs	-0.07%	-0.29%	-0.28%	-0.36%	-0.42%	-0.26%	-0.39%	-0.19%	-0.02%
	CUV/ minivan	1.72%	-0.77%	-0.28%	1.57%	1.61%	1.36%	1.12%	1.82%	1.72%

* 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.
Estimates that are statistically significant at the 95% level are shown in red.

- Finally, in part because of high gas prices and the poor economy, households have been purchasing smaller and lighter vehicles in the last decade. For example, the explosion of CUVs appears to have led to a reduction in the market share of minivans, cars, and in recent years (MY05 to MY07) SUVs and pickups. It is likely that these trends would continue, even in the absence of stronger CAFE and GHG emission standards. Any future market shifts from SUVs or pickups to cars or car-based CUVs and minivans will result in much larger reductions in fatality risk than the relatively small increases in risk expected from mass or footprint reduction. For example, we estimate that a large-scale shift in the market share of pickups and SUVs to CUVs, minivans, and cars will reduce overall fatalities by over 3% (Section 6.3).

Table 7.3 shows the results of additional sensitivity tests NHTSA conducted in response to comments from the peer reviewers of its preliminary 2012 report. Alternative 15 in Table 7.3 indicates that using only stopped vehicles, and not all vehicles judged to be not-at-fault in two-vehicle crashes, substantially reduces the estimated detrimental effect of mass reduction on risk in all types of vehicles, while substantially increasing the estimated detrimental effect of footprint reduction on risk in cars. Replacing vehicle footprint with its two components, track width and wheelbase, similarly reduces the estimated detrimental effect of mass reduction, as shown in Alternative 16; an increase in risk is associated with decreasing track width in cars and light trucks, but with decreasing wheelbase in CUVs/minivans. Alternative 17 indicates that combining these two sensitivities, i.e. using stopped vehicles as the measure of exposure and replacing footprint with track width and wheelbase, further reduces the estimated detrimental effect of mass reduction, such that fatality risk is estimated to increase in light cars by a statistically non-significant 0.26%. Weighting the distribution of fatalities in CUVs and minivans by their respective shares of sales in 2010 (which reflects more CUVs and fewer minivans) causes the estimated effects to change signs, with decreasing mass now associated with an estimated increase in risk, and decreasing footprint with an estimated reduction in risk,

Table 7.3. Estimated effect of mass or footprint reduction on US fatality risk per VMT, under alternative regression model specifications suggested by NHTSA peer reviewers

Variable	Case vehicle type	NHTSA preferred model (fatalities per VMT)	15. Using stopped instead of non-culpable vehicles for induced exposure	16. Including track width and wheelbase instead of footprint	17. Using stopped vehicles and track width/wheelbase	18. Reweighting CUVs and minivans by 2010 sales	19. Excluding non-significant control variables
Mass reduction	Cars < 3106 lbs	1.55%*	0.97%	0.95%	0.26%	1.55%	1.63%
	Cars > 3106 lbs	0.51%	-0.63%	0.24%	-0.90%	0.51%	0.69%
	LTs < 4594 lbs	0.52%	0.35%	-0.07%	-0.10%	0.52%	0.35%
	LTs > 4594 lbs	-0.34%	-0.80%	-0.58%	-0.97%	-0.34%	-0.54%
	CUV/ minivan	-0.38%	-0.33%	-0.25%	-0.14%	0.55%	-0.46%
Footprint reduction	Cars	1.87%	3.43%	—	—	1.87%	1.73%
	LTs	-0.07%	-0.03%	—	—	-0.07%	0.11%
	CUV/ minivan	1.72%	1.81%	—	—	-0.61%	1.97%
Track width reduction	Cars	—	—	4.36%	6.03%	—	—
	LTs	—	—	1.07%	0.90%	—	—
	CUV/ minivan	—	—	0.08%	-0.55%	—	—
Wheel base reduction	Cars	—	—	-0.09%	0.38%	—	—
	LTs	—	—	-0.09%	-0.09%	—	—
	CUV/ minivan	—	—	1.16%	1.45%	—	—

* 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.

for CUVs and minivans (Alternative 18). Alternative 19 removes non-significant control variables from each of the regression models; the result is slightly larger estimated detrimental effects of reduced mass in cars, and slightly smaller estimated effects in light trucks.

Table 7.4 compares the results from NHTSA's 2003, 2010, and 2012 analyses with the alternative model specifications examined in this report (again, results that are statistically significant are shown in red in the table). The first two columns of the table indicate that NHTSA's 2012 analysis of a simultaneous reduction in mass and footprint (i.e. excluding a control variable for footprint in the regression model) results in a smaller estimated increase in fatalities than in NHTSA's 2003 analysis, particularly for lighter cars (a 2.74% increase rather than a 4.39% increase) and light trucks (a 0.47% increase rather than a 2.90% increase). The third and fourth columns of the table indicate a similar reduction in estimated additional fatalities for cars when footprint is held constant (i.e. when a control variable for footprint is included in the regression model). However, holding footprint constant increases the estimated effect of mass reduction slightly in light trucks (a 0.52% increase rather than a 0.17% increase in fatalities for lighter light trucks, and a 0.34% reduction rather than a 1.90% reduction in fatalities for the heavier light trucks). This small estimated increase in light truck risk may be due to NHTSA analyzing crossover utility vehicles and minivans as a separate vehicle class, rather than as light trucks, in the 2012 analysis.

The last column in Table 7.4 shows that the results of the alternative model specifications examined in this report are, in nearly all cases, lower than the results of the 2003 NHTSA report, and often lower than the results of the 2010 and 2012 analyses.

Table 7.4. Previous NHTSA results of the estimated effect of mass and footprint reduction on US fatality risk per VMT, compared with different scenarios analyzed in this report

Variable	Case vehicle type	NHTSA (2003) excluding footprint	NHTSA (2012) excluding footprint	NHTSA (2010) including footprint	NHTSA (2012) including footprint	Range of different scenarios analyzed in this report
Mass reduction	Cars < 3106 lbs	4.39%	2.74%	2.21%	1.55%	-0.22% to 2.74%
	Cars > 3106 lbs	1.98%	1.95%	0.89%	0.51%	-1.45% to 2.40%
	LTs < 4594 lbs	2.90%	0.47%	0.17%	0.52%	-1.13% to 1.20%
	LTs > 4594 lbs	0.48%	-0.39%	-1.90%	-0.34%	-0.97% to 0.30%
	CUV/ minivan	—	0.60%	—	-0.38%	-0.92% to 1.62%
Footprint reduction	Cars	—	—	—	1.87%	-0.09% to 3.43%
	LTs	—	—	—	-0.07%	-1.30% to 0.22%
	CUV/ minivan	—	—	—	1.72%	-0.77% to 2.26%

The 2012 NHTSA study, and this report, conclude that the estimated effect of mass reduction while maintaining footprint on societal US fatality risk is small, and statistically non-significant for all but the lightest cars. This report indicates that although the estimated effects are sensitive to what variables and data are included in the regression analysis, in nearly all cases the effects are less, in some cases dramatically less, than reported in the 2003 NHTSA study. This report also finds that the estimated effects of 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, on risk are much larger, in some cases two orders of magnitude larger, than the estimated effect of mass or footprint reduction on risk. Finally, this report shows that after accounting for the many vehicle, driver, and crash variables NHTSA used in its regression analyses, there remains a wide variation in risk by vehicle make and model, and this variation is unrelated to vehicle mass.

Although the purpose of the NHTSA and LBNL reports is to estimate the effect of vehicle mass reduction on societal risk, this is not exactly what the regression models are estimating. Rather, they are estimating the recent historical relationship between mass and risk, after accounting for most measurable differences between vehicles, drivers, and crash times and locations. In essence, the regression models are comparing the risk of a 2600-lb Dodge Neon with that of a 2500-lb Honda Civic, after attempting to account for all other differences between the two vehicles. The models are not estimating the effect of literally removing 100 lbs from the Neon, leaving everything else unchanged.

In addition, the analyses 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. Therefore, throughout this report we use the phrase "the estimated effect of mass (or footprint) reduction on risk" as shorthand for "the estimated change in risk as a function of its relationship to mass (or footprint) for vehicle models of recent design."
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). The new study updates the previous analyses in several ways: updated FARS data from 2002 to 2008 for 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.

Using the updated databases, NHTSA estimates that reducing vehicle mass by 100 lbs while holding footprint fixed would increase fatality risk per VMT by 1.55% for lighter-than-average cars, 0.51% for heavier-than-average cars, and 0.52% for lighter-than-average light-duty trucks, but reduce risk by 0.34% for heavier-than-average light-duty trucks and by 0.38% for CUVs/minivans. NHTSA found that only the estimated effect of mass reduction on lighter than average cars is statistically significant. NHTSA concludes that, when footprint is held fixed, "no judicious combination of mass reductions in the various classes of vehicles results in a statistically significant fatality increase and many potential combinations are safety-neutral as point estimates".

The effect of mass reduction on risk that NHTSA estimated in 2012 is much smaller than in its 2003 and 2010 studies, particularly for cars. NHTSA attributes this reduction in the importance of mass reduction on safety to the phase-out of relatively light cars that had unusually high fatality risk, an observed improvement in how light, small cars are driven which reduces their tendency to be involved in serious crashes, and voluntary improvements made to light trucks to improve their compatibility with other vehicles. The 2012 NHTSA analysis estimates that reducing vehicle footprint by one square foot while holding mass fixed would increase fatality risk per VMT by 1.87% in cars and 1.72% in CUVs and minivans (the effect on risk in light trucks is small and not statistically significant).

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