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Assessment of NHTSA's Report "Relationships Between Fatality Risk, Mass, and Footprint in Model Year 2004-2011 Passenger Cars and LTVs" (LBNL Phase 1)

Author

Wenzel, TP

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Assessment of NHTSA's Report "Relationships Between Fatality Risk, Mass, and Footprint in Model Year 2004-2011 Passenger Cars and LTVs" (LBNL Phase 1)

Prepared for the Office of Energy Efficiency and Renewable Energy,
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Tom Wenzel
Energy Technologies Area
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

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Executive Summary

The Department of Energy's (DOE) Vehicle Technologies Office funds research on development of technologies to improve the fuel economy of both light- and heavy-duty vehicles, including advanced combustion systems, improved batteries and electric drive systems, and new lightweight materials. Of these approaches to increase fuel economy and reduce fuel consumption, reducing vehicle mass through more extensive use of strong lightweight materials is perhaps the easiest and least expensive method; however, there is a concern that reducing vehicle mass may lead to more fatalities.

The relationship between vehicle mass and safety has been debated for many years. This debate has become more relevant with the advent of much more stringent federal fuel economy and greenhouse gas emission standards for new light-duty vehicles. The model year 2017 to 2025 standards are based on the footprint (wheelbase times track width) of each vehicle, with more stringent standards for smaller vehicles; the intent is to encourage manufacturers to make vehicles lighter to meet the standards while maintaining size, without compromising safety.

Lawrence Berkeley National Laboratory (LBNL) has conducted several analyses to better understand the relationship between vehicle mass, size and safety, in order to ameliorate concerns that down-weighting vehicles will inherently lead to more fatalities. These analyses include recreating the regression analyses conducted by the National Highway Traffic Safety Administration (NHTSA) that estimate the relationship between mass reduction and U.S. societal fatality risk per vehicle mile of travel (VMT), while holding vehicle size (i.e. footprint, wheelbase times track width) constant; this particular analysis is referred to as the LBNL Phase 1 analysis.

NHTSA recently completed a logistic regression analysis updating its earlier studies of the relationship between vehicle mass and U.S. societal fatality risk per vehicle mile of travel (VMT; Kahane 2010, Kahane 2012, Puckett and Kindelberger 2016). Societal fatality risk considers fatalities in both the case vehicle and any crash partner, including pedestrians, cyclists, and heavy-duty vehicles. The new study updates the 2016 analysis using NHTSA's Fatality Analysis Reporting System (FARS) data from 2006 to 2012 for model year 2004 to 2011 vehicles. Using the updated databases, NHTSA estimates that reducing vehicle mass by 100 pounds while holding footprint fixed would increase fatality risk per VMT by 1.20% for lighter-than-average cars, by 0.42% for heavier-than-average cars, and by 0.31% for lighter-than-average light trucks, but reduce risk by 0.61% for heavier-than-average light-duty trucks, and by 0.25% for CUVs/minivans. Using a jack knife method to estimate the statistical uncertainty of these point estimates, NHTSA finds that none of these estimates are statistically significant at either the 95% or 90% confidence level. NHTSA's updated estimates of the effect of mass reduction in cars on risk are less detrimental than in its 2016 study; however, the 2018 estimates are more detrimental in lighter-than-average light trucks and less beneficial in heavier-than-average light trucks and, especially, CUVs and minivans. It appears that the 2016 study overestimated the benefits of mass reduction in lighter light trucks and CUVs/minivans, and to a lesser extent in heavier light trucks. This overestimation is likely due to some CUVs being misidentified as SUVs in the 2016 study, differences in the odometer adjustment factors by vehicle model NHTSA used in the 2016 and current study, and the introduction of new CUV models in model year 2011 in the current study.

The current NHTSA analysis estimates that reducing vehicle footprint by one square foot while holding mass constant would increase fatality risk per VMT by 0.23% in cars, by 0.08% in light trucks, and by 0.52% in CUVs and minivans, none of which is statistically significant.

This report replicates the NHTSA update of the 2016 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. 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. The results of the NHTSA baseline results, and these alternative analyses, are summarized in Table ES.1; statistically significant estimates, based on the confidence intervals output by the logistic regression models, are shown in red in the tables. We found that NHTSA's reasonable assumption that all vehicles will have ESC installed by 2017 in its baseline regression model slightly increases the estimated increase in risk from mass reduction in cars, slightly decreases the estimated increase in lighter light trucks, has no effect on heavier light trucks, and slightly reduces the beneficial effect from mass reduction in CUVs/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 (Alternative 2) results in essentially the same estimates of the relationship between mass and risk as Alternative 1 in Table ES.1.

<u>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</u>. For example, installing torso side airbags, electronic stability control, or an assisted braking system in a car is estimated to reduce fatality risk by about 7% to 16%; cars driven by men are estimated to have a 37% 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 twice that of cars driven during the daytime on low-speed non-rural roads. The relatively small estimated effects of mass reduction are overwhelmed by these other vehicle, driver, and crash factors.

Using two or more variables that are strongly correlated in the same regression model (referred to as multicollinearity) can lead to inaccurate results. However, the correlation between vehicle mass and footprint may not be strong enough to cause serious concern. NHTSA included several analyses to address possible effects of the near-multicollinearity between mass and footprint.

First, NHTSA ran a sensitivity case where footprint is not held constant, but rather allowed to vary as mass varies (i.e., NHTSA ran a regression model which includes mass but not footprint); LBNL recreated this analysis (Model 6 in Table ES.1), using updated data through 2012. If the multicollinearity was so great that including both variables in the same model gave misleading results, removing footprint from the model would give much different results than keeping it in the model. NHTSA's sensitivity test estimates that when footprint is allowed to vary with mass, the effect of mass reduction on risk becomes more detrimental or less beneficial for all vehicles types: from a 1.20% increase to a 1.36% increase for lighter cars, from a 0.42% increase to a 0.57% increase for heavier cars, and from a 0.31% increase to a 0.40% increase for lighter light trucks; from a 0.61% decrease to a 0.57% decrease for heavier light trucks; and from a 0.25% decrease to a 0.11% increase for CUVs and minivans.

Second, NHTSA conducted a stratification analysis of the effect of mass reduction on risk by dividing vehicles into deciles based on their footprint, and running a separate regression model for each vehicle and crash type, for each footprint decile (3 vehicle types times 9 crash types times 10 deciles equals 270 regressions). This analysis estimates the effect of mass reduction on risk separately for vehicles with similar footprint. LBNL replicated this analysis, and updated it for data through 2012; the analysis indicates that reducing vehicle mass 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 only 6 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 16 of the 27 crash and vehicle combinations; in some cases these risk reductions are large and statistically significant.[1] If reducing vehicle mass while maintaining footprint inherently leads to an increase in risk, the coefficients on mass reduction should be more consistently positive, and with a larger R^2, across the 27 vehicle/crash combinations, than shown in the analysis. These findings are consistent with the conclusion of the basic regression analyses; namely, that the effect of mass reduction while holding footprint constant, if any, is small.

One limitation of using logistic regression to estimate the effect of mass reduction on risk is that a standard statistic to measure the extent to which the variables in the model explain the range in risk, equivalent to the R^2 statistic in a linear regression model, does not exist. (SAS does generate a pseudo-R^2 value for logistic regression models; in almost all of the NHTSA regression models this value is less than 0.10). For this reason LBNL conducted an analysis of risk versus mass by vehicle model, for 234 models with at least 10 billion VMT, or at least 100 fatalities (86 car models, 102 light truck models, and 46 CUV/minivan models); these 234 models represent nearly 90% of all fatalities, vehicle registration-years, and VMT. 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 is also 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.

LBNL tested the sensitivity of the NHTSA estimates of the relationship between vehicle weight and risk using 31 different regression analyses that changed the measure of risk, the control variables used, or the data used in the regression models. The intent in running the alternative regression models is not to develop a regression model that is "more correct" than the NHTSA

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[1] And in the remaining 5 of the 27 crash and vehicle combinations, risk increased in 5 deciles and decreased in 5 deciles with decreasing vehicle mass.

baseline model; rather, the intent is to test how sensitive the results from the baseline model are to changes in the data and variables used, as well as to gain an understanding of how accounting for various factors (such as driver alcohol/drug use or driving behavior, or quality of vehicle design) influences the relationship between vehicle mass, size, and societal fatality risk. LBNL analyzed alternative models 1 through 19 in its assessments of the NHTSA 2012 and 2016 reports; the results from these models using data updated through 2012 are shown in Table ES.1. Table ES.1 also shows the results of the 12 alternative regression models conducted as part of LBNL's 2016 assessment.[2] Models 20 through 23 explore two changes to how light trucks are classified: excluding light trucks with a GVWR rating over 10k pounds, and treating small (1/2-ton capacity) pickups and SUVs as a separate class distinct from large (3/4- and 1-ton capacity) pickups. As noted in the table footnotes, the median weight was recalculated for each alternate truck category. Models 24 through 27 test the sensitivity to which cars are included. Models 28 through 30 add a two-piece variable for CUV/minivan curb weight, based on the median CUV/minivan curb weight, as was done for cars and light trucks in the NHTSA baseline model, and two-piece variables for footprint for all vehicle types, based on the median footprint by vehicle type. And Model 31 removes the kink in the VMT schedule by vehicle age that NHTSA used to develop VMT weights for its analysis. Effects that are statistically significant are shown in red in the table; significance is based on the 95% confidence interval derived from the standard error output by the logistic regression model, rather than using the jack-knife method NHTSA employed in their reports.

Table ES.1 indicates that, for cars < 3,201 pounds, all alternative models estimate that mass reduction is associated with an increase in societal fatality risk, ranging from a 0.26% increase (Model 10) to a 2.34% increase (Model 12). 15 of the 31 alternative models estimate a smaller increase in risk, and 10 estimate a larger increase in risk, than the NHTSA baseline model (the remaining 6 alternative models, shaded in grey in Table ES.1, do not make changes to the regression model for cars). For cars ≥ 3,201 pounds, all but four of the alternative models estimate that mass reduction is associated with an increase in societal fatality risk, ranging from a 0.21% decrease (Model 13) to a 3.10% increase (Model 5). 11 of the 31 alternative models estimate a smaller increase, or a decrease, in risk, and 14 estimate a larger increase in risk, than the NHTSA baseline model (6 alternative models do not make changes to the regression model for cars).

For light trucks < 5,014 pounds, Table ES.1 indicates that all but six of the 29 applicable alternative models[3] estimate that mass reduction is associated with an increase in fatality risk: ranging from a 0.77% decrease in risk (Model 17) to a 1.15% increase in risk (Model 8). 12 of the 29 applicable alternative models estimate a larger increase in risk, and 13 estimate the same, a smaller increase, or a decrease, in risk, than the NHTSA baseline model (six alternative models do not make changes to the regression model for light trucks). In the two models restricted to analyses of large pickups, trucks < 6,119 pounds (Model 22) and < 6,080 pounds (Model 23), mass reduction is associated with decreases in fatality risk (3.1% and 3.5% decreases in risk, respectively) an order of magnitude larger than in the baseline NHTSA model (0.31% increase).

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[2] The estimated effect of footprint reduction on risk under these alternative models are shown in Table 5.13.

[3] Not including Models 22 and 23, which apply to large pickups only, and use much higher median weights (6,119 and 6,080 pounds, respectively) to define lighter and heavier large pickups than in the baseline model.

The classification of relatively light (i.e., below the median) trucks in Models 22 and 23 is distinct to the classification of relatively light trucks in the other models.

For light trucks ≥ 5,014 pounds, only two of the 29 applicable alternative models[4] estimate that mass reduction is associated with an increase in fatality risk, and range from a 1.91% decrease in risk (Model 17) to a 0.52% increase in risk (Model 8). 15 of the 29 applicable alternative models estimate the same or a larger decrease in risk, and 8 estimate a smaller decrease, or an increase, in risk, than the NHTSA baseline model (six alternative models do not make changes to the regression model for light trucks). In the two models restricted to analyses of large pickups, trucks ≥ 6,119 pounds (Model 22) and ≥ 6,080 pounds (Model 23), mass reduction is associated with large increases in fatality risk relative to the baseline NHTSA model (1.7% and 2.1% increases in risk, respectively). Again, the classification of relatively heavy (i.e., above the median) trucks in Models 22 and 23 is distinct to the classification of relatively heavy trucks in the other models.

For CUVs/minivans, all but five of the 29 applicable alternative models[5] estimate that mass reduction is associated with a decrease in fatality risk, and range from a 1.00% decrease in risk (Model 9) to a 0.14% increase in risk (Model 19). 11 of the 29 applicable alternative models estimate a larger decrease in risk, and nine estimate a smaller decrease, or an increase, in risk, than the NHTSA baseline model (9 alternative models do not make changes to the regression model for CUVs/minivans). In the two models which estimate the effect of mass reduction for lighter- and heavier-than-average CUVs/minivans (Models 28 and 30), mass reduction is associated with increases in fatality risk for lighter-than-average CUVs/minivans (0.27% and 1.25% increases in Models 28 and 30, respectively) but decreases in fatality risk for heavier-than-average CUVs/minivans (0.54% and 0.68% decreases in Models 28 and 30, respectively).

If the relationship between mass reduction and societal fatality risk is strong, one would expect that the estimated effects from NHTSA's baseline model would be robust to changes in the variables and data used. However this is not the case; the baseline results can be sensitive, especially for cars, to changes in the variables and data used. For instance, accounting for vehicle manufacturer (Model 8), or removing crashes involving alcohol, drugs, or bad drivers (Model 12), substantially increases the detrimental effect of mass reduction in lighter-than-average cars on risk. On the other hand, the DRI measures (using stopped instead of non-culpable vehicles and replacing footprint with wheelbase and track width, Model 17), or including AWD cars but excluding three high-risk sporty compact cars (Model 27), substantially decreases the detrimental effect of mass reduction in lighter-than-average cars on risk.

The differences among the point estimates of the alternative regression models in Table ES.1 are within the uncertainty bounds NHTSA estimated using a jack knife method. However, because the Volpe model NHTSA uses, and the OMEGA model EPA uses, to estimate changes in energy consumption and CO_2 emissions from mass reduction and other technologies uses the point estimates, and not the uncertainty bounds, using the estimates from one of the alternative models

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[4] Not including Models 22 and 23, which apply to large pickups only, and use much higher median weights (6,119 and 6,080 pounds, respectively) to define lighter and heavier large pickups than in the baseline model.

[5] Not including Models 28 and 30, which estimate the effect of mass reduction on risk separately for lighter (< 3,955 pounds) and heavier (≥ 3,955 pounds) CUVs/minivans.

Table ES.1. Estimated effect of mass reduction on U.S. fatalities, baseline model and 33 alternative regression models analyzed in this report

	Cars		Light trucks[1]		
Regression model	<3,201 lbs	≥3,201 lbs	<5,014 lbs	≥5,014 lbs	CUV/ minivan
Baseline model	1.20%	0.42%	0.31%	-0.61%	-0.25%
1.Weighted by current distribution of fatalities	1.06%	0.30%	0.38%	-0.61%	-0.48%
2.Single regression model across all crash types	1.05%	0.30%	0.37%	-0.61%	-0.48%
3.Fatal crashes per VMT	1.40%	0.61%	0.31%	-0.64%	-0.59%
4.Fatalities per induced exposure crash	0.36%	0.41%	-0.65%	-0.97%	-0.67%
5.Fatalities per registered vehicle-year	1.43%	3.10%	-0.03%	-0.99%	0.22%
6.Allow footprint to vary with mass[2]	1.36%	0.57%	0.40%	-0.57%	0.11%
7.Account for 14 vehicle manufacturers	2.09%	1.59%	1.14%	0.32%	0.00%
8.Account for 14 manufacturers + 5 luxury brands	2.26%	2.74%	1.15%	0.52%	-0.52%
9.Account for initial vehicle purchase price	1.10%	0.83%	0.05%	-0.83%	-1.00%
10.Exclude CY variables	0.26%	-0.07%	0.35%	-0.14%	-0.58%
11.Exclude crashes with alcohol/drugs	1.81%	1.13%	0.38%	-0.72%	-0.20%
12.Exclude crashes with alcohol/drugs, and bad drivers	2.34%	1.62%	0.54%	-0.51%	-0.47%
13.Account for median household income	1.01%	-0.21%	0.31%	-0.57%	-0.99%
14.Include sports, police, and AWD cars, and full vans	1.21%	0.55%	0.33%	-0.76%	-0.25%
15.Use stopped instead of non-culpable vehicles	1.32%	-0.17%	0.21%	-1.55%	-0.08%
16.Replace footprint with track width & wheelbase	0.66%	0.54%	-0.44%	-0.90%	-0.48%
17.Above two models combined (15 & 16)	0.73%	-0.02%	-0.77%	-1.91%	-0.18%
18.Reweight CUV/minivans by 2010 sales	1.20%	0.42%	0.31%	-0.61%	0.04%
19.Exclude non-significant control variables	0.99%	0.35%	0.36%	-0.50%	0.14%
20.Exclude LTs over 10k GVWR[3]	1.20%	0.42%	0.43%	-0.83%	-0.25%
21.Small pickups and SUVs only[3]	1.20%	0.42%	0.23%	-0.45%	-0.25%
22.Large pickups only[3]	1.20%	0.42%	-3.07%	1.74%	-0.25%
23.Large pickups only, exclude those > 10k GVWR[3] (20 & 22)	1.20%	0.42%	-3.52%	2.11%	-0.25%
24. Include AWD, but not muscle or police, cars	1.05%	0.83%	0.31%	-0.61%	-0.25%
25. Include muscle and police, but not AWD, cars	1.37%	0.23%	0.31%	-0.61%	-0.25%
26. Exclude 3 high-risk car models	1.11%	0.25%	0.31%	-0.61%	-0.25%
27. Include AWD cars, exclude 3 high-risk car models (24 & 26)	0.94%	0.59%	0.31%	-0.61%	-0.25%
28. 2-piece variable for CUV weight[4]	1.20%	0.42%	0.31%	-0.61%	0.27% -0.54%
29. 2-piece variable for PC and LT footprint	0.65%	1.12%	-0.07%	-0.66%	-0.19%
30. 2-piece variable for weight and for footprint[4] (28 & 29)	0.65%	1.12%	-0.07%	-0.66%	1.25% -0.68%
31. Remove kinks in NHTSA VMT schedules	1.20%	0.41%	0.31%	-0.61%	-0.26%

Red font indicates estimate is statistically significant at 95% confidence interval.

Gray shading indicates estimate is not changed from baseline regression model in alternative regression model.

[1] Light trucks includes pickups and truck-based SUVs, and excludes car-based CUVs and minivans.

[2] In model 6 footprint is allowed to vary with mass.

[3] The median weights used for Models 20-23 are: 4,992 pounds for Model 20; 4,818 pounds for Model 21; 6,119 pounds for Model 22; and 6,080 pounds for Model 23.

[4] The two estimates for CUV/minivan mass in Models 28 and 30 are for vehicles under and over the median mass (3,955 pounds).

could result in large changes in the estimated change in fatalities from mass reduction. For example, if NHTSA used the estimated relationship between mass reduction in pickup trucks and societal fatality risk from Model 17 (a 0.77% decrease and a 1.91% decrease in risk in lighter- and heavier-than-average pickups, respectively), rather than the estimate from the baseline model (a 0.31% increase and a 0.61% decrease, respectively), the Volpe and OMEGA models would enable manufacturers to make much larger reductions in the mass of pickup trucks without compromising safety. LBNL recommends that the agencies use a second set of estimates of the relationship between mass reduction and fatality risk, constructed by combining Models 17, 18 and 31 in Table ES.1, in their models, which would allow manufacturers to employ greater mass reduction, and reduce the incremental cost for vehicles to comply with the standards, without compromising overall safety.

Table ES.2 compares the results from NHTSA's 2003/2010, 2012, and 2016 analyses with those from the current analysis (again, results that are statistically significant, based on the standard errors from the regression models, are shown in red in the table). The first four columns of the table show the estimates from a simultaneous reduction in mass and footprint (i.e. excluding a control variable for footprint in the regression model), while the last four columns show the estimates from mass reduction while holding footprint constant (and the estimates from footprint reduction while holding mass constant). In nearly all cases simultaneous reduction in footprint and mass is associated with larger increases or smaller decreases in fatality risk than when holding footprint constant. In addition the right hand side of the table suggests that, between the 2012 and 2018 analyses, mass reduction in cars and heavier light trucks, and footprint reduction in cars and CUVs/minivans, has become less detrimental/more beneficial over time.

Table ES.2. Previous NHTSA results of the estimated effect of mass and footprint reduction on U.S. societal fatality risk per VMT

Variable	Case vehicle type and weight	NHTSA (2003) w/o footprint	NHTSA (2012) w/o footprint	NHTSA (2016) w/o footprint	NHTSA (2018) w/o footprint	NHTSA (2010) with footprint	NHTSA (2012) with footprint	NHTSA (2016) with footprint	NHTSA (2018) with footprint
Mass reduction	Cars < median	4.39%	2.74%	1.71%	1.36%	2.21%	1.55%	1.49%	1.20%
	Cars ≥ median	1.98%	1.95%	0.68%	0.57%	0.89%	0.51%	0.50%	0.42%
	LTs < median	2.90%	0.47%	0.26%	0.40%	0.17%	0.52%	-0.10%	0.31%
	LTs ≥ median	0.48%	-0.39%	-0.55%	-0.57%	-1.90%	-0.34%	-0.71%	-0.61%
	CUV/ minivan	—	0.60%	-0.25%	0.11%	—	-0.38%	-0.99%	-0.25%
Footprint reduction	Cars	—	—	—	—	—	1.87%	0.28%	0.23%
	LTs	—	—	—	—	—	-0.07%	0.38%	0.08%
	CUV/ minivan	—	—	—	—	—	1.72%	1.18%	0.52%

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

In its 2012 report NHTSA simulated the effect four fleetwide mass reduction scenarios would have on the change in annual fatalities. NHTSA estimated that the most aggressive of these scenarios (reducing mass 5.2% in heavier light trucks and 2.6% in all other vehicles types except lighter cars) would result in a small reduction in societal fatalities. LBNL replicated the methodology NHTSA used to simulate six mass reduction scenarios, including the mass reductions recommended in the 2015 NRC committee report, and estimated in 2021 and 2025 by EPA in the TAR, using the updated data through 2012. The analysis indicates that the estimated change in fatalities under each scenario based on the updated analysis is comparable to that in the 2012 analysis, but less beneficial or more detrimental than that in the 2016 analysis. For example, an across the board 100-lb reduction in mass would result in an estimated 157 additional annual fatalities based on the 2012 analysis, but would result in only an estimated 91 additional annual fatalities based on the 2016 analysis, and an additional 87 fatalities based on the current analysis. The mass reductions recommended by the 2015 NRC committee report[6] would result in a 224 increase in annual fatalities in the 2012 analysis, a 344 decrease in annual fatalities in the 2016 analysis, and a 141 increase in fatalities in the current analysis. The mass reductions EPA estimated for 2025 in the TAR[7] would result in a 203 decrease in fatalities based on the 2016 analysis, but an increase of 39 fatalities based on the current analysis. These results support NHTSA's conclusion from its 2012 study 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."

Like the previous NHTSA studies, this updated report concludes that the estimated effect of mass reduction while maintaining footprint on societal U.S. fatality risk is small, and not statistically significant at the 95% or 90% confidence level for all vehicle types based on the jack-knife method NHTSA used. 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 pounds 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 2004 to 2011). 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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[6] Mass reductions of 5%, 10%, and 15% for small, midsize, and large cars, respectively, and 20% for light trucks, CUVs, and minivans.

[7] Mass reductions of 0.9% for lighter cars, 7.3% for heavier cars, 9.1% and 9.2% for lighter and heavier light trucks, respectively, and 11.2% for CUVs and minivans.

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1. Introduction

The Department of Energy's (DOE) Vehicle Technologies Office funds research on development of technologies to improve the fuel economy of both light- and heavy-duty vehicles, including advanced combustion systems, improved batteries and electric drive systems, and new lightweight materials. Of these approaches to increase fuel economy and reduce fuel consumption, reducing vehicle mass through more extensive use of strong lightweight materials is perhaps the easiest and least expensive method; however, there is a concern that reducing vehicle mass may lead to more fatalities.

The relationship between vehicle mass and safety has been debated for many years. This debate has become more relevant with the advent of much more stringent federal fuel economy and greenhouse gas emission standards for new light-duty vehicles. The model year 2017 to 2025 standards are based on the footprint (wheelbase times track width) of each vehicle, with more stringent standards for smaller vehicles; the intent is to encourage manufacturers to make vehicles lighter to meet the standards while maintaining size, without compromising safety.

Lawrence Berkeley National Laboratory (LBNL) has conducted several analyses to better understand the relationship between vehicle mass, size and safety, in order to ameliorate concerns that down-weighting vehicles will inherently lead to more fatalities. These analyses include recreating the regression analyses conducted by the National Highway Traffic Safety Administration (NHTSA) that estimate the relationship between mass reduction and U.S. societal fatality risk per vehicle mile of travel (VMT), while holding vehicle size (i.e. footprint, wheelbase times track width) constant; this particular analysis is referred to as the LBNL Phase 1 analysis.

NHTSA recently completed a logistic regression analysis updating its previous studies of the relationship between vehicle mass and U.S. fatality risk per vehicle mile of travel (VMT; Kahane 2010, Kahane 2012, Puckett and Kindelberger 2016). The new study updates the 2016 analysis using updated FARS data for 2006 to 2012 involving model year 2004 to 2011 vehicles. As in the 2016 analysis, induced exposure data from police reported crashes in thirteen states are used; car-based crossover utility vehicles (CUVs) and minivans are combined and analyzed separately from passenger cars and light trucks (pickups and truck-based SUVs); crashes with other light-duty vehicles are divided into two groups based on the crash partner vehicle's weight; and 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 preliminary 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 U.S. fatality risk per vehicle miles traveled (VMT), for model year 2004 to 2011 light-duty vehicles involved in fatal crashes between 2006 and 2012. 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.

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 reduce 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 of its 2012 report, 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 choose 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 U.S. fatality risk per VMT, NHTSA used information on all U.S. 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 IHS Automotive (formerly R.L. Polk & Co.). 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 model year 2004 to 2011 light-duty vehicles between 2006 and 2012. 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 IHS Automotive. The data can be used to estimate U.S. 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 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.

NHTSA ran a separate logistic regression model for each of three vehicle types (passenger cars, comprised of two- and four-door cars; light trucks, comprised of pickup trucks and truck-based SUVs; and car-based crossover utility vehicles (CUVs) and minivans), and for each of nine crash types, for a total of 27 regressions. Crashes with another light-duty vehicle were categorized into four types based on the type and weight of the crash partner: a car, CUV or minivan lighter or heavier than average (3,187 pounds), and a pickup or truck-based SUV lighter or heavier than average (4,360 pounds). 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 U.S. 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. In the 2018 analysis NHTSA also excluded certain model year 2008 and 2009 Chevrolet Tahoe SUVs that were designed as police vehicles. 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 median weight for each vehicle type: 3,201 pounds for cars and 5,014 pounds 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 previous 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. As in the 2016 analysis, for the current analysis NHTSA included the control variable ROLLCURT airbags only in the regression models for rollover crashes involving cars or CUVs/minivans; regression models of pedestrian crashes do not include any control variables for airbags; and the control variables for CURTAIN, COMBO, and TORSO airbags are included in regression models for all other crashes involving cars or CUVs/minivans. No airbag variables were included in the regression models for light trucks.

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

Control variable	Cars	LTVs	CUVs/minivans
UNDRWT00	C	C	
OVERWT00	C	C	
LBS100			C
FOOTPRINT	C	C	C
TWODOOR	D		
SUV		D	
HD_PKP		D	
BLOCKER1		D	
BLOCKER2		D	
MINIVAN			D
ROLLCURT *	C #		C #
CURTAIN *	C #		C #
COMBO *	C #		C #
TORSO *	C #		C #
ABS	C #		C #
ESC	C #	C #	C #
AWD		C #	C #
DRVMALE	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
CY2006	D	D	D
CY2007	D	D	D
CY2008	D	D	D
CY2010	D	D	D
CY2011	D	D	D
CY2012	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. There is conflicting information about rollover curtain airbags for 2008 and newer Saab 9-3 cars. 2 FARS records and 424 induced exposure records from the state crash data for these cars with missing rollover curtain airbags were dropped for the car rollover regression models.

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, 2012 and 2016 studies, NHTSA derives the baseline fatalities from model year 2008 to 2011 vehicles in crashes between 2008 and 2012. 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 an updated NHTSA analysis that found that ESC reduces fatal rollovers by 60% in cars and 74% in light trucks; fixed-object impacts by 31% in cars and 45% in light trucks; and other non-pedestrian crashes by 7% in cars and by 6% in light trucks.[8] 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: MY07-10 vehicles in CY07-11			Adjusted for full penetration of ESC			Percent difference		
Crash type	Cars	LTVs	CUVs/ minivans	Cars	LTVs	CUVs/ minivans	Cars	LTVs	CUVs/ minivans
1: Rollovers	390	274	33	224	120	26	-43%	-56%	-21%
2: w/object	1,798	659	306	1,459	505	292	-19%	-23%	-5%
3: Ped etc.	1,701	997	707	1,701	997	707	0%	0%	0%
4: w/HDT	609	329	202	587	319	201	-4%	-3%	0%
5: w/lgt car	978	698	414	942	680	413	-4%	-3%	0%
6: w/hvy car	1,062	648	342	1,022	632	341	-4%	-2%	0%
7: w/lgt LT	554	325	178	533	315	178	-4%	-3%	0%
8: w/hvy LT	695	282	203	665	274	202	-4%	-3%	0%
9: Other	2,374	1,277	938	2,290	1,244	934	-4%	-3%	0%
Total	10,161	5,489	3,323	9,423	5,086	3,294	-7%	-7%	-1%

All of the regression coefficients presented in the NHTSA 2012 and this 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).[9]

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[8] Kahane C.J. (2014). *Updated Estimates of Fatality Reduction by Electronic Stability Control*, NHTSA Evaluation Note No. DOT HS 812 020. Washington, DC: National Highway Traffic Safety Administration.

[9] 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 our 2012 report, we converted the SAS outputs from log-space to linear space, and from odds to probabilities, to obtain the percent change in the probability of fatality. We used 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). In this report the estimated coefficients and standard errors are the log-odds output by the SAS LOGIST procedure.

2.2. Regression results

Figure 2.1 presents the regression coefficients from the baseline regression model in the NHTSA report; 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 figure indicates that lower mass is associated with an increase in societal[10] fatality risk of 1.20% for lighter-than-average cars, a 0.42% increase for heavier-than-average cars, and a 0.31% increase for lighter-than-average light trucks. However, lower mass is associated with a 0.61% decrease in fatality risk for heavier light trucks, and a 0.25% decrease in fatality risk for CUVs and minivans. The 95% confidence intervals in the figure indicate that the changes in risk for lighter cars and heavier 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 2016 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 2016 report indicates that none of the estimated changes in risk associated with mass reduction are statistically significant at the 95% or 90% confidence level.

Figure 2.1 also shows that lower footprint is associated with increased risk for all three types of vehicles, especially CUVs/minivans. A 1-square foot reduction in footprint is estimated to increase fatality risk by 0.23% in cars, by 0.07% in light trucks, and by 0.52% in CUVs/minivans, in NHTSA's baseline model; based on the standard errors output by SAS, none of the estimated effects of footprint reduction are statistically significant.

Figure 2.2 compares the results from the NHTSA baseline regression model (in light blue) with those from a single regression analysis across all crash types (in dark turquoise), as well as 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 in cars and CUVs/minivans, as the NHTSA weighted values (in light blue) are all higher than the unweighted values (in light turquoise). On the other hand, full ESC penetration reduces the estimated safety penalty from a reduction in footprint, for all vehicle types.

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[10] All of the fatality risks reported in the 2016 NHTSA report are societal risk, that is fatalities to all vehicle occupants and non-occupants involved in the crash are included. Unless specified otherwise, all risks in this report also are societal risk.

Figure 2.1. Estimated effect of mass or footprint reduction on U.S. societal fatality risk per VMT, from NHTSA baseline model, by vehicle type

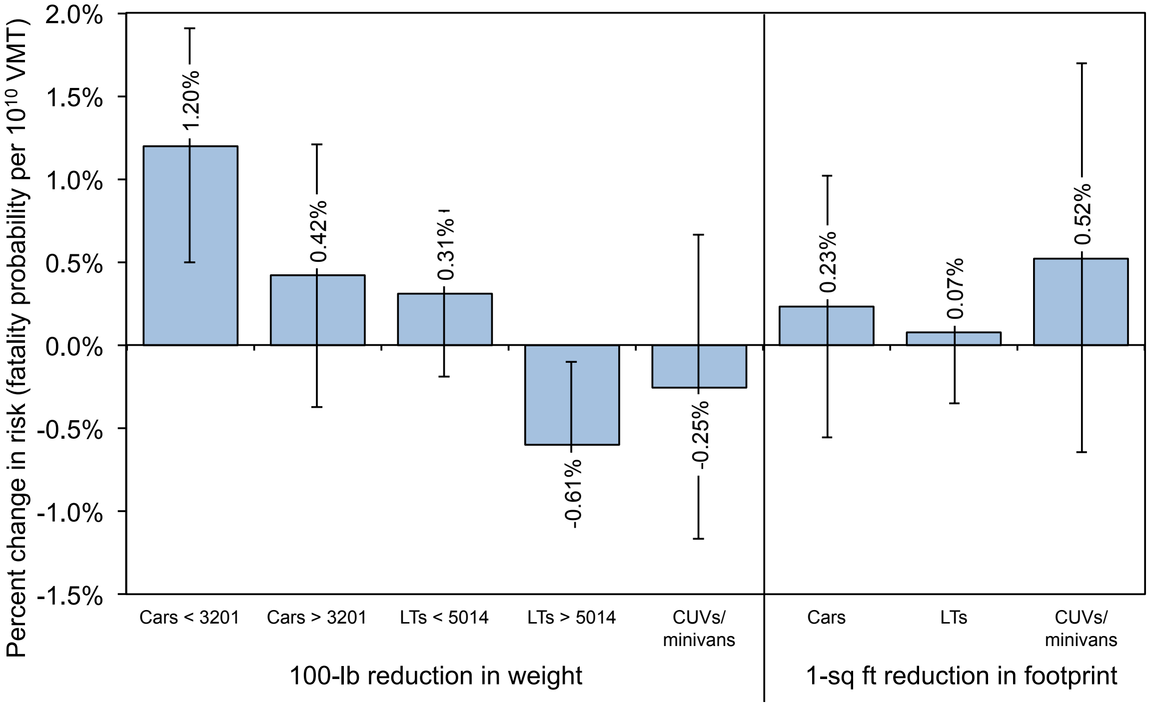
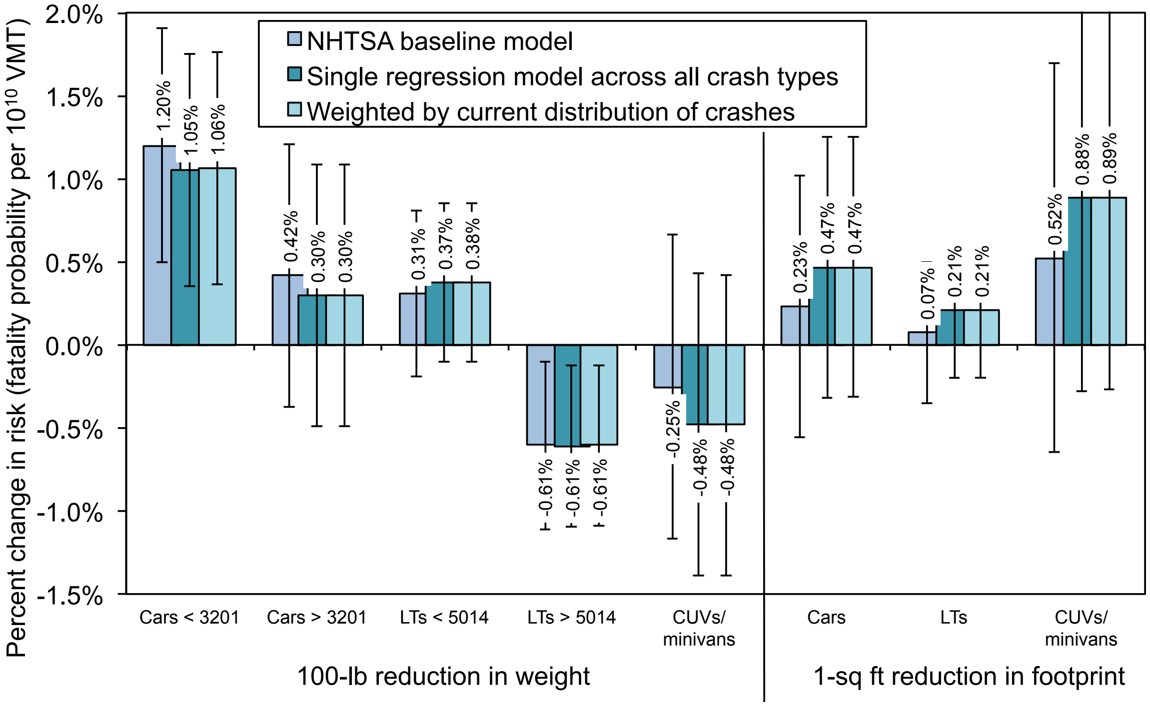


Figure 2.2. Estimated effect of mass or footprint reduction on U.S. societal fatality risk per VMT, across all crash types and based on current distribution by crash type, by vehicle type



Figures 2.3 through 2.5, 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 associated with an increase in risk in all crash types except rollovers, and for lighter-than-average cars crashe with another light car, and for heavier-than-average cars crashes with a stationary object, as shown in Figure 2.3. 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 mass reduction is estimated to reduce risk most in rollovers, NHTSA's baseline weighted regression results for 2017-2025 show a slightly larger increase in overall risk than the unweighted results based on recent crashes (shown in light turquoise in Figure 2.2). On the other hand, lower footprint is associated with the largest increase in risk in rollovers, nearly a 10% increase (Figure 2.3), so removing fatalities in rollovers by 2017 is estimated to reduce the detrimental effects of footprint reduction, from a 0.47% increase to a 0.23% increase after accounting for full market penetration of ESC.

Mass reduction in both lighter and heavier cars is associated with relatively large increases in societal risk in crashes with heavy-duty trucks; mass reduction in heavier cars is associated with a decrease in societal risk in crashes with a stationary object, but an increase in risk in crashes with heavier light trucks. A reduction in car footprint is associated with a large increase in risk in rollovers.

Figure 2.4 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 oftern are not statistically significant. Lower mass in lighter trucks is associated with a 2.1% increase in societal risk in crashes with heavy-duty trucks, while lower mass in heavier trucks is associated with a 2.6% decrease in societal risk in crashes with a lighter car. A reduction in light truck footprint is associated with a 1.7% increase in risk in crashes with stationary objects; the estimated effects of footprint reduction in other crash types are small and not statistically significant.

The estimated effect of reductions in mass and footprint on risk in crashes involving CUVs and minivans are shown in Figure 2.5. The estimated effects from mass or footprint reduction in CUVs and minivans tend to be similar to those in cars: lower mass is associated with a 3.4% reduction in risk in rollovers and an 3.8% increase in risk in crashes with heavy-duty trucks, while lower footprint is associated with a nearly 8% increase in risk in rollovers. 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 a smaller decrease in the estimated effect of mass reduction (from a 0.48% decrease to a 0.25% decrease), and a decrease in the estimated effect of footprint reduction (from a 0.89% decrease to a 0.52% decrease), on risk in CUVs and minivans indicated in Figure 2.1.

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

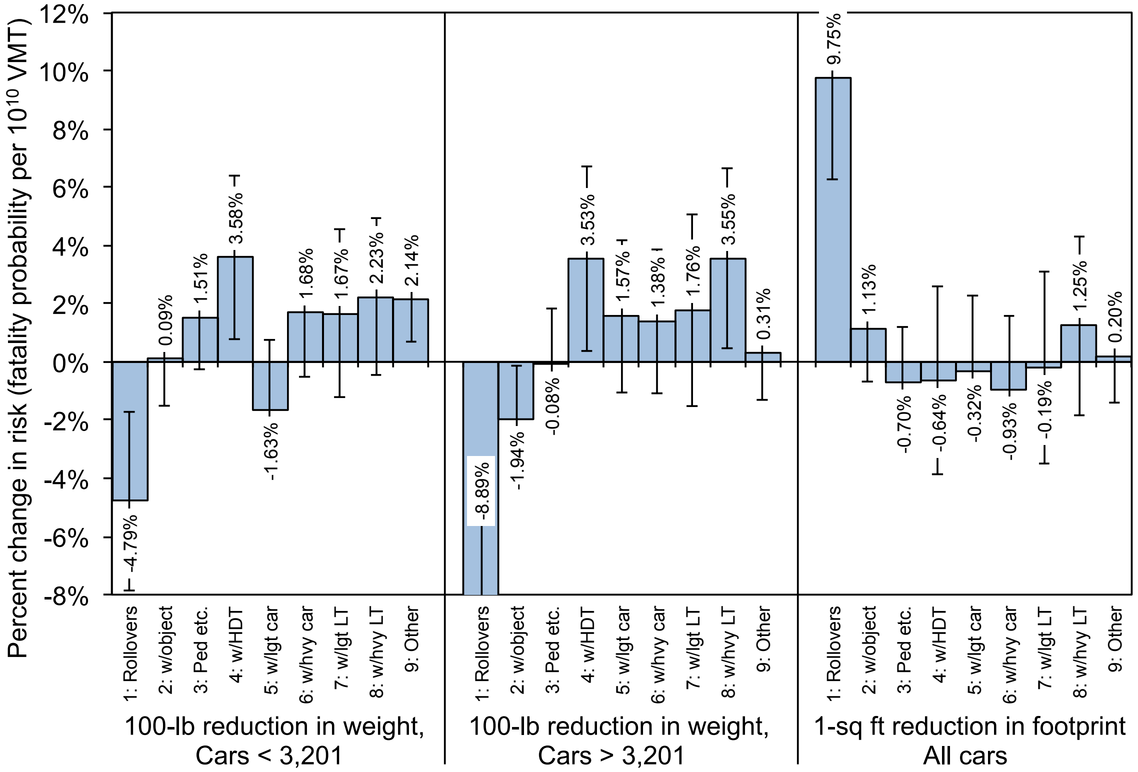


Figure 2.4. Estimated effect of mass or footprint reduction on risk in light trucks, by type of crash

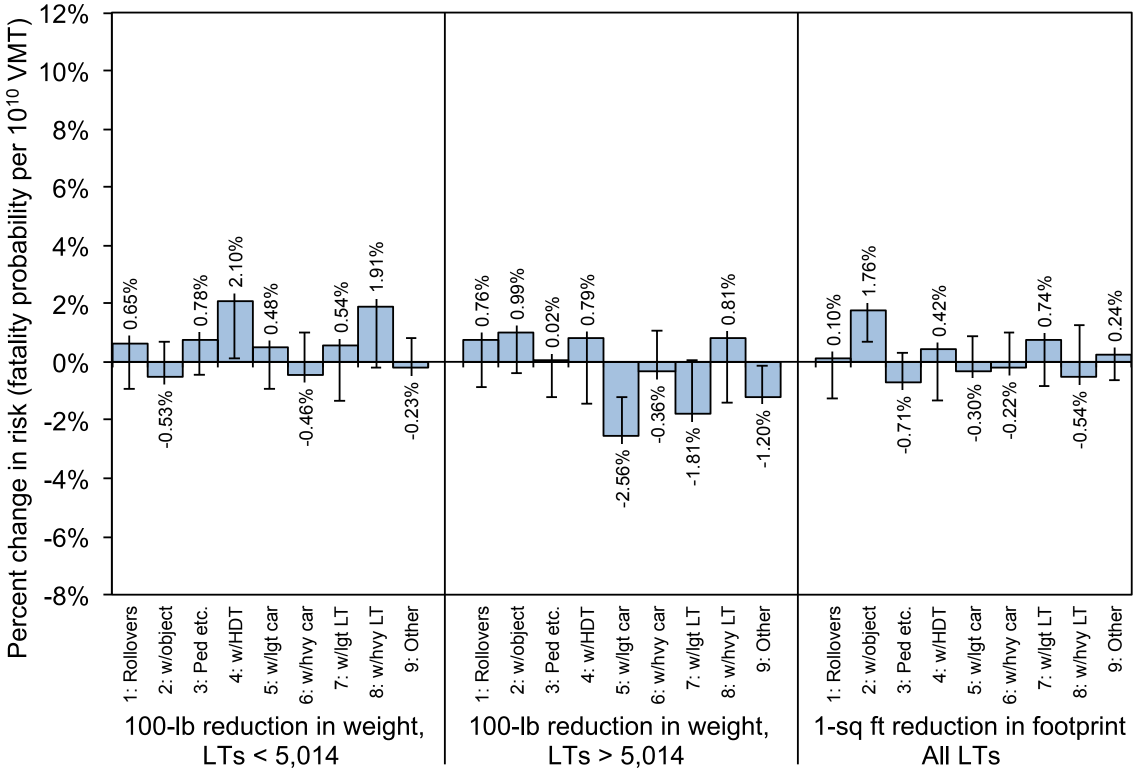


Figure 2.5. Estimated effect of mass or footprint reduction on risk in CUVs/minivans, by type of crash

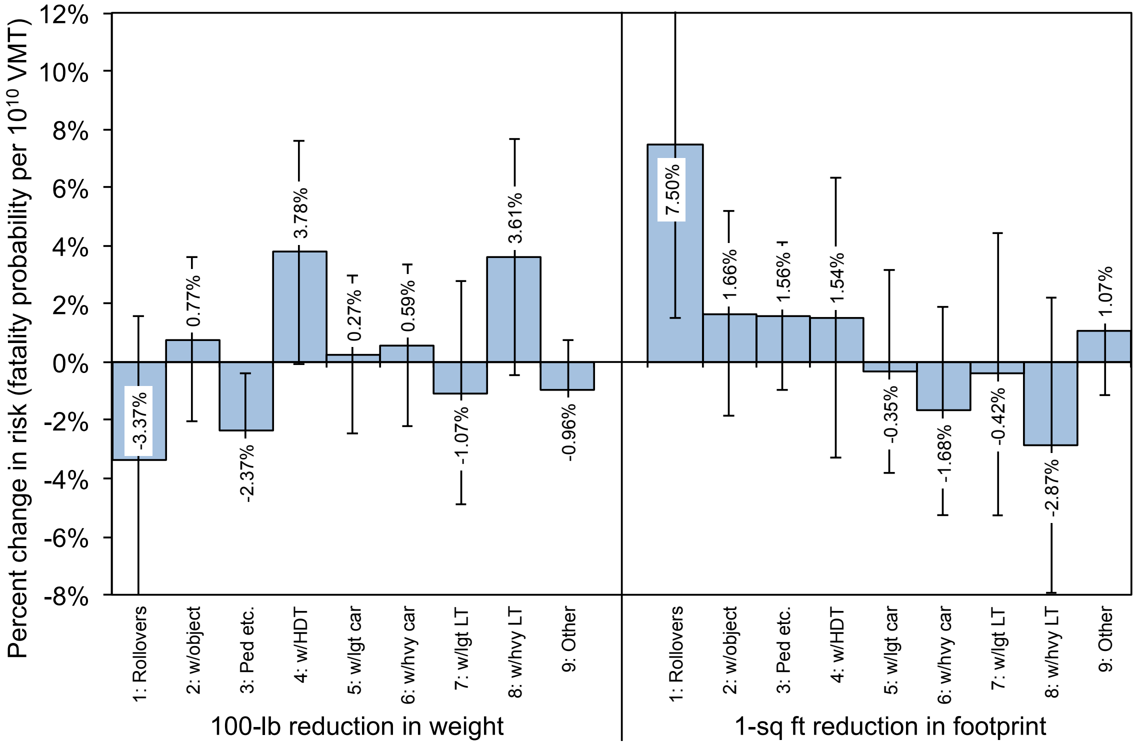


Table 2.3. Estimated effect of mass or footprint reduction on U.S. fatality risk per VMT, by type of crash

	Mass reduction					Footprint reduction		
Type of crash	Cars < 3201 lbs	Cars ≥ 3201 lbs	LTs < 5014 lbs	LTs ≥ 5014 lbs	CUVs/ minivans	Cars	LTs	CUVs/ minivans
1: Rollovers	-4.79%	-8.89%	0.65%	0.76%	-3.37%	9.75%	0.10%	7.50%
2: w/object	0.09%	-1.94%	-0.53%	0.99%	0.77%	1.13%	1.76%	1.66%
3: Ped etc.	1.51%	-0.08%	0.78%	0.02%	-2.37%	-0.70%	-0.71%	1.56%
4: w/HDT	3.58%	3.53%	2.10%	0.79%	3.78%	-0.64%	0.42%	1.54%
5: w/lgt car	-1.63%	1.57%	0.48%	-2.56%	0.27%	-0.32%	-0.30%	-0.35%
6: w/hvy car	1.68%	1.38%	-0.46%	-0.36%	0.59%	-0.93%	-0.22%	-1.68%
7: w/lgt LT	1.67%	1.76%	0.54%	-1.81%	-1.07%	-0.19%	0.74%	-0.42%
8: w/hvy LT	2.23%	3.55%	1.91%	0.81%	3.61%	1.25%	-0.54%	-2.87%
9: Other	2.14%	0.31%	-0.23%	-1.20%	-0.96%	0.20%	0.24%	1.07%
All	1.20%	0.42%	0.31%	-0.61%	-0.25%	0.22%	0.07%	0.52%

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

Figures 2.6 through 2.8, 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 U.S. fatality risk per VMT by 17%, while TORSO side airbags, assisted braking systems (ABS), and electronic stability control (ESC), are estimated to reduce risk by about 7% to 16%. Male drivers are estimated to increase U.S. fatality risk per VMT by 37%, while young and elderly drivers (male and female) increase fatality risk from 3% to 8%. The three crash circumstance variables in Figure 2.6, NITE, RURAL, and SPDLIM55, have the largest estimated effect on risk of all the control variables included in the model; each are estimated to more than double fatality risk per VMT.[11] A crash occurring in a high-fatality state carries an estimated 28% higher fatality risk per VMT than a crash in other states. Car age causes a small estimated increase in risk, while a brand new car is estimated to increase risk by 41%, 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 26% increase in risk in 2006 to an estimated 4% reduction in risk in 2012. 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 2.6. For instance, a 100-lb reduction in curb weight for an underweight car is estimated to increase risk by 1.20%, while installing ABS would reduce risk by 16.2%; the models estimate that the beneficial effect of adding ABS is nearly ten times that of reducing mass by 100 pounds. And driving on a roadway with a posted speed limit greater than 55 miles per hour is estimated to increase risk more than 2.5 times, which suggests that a 0.8% increase in driving on high-speed roads would result in the same increase in fatalities as estimated for a 100-pound reduction in mass for every car (1.20% / 153% = 0.8%).

Figure 2.7 presents the estimated effect of the control variables on fatality risk in crashes involving light-duty trucks. SUVs (19%), 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, is associated with a slight increase in fatalities, while BLOCKER2, employment of an additional blocker beam behind the bumper, is associated with a 3.7% increase in fatalities. ESC is estimated to reduce risk by 24% in light trucks (Figure 2.7) as opposed to only 7% in cars (Figure 2.6); all-wheel drive (AWD) is estimated to reduce risk in light trucks by 24%. As with cars, risk is estimated to be 26% higher with male drivers, as well as young and elderly drivers. As in cars, driving at night, in rural areas, and on roadways with high speed limits are estimated to more than double the risk in trucks, while driving in high fatality states is associated with a 17% increase in risk. Brand new light trucks (23%) have a lower estimated increase in risk than brand new cars (41%), 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

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[11] As discussed above the output from the SAS LOGIST procedure reflects the percent change in the log-odds of fatality per billion VMT for a one-unit increase in the explanatory variable. In the 2012 analysis, as well as in Figures 2.3 through 2.5 and Table 2.4 of the 2016 Phase 1 report, we converted the estimated effects of the variables from the SAS outputs from log-space to linear space, and from odds to probabilities, to obtain the percent change in the probability of fatality. We used 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 when the estimated log-odds ratios are low, but has a large effect when the log-odds ratios are high. For example, this conversion increases the estimated increase in societal fatality risk in log-odds of 121%, 112%, and 153% for driving at night, in a rural county, and on a high-speed road, respectively, to percent increases of 237%, 206%, and 360%, for cars.

[11] All of the fatality risks reported in the 2016 NHTSA report are societal risk, that is fatalities to occupants in the case vehicle as well as in any crash partners, including pedestrians and cyclists.

decline is greater than in cars, from an estimated 30% increase in risk in 2006 to an estimated 6% decrease in risk in 2012. The calendar year variables are discussed in more depth in Section 5.3.

Figure 2.8 indicates that minivans are associated with an estimated 11% lower fatality risk than CUVs. For CUVs and minivans, curtain, combination and torso side airbags are associated with a 2% to 6% reduction in risk. ABS in CUVs and minivans is associated with slightly lower reduction in risk (13%) as in cars, while ESC is associated with a larger reduction in risk (12%) than in cars (7%) but a lower reduction than in light trucks (24%). As with light trucks, AWD in CUVs and minivans is associated with a 24% reduction in risk. In terms of driver characteristics, males are associated with a 25% increase in risk; young and elderly drivers also are associated with higher risk. As in cars and light trucks, driving at night, in rural areas, and on roadways with high speed limits are estimated to more than double the risk in CUVs and minivans, while driving in high fatality states is associated with a similar increase in risk (22%). The coefficients on the calendar year control variables are similar to those for light trucks, from a 27% increase in 2006 to a 10% decrease in 2012; these are discussed in more detail in Section 5.3.

The estimated effects of all of the control variables are shown by vehicle type in Table 2.4.

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

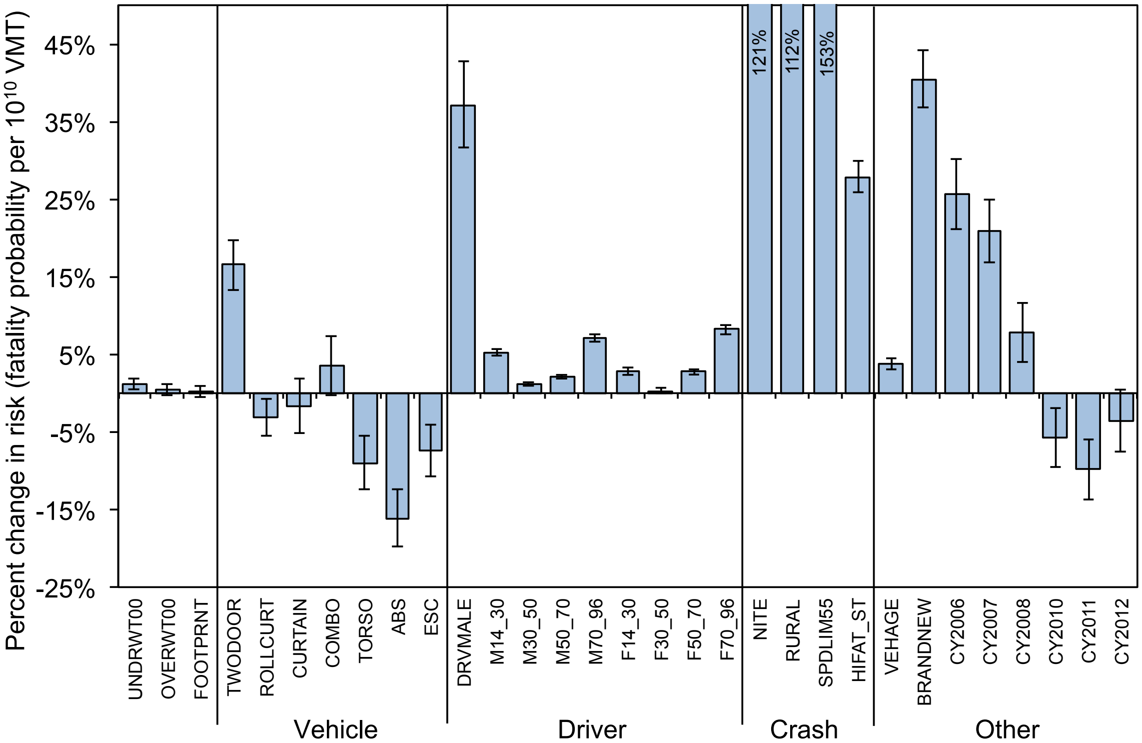


Figure 2.7. Estimated effect of selected control variables on risk, light trucks

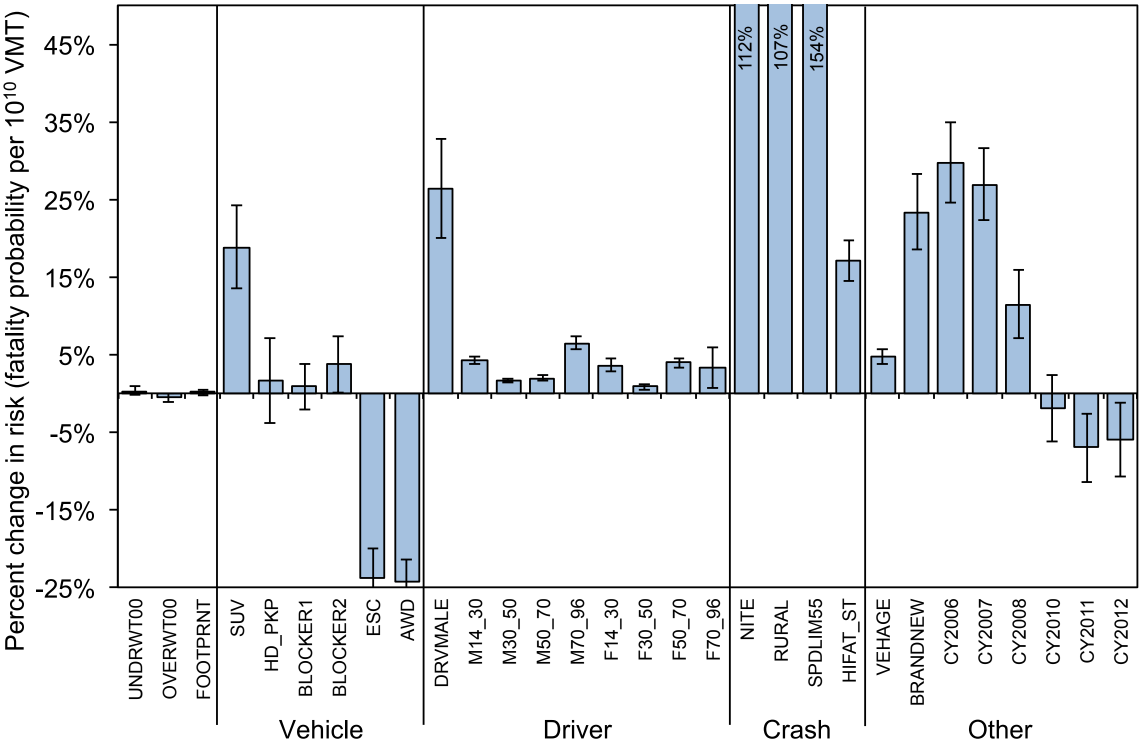


Figure 2.8. Estimated effect of selected control variables on risk, CUVs and minivans

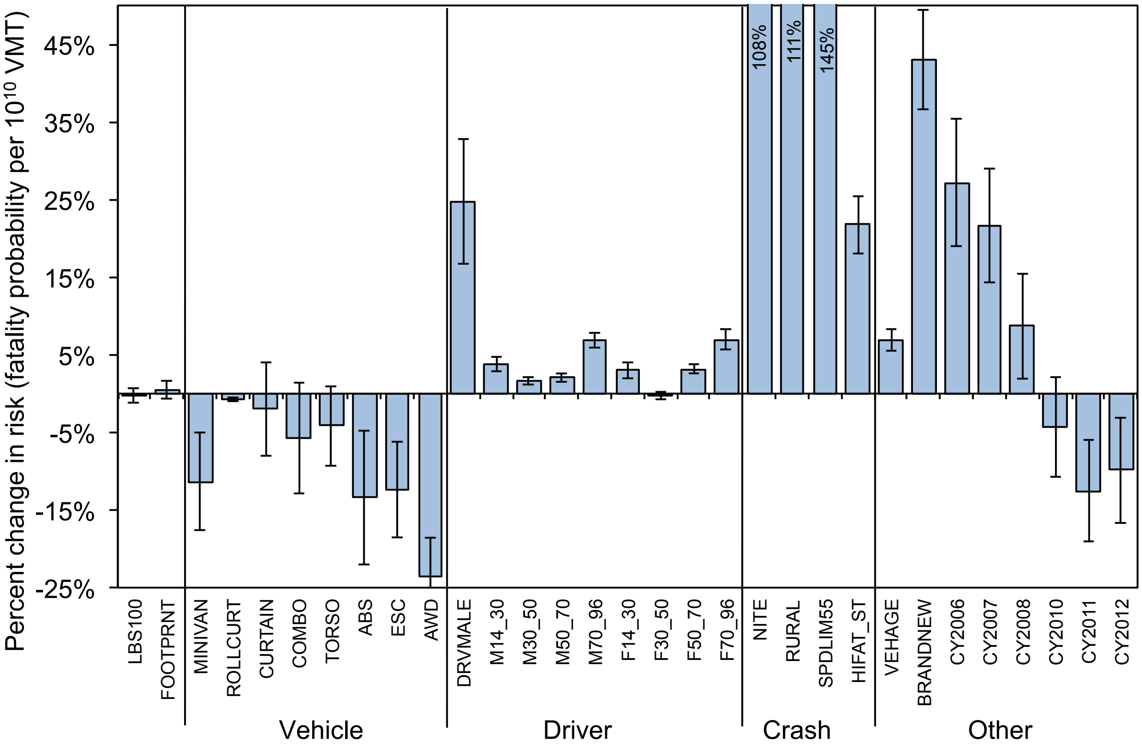


Table 2.4. Estimated effect on U.S. fatality risk per VMT, by vehicle type

		Cars		Light-duty trucks		CUVs/ minivans	
Type	Control variable	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Vehicle variables	UNDRWT00	1.20%	0.71%	0.31%	0.50%		
	OVERWT00	0.42%	0.79%	-0.61%	0.51%		
	LBS100					-0.25%	0.92%
	FOOTPRINT	0.23%	0.79%	0.07%	0.42%	0.52%	1.17%
	TWODOOR	16.5%	3.29%				
	SUV			18.9%	5.39%		
	HD_PKP			1.67%	5.52%		
	BLOCKER1			0.88%	2.94%		
	BLOCKER2			3.71%	3.64%		
	MINIVAN					-11.3%	6.24%
	ROLLCURT	-3.14%	2.35%			-0.68%	0.29%
	CURTAIN	-1.61%	3.54%			-2.03%	5.98%
	COMBO	3.48%	3.80%			-5.80%	7.11%
	TORSO	-8.98%	3.42%			-4.15%	5.19%
	ABS	-16.2%	3.69%			-13.4%	8.62%
	ESC	-7.43%	3.40%	-23.7%	4.03%	-12.3%	6.20%
	AWD			-24.4%	2.99%	-23.6%	5.07%
	VEHAGE	3.78%	0.78%	4.69%	0.94%	6.88%	1.36%
	BRANDNEW	40.5%	3.75%	23.3%	4.85%	43.0%	6.40%
Driver variables	DRVMALE	37.2%	5.52%	26.4%	6.45%	24.8%	8.07%
	M14_30	5.29%	0.45%	4.20%	0.48%	3.85%	0.97%
	M30_50	1.24%	0.28%	1.57%	0.25%	1.61%	0.49%
	M50_70	2.11%	0.34%	1.95%	0.32%	2.04%	0.52%
	M70_96	7.07%	0.52%	6.47%	0.82%	6.85%	0.97%
	F14_30	2.82%	0.52%	3.62%	0.83%	3.00%	1.03%
	F30_50	0.32%	0.32%	0.83%	0.44%	-0.28%	0.48%
	F50_70	2.78%	0.38%	3.95%	0.65%	3.16%	0.56%
	F70_96	8.20%	0.65%	3.21%	2.62%	6.98%	1.37%
Crash variables	NITE	121%	2.16%	112%	2.52%	108%	3.89%
	RURAL	112%	2.19%	107%	2.53%	111%	3.79%
	SPDLIM55	153%	2.13%	154%	2.50%	145%	3.73%
	HIFAT_ST	27.9%	2.07%	16.9%	2.59%	21.8%	3.72%
	CY2005	25.6%	4.52%	29.8%	5.20%	27.1%	8.17%
	CY2006	20.8%	4.07%	26.9%	4.65%	21.6%	7.27%
	CY2007	7.87%	3.87%	11.5%	4.44%	8.7%	6.80%
	CY2008	-5.76%	3.75%	-1.79%	4.37%	-4.27%	6.46%
	CY2010	-9.88%	3.82%	-6.91%	4.52%	-12.5%	6.55%
	CY2011	-3.51%	4.02%	-5.72%	4.80%	-9.8%	6.82%

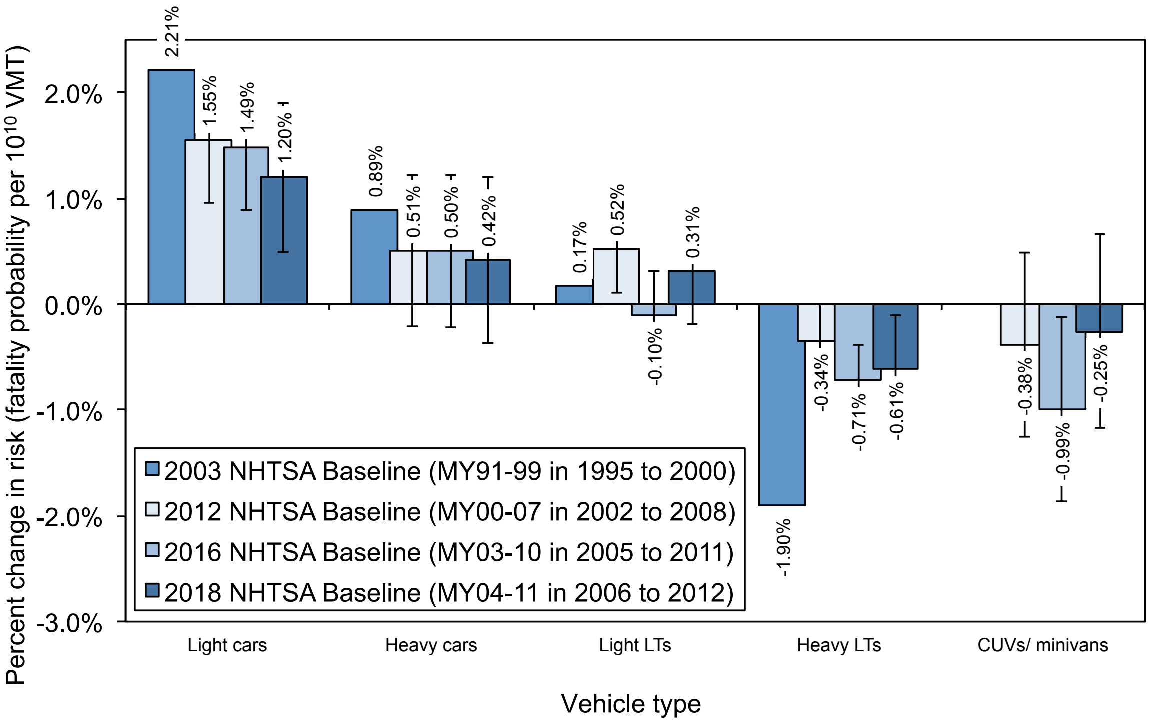
Estimates that are statistically significant at the 95% level are shown in red.

2.3. Comparison with previous analyses

Figure 2.9 compares the estimated relationship between mass reduction and societal fatality risk per VMT from the three baseline regression models NHTSA developed for the 2003, 2012, and 2016 analyses. In 2010 NHTSA re-analyzed the 2003 data and included curb weight and footprint in the same regression model; however, this analysis included CUVs and minivans as light-than-average trucks instead of in their own category. The estimated detrimental effect of mass reduction in cars on societal fatality risk per VMT decreased substantially between the 2003 and 2012 analyses, is nearly identical to 2012 in the 2016 analysis, and decreased again in the current analysis. The large estimated decrease in risk from mass reduction in heavier light trucks in the 2003 analysis was much smaller in the 2012 analysis, but was substantially larger in the 2016 and current analyses. Similarly, the decrease in risk from mass reduction in CUVs/minivans more than doubled between the 2012 and 2016 analyses, but in the current analysis has declined to a decrease in risk smaller than in the 2012 analysis.

The trends in the relationship between mass reduction and fatality risk between the 2012, 2016, and 2018 analyses are similar for lighter-than-average light trucks and CUVs/minivans, with mass reduction becoming more beneficial in the 2016 analysis but less beneficial/more detrimental in the 2018 analysis. Mass reduction in lighter-than-average light trucks was associated with a 0.52% increase in risk in the 2012 analysis, a 0.10% decrease in risk in the 2016 analysis, and a 0.31% increase in risk in the 2018 analysis, while mass reduction in CUVs/minivans was associated with a 0.38% decrease in risk in the 2012 analysis, a 0.99% decrease in risk in the 2016 analysis, and a 0.25% decrease in risk in the 2018 analysis (the trend for heavier-than-average light trucks is also similar, but not as large, as the trends for lighter-than-average light trucks and CUVs/minivans).

Figure 2.9. Estimated effect of mass reduction on U.S. fatality risk per VMT by vehicle type, from NHTSA baseline models in 2003, 2012, 2016 and 2018 analyses



One would not expect such large differences in the estimated relationship between mass reduction and risk between the 2016 and 2018 analyses, as the current analysis only includes one additional year of data. LBNL examined several factors that may account for the fluctuation in the estimated change in fatality risk from mass reduction in lighter-than-average light trucks and CUVs/minivans over the three analyses.

1) In its 2016 analysis NHTSA mischaracterized several CUV models as SUVs;[12] these models accounted for only 202 case vehicles, and 238 total fatalities. Mischaracterizing them slightly under-estimated the relationship between mass reduction and risk in lighter-than-average light trucks (a 0.10% decrease rather than no change) but had virtually no effect on the estimated effect of mass reduction on CUVs/minivans (a 0.99% decrease rather than a 0.97% decrease).

2) Comparisons of fatality risk per VMT by vehicle model indicate that there is greater agreement between the 2016 and 2018 analyses than between the 2012 and 2016 analyses; this is to be expected because three years separate the 2012 and 2016 analyses, whereas only one year separates the 2016 and 2018 analyses. However, large pickups have relatively lower risk per VMT in 2016 than in 2012 compared with the other vehicle types. Curb weights by model are highly correlated between the 2016 and 2018 analyses; however, footprint varies substantially for five pickup truck models[13] between the two analyses. VMT by vehicle model is very similar between the 2016 and 2018 analyses, except for the Ford Taurus.

3) There is no induced exposure record, and therefore VMT weight, for the 2007 Subaru Outback in the 2016 database; in addition, the VMT weights for the 2005 and 2006 Outback are much lower in the 2016 database than in the 2018 database. Replacing the VMT weights in the 2016 data base for those model years of the Outback with the weights from the 2018 database reduces the fatality risk per VMT for the Outback from 150 to 58, identical to the risk per VMT in the 2018 database. There is only one other model, the 2010 Elantra, that has an appreciable number of fatalities (33) but no induced exposure record in the 2016 NHTSA database.

4) In its 2016 analysis NHTSA developed VMT weights for each vehicle based on two components: a VMT schedule by vehicle age and type (cars vs. light trucks), from analysis of the 2009 National Household Travel Survey (NHTS); and an adjustment factor by vehicle model, from a database of odometer readings provided by IHS/Polk/CarFax. NHTSA used a new odometer database to derive adjustment factors by vehicle model for the 2018 analysis. A comparison of the VMT adjustment factors by vehicle model indicates that, for the most part, the adjustment factors used in the 2016 analysis are very similar to those used in the 2018 analysis, although there are some large differences for certain models. However, the correlation between the adjustment factors by vehicle model that NHTSA developed from the Polk odometer data and those from a large dataset of odometer readings from virtually every vehicle registered in Texas is not strong, especially for small and large pickup models, with an R^2 of 0.25 and 0.14, respectively.

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[12] Dodge Journey, Ford Flex, Lincoln MKT, Cadillac SRX, VW Tiguan, Nissan Cube, Honda Accord Crosstour, Mercedes GLK350, Subaru Forester, Toyota Venza, Infiniti FX35, and Lexus RX330.

[13] Toyota Tundra Access Cab 2x4 and 4x4, Toyota Tundra Double Cab, Ford F-350 Crew Cab, and Ford F-350 4x4 Super Cab.

5) About a third of the fatalities in CUVs in the 2018 analysis were in model year 2011 CUV models that did not exist in the 2016 analysis;[14] the introduction of these CUV models in the 2018 analysis is the likely cause of the large decrease in the estimated decrease in fatalities from mass reductions in CUVs between the 2016 and 2018 analyses (from a 0.99% decrease in 2016 to a 0.25% decrease in 2018). Comparing the changes in fatality risk per VMT of all vehicles included in both the 2016 and 2018 analyses indicates that the fatality risk per VMT increased 2% in cars, but decreased about 10% in light trucks and CUVs/minivans; since the two analyses used the same fatal crash cases, the large decrease in fatality risk per VMT in light trucks is likely due to changes in the VMT weights NHTSA developed for light trucks for the 2018 analysis.

Detailed analysis of these factors is included in Appendix A. Although not definitive, this analysis suggests that a combination of mischaracterization of certain CUV models as SUVs in the 2016 analysis, differences in the odometer adjustment factors by vehicle model used to create the VMT weights in the 2016 and 2018 analyses, and the introduction of new CUV models in MY11 in the 2018 analysis account for much of the fluctuation in the effect of mass reduction on risk between the 2012, 2016, and 2018 analyses.

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[15] "begins to get concerned" with VIF values greater than 2.5, while Menard[16] 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[17] 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 U.S. fatality risk per VMT (Van Auken and Zellner 2002, 2003, 2004, 2005a, 2005b). Starting in its 2010 analysis, 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, Puckett and Kindelberger 2016).

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[14] Such as Chevrolet HHR, Buick Enclave/GMC Acadia/Chevrolet Traverse, Ford Edge/Lincoln MKX/Mazda CX-9, Nissan Rogue, and Pontiac Torrent/GMC Terrain, and others.

[15] Allison, P.D.. *Logistic Regression Using SAS, Theory and Application*. SAS Institute Inc., Cary NC, 1999.

[16] Menard, S. *Applied Logistic Regression Analysis, Second Edition*. Sage Publications, Thousand Oaks CA, 2002.

[17] O'Brien, R.M. "A Caution Regarding Rules of Thumb for Variance Inflation Factors," Quality and Quantitiy, (41) 673-690, 2007.

Figure 3.1 shows the correlation between curb weight and footprint by vehicle model in the NHTSA database; only the most popular 234 models, with at least 10 billion VMT or 100 fatalities, are included in the figure (86 car models, 102 light truck models, and 46 CUV/minivan models). The figure indicates that curb weight and footprint are more highly correlated for cars (Pearson correlation coefficient, or r, of 0.93) than for light trucks (r=0.76) or CUVs/minivans (r=0.82). Figure 3.2 shows the same data as Figure 3.1, but uses seven vehicle types. Here the correlation ranges from 0.90 or higher for 4-door cars and small pickups, 0.79 or higher for 2-door cars, SUVs and CUVs, to only 0.58 for large pickups and 0.26 for minivans. The correlation of 0.76 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: 0.88 for SUVs and 0.90 for small pickups, but only 0.58 for large pickups. On the other hand, separating CUVs from minivans improves the correlation between curb weight and footprint for CUVs (r=0.88) but not for minivans (r=0.26). The correlation is so poor for minivans in part because of the Kia Sedona, which has a much higher weight (4,597 pounds) for its footprint (52.7 sq ft) than other minivans; removing this model improves the correlation for minivans to 0.48.

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

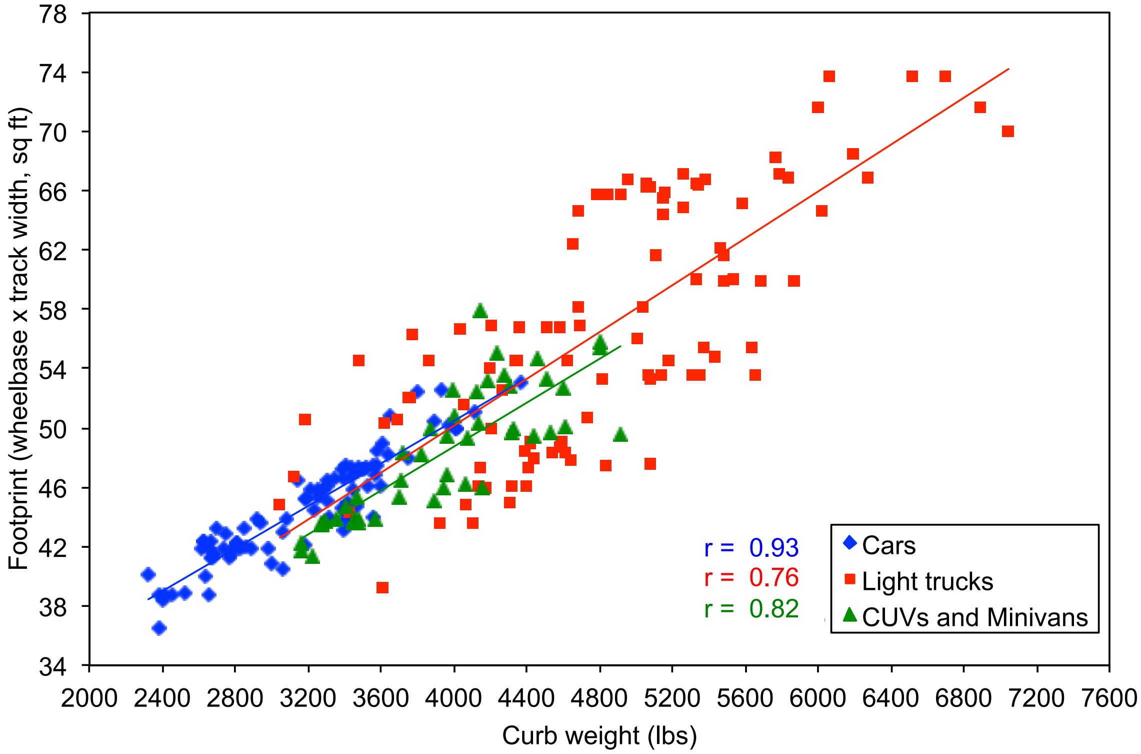

Figure 3.2. Correlation between vehicle curb weight and footprint, by vehicle model and seven vehicle types

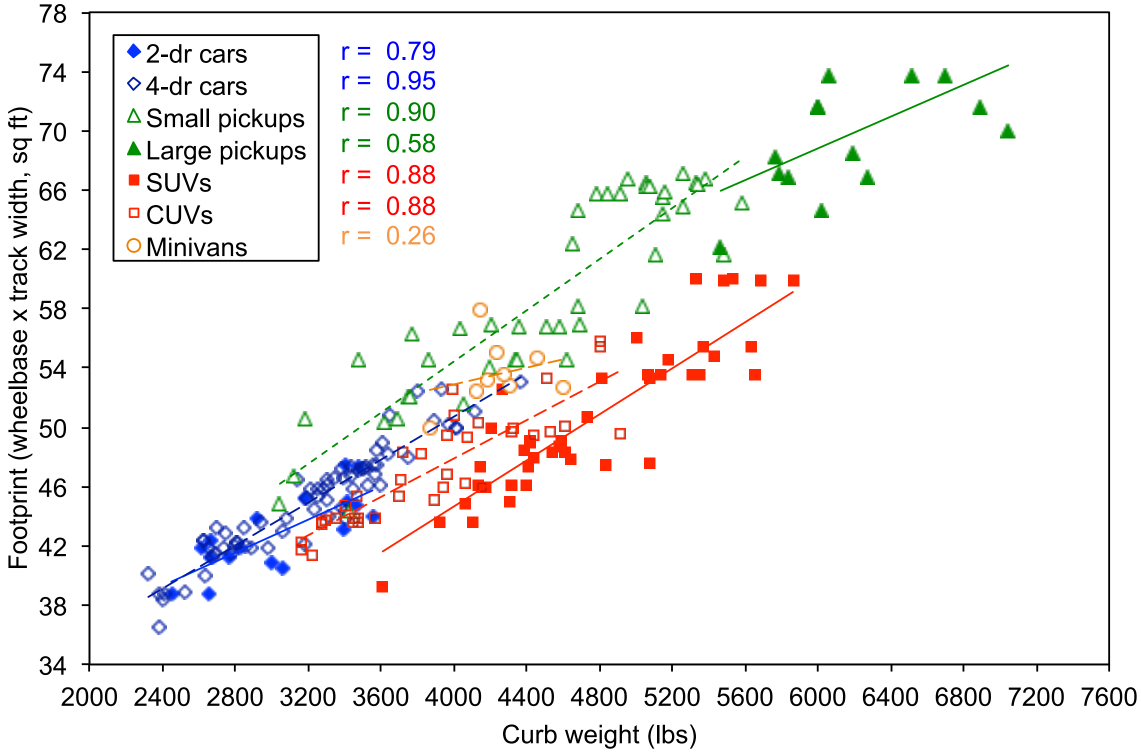

Table 3.1 shows the correlation coefficients of curb weight with footprint, and variance inflation factors, by vehicle type. The values in the table include all vehicles in the database, and not just the 234 most popular models shown in Figures 3.1 and 3.2; the values are weighted by the VMT weights NHTSA assigned to individual vehicles. As in Figure 3.1, Table 3.1 indicates that curb weight is most highly correlated with footprint in cars (r=0.88), followed by CUVs/minivans (r=0.85) and light trucks (r=0.75). However, as in Figure 3.2, the correlations vary substantially among the seven vehicle types, as shown in the bottom panel of the table: while the correlation is high for 4-door cars (r=0.90), it is substantially lower for 2-door cars (r=0.73). Small pickups and SUVs have a relatively high correlation between curb weight and footprint (r over 0.85), but large pickups have a much lower correlation (r=0.63). Similarly, the correlation is much lower for minivans (r=0.48) than for CUVs (r=0.89); 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 in minivans to 0.63. Table 3.1 also indicates that five of the seven vehicle types (all except large pickups and minivans) have a VIF associated with curb weight greater than 2.5 after accounting for driver and crash variables,[18] the point at which multi-collinearity becomes a concern. The final

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[18] Following NHTSA 2012, we combine the eight driver gender and age variables into two variables, DRVAGE and DRVMALE, and include the vehicle variables CURBWT, FOOTPRNT, ESC, and VEHAGE, and the crash circumstance variables NITE, RURAL, SPDLIM55, and HIFAT_ST. To calculate the VIFs for the seven vehicle types we remove the vehicle type variables TWODOOR, HD_PKP, SUV, and MINIVAN from the regression models.

columns in Table 3.1 show that the VIFs associated with curb weight and footprint tend to be higher after accounting for all of the variables in the baseline regression model.[19]

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

Vehicle type	Correlation coefficient (r)	Variance inflation factor (VIF)			
		Accounting for driver and crash variables		Accounting for all variables	
		CURBWT	FOOTPRNT	CURBWT	FOOTPRNT
Cars	0.882	5.3	5.0	6.2	5.5
Light trucks	0.754	5.8	8.9	6.8	9.8
CUVs/minivans	0.845	4.7	7.1	6.5	9.4
2-dr cars	0.725	3.1	2.5	4.0	3.3
4-dr cars	0.901	5.9	5.4	7.0	6.0
Sm pickups	0.859	3.9	3.9	4.8	4.3
Lg pickups	0.631	1.7	1.7	2.4	1.9
SUVs	0.877	4.6	4.5	5.6	1.0
CUVs	0.888	5.3	5.0	8.6	7.6
Minivans	0.475	1.5	1.5	1.9	3.1

Figure 3.3 compares NHTSA's baseline model, in light blue from Figure 2.1, with two alternative model specifications to test the sensitivity of the results from the baseline 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 all five types of vehicles, especially CUVs and minivans (from an estimated 0.25% decrease in risk to an estimated 0.11% increase in risk). The increase in risk associated with allowing car footprint to vary with mass is much smaller with the 2017 updated data (1.36% for lighter cars and 0.57% for heavier cars) than in the 2015 analysis (1.71% and 0.68%, respectively).

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 0.23% increase to an estimated 1.18% increase, but decreases the effect of footprint reduction on CUV/minivan risk, from an estimated 0.52% increase to an estimated 0.23% 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 little effect on the variables for light trucks.

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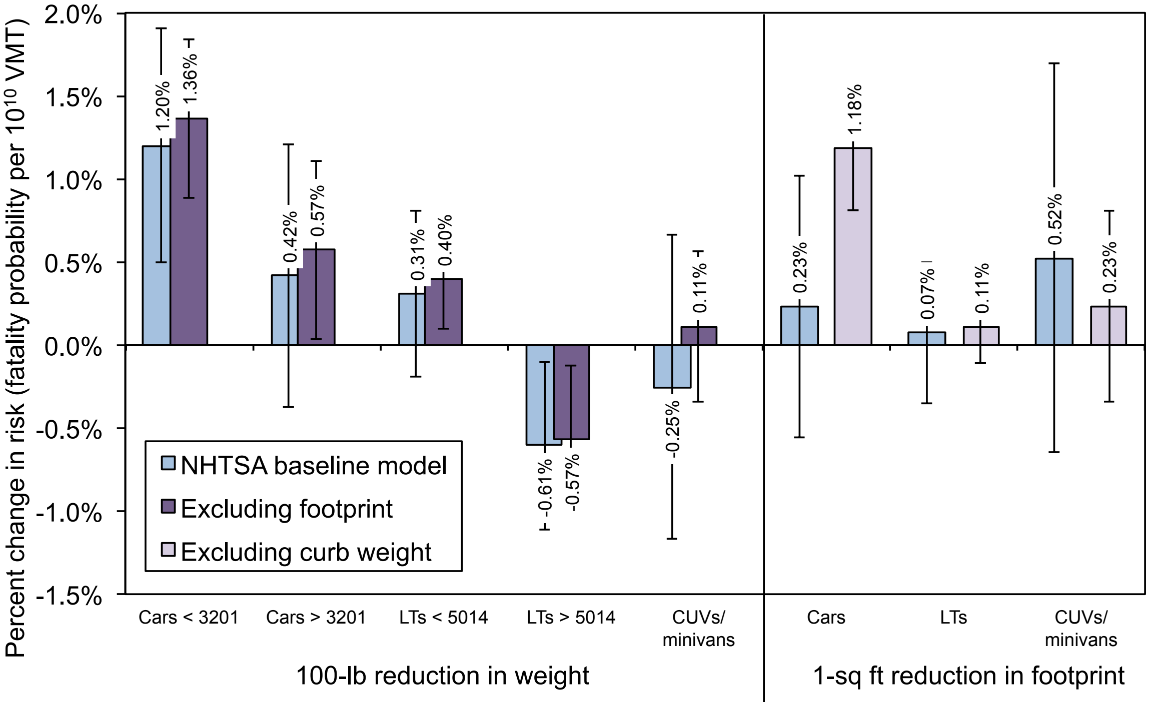
[19] Following NHTSA 2012 we combine the BLOCKER1 and BLOCKER2 variables for light trucks into a single BLOCKER variable.

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



Figures 3.4 through 3.6 show the effect of these two sensitivities by crash type; in contrast to Figures 2.3 through 2.5, the figures indicate that including only mass in the regression models (i.e. allowing footprint to vary with mass) greatly reduces or eliminates the large estimated decreases in risk in rollover crashes in cars and CUVs/minivans.

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

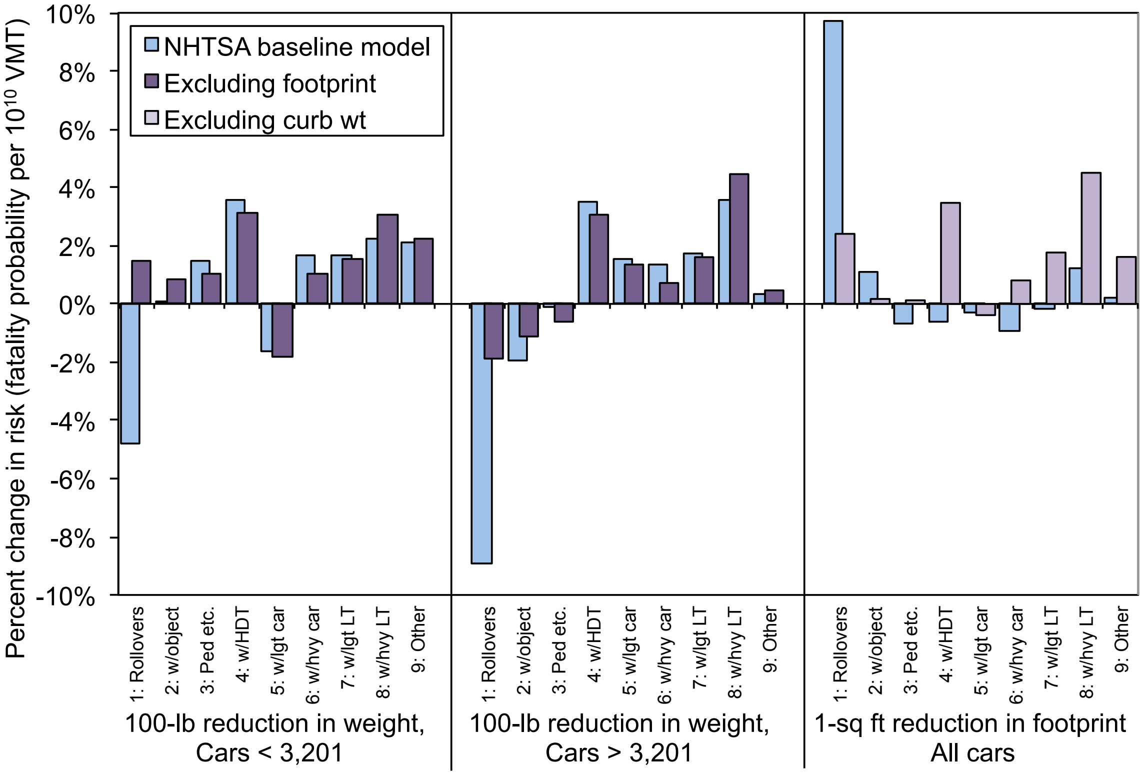


Figure 3.5. Estimated effect of reduction in light-duty truck mass or footprint on U.S. fatality risk per VMT, by crash type

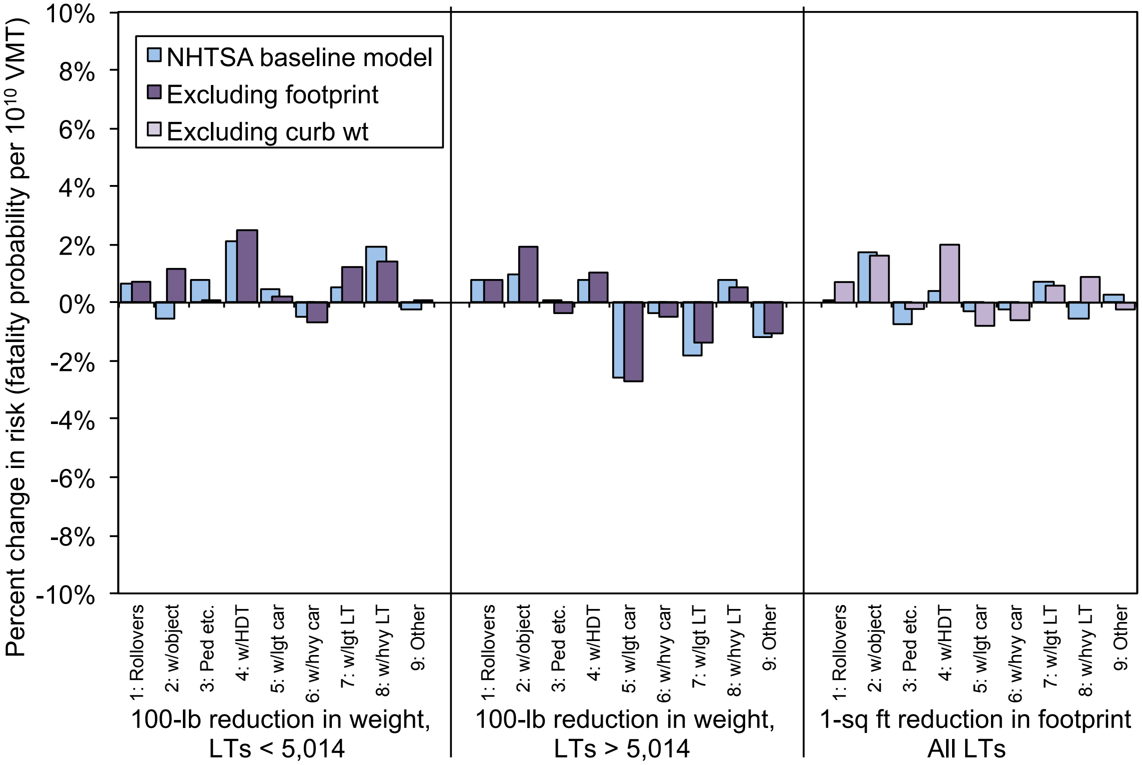
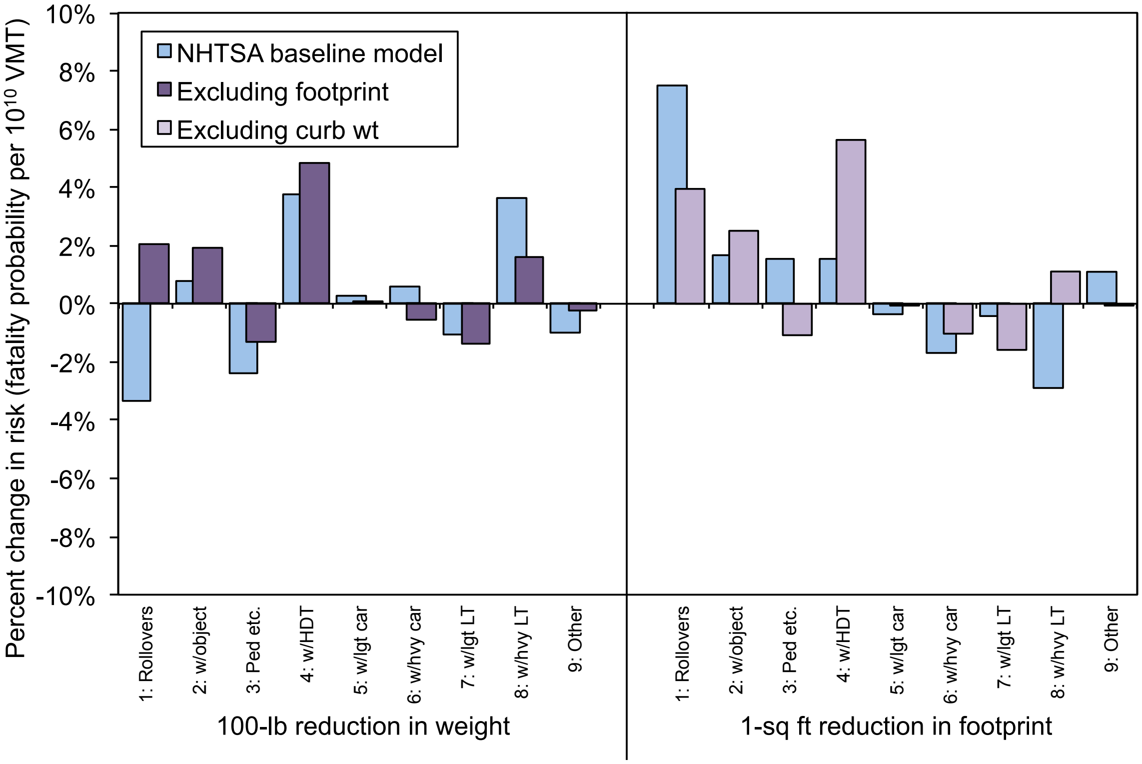


Figure 3.6. Estimated effect of reduction in CUV/minivan mass or footprint on U.S. fatality risk per VMT, by crash type

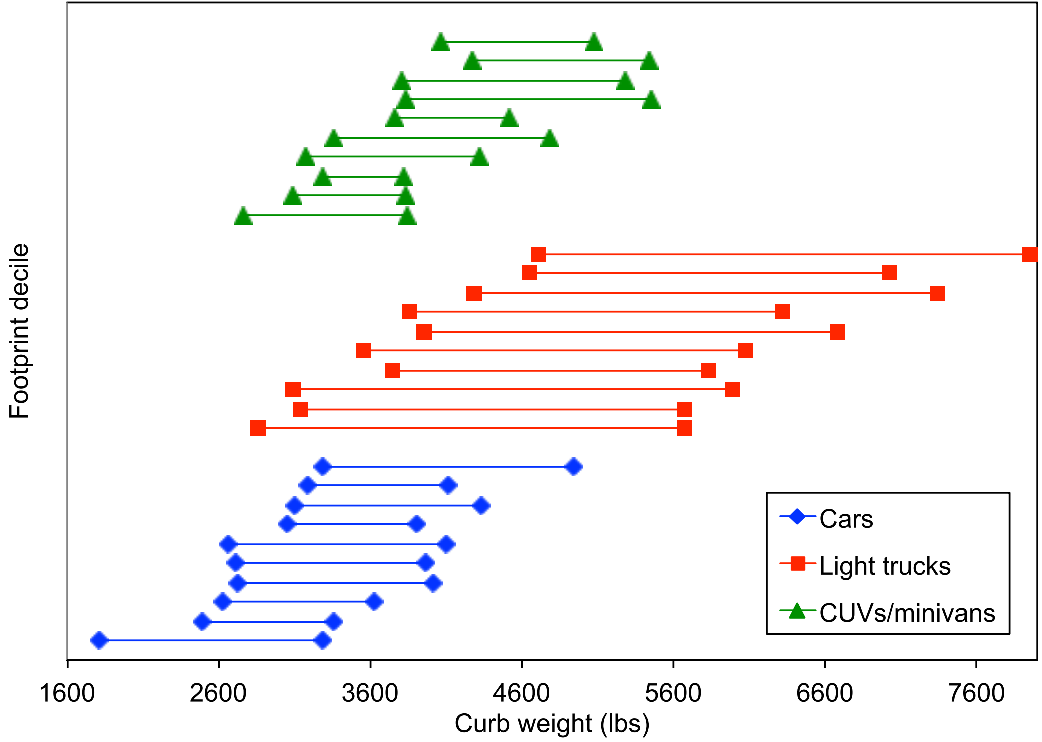


In its 2016 analysis NHTSA examined the relationship between curb weight and fatality risk for deciles of vehicles with roughly the same footprint. LBNL updated this analysis through 2012; Figure 3.7 shows the range in curb weights for the footprint deciles LBNL used for the three vehicle types. The 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.

In its 2012 report 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.

Table 3.2 replicates this analysis using data through 2012, 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 font 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

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



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 only two footprint deciles, and only one of those increases is statistically significant. On the other hand, lower mass in car rollover crashes is associated with decreased risk in the remaining eight footprint deciles, and five of those eight decreases are statistically significant. Table 3.2 indicates that lower car mass is associated with increased risk in a majority of footprint deciles in only three crash types: with a heavy-duty truck, a light light-duty truck, and other crashes; however, only five of these 21 increases are statistically significant. Lower light truck mass is associated with increased risk for six deciles in rollover crashes and in crashes with heavy-duty trucks, but only three of these 12 increases are statistically significant. Lower CUV/minivan mass is associated with increased risk for six deciles in crashes with heavy-duty trucks, and three of those six increases are statistically significant.

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 filled blue diamonds) in eight deciles, by over 20% in footprint deciles five, six, seven, and nine, and by over 10% in footprint decile three. Figure 3.10 indicates that mass reduction in CUVs/minivans is estimated to reduce risk in rollover crashes (shown as filled blue diamonds) in seven of the footprint deciles, and that these reductions are relatively large (over 10%), but not statistically significant, for footprint deciles one, three (a 91% reduction, not shown), five, and six. 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.

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

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

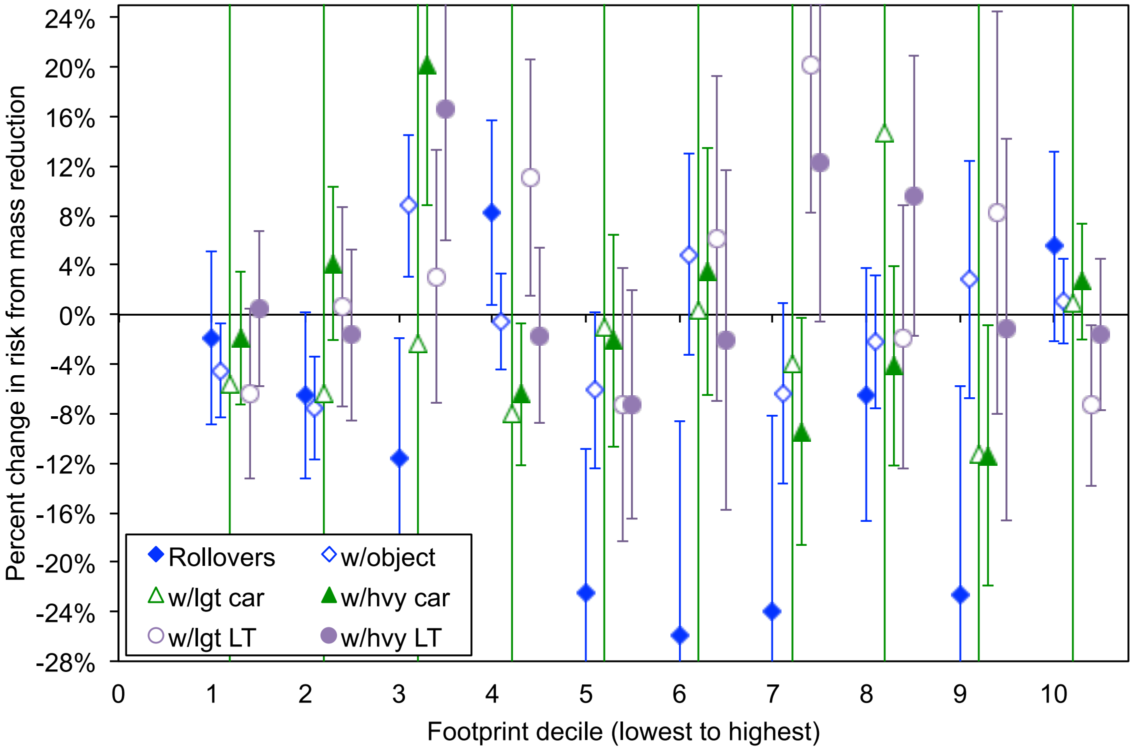


Figure 3.9. Estimated effect of light truck mass reduction on fatality risk, by footprint decile and crash type

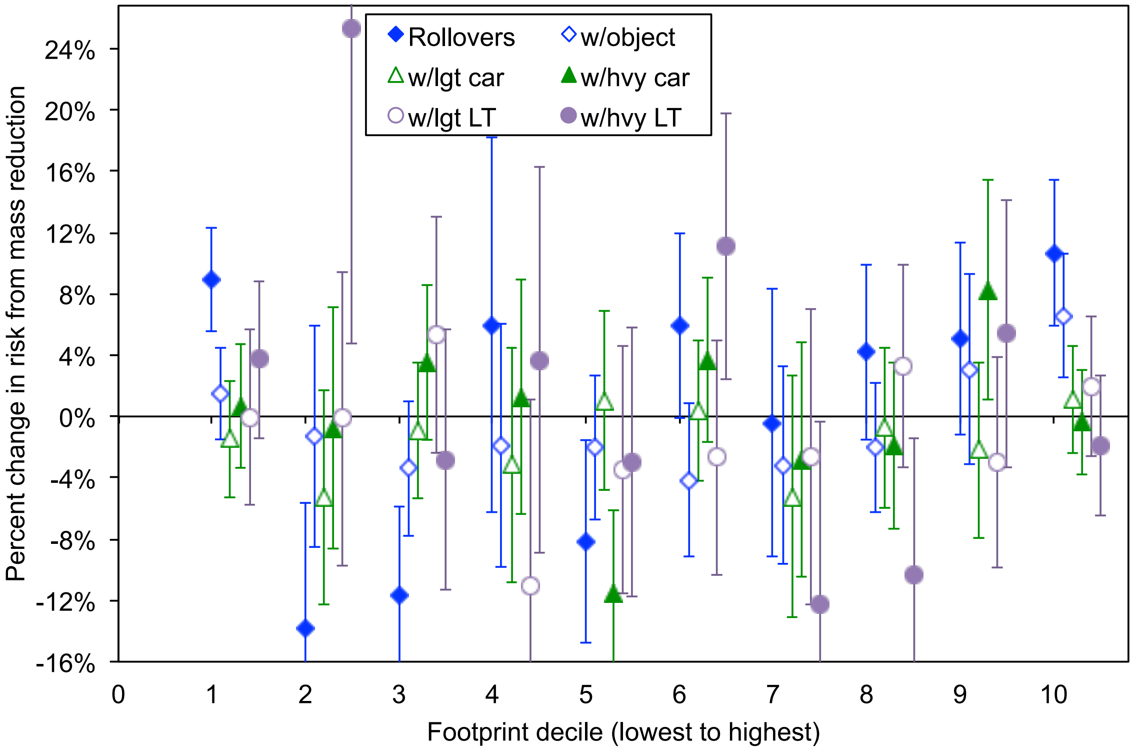
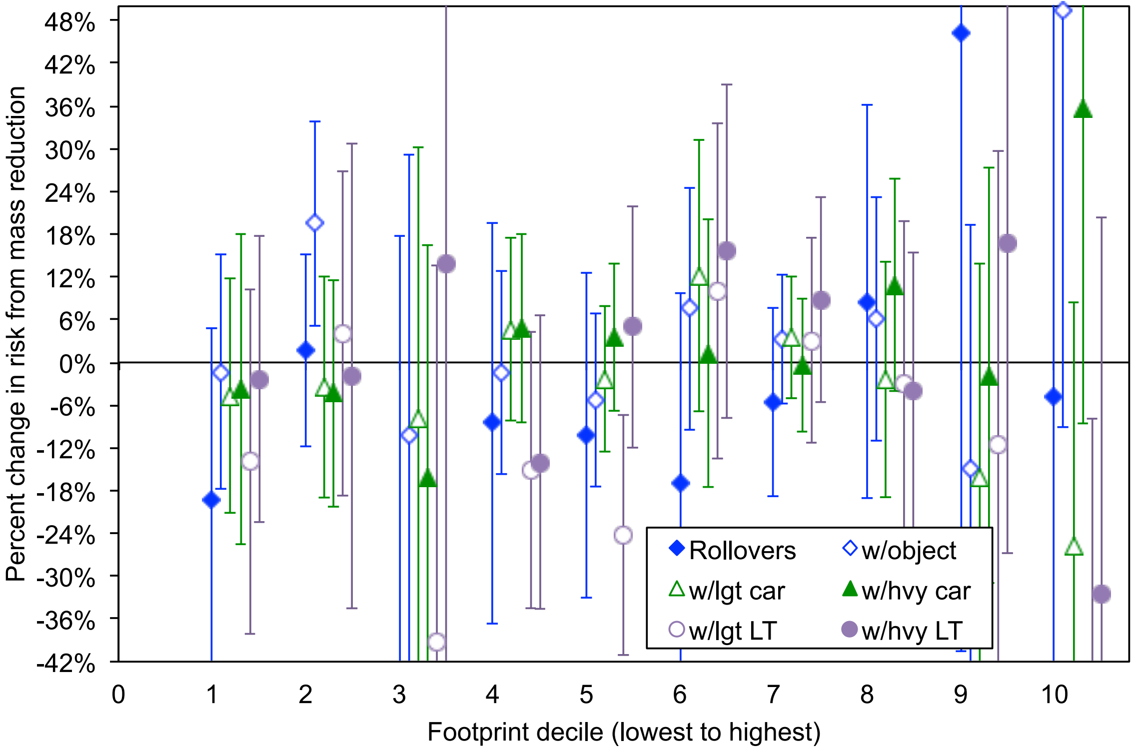


Figure 3.10. Estimated effect of CUV/minivan mass reduction on fatality risk, by footprint decile and crash type



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, including pedestrians and cyclists, 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 U.S. 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 of only 0.36 for cars and 0.58 for CUVs/minivans. Societal risk actually increases as light truck mass increases, and the correlation is low (r of -0.32).

Figures 4.2 through 4.4 show the relationship between unadjusted risk and mass by more detailed vehicle type; the lightest and heaviest vehicles are not shown in the figures as there are relatively few observations in these weight categories. Figure 4.2 indicates that the relationship between curb weight and fatality risk is weaker for 4-door cars than for 2-door cars. Note that the four lightest groups of 2-door cars have much lower risk than the next five groups of 2-door cars. Figure 4.3 indicates 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 U.S. societal fatality risk and curb weight, with vehicles grouped into 100-lb increments of curb weight, by vehicle type

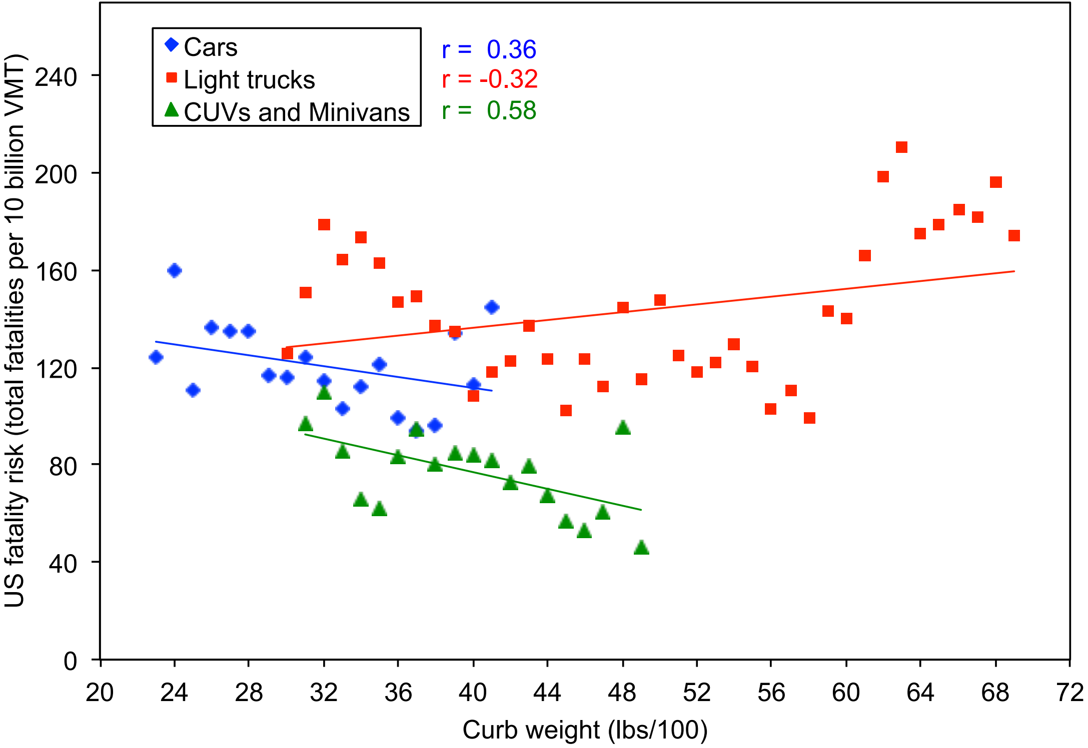


Figure 4.2. Relationship between U.S. societal fatality risk and curb weight, with vehicles grouped into 100-lb increments of curb weight, passenger cars

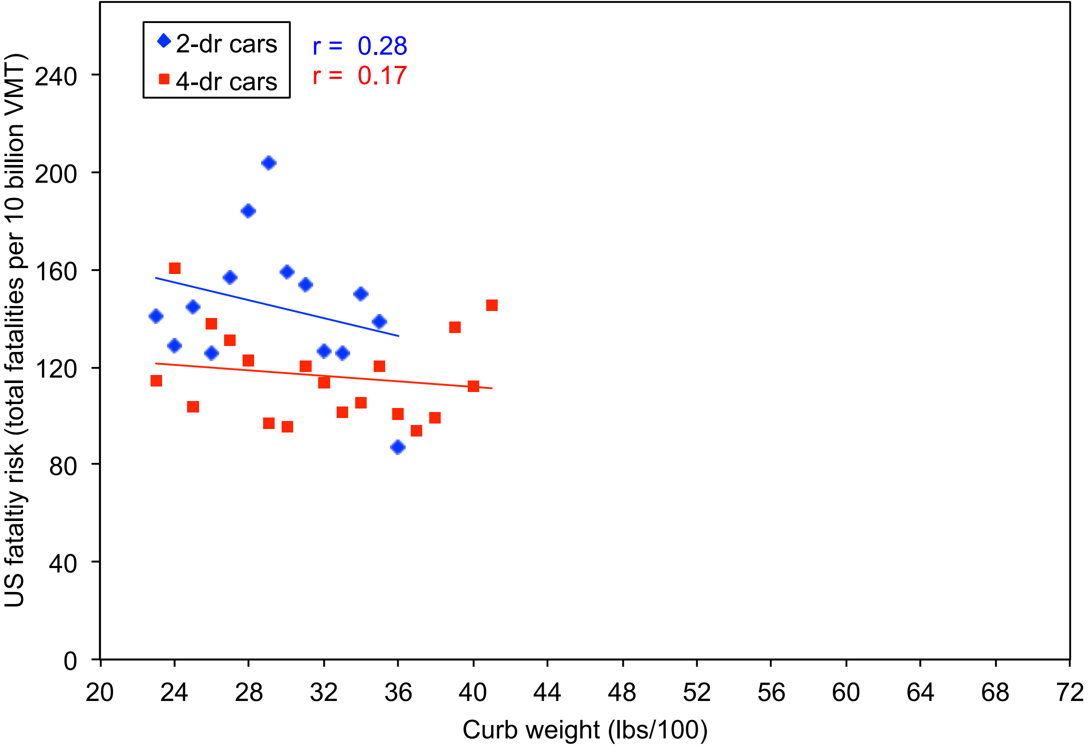


Figure 4.3. Relationship between U.S. societal fatality risk and curb weight, with vehicles grouped into 100-lb increments of curb weight, light trucks

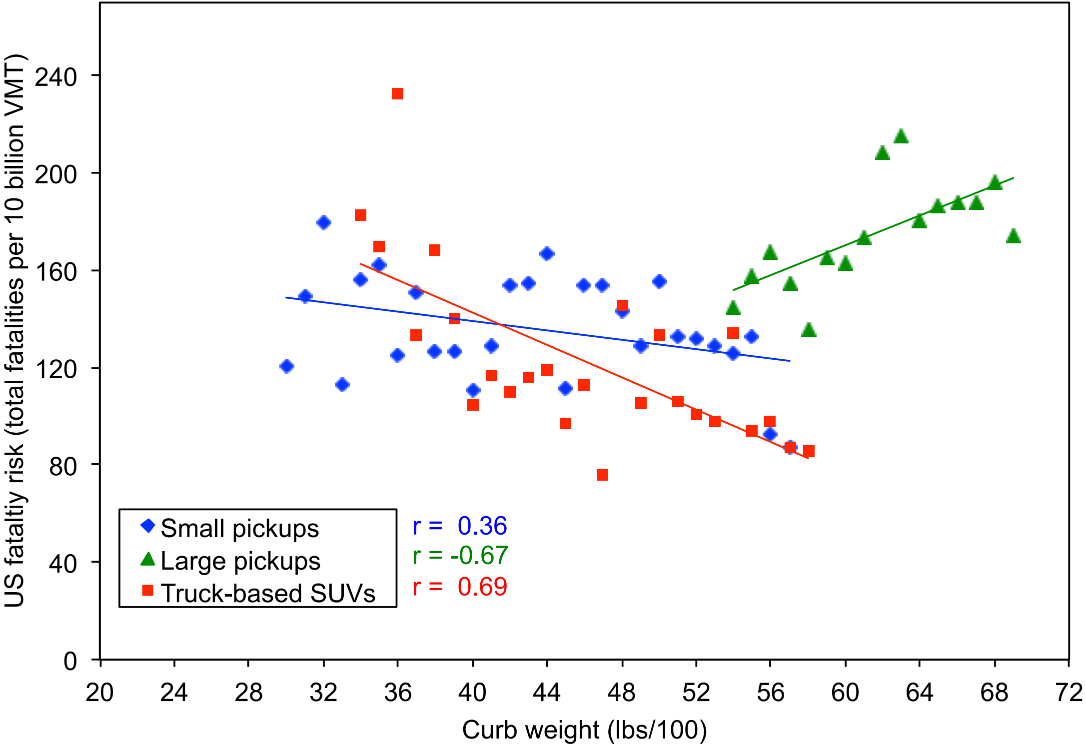
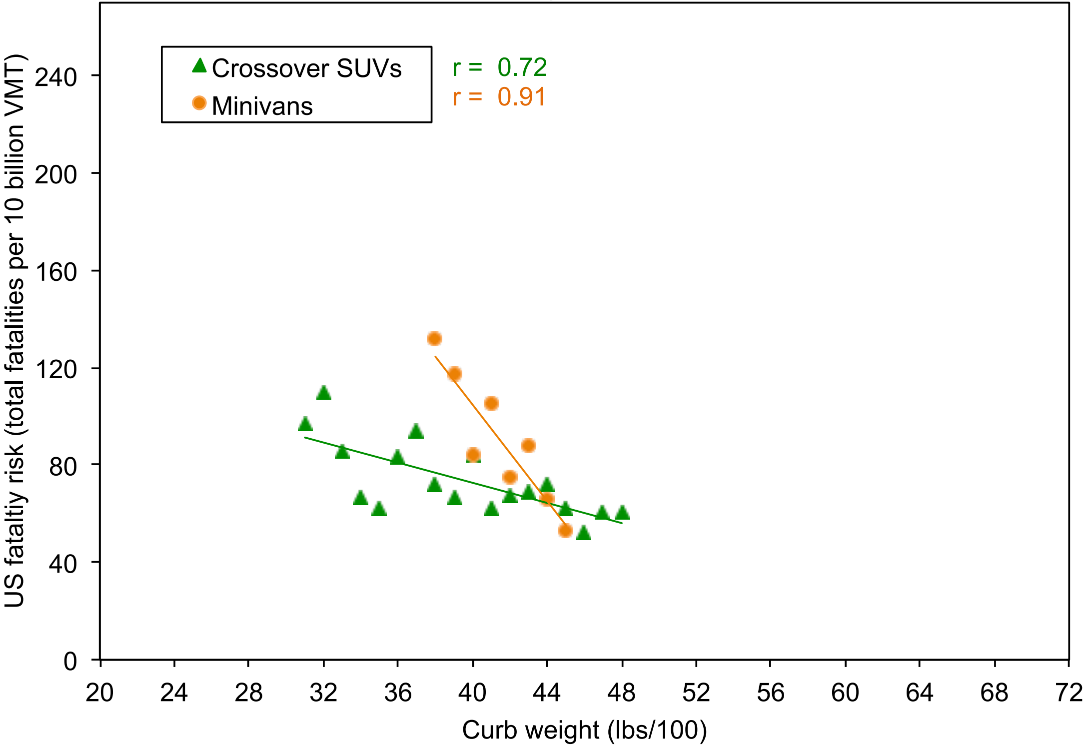


Figure 4.4. Relationship between U.S. societal fatality risk and curb weight, with vehicles grouped into 100-lb increments of curb weight, CUVs and minivans



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 correlation between car mass and risk in crashes with stationary objects improves substantially over that for all crashes (from an r of 0.36 in Figure 4.1 to 0.46 in Figure 4.5) and the correlation for CUVs is unchanged, while the fatality risk in crashes with objects now decreases with increasing mass for light trucks, with the degree of correlation unchanged, than in all types of crashes.

The correlations in Figures 4.1 through 4.5 are sensitive to the mass bins included in the analysis; vehicles with relatively low and high mass are not shown, since there are relatively few vehicles in those bins. Including those bins with low and high mass would reduce the correlation between mass and fatality risk.

Note that, for a given vehicle weight, light trucks have a slightly 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 after striking a stationary object, their increased use on more dangerous rural roads, and perhaps more passenger fatalities in light trucks than in cars.

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

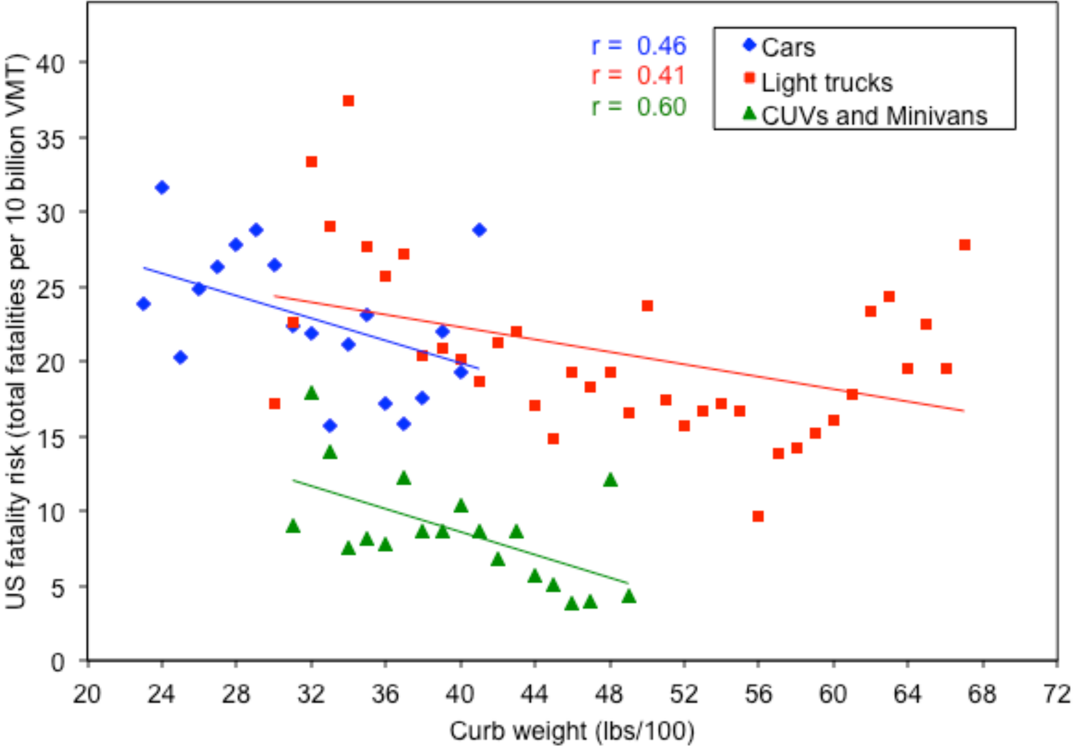


Table 4.1 summarizes the correlations between risk and a decrease in curb weight by 100-lb weight bins, by vehicle type, presented in Figures 4.1 through 4.5; the correlations shown in Table 4.1 include all vehicle models, whereas Figures 4.1 through 4.5 exclude weight bins with relatively few vehicles.

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

	U.S. fatality risk, all crashes			U.S. fatality risk, crashes with stationary objects		
Vehicle type	Estimate	r	R^2	Estimate	r	R^2
Cars	0.73%	0.25	0.06	0.37% *	0.46	0.21
Light trucks	-0.80% *	-0.32	0.10	0.21% *	0.41	0.17
CUVs/minivans	1.72% *	0.58	0.34	0.38% *	0.60	0.36
2-dr cars	1.83%	0.27	0.08	0.37%	0.10	0.01
4-dr cars	0.28%	0.09	0.01	0.11%	0.15	0.02
Sm pickups	0.32%	0.13	0.02	0.20%	0.28	0.08
Lg pickups	-3.07% *	-0.67	0.45	0.02%	0.03	0.00
SUVs	3.33% *	0.69	0.47	0.78% *	0.76	0.57
CUVs	2.19% *	0.76	0.58	0.45% *	0.72	0.53
Minivans	9.89% *	0.91	0.83	1.09% *	0.90	0.81

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. As in Figures 3.1 and 3.2, only 234 models with at least 10 billion VMT, or at least 100 fatalities, are included (86 car models, 102 light truck models, and 46 CUV/minivan models); these 234 models represent nearly 90% of all fatalities, vehicle registration-years, and VMT. Here we see that, on average, fatality risk declines with increasing mass for cars, and at a lower rate for CUVs and minivans, while, on average, risk increases slightly as mass increases for light trucks. However, although risk declines with increasing car weight, the low R^2 (0.04) 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 four-door car model labeled as A in the figure, which weighs 2,623 pounds, has a fatality risk of 258 per 10 billion VMT, while model B, which weighs 100 pounds less (2,523 pounds) has a fatality risk of only 71.

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.[20] 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 fatalities in each make and model by their total VMT, to obtain predicted risk, the number of predicted fatalities per 10 billion VMT. We excluded footprint as well as mass in the predicted risks we calculated from the NHTSA regressions, as the two vehicle attributes are moderately correlated.

We then estimated standardized risks for each vehicle model for a 50-year old male driving a 4-year old vehicle in the day, in a non-rural county, in a low-risk state, on a high-speed road. This was accomplished by running an additional regression model for each of the three vehicle types, which included all of the variables in NHTSA's baseline regression model, including vehicle mass and footprint. The coefficients for DRVMALE and SPDLIM55 from these regressions were multiplied by 1, while the VEHAGE coefficient was multiplied by 4, for each vehicle in the induced exposure dataset; the coefficients for the other driver and crash variables were multiplied by 0. The coefficients for the vehicle characteristics were multiplied by the value for each vehicle in the induced exposure dataset, in order to retain the effect that differences among vehicle models have on risks. The standardized fatalities were then multiplied by the VMT weight each induced exposure vehicle represents, summed across vehicle make and model, and divided by their total VMT.

For each vehicle model, the standardized risk was then multiplied by the ratio of actual risk to predicted risk, to estimate adjusted risk per 10 billion VMT accounting for common values of all driver and crash variables [(actual risk / predicted risk) * standardized risk].

Figure 4.7 shows the adjusted risks predicted by the regression model coefficients after accounting for all control variables except vehicle mass and footprint. Note that the adjusted risks in Figure 4.7 are quite a bit lower than the actual risks in Figure 4.6, and that the correlation between mass and adjusted risk is better than the correlation between mass and actual risk. However, 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, and including the residual risk not explained by the variables in the regression model, there still is a large range in fatality risk across vehicle models of similar weight, for all three vehicle types, as indicated by the low R^2 values: 0.30 for cars, 0.13 for light trucks, and 0.03 for CUVs/minivans. For example, the adjusted fatality risk of the four-door car model A (208 per 10 billion VMT) is over twice that of car model B (101 per 10 billion VMT), which weighs 100 pounds less (2,523 vs 2,623 pounds). Also note that, after controlling for all driver, crash and vehicle variables other than mass and footprint, adjusted fatality risk decreases as mass increases in light trucks, as well as in cars and CUVs/minivans.

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[20] 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.

Figure 4.6. Actual U.S. societal fatality risk per VMT and curb weight, by vehicle model

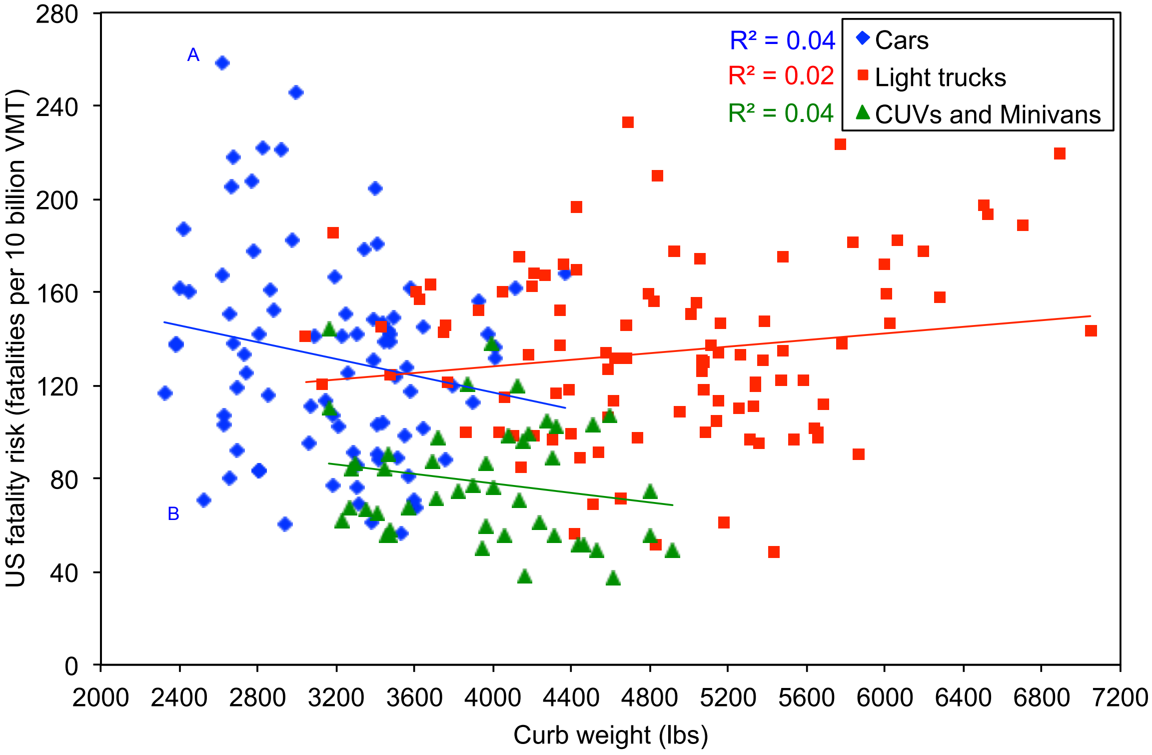
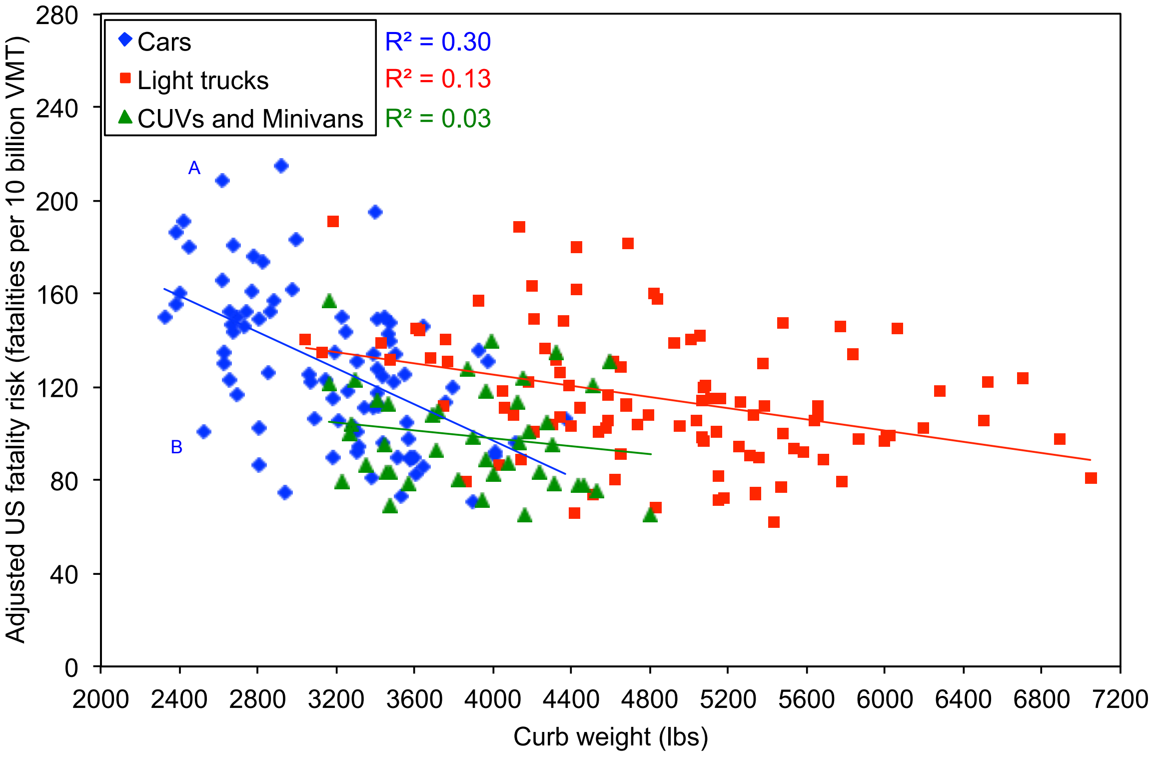


Figure 4.7. Adjusted U.S. societal fatality risk per VMT after accounting for all driver, crash, and vehicle variables except mass and footprint, vs. curb weight



Figures 4.8 and 4.9 show similar plots for 86 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 A provides an example of the values shown in Figures 4.8 and 4.9. This model has an actual risk of 258 fatalities per 10 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 208 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, 50 fatalities per 10 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 4.9 indicates that, after accounting for all vehicle, driver, and crash variables other than weight and footprint, as well as the residual risk not explained by the baseline regression model, 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 A, which weighs 2,623 pounds and has a footprint of 42.3 square feet, has an adjusted fatality risk twice that of model B, which weighs 2,523 pounds and has a footprint of 38.9 square feet (208 vs. 101 fatalities per 10 billion VMT). Similarly, model C (2,976 pounds, 41.9 sq ft, 161 fatalities per 10 billion VMT) has an adjusted fatality risk over twice that of model D (2,936 pounds, 43.6 sq ft, 74 fatalities per 10 billion VMT), while model E (3,644 pounds, 48.2 sq ft, 146 fatalities per 10 billion VMT) has an adjusted risk twice that of model F (3,532 pounds 46.1 sq ft, 73 fatalities per 10 billion VMT). Models B, D, and F all have adjusted risk similar to or lower than that of models G and H, which are both substantially larger and heavier (G: 4,111 pounds, 51.1 sq ft, 96 fatalities per 10 billion VMT; H: 4,368 pounds, 53.1 sq ft, 106 fatalities per 10 billion VMT). Clearly differences in vehicle design can, and already do, mitigate any safety penalty from reduced mass. The fact that NHTSA attributed 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 4.9 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.

Figures 4.10 and 4.11 show the actual and adjusted risks vs. curb weight for 102 pickup truck and truck-based SUV models. Adjusted risk declines with increasing curb weight for small pickups and SUVs, but is essentially flat with increasing weight for large pickups. And the correlations between adjusted fatality risk and curb weight are very weak, even after accounting for all of the driver, crash, and other vehicle variables in the NHTSA logistic regression model. Actual and adjusted risk for 46 CUV and minivan models are shown in Figures 4.12 and 4.13. Again, there is little correlation between adjusted risk and curb weight for CUVs or minivans, even after accounting for all variables except vehicle mass and footprint.

Figure 4.8. Actual U.S. societal fatality risk per VMT vs. curb weight, car models

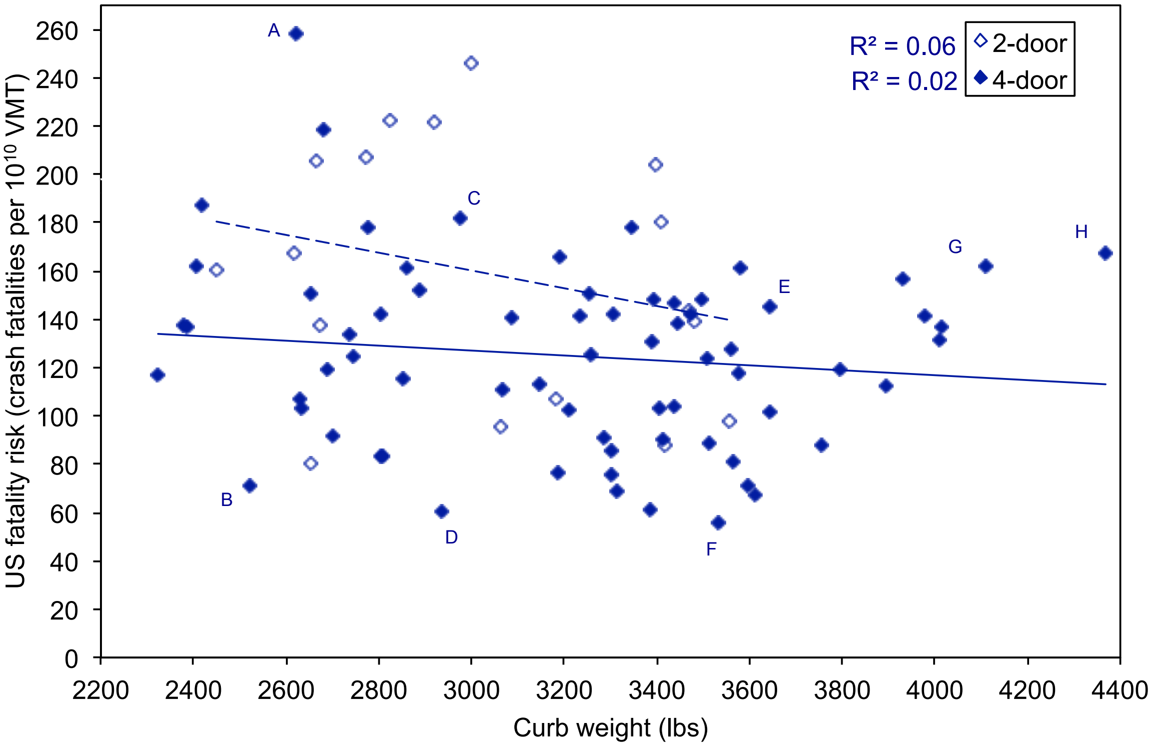


Figure 4.9. Adjusted U.S. societal fatality risk per VMT after accounting for all driver, crash, and vehicle variables except mass and footprint vs. curb weight, car models

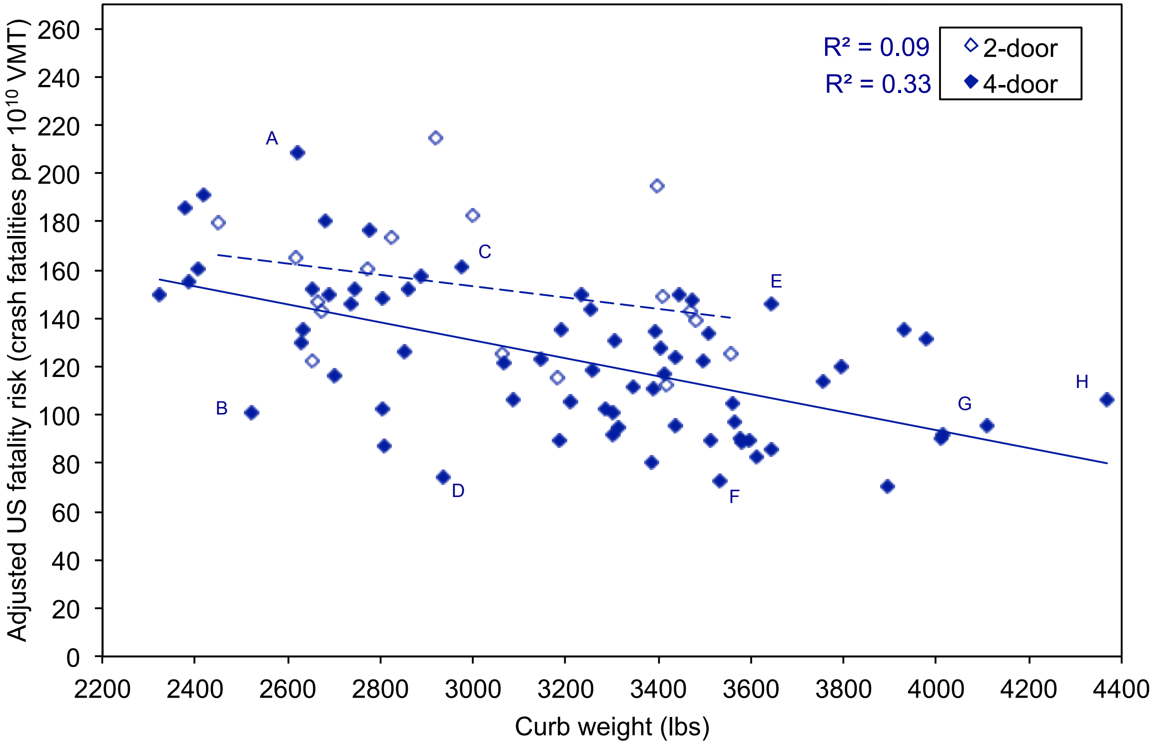


Figure 4.10. Actual U.S. societal fatality risk per VMT vs. curb weight, light truck models

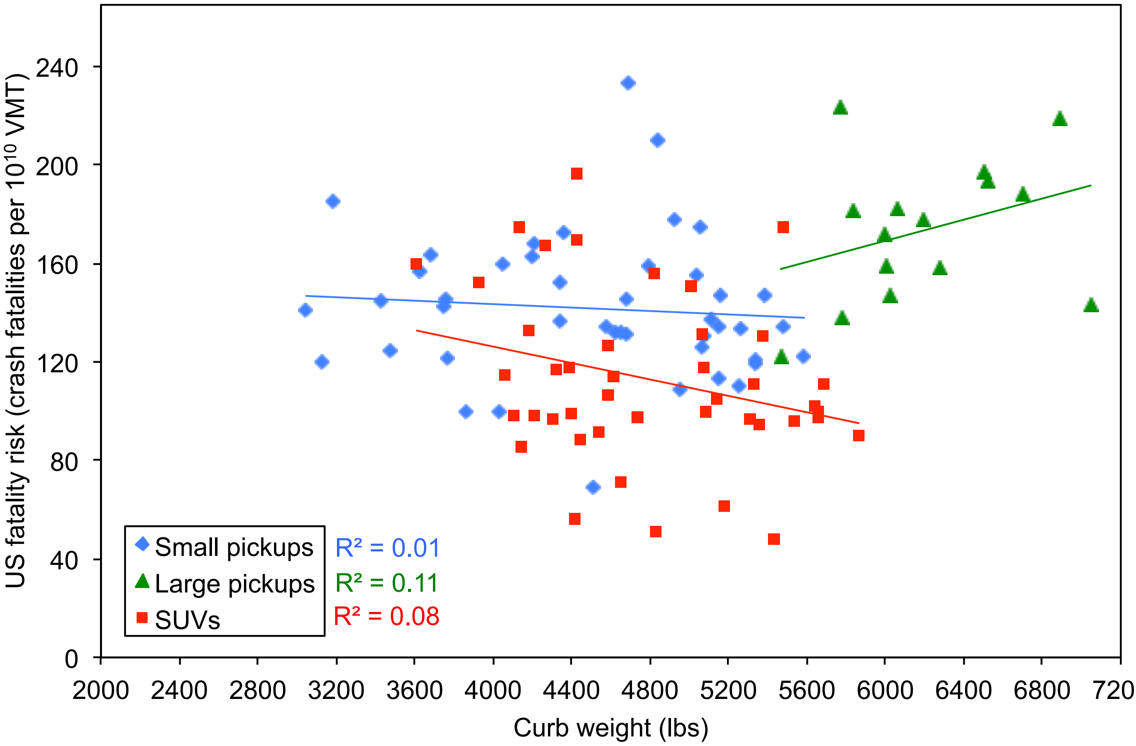


Figure 4.11. Adjusted U.S. societal fatality risk per VMT after accounting for all driver, crash, and vehicle variables except mass and footprint vs. curb weight, light truck models

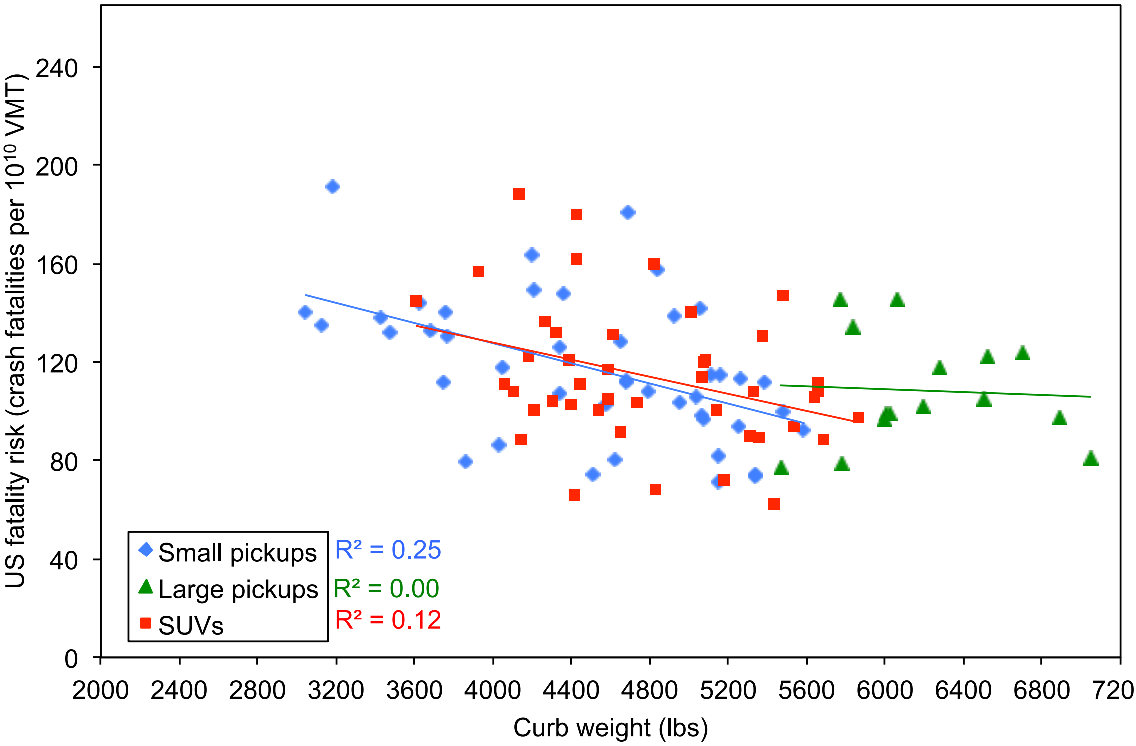


Figure 4.12. Actual U.S. societal fatality risk per VMT vs. curb weight, CUV/Minivan models

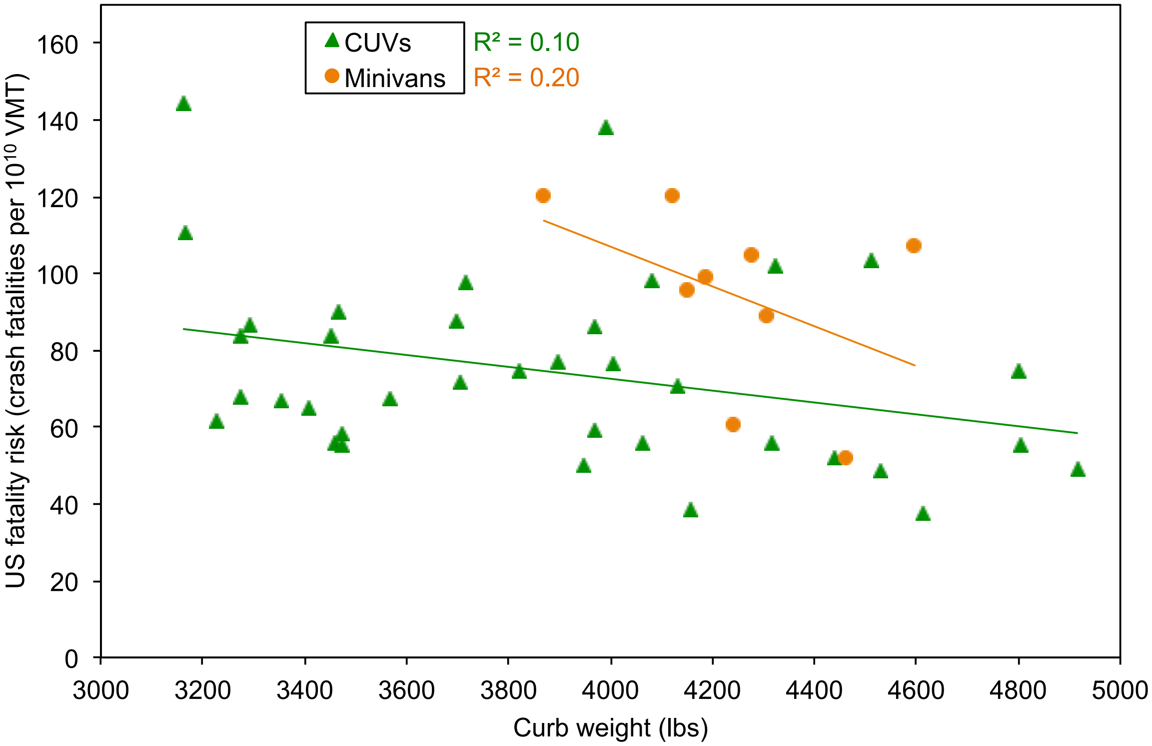


Figure 4.13. Adjusted U.S. societal fatality risk per VMT after accounting for all driver, crash and vehicle variables except mass and footprint vs. curb weight, CUV/Minivan models

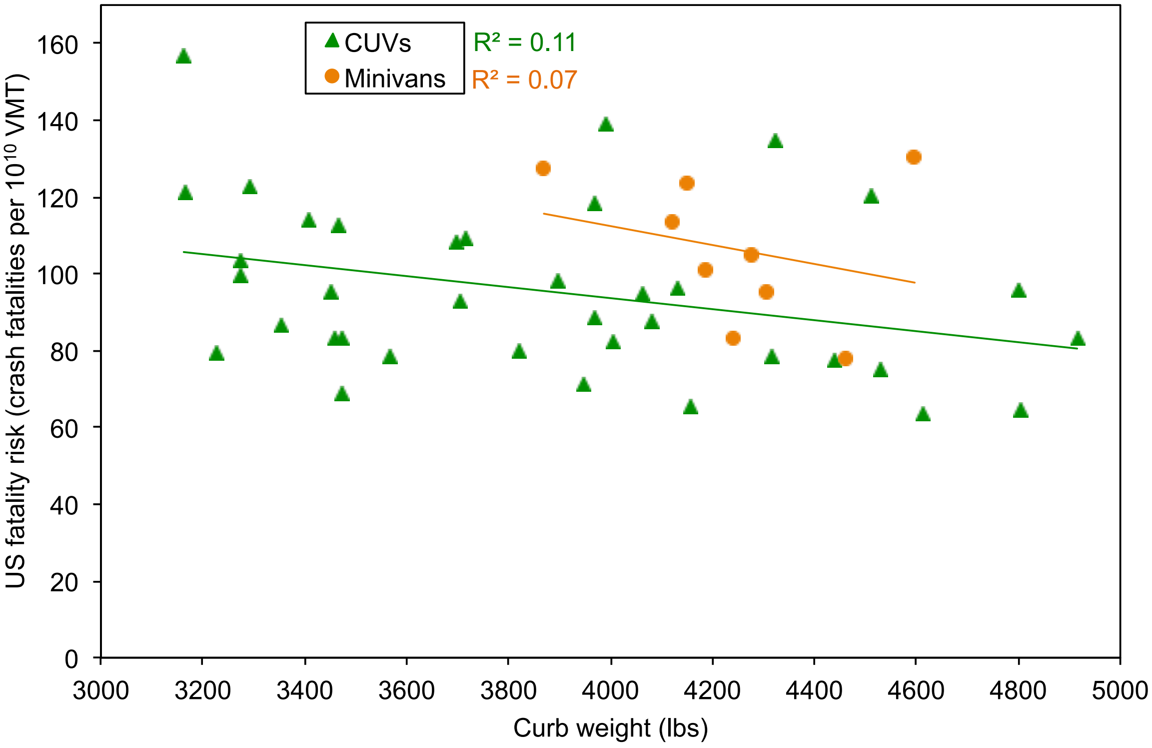


Table 4.2 summarizes the relationships between actual and adjusted, as well as the intermediate steps predicted and residual, fatality risk and vehicle curb weight that are presented in Figures 4.6 through 4.17. The table shows the estimated percent change in each type of fatality risk per 100-pound 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 both actual (1.8%) and adjusted (3.9%) fatality risk increases as weight decreases for cars, on average; while the increases in actual risk are not statistically significant for either two-door (3.6%) or four-door (1.0%) cars, the increases in adjusted risk for four-door cars (3.7%) is statistically significant, but not for two-door cars (2.3%), after accounting for all variables included in NHTSA's regression models except vehicle mass and footprint. While there is a wide range in actual risk for cars of similar mass, as evidenced by the rather low R^2 values, the correlation between adjusted risk and mass is stronger, with R^2 values of 0.30 for all cars and 0.33 for four-door cars, but only 0.09 for two-door cars. On the other hand, fatality risk <u>decreases</u> as weight decreases for heavy-duty pickups, although the estimated effect decreases from a 2.4% decrease in actual risk to a 0.2% increase in adjusted risk after accounting for all variables except vehicle mass and footprint. The correlation between actual or adjusted risk and weight is low for all types of light trucks. Both actual and adjusted risk increase as CUV and minivan weight decreases, although the correlations between risk and mass are low.

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 U.S. fatality risk		Predicted risk		Residual risk		Adjusted risk	
Vehicle type	Est.	R^2	Est.	R^2	Est.	R^2	Est.	R^2
Cars	1.8%	0.04	0.8%	0.01	1.0%	0.03	3.9%	* 0.30
Light trucks	-0.7%	0.02	-1.0%	* 0.07	0.3%	0.02	1.2%	* 0.13
CUVs/minivans	1.0%	0.04	1.1%	0.06	-0.1%	0.00	1.1%	0.05
2-dr cars	3.6%	0.06	5.2%	0.15	-1.6%	0.05	2.3%	0.09
4-dr cars	1.0%	0.02	-0.4%	0.00	1.4% *	0.07	3.7%	* 0.33
Small pickups	0.3%	0.01	0.0%	0.00	0.4%	0.01	2.0%	* 0.24
Heavy-duty PUs	-2.4%	0.13	-2.7%	* 0.23	0.3%	0.00	0.2%	0.00
SUVs	1.7%	0.08	1.3%	0.07	0.4%	0.01	1.8%	* 0.13
CUVs	1.6% *	0.10	1.5%	* 0.11	0.1%	0.00	1.4%	* 0.11
Minivans	5.0%	0.19	3.9%	0.21	1.1%	0.04	2.4%	0.07
Cars < 3201	1.9%	0.01	-0.8%	0.00	2.7%	0.06	5.3%	* 0.15
Cars ≥ 3201	-2.7%	0.04	-3.9%	0.07	1.2%	0.02	2.4%	0.06
LTs < 5014	1.1%	0.02	0.9%	0.02	0.2%	0.00	1.9%	* 0.08
LTs ≥ 5014	-3.6% *	0.25	-3.7%	* 0.31	0.1%	0.00	0.1%	0.00
CUVs/ minivans	1.0%	0.04	1.1%	0.06	-0.1%	0.00	1.1%	0.05

* statistically significant at the 95% confidence level

In his peer review of the 2011 LBNL preliminary 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 indicates that, after also accounting for footprint, the estimated effect of mass reduction on adjusted risk is the same or less detrimental for all seven vehicle types than in Table 4.2, and the correlations between adjusted risk and mass also are lower in Table 4.3 than in Table 4.2.

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, actual fatality risk for heavy-duty pickups decreases (by 4.4%) as footprint decreases, but less so after adjusting for all variables (1.8% decrease). In general, actual or adjusted risk by vehicle model is less correlated with footprint than with mass, for all vehicle types. Table 4.5 indicates that, after also accounting for footprint, the estimated effect of footprint reduction on adjusted risk is less detrimental for five of the seven vehicle types than in Table 4.4, and the correlations between adjusted risk and footprint are the same or lower.

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

Vehicle type	Actual U.S. fatality risk		Predicted risk		Residual risk		Adjusted risk	
	Est.	R^2	Est.	R^2	Est.	R^2	Est.	R^2
Cars	1.8%	0.04	1.5%	0.04	0.3%	0.00	3.3% *	0.19
Light trucks	-0.7%	0.02	-1.1% *	0.07	0.4%	0.02	1.0% *	0.11
CUVs/minivans	1.0%	0.04	1.4%	0.07	-0.3%	0.01	0.9%	0.04
2-dr cars	3.6%	0.06	5.5%	0.20	-1.9%	0.06	1.7%	0.04
4-dr cars	1.0%	0.02	0.5%	0.01	0.6%	0.01	3.0% *	0.21
Small pickups	0.3%	0.01	0.1%	0.00	0.3%	0.01	1.6% *	0.20
Heavy-duty PUs	-2.4%	0.13	-3.2%	0.23	0.8%	0.02	0.2%	0.00
SUVs	1.7%	0.08	1.4%	0.07	0.3%	0.01	1.6% *	0.13
CUVs	1.6% *	0.10	1.8% *	0.13	-0.2%	0.00	1.2%	0.09
Minivans	5.0%	0.19	4.2%	0.21	0.8%	0.02	2.3%	0.08
Cars < 3201	1.9%	0.01	0.4%	0.00	1.6%	0.02	4.1%	0.08
Cars ≥ 3201	-2.7%	0.04	-2.7%	0.04	0.1%	0.00	1.7%	0.02
LTs < 5014	1.1%	0.02	1.4%	0.04	-0.3%	0.00	1.3%	0.05
LTs ≥ 5014	-3.6% *	0.25	-4.1% *	0.31	0.5%	0.02	0.1%	0.00
CUVs/ minivans	1.0%	0.04	1.4%	0.07	-0.3%	0.01	0.9%	0.04

* statistically significant at the 95% confidence level

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 U.S. fatality risk		Predicted risk		Residual risk		Adjusted risk	
	Est.	R^2	Est.	R^2	Est.	R^2	Est.	R^2
Cars	1.8%	0.02	0.4%	0.00	1.4%	0.04	4.9% *	0.28
Light trucks	-1.8% *	0.17	-1.9% *	0.28	0.1%	0.00	0.7% *	0.04
CUVs/minivans	-0.7%	0.02	-0.2%	0.00	-0.5%	0.02	-0.1%	0.00
2-dr cars	2.2%	0.01	4.0%	0.04	-1.8%	0.03	2.4%	0.04
4-dr cars	0.7%	0.00	-1.2%	0.02	1.9% *	0.08	4.6% *	0.29
Small pickups	0.4%	0.01	-0.1%	0.00	0.4%	0.02	1.7% *	0.16
Heavy-duty PUs	-4.4% *	0.38	-1.7%	0.08	-2.7%	0.21	-1.8%	0.11
SUVs	0.5%	0.00	-0.2%	0.00	0.6%	0.03	1.2%	0.05
CUVs	0.2%	0.00	0.3%	0.00	-0.1%	0.00	0.6%	0.01
Minivans	5.8%	0.28	5.4% *	0.44	0.5%	0.01	2.3%	0.07
Cars < 3201	1.3%	0.00	-0.9%	0.00	2.2%	0.03	5.1% *	0.10
Cars ≥ 3201	-3.3%	0.05	-5.4% *	0.12	2.0%	0.04	3.1% *	0.09
LTs < 5014	-2.2% *	0.10	-2.0% *	0.16	-0.2%	0.00	0.1%	0.00
LTs ≥ 5014	-3.9% *	0.50	-3.6% *	0.52	-0.3%	0.01	-0.3%	0.01
CUVs/ minivans	-0.7%	0.02	-0.2%	0.00	-0.5%	0.02	-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

	Actual U.S. fatality risk		Predicted risk		Residual risk		Adjusted risk	
Vehicle type	Est.	R^2	Est.	R^2	Est.	R^2	Est.	R^2
Cars	1.8%	0.02	1.5%	0.02	0.3%	0.00	3.9% *	0.16
Light trucks	-1.8% *	0.17	-1.8% *	0.23	0.0%	0.00	0.6% *	0.04
CUVs/minivans	-0.7%	0.02	-0.2%	0.00	-0.6%	0.03	-0.3%	0.00
2-dr cars	2.2%	0.01	5.4%	0.08	-3.2%	0.09	0.8%	0.00
4-dr cars	0.7%	0.00	-0.1%	0.00	0.8%	0.01	3.4% *	0.16
Small pickups	0.4%	0.01	0.5%	0.03	-0.1%	0.00	1.3% *	0.11
Heavy-duty PUs	-4.4% *	0.38	-2.2%	0.11	-2.2%	0.12	-1.9%	0.12
SUVs	0.5%	0.00	0.0%	0.00	0.5%	0.01	1.1%	0.04
CUVs	0.2%	0.00	0.4%	0.00	-0.2%	0.00	0.3%	0.00
Minivans	5.8%	0.28	5.4% *	0.44	0.5%	0.01	2.3%	0.09
Cars < 3201	1.3%	0.00	0.5%	0.00	0.7%	0.00	3.1%	0.03
Cars ≥ 3201	-3.3%	0.05	-4.9% *	0.12	1.6%	0.03	2.1%	0.03
LTs < 5014	-2.2% *	0.10	-1.7% *	0.12	-0.5%	0.01	0.0%	0.00
LTs ≥ 5014	-3.9% *	0.50	-3.7% *	0.52	-0.2%	0.00	-0.2%	0.01
CUVs/ minivans	-0.7%	0.02	-0.2%	0.00	-0.6%	0.03	-0.3%	0.00

* statistically significant at the 95% confidence level

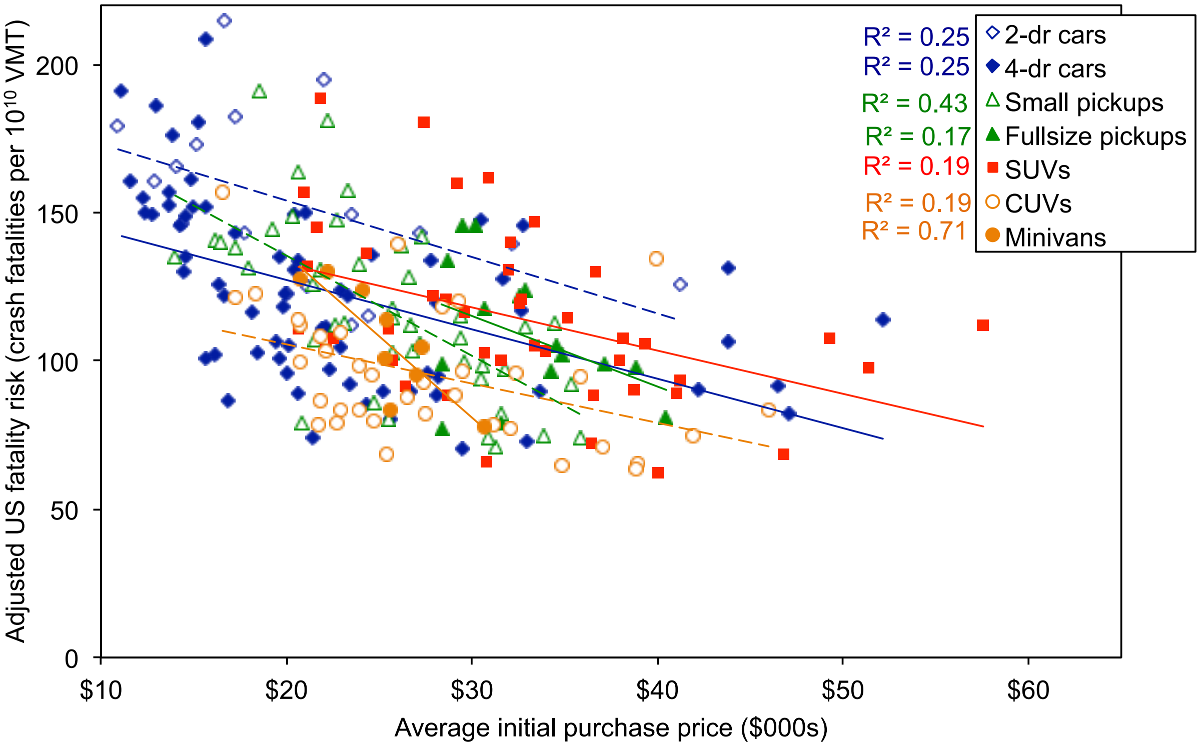
It is possible that other differences in vehicle models, particularly other aspects of vehicle design or subtle differences in driver behavior, explain some of the remaining variation in risk for vehicles of similar weight. We examined the relationship between fatality risk, vehicle mass, and two other 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 IHS 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 U.S. 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 4.14 plots adjusted U.S. fatality risk per 10 billion VMT by vehicle initial purchase price, by vehicle type and model, while Figure 4.15 plots vehicle purchase price by curb weight. Figure 4.14 indicates that adjusted fatality risk tends to decrease as vehicle purchase price increases, although the correlation between adjusted fatality risk and vehicle price is fairly weak for all vehicle types except small pickups (R^2 of 0.43) and minivans (R^2 of 0.71). However,

Figure 4.15 indicates that the correlation between vehicle weight and purchase price is strong for all vehicle types except minivans, with price increasing as weight increases.[21]

Figures 4.16 and 4.17 show the relationships between average median household income and adjusted U.S. fatality risk (Figure 4.16) and vehicle curb weight (Figure 4.17). Figure 4.16 indicates that adjusted fatality risk decreases as household income increases for all vehicle types except large pickups, and that the correlation between adjusted fatality risk and household income is fairly weak for cars (R^2 of 0.25 for two-door cars and R^2 of 0.29 for four-door cars), but relatively strong for other vehicle types, especially minivans (R^2 of 0.72). Figure 4.17 indicates that vehicle weight tends to increase as household income increases for a all types of vehicles except for small and large pickups, but the correlations between household income and vehicle weight are very low; the trend of increasing adjusted fatality risk as income declines does not appear to be explained by low income households driving lighter vehicles.

Figure 4.14. Relationship between vehicle initial purchase price and adjusted U.S. societal fatality risk per VMT, by vehicle model



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[21] 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 0.95.

Figure 4.15. Relationship between vehicle mass and initial purchase price, by vehicle model

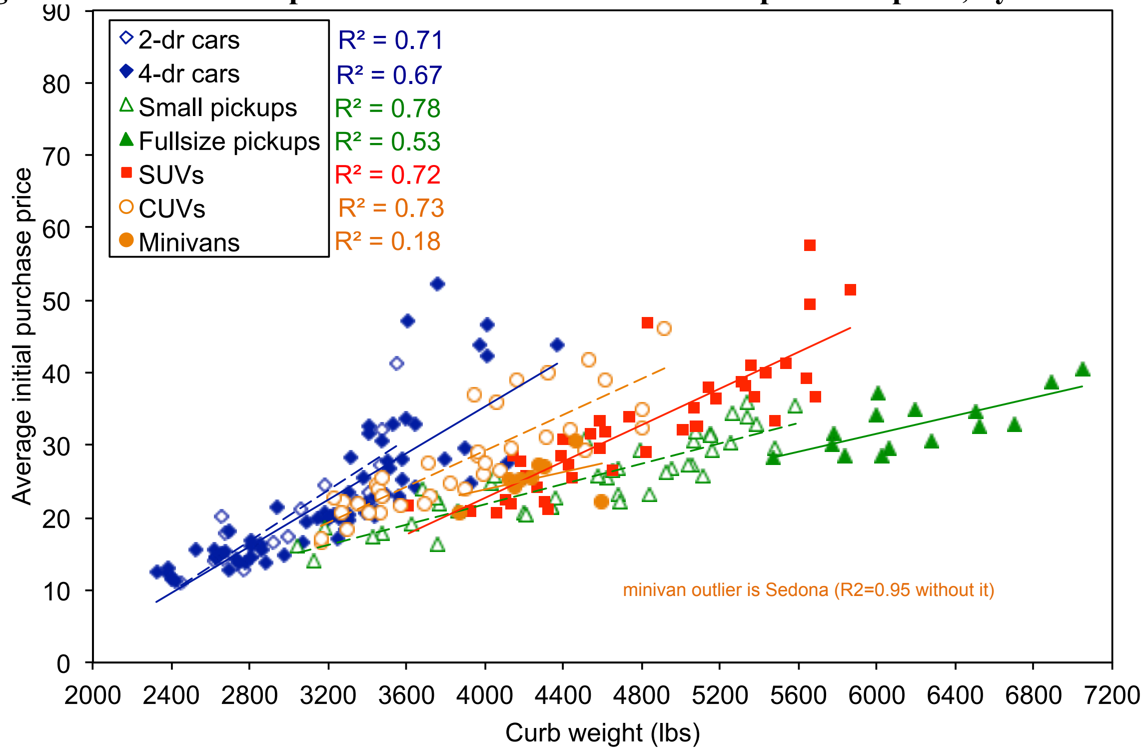


Figure 4.16. Relationship between household income and adjusted U.S. societal fatality risk per VMT, by vehicle model

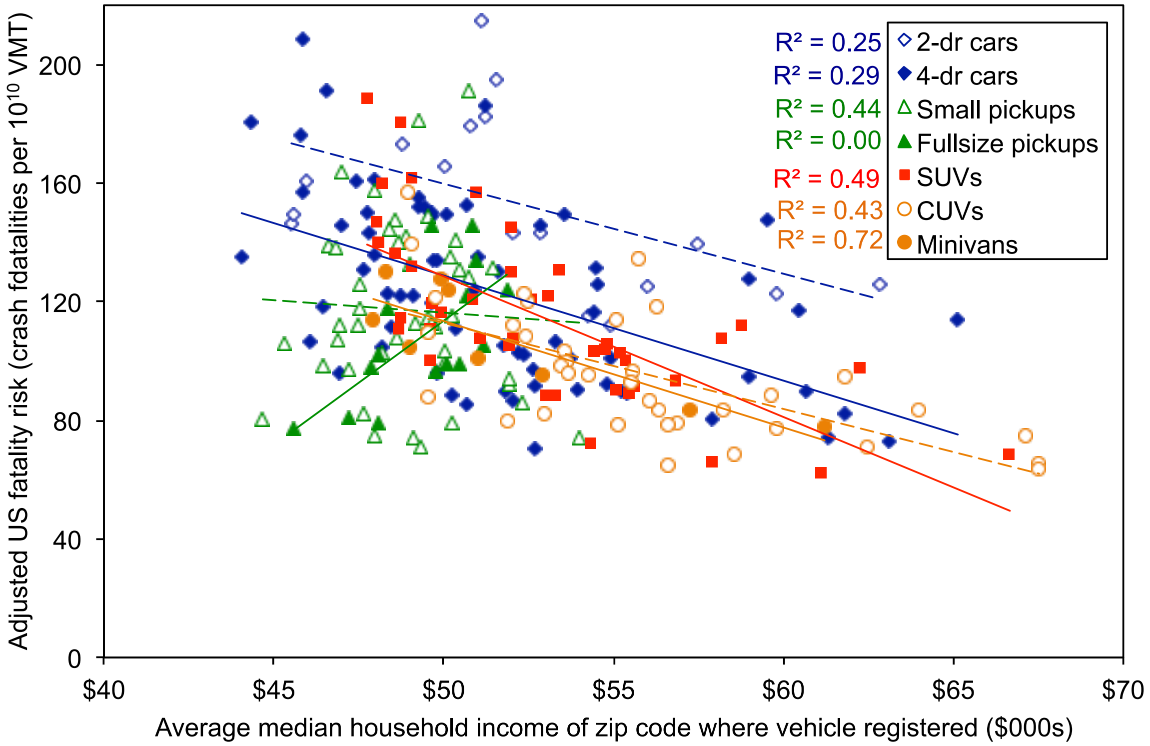


Figure 4.17. Relationship between vehicle mass and household income, by vehicle model

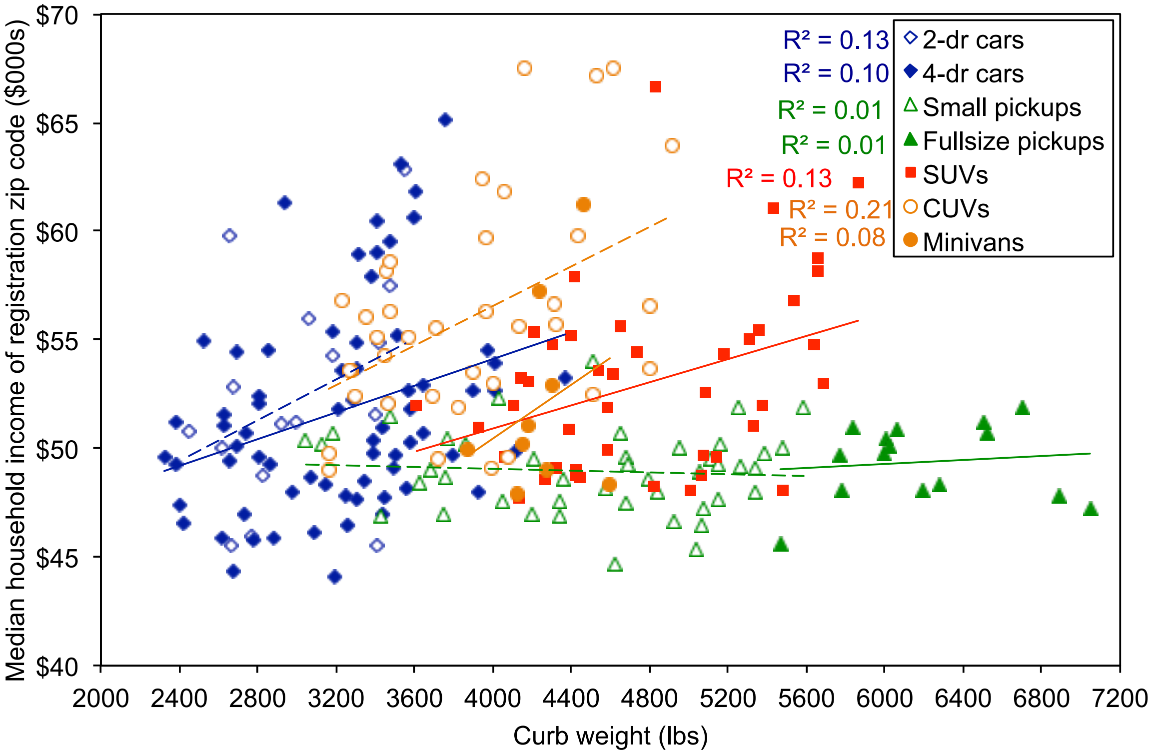


Figure 4.18 indicates that initial vehicle purchase price tends to increase as median household income increases, again except for small and large pickups; however, purchase price is most strongly correlated with median household income for CUVs (R^2 of 0.58), and less strongly for cars, SUVs, and minivans (R^2 of between 0.38 and 0.49), while pickup price is not correlated with household income.

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 in Section 5.2.3, while some of 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 U.S. fatality risk after accounting for initial vehicle purchase price and average median household income in Sections 5.2 and 5.4.

Figure 4.18. Relationship between vehicle initial purchase price and median household income, by vehicle model

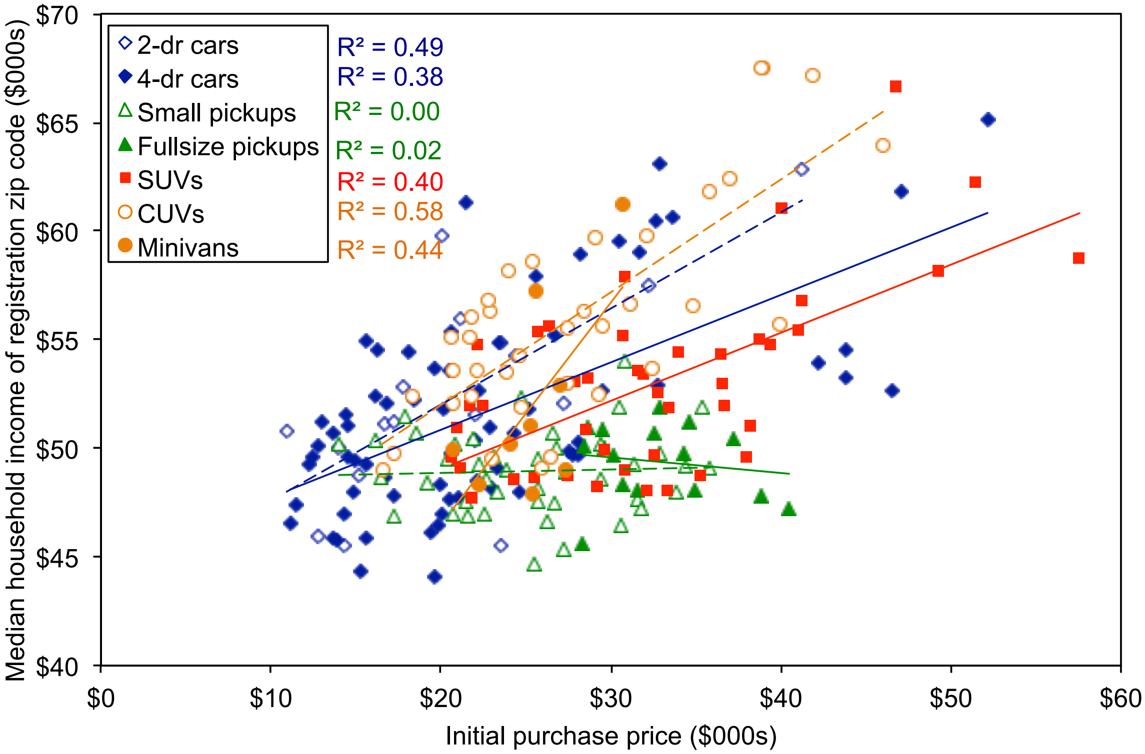


Table 4.6. Relationship between adjusted fatality risk, mass, and initial vehicle purchase price, by vehicle type and model

	Adjusted risk and initial purchase price (Figure 4.18)			Initial purchase price and mass (Figure 4.19)		
Vehicle type	Estimate		R^2	Estimate		R^2
Cars	-1.8%	*	0.25	1.6%	*	0.68
Light trucks	-1.7%	*	0.23	0.7%	*	0.51
CUVs/minivans	-1.5%	*	0.22	1.0%	*	0.56
2-dr cars	-1.9%	*	0.24	1.7%	*	0.71
4-dr cars	-1.7%	*	0.25	1.6%	*	0.68
Small pickups	-3.4%	*	0.42	0.7%	*	0.78
Heavy-duty pickups	-2.3%		0.14	0.6%	*	0.49
SUVs	-1.5%	*	0.19	1.3%	*	0.73
CUVs	-1.3%	*	0.19	1.2%	*	0.73
Minivans	-5.4%	*	0.71	0.6%		0.16
Cars < 3201	-6.1%	*	0.34	1.0%	*	0.58
Cars ≥ 3201	-0.6%		0.04	2.2%	*	0.45
LTs < 5014	-2.5%	*	0.21	0.9%	*	0.50
LTs ≥ 5014	-0.9%		0.07	0.3%		0.06
CUVs/ minivans	-1.5%	*	0.22	1.0%	*	0.56

* statistically significant at the 95% confidence level

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

	Adjusted risk and household income (Figure 4.20)			Household income and mass (Figure 4.21)			Household income and initial purchase price (Figure 4.22)		
Vehicle type	Estimate		R^2	Estimate		R^2	Estimate		R^2
Cars	-3.3%	*	0.22	0.3%	*	0.10	0.3%	*	0.39
Light trucks	-2.6%	*	0.11	0.0%		0.01	0.3%	*	0.30
CUVs/minivans	-3.0%	*	0.49	0.3%	*	0.09	0.6%	*	0.54
2-dr cars	-3.0%	*	0.24	0.5%		0.13	0.4%	*	0.49
4-dr cars	-3.6%	*	0.29	0.3%	*	0.10	0.3%	*	0.38
Small pickups	-1.0%		0.00	0.0%		0.00	0.0%		0.00
Heavy-duty pickups	8.6%	*	0.43	0.1%		0.02	-0.1%		0.02
SUVs	-4.7%	*	0.49	0.3%	*	0.14	0.3%	*	0.41
CUVs	-2.9%	*	0.43	0.5%	*	0.21	0.5%	*	0.57
Minivans	-3.6%	*	0.73	0.6%		0.08	1.0%	*	0.45
Cars < 3201	-4.6%	*	0.31	0.1%		0.01	0.6%	*	0.26
Cars ≥ 3201	-1.4%		0.07	0.2%		0.01	0.4%	*	0.41
LTs < 5014	-4.1%	*	0.24	0.1%		0.03	0.4%	*	0.39
LTs ≥ 5014	-1.0%		0.03	0.0%		0.00	0.4%	*	0.54
CUVs/ minivans	-3.0%	*	0.49	0.3%	*	0.09	0.6%	*	0.54

* 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 U.S. fatality risk per VMT. We examine the effect of using a different measure of risk, as opposed to fatality risk per VMT, and how sensitive the results from the baseline model are to including or excluding certain control variables, and subsets of the data. Below are the 31 alternative regression models we estimated. Alternate Models 1 and 2 were discussed in Section 2, while Alternate Model 6 was discussed in Section 3. Alternative Models 1 through 19 were analyzed in the 2012 LBNL Phase 1 report (Wenzel 2012), while Models 20 through 31 are new sensitivities conducted for thee 2016 analysis and this updated analysis.

Alternative measures of risk

1. Weighted by current distribution of fatalities (rather than after 100% ESC)
2. Single regression model across all crash types (rather than by crash type)
3. Fatal crashes (rather than fatalities) per VMT
4. Fatalities per induced exposure crash (rather than VMT)
5. Fatalities per registered vehicle-year (rather than VMT)

Including or excluding certain control variables or data

6. Allow footprint to vary with mass (and vice versa)
7. Account for 14 vehicle manufacturers
8. Account for 14 manufacturers + 5 additional luxury vehicle brands
9. Include initial vehicle purchase price (based on Polk VIN decoder)
10. Exclude CY variables
11. Exclude crashes with alcohol/drugs
12. Exclude crashes with alcohol/drugs, and drivers with poor driving record
13. Include median household income
14. Include sports, police, and all-wheel drive cars, and full size vans

Proposed by DRI or peer reviewers

15. Use stopped instead of non-culpable vehicles for induced exposure
16. Replace footprint with track width and wheelbase
17. Above two models combined
18. Reweight CUV/minivans by 2010 sales
19. Exclude non-significant control variables

New alternatives analyzed in this report

20. Exclude LTs over 10k GVWR
21. Small pickups and SUVs analyzed separately from large pickups
22. Large pickups analyzed separately from small pickups and SUVs
23. Above two models combined for large pickups (Models 20 and 22)
24. Include AWD cars, but not muscle or police cars
25. Include muscle and police cars, but not AWD cars
26. Exclude three high-risk car models
27. Include AWD cars, exclude three high-risk car models (Models 24 and 26)
28. Two-piece variable for CUV weight
29. Two-piece variable for PC and LT footprint
30. Two-piece variable for CUV weight, and for all footprint (Models 28 and 29)
31. Remove kinks in NHTSA VMT schedules

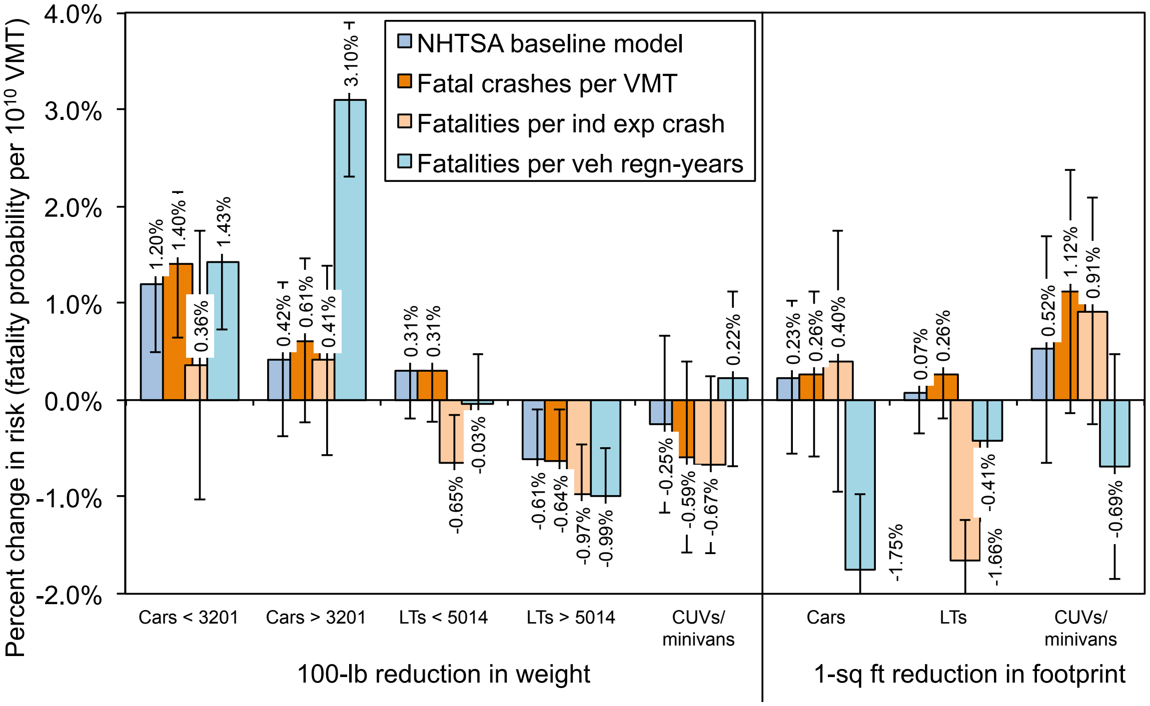
5.1. Alternative measures of risk

Figure 5.1 compares the estimates for U.S. fatality risk per VMT using NHTSA's preferred regression model specification (in light blue) with two other measures of U.S. 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, its crash partner, and any pedestrian or cyclist fatalities, 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 10 billion VMT (shown in dark orange) increases the estimated detrimental effect of mass reduction on risk in cars, from 1.20% to 1.40% for lighter-than average cars, and from 0.42% to 0.61% for heavier cars, but increases the estimated beneficial effect of mass reduction on risk in CUVs/minivans, from a 0.25% decrease in risk to a 0.59% decrease. Analyzing risk of fatal crash per VMT has essentially no impact on the estimated effect of mass reduction in light trucks.

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 U.S. fatality risk per induced exposure crash from the 13 states (rather than VMT). Using induced exposure crashes as the measure of exposure decreases the estimated detrimental effect of mass reduction on risk in lighter-than-average cars, increases the estimated beneficial effect in heavier-than-average light trucks and CUVs/minivans, and changes the sign of the estimated effect of mass reduction in lighter-than-average light trucks, and footprint reduction in light trucks, on risk. 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.

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 addition, there likely are biases in what crashes are reported in particular states, for two reasons: states have different requirements regarding how serious a crash must be for it to be included in state-wide databases, and not all crashes are reported to police.

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



In his review of the 2011 LBNL preliminary 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), and changes in vehicle registrations by vehicle type or over time may not mirror changes in miles driven by vehicle type or over time. 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 sensitivity of the NHTSA baseline results to the estimated VMT weights NHTSA used is examined later in this section. LBNL conducted a sensitivity using vehicle registration years rather than VMT as the measure of exposure (shown in light turquoise in Figure 5.1). This alternative estimates more beneficial effects of mass reduction on risk in cars, especially heavier cars (from an estimated 0.42% increase to an estimated 3.1% increase in risk), more beneficial effect in light trucks, but changes sign in CUVs/minivans (from an estimated 0.25 % decrease in risk to an estimated 0.22% increase in risk), as shown in Figure 5.1.

5.2. Including or excluding certain control variables or data

In this section we discuss several alternative regression models that add or exclude certain control variables, or add or exclude certain cases, from the NHTSA baseline regression model.

5.2.1. 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.[22] 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.[23]

Figure 5.2 compares the estimated effect of adding variables for each of the 14 manufacturers (shown in red) to NHTSA's baseline regression model specification (shown in light blue). Accounting for 14 vehicle manufacturers greatly increases the estimated detrimental effect of mass reduction for all vehicle types, and increases the fatality risk from footprint reduction in CUVs and minivans, but reduces fatality risk from footprint reduction in cars and light trucks.

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 effect of mass reduction on risk is even more detrimental for four of the five vehicle types, especially heavier cars. Including the five luxury brands is associated with a more beneficial effect of footprint reduction in cars and light trucks, but with a more detrimental effect of footprint reduction in CUVs/minivans.

Initial vehicle purchase price, rather than manufacturer nameplate, is another proxy for the general quality of vehicle design. LBNL 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 0.14% (+/- 0.24%), but decrease risk by 0.29% (+/- 0.26%) in light trucks and by 0.68% (+/- 0.49%) in CUVs/minivans. Figure 5.2 compares how accounting for vehicle purchase price changes the estimated effect of mass or footprint reduction on risk, with the other measures of quality of vehicle design. Relative to the NHTSA baseline model, including initial purchase price in the regression models reduces fatality risk in all vehicle types except heavier-than-average cars, whose risk increases from a 0.42% increase to a 0.83% increase. Accounting for initial vehicle purchase price has little effect on the relationship between footprint reduction in all three vehicle types and risk. Accounting for vehicle purchase price has a smaller effect on the estimated effect of mass reduction on risk than accounting for vehicle manufacturer for cars and light trucks, but not for CUVs/minivans.

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

[23] The manufacturers included in the Other category are: AM General, Audi, Daewoo, Isuzu, Jaguar, Land Rover, Mini, Porsche, Saab, and Suzuki. In cases where there were no fatalities for a given manufacturer in a given type of crash, the induced exposure records for that manufacturer were reassigned to the Other category.

Figure 5.2. Estimated effect of mass or footprint reduction on U.S. fatalities per VMT, after controlling for vehicle manufacturer or for initial vehicle purchase price, by vehicle type

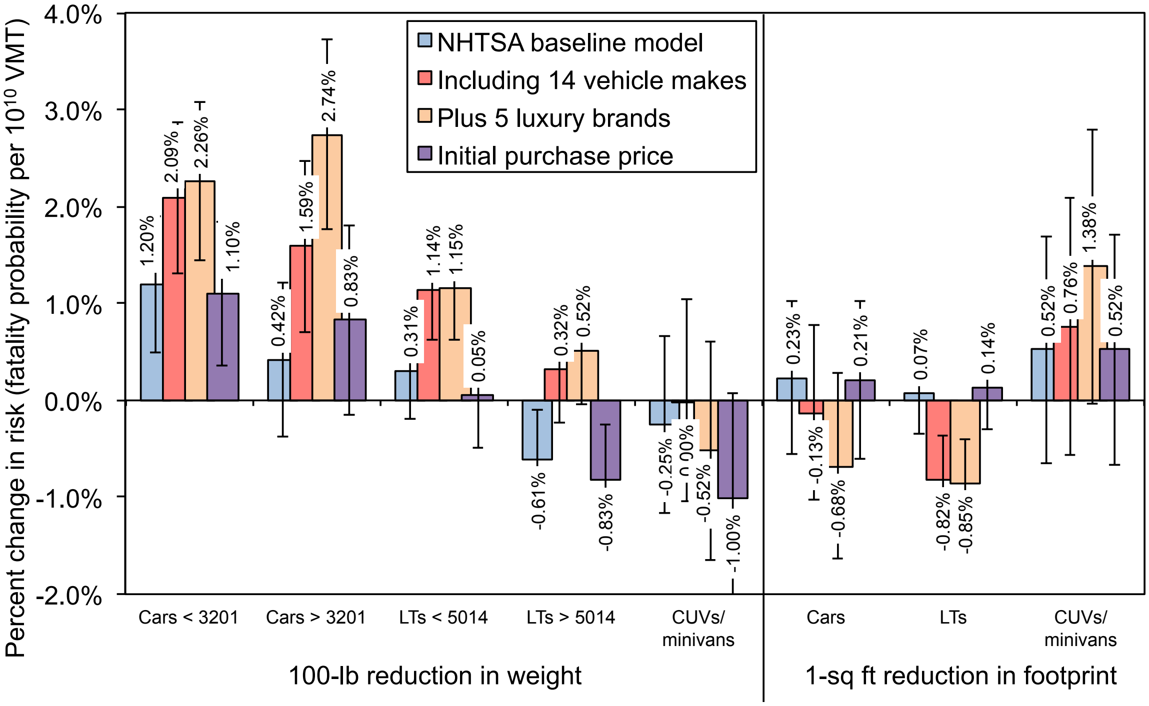


Table 5.1 shows the correlation and VIF between curb weight and initial purchase price, by vehicle type. The table indicates that vehicle mass is correlated fairly strongly with initial purchase price with r greater than 0.74 for five of the seven vehicle types; however, the correlation between curb weight and initial purchase price is much lower for minivans (0.43) and large pickups (0.48).

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 driver and crash variables	
		CURBWT	PRICE000
Cars	0.736	7.0	2.6
Light trucks	0.636	4.7	2.3
CUVs/minivans	0.706	7.8	2.8
2-dr cars	0.743	4.8	3.2
4-dr cars	0.751	7.4	2.6
Sm pickups	0.804	5.1	3.0
Lg pickups	0.482	1.9	1.4
SUVs	0.787	8.3	2.9
CUVs	0.826	10.6	3.8
Minivans	0.431	1.6	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.

5.2.2. Calendar year variables

One interesting effect is the reduction in risk over time, as indicated in the calendar year control variables. This is relatively consistent for each vehicle type, and slightly larger for light trucks and CUVs/minivans, as shown in Figure 5.3. 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 5.3. Effect of calendar year variables on risk, by vehicle type

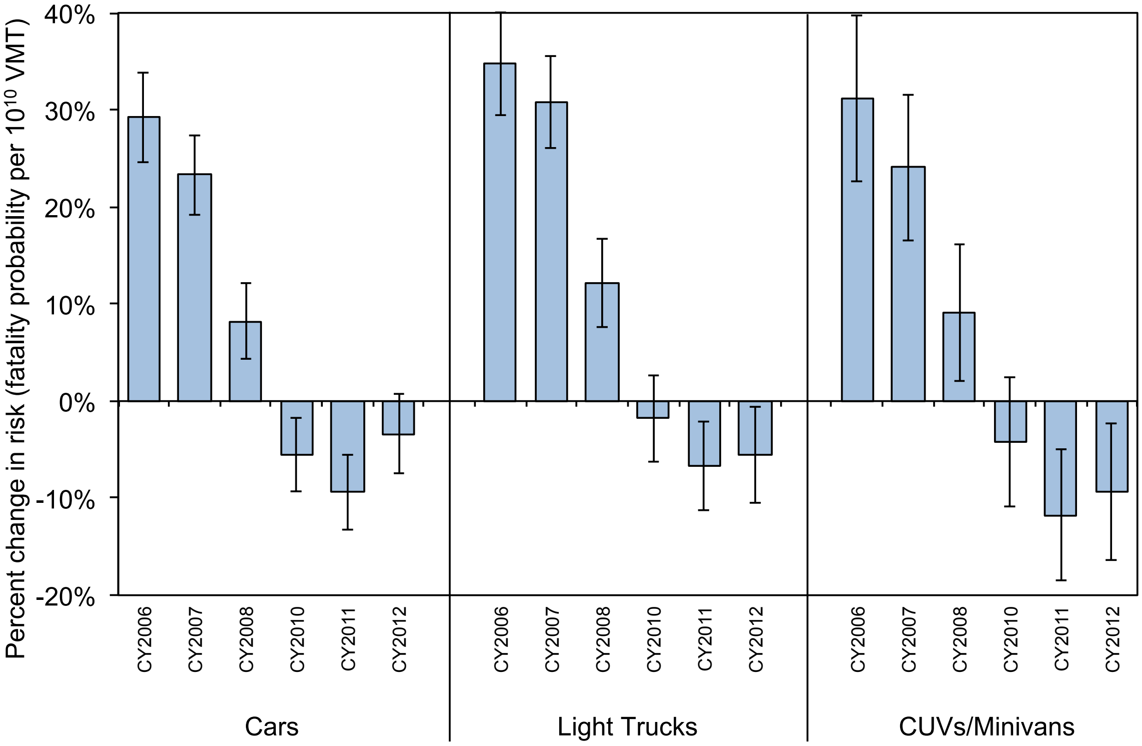


Figure 5.4 indicates that the effect of the calendar year variables on light truck risk is strong for crashes with lighter cars and lighter light-duty trucks. In its 2012 study NHTSA stated that this may be the result of the removal over time of very light and unsafe cars and light trucks as potential crash partners for light trucks. However, Figure 5.4 indicates that there also are consistent and large decreases over time in light truck risk in rollovers, crashes with heavier 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 (Figure 5.5) 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 lighter cars, lighter light trucks, and other crashes). NHTSA has speculated that the risk associated with light trucks (and cars and CUVs/minivans) 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 (2006 to 2012) on light truck risk, by crash type

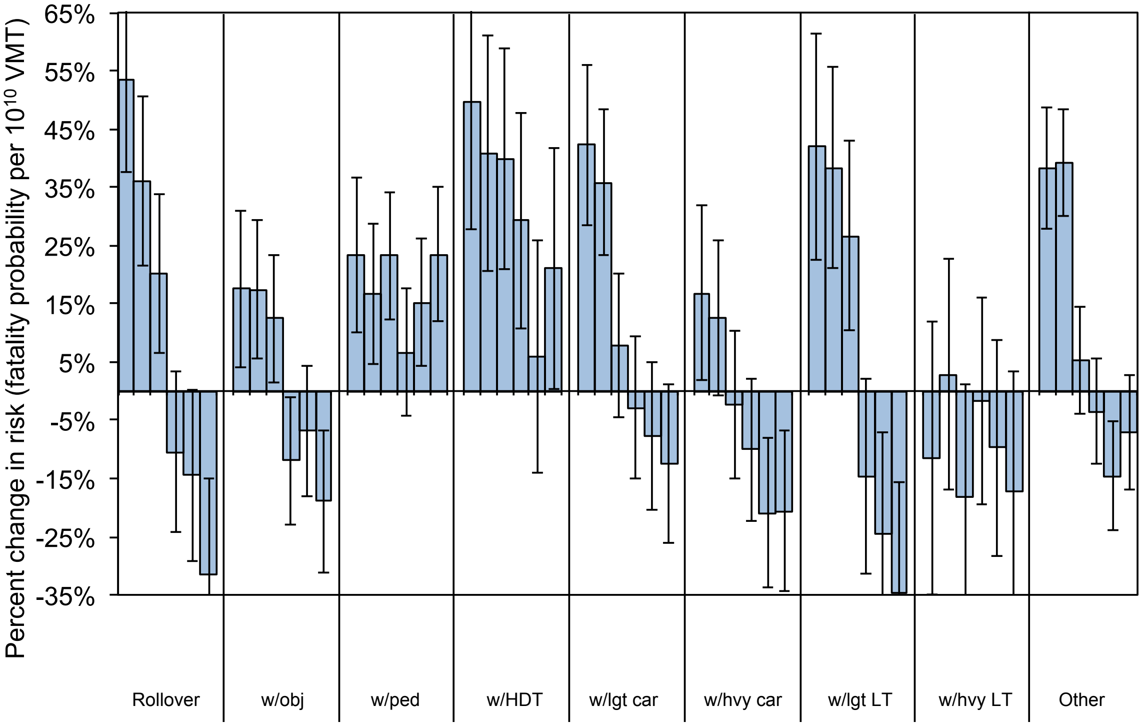
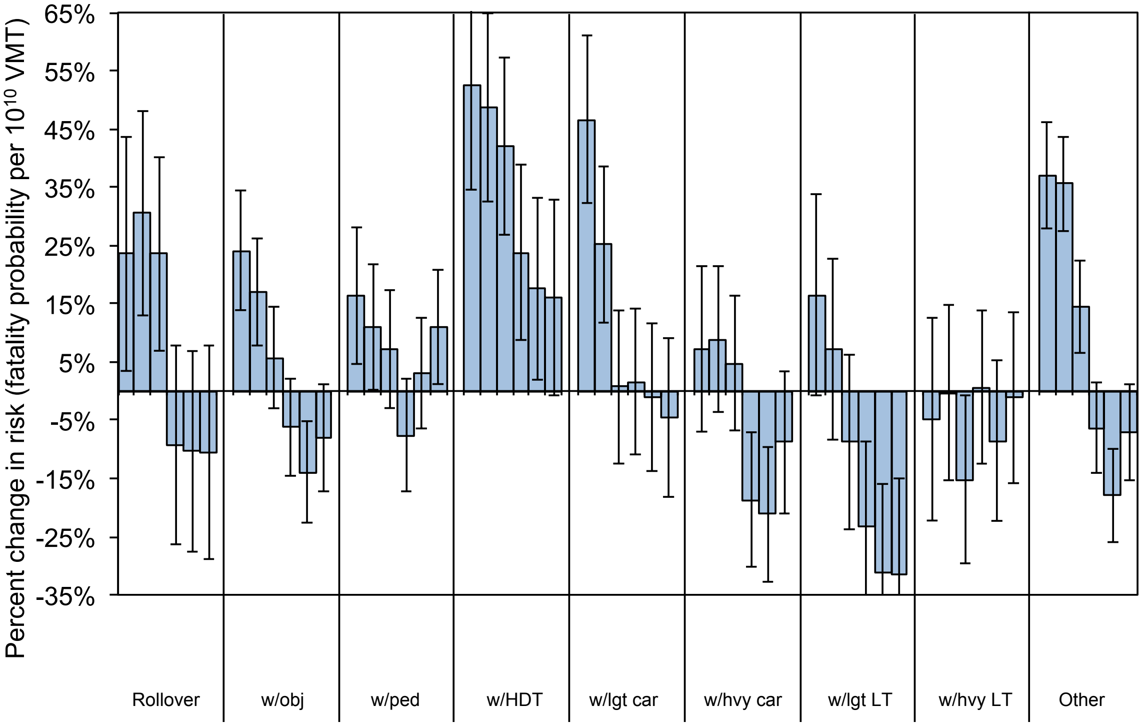


Figure 5.5. Effect of calendar year variables (2006 to 2012) on car risk, by crash type



In its 2003 report, NHTSA included calendar year variables for 1995 to 2000 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 current analysis (shown in Figure 5.3), and there is not the consistent decrease of the effect of calendar year on risk in later years as in the current analysis.

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 5.6. NHTSA 2003 effect of calendar year variables (1995 to 2000) on risk, by vehicle type

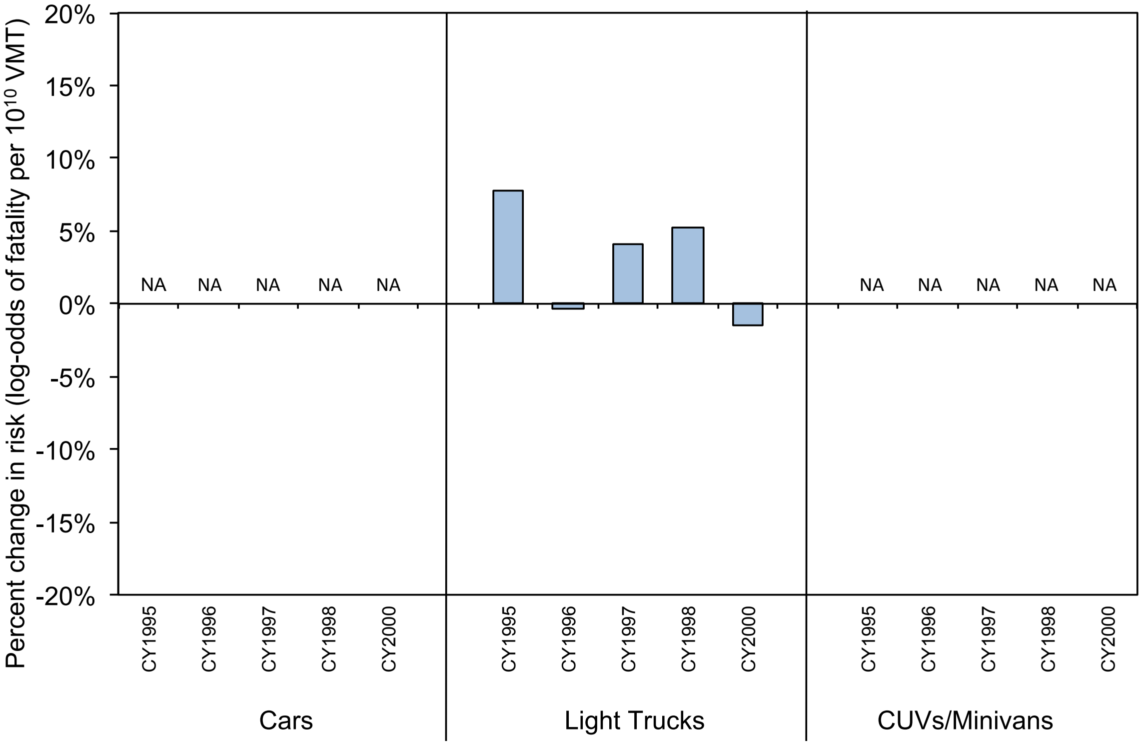
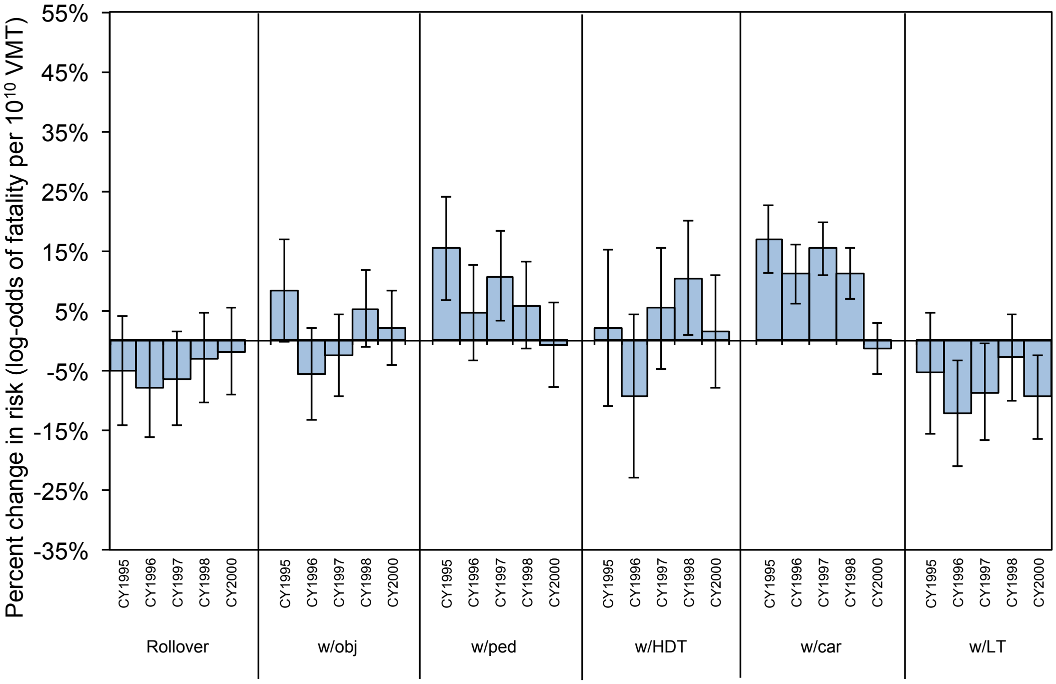
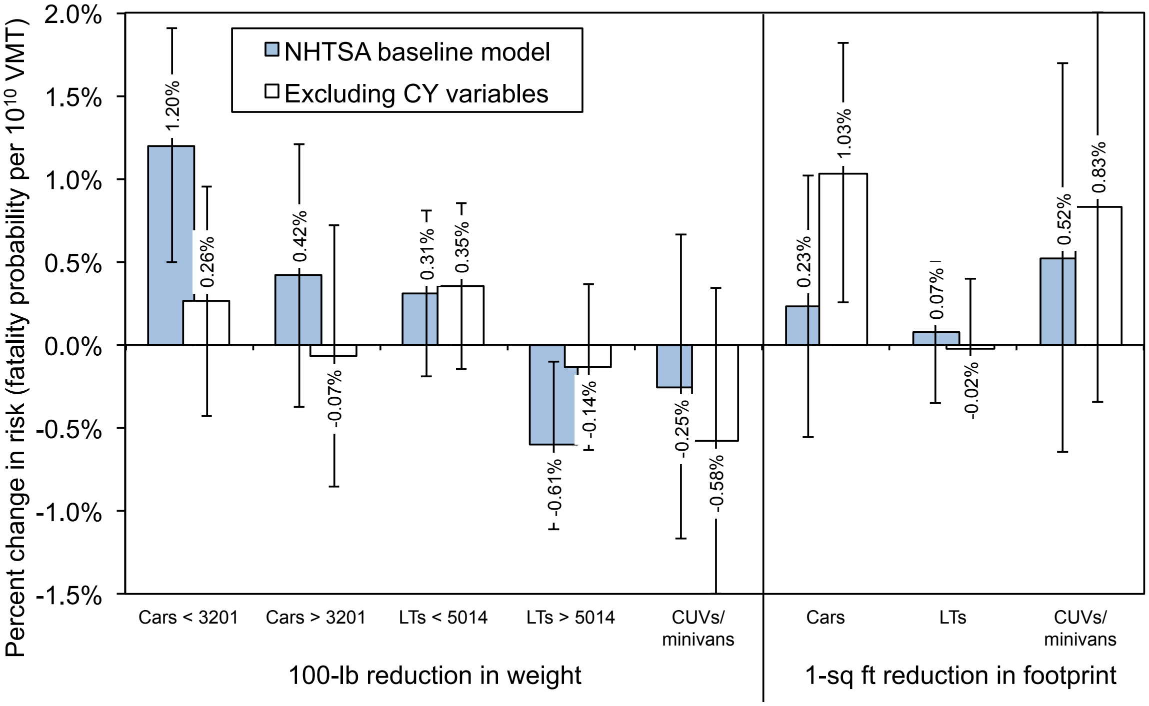


Figure 5.7. NHTSA 2003 effect of calendar year variables (1995 to 2000) on light truck risk, by crash type



Figures 5.8 through 5.11 show the effect of removing the calendar year variables from NHTSA's baseline regression model (shown in light blue). Figure 5.8 indicates that excluding the calendar year variables has little effect on the estimated coefficients for mass reduction in lighter light trucks or footprint reduction in light trucks. However, removing the calendar year variables substantially decreases the fatality risk from mass reduction in cars and CUVs/minivans, but increases the fatality risk from mass reduction in heavier light trucks, and substantially increases the fatality risk from footprint reduction in cars and CUVs/minivans.

Figure 5.8. 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 baseline model. Figures 5.9 through 5.11 show the effect on the vehicle control variables; there is little to no effect on the driver or crash control variables (not shown). Figures 5.9 through 5.11 indicate that removing the calendar year variables has a large effect on the curtain side airbag variable in cars, the SUV and ESC variables in light trucks, and the curtain side airbag and ESC variables in CUVs/minivans. 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 5.8 through 5.11 suggest that NHTSA's inclusion of the calendar year variables in their baseline model dilutes the estimated effect of curtain side airbag technologies in cars and CUVs/minivans, and ESC in light trucks and CUVs/minivans.

Figure 5.9. Estimated effect of selected control variables on car risk, including and excluding calendar year variables

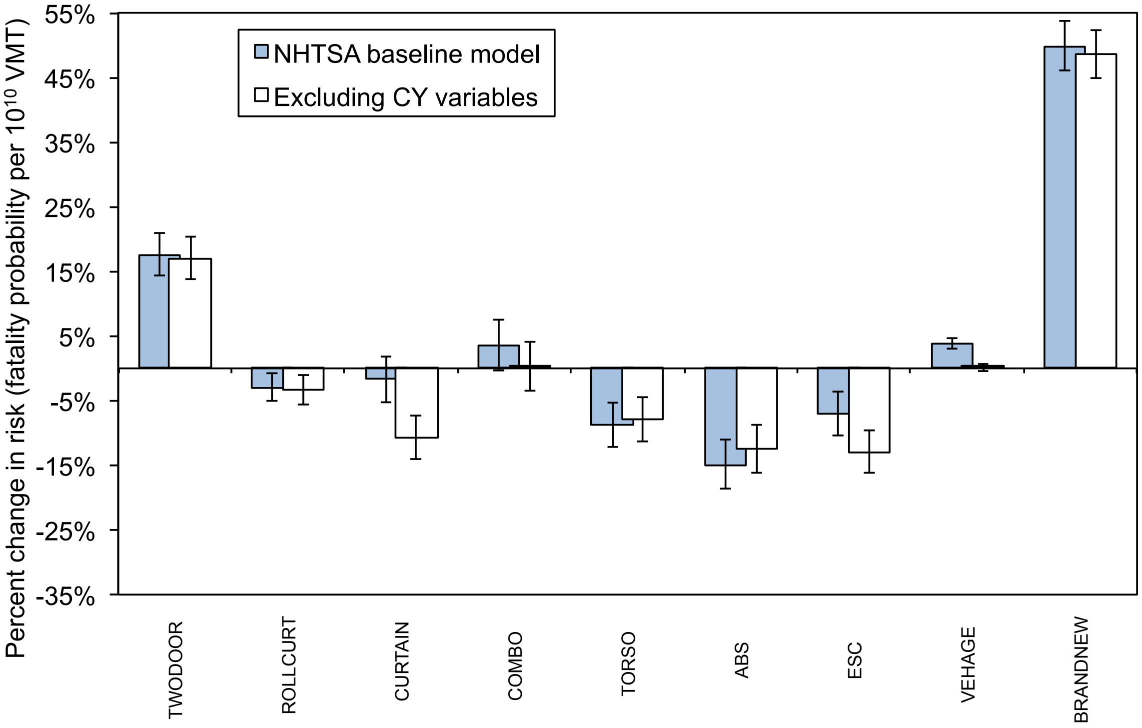


Figure 5.10. Estimated effect of selected control variables on light truck risk, including and excluding calendar year variables

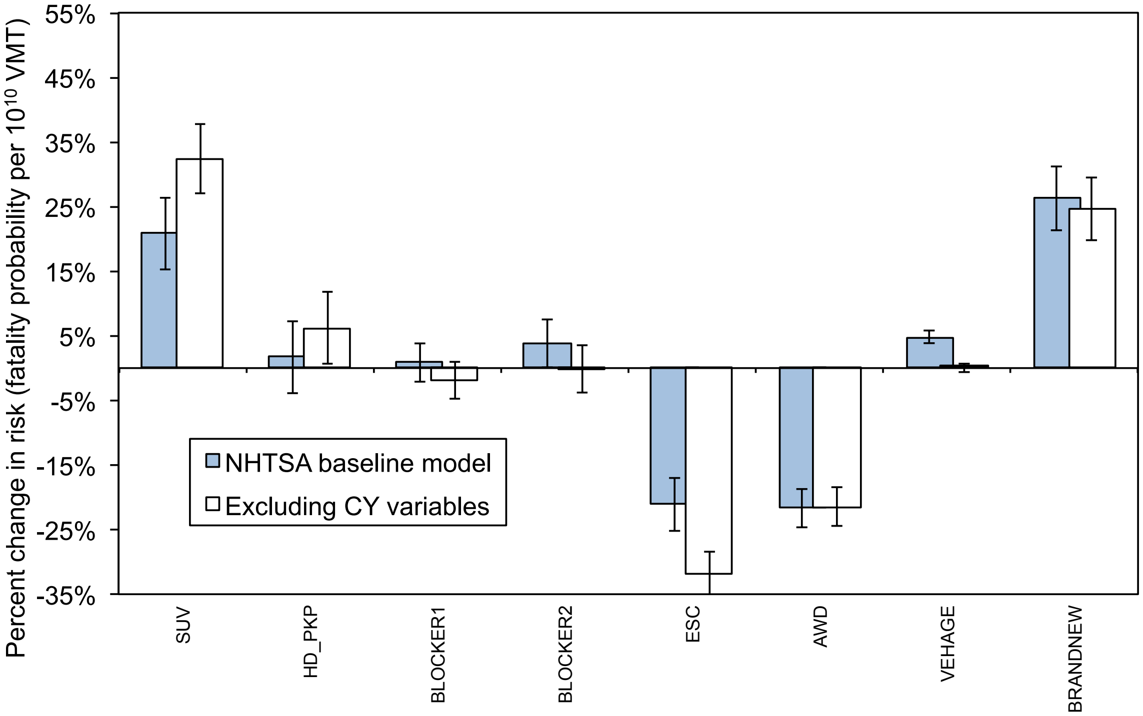
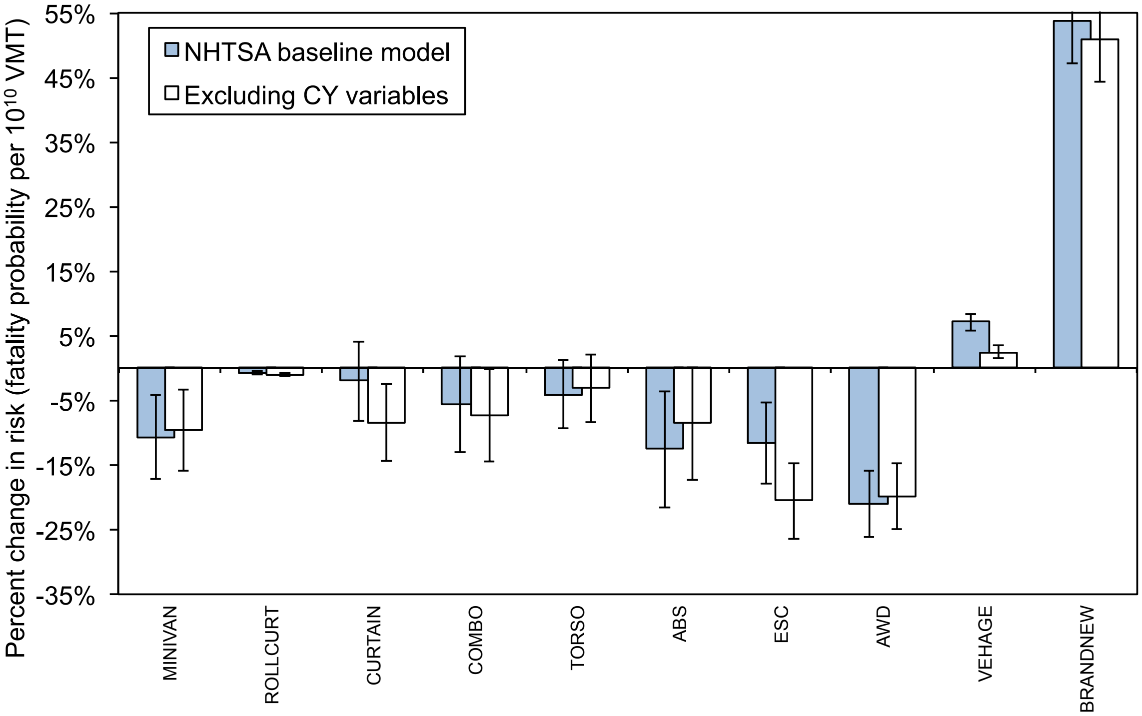


Figure 5.11. Estimated effect of selected control variables on CUV/minivan risk, including and excluding calendar year variables



5.2.3. Effect of alcohol/drug use and driving behavior

FARS indicates about 17% of car and light truck drivers, and 10% 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.[24] The dark green columns in Figure 5.12 indicate that removing from the analysis the FARS cases where alcohol or drug used was involved substantially increases the estimated effect of mass reduction on risk in cars, but slightly reduces the estimated effect of footprint reduction on risk in all three types of vehicles, as compared with NHTSA's baseline 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 one or more drivers were driving without a valid license or recklessly in the current crash, and the driver's driving record in the last three years. These additional "bad" drivers account for another 15% of car and light truck drivers, and another 11% of CUV/minivan drivers, in the FARS cases. The light green columns in Figure 5.12 indicate that also excluding these bad drivers from the analysis further increases the estimated effect of mass reduction on risk in cars and lighter-than-average light trucks. For

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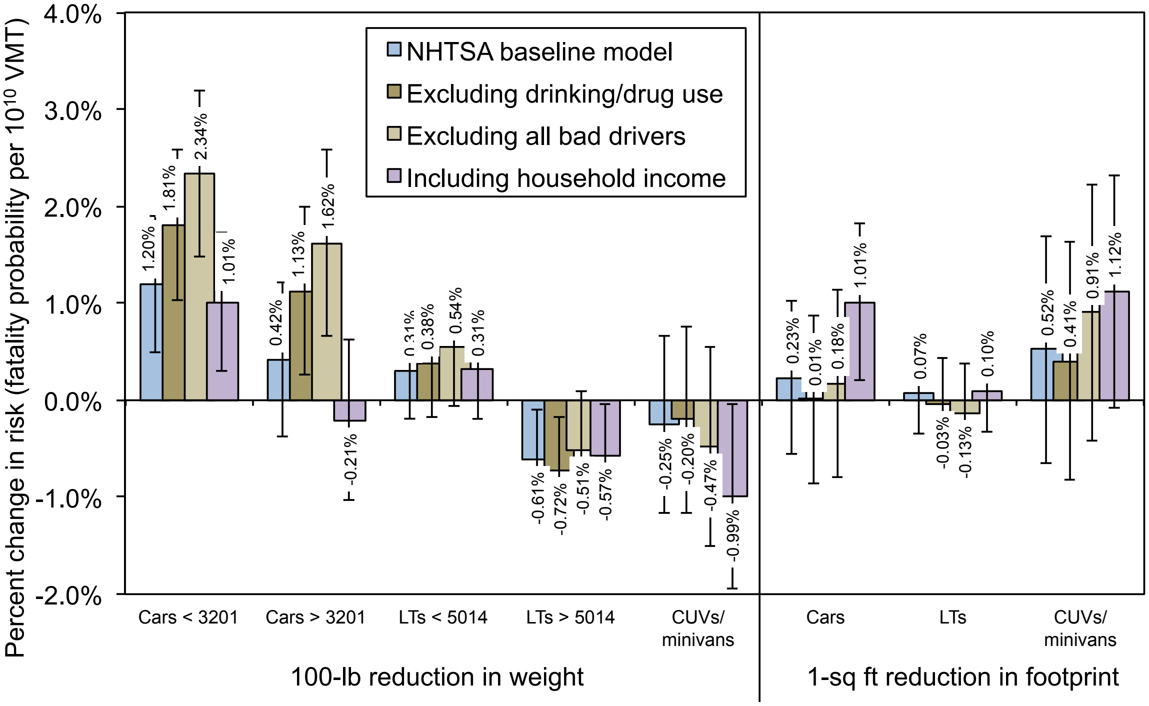
[24] Most states report suspected driver alcohol or drug use, so we could exclude these induced exposure cases and recalculate the vehicle registration annual VMT weights used in calculating vehicle exposure.

example, excluding all bad drivers increases the estimated increase in risk from mass reduction from 1.20% to 1.81% in lighter cars, from 0.42% to 1.62% in heavier cars, and from 0.31% to 0.54% in lighter light trucks. On the other hand, excluding all bad drivers from the analysis further reduces the estimated effect of footprint reduction on risk for light trucks, but increases risk for CUVs/minivans. 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 rollovers involving cars and CUVs/minivans (as shown in Figures 2.3 and 2.5 above), removing crashes involving these drivers from the analysis makes overall mass reduction more harmful, and footprint reduction less harmful, at least for cars.

Figure 5.12. Estimated effect of mass or footprint reduction on U.S. 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 U.S. fatality risk per VMT 1.9% (+/- 0.30%) for cars, 0.08% (+/- 0.36%) for light trucks, and 1.6% (+/- 0.49%) 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 substantially reduces the estimated effect of mass reduction in heavier-than-average cars and CUVs/minivans, and substantially increases the estimated effect of footprint reduction in cars and CUVs/minivans. 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 (0.50) 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

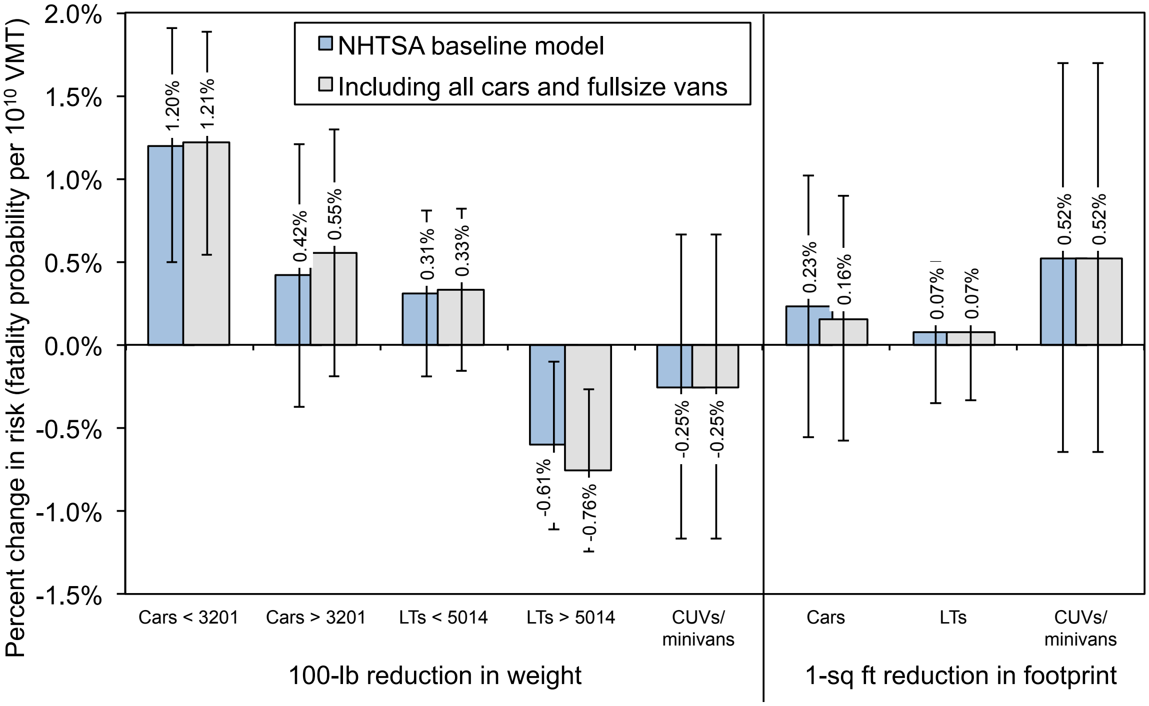
Vehicle type	Correlation coefficient (r)	Variance inflation factor (VIF) accounting for driver and crash variables	
		CURBWT	INC000
Cars	0.234	5.5	1.5
Light trucks	0.087	3.1	1.5
CUVs/minivans	0.347	4.9	1.7
2-dr cars	0.401	3.6	2.3
4-dr cars	0.229	6.2	1.4
Sm pickups	0.070	3.9	1.1
Lg pickups	0.145	1.7	1.1
SUVs	0.341	6.0	1.5
CUVs	0.502	8.3	2.2
Minivans	0.352	1.5	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.

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

As mentioned above, NHTSA excluded models used as sports cars, police cars and SUVs, car models with all-wheel drive, all Ford Crown Victorias, and fullsize passenger and cargo vans, from its baseline regression model. Including these vehicles in the analysis, and adding five control variables for the additional vehicle types, increases the estimated detrimental effect of mass reduction in heavier-than-average cars, increases the estimated beneficial effect of mass reduction on heavier-than-average light trucks, and has little change in lighter cars and lighter light trucks, as shown in Figure 5.13. Including these vehicles has little effect on the estimated effect of footprint reduction on risk in any of the three vehicle types.

Figure 5.13. Estimated effect of mass and footprint reduction on U.S. fatality risk per VMT, after including sports, police, and all-wheel drive cars, and fullsize passenger and cargo vans, by vehicle type



5.3. 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 (Van Auken and Zellner 2013a and 2013b). Because they avoided the crash, these vehicles/drivers are not included in the non-culpable vehicle dataset. 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 2013b).

Table 5.3 shows the results of the additional sensitivity tests NHTSA conducted in response to the DRI comments. Model 15 in Table 5.3 indicates that using only stopped vehicles, and not all vehicles judged to be not-at-fault, in two-vehicle crashes substantially increases the estimated beneficial effect of mass reduction on risk in heavier-than-average cars and light trucks, decreases the beneficial effect of mass reduction in CUVs/minivans, slightly decreases risk from mass reduction in lighter-than-average light trucks, and slightly increases risk from mass reduction in lighter-than-average cars. Using stopped vehicles substantially increases risk associated with footprint reduction in cars, but decreases risk associated with footprint reduction in light trucks and CUVs/minivans. Replacing vehicle footprint with its two components, track width and wheelbase, decreases the estimated detrimental effect of mass reduction in all vehicle types except heavier-than-average cars, as shown in Model 16. Model 16 also indicates that track width reduction is associated with large increases in risk in all three vehicle types, while wheelbase reduction is associated with a large decrease in risk in cars. 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 (Model 17), further reduces the estimated detrimental effect of mass reduction, such that mass reduction in lighter cars is associated with only an 0.73% increase in fatality risk, while mass reduction in the other vehicle types is associated with a 0.02% reduction in fatality risk in heavier cars to a 1.91% reduction in fatality risk in heavier light trucks.

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

Variable	Case vehicle type	NHTSA baseline	15. Using stopped vehicles	16. Replace footprint with track width/ wheelbase	17. Using stopped vehicles and track width/ wheelbase
Mass reduction	Cars < 3197 lbs	1.20%	1.32%	0.66%	0.73%
	Cars ≥ 3197 lbs	0.42%	-0.17%	0.54%	-0.02%
	LTs < 4947 lbs	0.31%	0.21%	-0.44%	-0.77%
	LTs ≥ 4947 lbs	-0.61%	-1.55%	-0.90%	-1.91%
	CUV/ minivan	-0.25%	-0.08%	-0.48%	-0.18%
Footprint reduction	Cars	0.23%	0.88%	—	—
	LTs	0.07%	-0.19%	—	—
	CUV/ minivan	0.52%	0.09%	—	—
Track width reduction	Cars	—	—	5.18%	5.90%
	LTs	—	—	1.63%	1.81%
	CUV/ minivan	—	—	2.16%	0.87%
Wheel base reduction	Cars	—	—	-1.36%	-1.15%
	LTs	—	—	0.03%	-0.08%
	CUV/ minivan	—	—	-0.30%	-0.20%

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

In its 2012 report, NHTSA provided three reasons for not using stopped rather than non-culpable vehicles as the measure of induced exposure. First, NHTSA noted that using stopped vehicles would reduce the number of induced exposure cases from police-reported crashes in the 13 states by almost 75%. Second, NHTSA actually used stopped vehicles as the measure of induced exposure in its 1997 analysis. However, the 2003 NAS review panel, which included an exposure data expert, D.W. Reinfurt, commented that non-culpable vehicles were preferable to stopped vehicles as the measure of induced exposure. In his comments on the 2003 NHTSA study Reinfurt writes "Induced exposure using the traditional approach of utilizing non-culpable vehicles (drivers) in two vehicle crashes is a large improvement over the 1997 study." However, he gives no evidence why this should be the case. Third, NHTSA compared the distribution of VMT from the two induced exposure methods to that implicit in the 2009 National Highway

Travel Survey, and found that the two induced exposure measures understated the number of VMT attributable to the youngest and oldest drivers.

Regarding NHTSA's first objection, while it is true that the stopped vehicle database is a subset of only about 30% of the cases in the non-culpable vehicle database, the number of cases in the stopped vehicle database is still large: 276,000 cars, 161,000 light trucks, and 141,000 CUVs/minivans. The smaller number of records does increase the potential for random sampling bias; however, increasing the potential for sampling bias may be preferable to a larger sample with a known non-random bias. Because each record in the stopped vehicle database receives a higher VMT weight than each vehicle in the non-culpable vehicle database, the total number of VMT in each is nearly identical, and the standard errors associated with the estimated coefficients from the two regression models are similar.

Regarding the second objection, DRI argued that using non-culpable vehicles in two-vehicle crashes as a proxy for all vehicle/driver combinations travelling on roads may understate the exposure or VMT of vehicle/driver combinations that could have avoided a two-vehicle crash. As shown in Table 5.4, there were slightly smaller fractions of crashes at night, in rural counties, on high-speed roads, and by male, young, or elderly drivers, in stopped vehicles than in non-culpable vehicles in the 2012 analysis. This suggests that stopped vehicles in the 2012 analysis were less influenced by these risky crash or driver characteristics than non-culpable vehicles, which may support the DRI argument that the non-culpable vehicles are "missing" certain vehicle/driver combinations that were able to avoid a two-vehicle crash. However, in his review of the 2003 NHTSA report Donald Reinfurt argued that the lower fraction of young and male drivers in stopped vehicles may be biased because "young aggressive drivers might be expected to have fewer [stopped] induced-exposure crashes, because they have less of a tendency to wait patiently at intersections and stop lights for traffic to clear." So plausible explanations can be made that either the non-culpable or the stopped vehicle sample is biased and not necessarily representative of the vehicle/driver combinations traveling on the nation's roadways.

There are much larger fractions of vehicles characterized by these risk factors in the entire database of police-reported crashes, over 80% of which are non-injury crashes, than in the two subsets used for the induced exposure. This lends credence to NHTSA's claim that the stopped vehicle dataset understates the number of vehicle/driver combinations on the nation's roadways that exhibit these risk factors more than the non-culpable vehicle dataset. However, both subsets used for the induced exposure data substantially understate the number of crashes at night, in rural counties, or on high-speed roads, by male, young or old drivers, at least relative to the vehicle/driver combinations involved in all types of police-reported crashes.

The last two columns of Table 5.4 indicate that the fractions of vehicle/driver combinations in the updated 2017 non-culpable and stopped vehicle datasets are similar to those in 2012; however, in the 2017 databases there are similar fractions of male drivers in the non-culpable and stopped vehicle databases, but slightly higher percentages of police cars and small pickups in the stopped vehicle database than in the non-culpable vehicle database. LBNL has not yet analyzed all of the police-reported crashes from the thirteen states used to develop the two induced exposure datasets for 2017.

Table 5.4. Crash, driver, and vehicle characteristics of non-culpable and stopped vehicles used for induced exposure in 2012 and 2015 analyses

		Vehicles involved in two-vehicle crashes used for induced exposure (2012)		Vehicles in all crashes (2012)	Vehicles involved in two-vehicle crashes used for induced exposure (2017)	
Variable		Non-culpable	Stopped		Non-culpable	Stopped
NITE		16.0%	13.4%	21.7%	15.0%	12.9%
RURAL		23.9%	22.4%	26.6%	21.9%	19.3%
SPDLIM55		17.0%	12.4%	24.1%	17.5%	12.5%
DRVMALE		46.4%	45.0%	55.4%	45.9%	45.6%
DRVAGE	14 to 30	30.3%	27.2%	37.0%	27.4%	24.5%
	30 to 50	42.8%	45.9%	40.7%	42.0%	44.7%
	50 to 70	22.6%	23.4%	21.1%	25.8%	27.0%
	70 to 96	4.3%	3.5%	5.2%	4.7%	3.8%
VEHTYPE	2-dr car	7.8%	7.5%	8.2%	5.3%	5.3%
	4-dr car	42.8%	39.8%	42.9%	43.2%	38.6%
	Muscle car	1.3%	1.5%	1.5%	1.0%	1.2%
	Police car	0.9%	0.7%	1.1%	0.9%	1.9%
	AWD car	1.4%	2.0%	1.3%	2.5%	3.0%
	Sm pickup	10.1%	10.2%	11.0%	8.6%	9.5%
	Lg pickup	2.5%	2.3%	3.1%	2.2%	2.5%
	SUV	16.0%	17.6%	15.3%	12.5%	13.7%
	CUV	8.3%	9.2%	7.1%	16.2%	17.0%
	Minivan	6.8%	6.9%	6.1%	5.7%	5.4%
	Full van	2.0%	2.3%	2.5%	1.7%	2.0%

Note: green cells have a lower percentage in stopped than in non-culpable database; yellow cells have a higher percentage in stopped than in non-culpable database.

Regarding NHTSA's third objection, as shown in Table 5.4 both the non-culpable and stopped vehicle datasets used for induced exposure understate the fraction of young and old drivers, as well as the number of vehicles involved in risk crash situations, at least compared to all police-reported crashes. In its 2012 report NHTSA compared the VMT distribution by driver age from the non-culpable and stopped vehicle databases with that from the 2001 and 2009 National Highway Transportation Surveys, and concluded that the non-culpable and stopped vehicle databases overstate VMT from the youngest drivers, and understate VMT from the oldest drivers. LBNL notes that the VMT weights NHTSA used in its analysis vary by vehicle model, but not by the age of the driver.

One argument against using the non-culpable vehicle database is that it relies on the accurate determination of the at-fault vehicle in the police-reported crash databases. One argument in favor of using the stopped rather than non-culpable vehicle database is the effect it has on the explanatory power of the combination of variables included in the logistic regression models. In a logistic regression model, the pseudo-r^2 value measures how much of the variability in the independent variable, in this case fatalities, is explained by the control variables used in the model. Using stopped, rather than non-culpable, vehicles as the measure of induced exposure increases the psuedo-r^2 values from about 0.07 to 0.22 for cars, from 0.09 to 0.30 for light trucks, and from 0.06 to 0.16 for CUVs/minivans.

Perhaps the most important reason to use footprint rather than wheelbase and track width as the size variable is that the attribute-based standards are based on vehicle footprint. In its 2012 report NHTSA argued that it was better to use footprint as a control variable rather than track width and wheelbase, noting that the literature suggests that "combining parameters – i.e. track width and wheelbase into footprint – is generally advisable for alleviating multicollinearity issues." (p. 100) NHTSA noted that the highest VIF for any variable is below 3 for each of the three vehicle types when only curb weight is included in the regression model, but jumps to over 7 when footprint is added, and increases even higher when footprint is replaced with track width and wheelbase (p. 101).

Table 5.5 compares the correlations of four variables: curb weight, footprint, track width, and wheelbase, by the three and seven vehicle types. The correlations shown in the table weight each vehicle by NHTSA's VMT weight. The table indicates that, while there is a stronger correlation between weight and footprint (r of 0.88) than between weight and track width (r of 0.82) for cars, there is a weaker correlation between weight and footprint (r of 0.73) than between weight and track width (r of 0.82) for light trucks (there is roughly the same degree of correlation between weight and footprint or track width for CUVs/minivans). On the other hand, there is a consistently weaker correlation between weight and wheelbase than between weight and footprint, for all vehicle types, from an r value of 0.87 for 4-door cars to an r value of only 0.08 for large pickups. Table 5.5 also indicates that track width is best correlated with wheelbase in 4-door cars (r=0.81), and least correlated with wheelbase in large pickups (r=-0.15) and minivans (r=0.25).

Table 5.5. Correlation coefficients and variance inflation factors of curb weight with wheelbase and track width, by vehicle type

	Correlation coefficient (r)					
Vehicle type	Weight and footprint	Weight and track width	Weight and wheelbase	Track width and wheelbase	Footprint and track width	Footprint and wheelbase
Cars	0.882	0.818	0.847	1.000	0.914	0.969
Light trucks	0.754	0.818	0.652	0.673	0.820	0.974
CUVs/minivans	0.845	0.843	0.742	0.684	0.875	0.951
2-dr cars	0.725	0.691	0.622	0.573	0.814	0.942
4-dr cars	0.901	0.831	0.874	0.798	0.919	0.971
Sm pickups	0.859	0.845	0.719	0.566	0.817	0.937
Lg pickups	0.631	0.406	0.497	-0.229	0.057	0.959
SUVs	0.877	0.879	0.759	0.665	0.863	0.951
CUVs	0.888	0.857	0.771	0.656	0.890	0.928
Minivans	0.475	0.475	0.242	0.191	0.835	0.700

Table 5.6 shows the VIFs for curb weight, footprint, track width, and wheelbase, from the NHTSA baseline model and Model 16, with the highest VIF for each variable in each model

(reading from left to right) indicated in red. The table indicates that replacing footprint with track width and wheelbase lowers the maximum VIF for each of the three vehicle types (from 5.5, 10.4, and 9.4 for cars, light trucks, and CUVs/minivans, respectively, using footprint, to 4.6, 6.8, and 6.7 using track width and wheelbase). Replacing footprint with track width and wheelbase results in a lower maximum VIF for two of the seven vehicle types (4-door cars and CUVs) and has no effect on the maximum VIF for SUVs, but for the remaining four vehicle types (2-door cars, small and large pickups, and minivans) using track width and wheelbase results in a higher maximum VIF. [25]

In a recent email Chuck Kahane commented that “the differences in the VIFs by various procedures are fundamentally in the same range, not particularly dangerous, and support the same conclusions.”

Table 5.6. Variance inflation factors of weight and size variables after accounting for all variables, by vehicle type

	Variance inflation factor (VIF) accounting for all variables in baseline model, using DRI method*						
	NHTSA baseline			16. Replace footprint with track width and wheelbase			
Vehicle type	UNDR WT00	OVER WT00	Footprint	UNDR WT00	OVER WT00	Track	Wheelbase
Cars	3.1	3.2	5.5	3.2	3.1	3.9	4.6
Light trucks	4.1	4.0	10.4	6.8	4.3	6.7	6.3
CUVs/minivans	6.5	9.4	2.8	6.7	4.6	6.6	3.0
2-dr cars	3.1	2.2	3.4	3.5	2.2	2.9	2.7
4-dr cars	3.3	3.5	6.0	3.5	3.5	4.0	5.0
Sm pickups	5.7	1.8	5.3	12.1	1.9	7.8	2.6
Lg pickups	**	4.5	2.4	**	5.9	2.4	2.9
SUVs	4.2	2.5	5.7	5.7	2.9	5.7	2.9
CUVs	8.6	7.6	3.2	7.4	4.5	3.6	3.3
Minivans	1.9	3.1	4.3	1.9	6.2	1.8	4.5

* DRI used all variables from the NHTSA baseline regression model; NHTSA combined certain variables and dropped other variables.
** There are no large pickups with mass lower than the median for all light trucks (4,497 pounds).

The third reason NHTSA cites for not using wheelbase and track width as the size variables in the regression models is that they do not have the expected relationship on fatality risk. In the 2017 NHTSA baseline model, a one-inch reduction in track width is associated with an expected increase in rollover fatality risk: a 26% increase in rollover fatality risk in cars, and an 6% to 7% increase in rollover fatality risk in light trucks and CUVs/minivans. However, a one-inch reduction in wheelbase is not consistently associated with large increases in fatality risks in

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[25] In its VIF calculations, NHTSA used LBS100 for curb weight rather than the UNDRWT00 and OVERWT00 variables; combined the eight driver gender and age variables into two variables; dropped the ROLLCURT variable for cars and CUVs/minivans; and combined BLOCKER1 and BLOCKER2 variable for light trucks into a single BLOCKER variable. The VIFs in Table 5.5 were obtained using exactly the same 30 variables as NHTSA used in its baseline regression models.

crashes with objects or other light-duty vehicles. This may be because wheelbase is not as good a proxy for frontal crush space, as, say, overhang in frontal impacts, and a large percentage of fatalities in two-vehicle crashes are not frontal impacts that would be influenced by wheelbase or frontal overhang. So the regression coefficients for track width are consistent with crash theory, while the coefficients for wheelbase are not, perhaps because they are masked by other types of crashes in which frontal crush space is not expected to protect occupants.

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 5.14 shows the sensitivity of NHTSA's main results to these changes. The total number of fatalities involving CUVs increased from 6,708 in the 2012 analysis to 8,020 in the updated 2017 analysis, while fatalities involving minivans declined from 6,440 to 3,271; therefore the 2017 results are more influenced by a greater number of CUV fatalities. Weighting the distribution of fatalities in CUVs and minivans by their respective shares of sales in 2010[26] (which reflects more CUVs and fewer minivans) changes the estimated effect of mass reduction in CUVs and minivans to a 0.04% increase in risk, and footprint reduction to only a 0.18% increase in risk (shown in orange in Figure 5.14). Removing non-significant control variables from each of the regression models results in little change in the estimated effects of mass or footprint reduction from the NHTSA baseline model (shown in purple), with the exception of mass reduction in lighter-than-average cars (from a 1.2% increase to a 1.0% increase in fatality risk) and in CUVs/minivans (from a 0.25% decrease to a 0.14% increase in fatality risk).

In its 2012 report, NHTSA noted that the large changes in the estimated effect of mass reduction from adjusting CUV and minivan registration years with 2010 sales data indicated "the fragility of the [2012] CUV/minivan analysis, and in particular suggests the benefit for mass reduction estimated in the [2012] baseline analysis is a soft number." However, NHTSA did not include this change in its baseline model because of "the added complexity of re-weighting the data." NHTSA noted that excluding non-significant variables in the regression model for each crash type had little effect on the overall coefficients, and rejected this change because it resulted in a different combination of variables used in the regression models by crash type.

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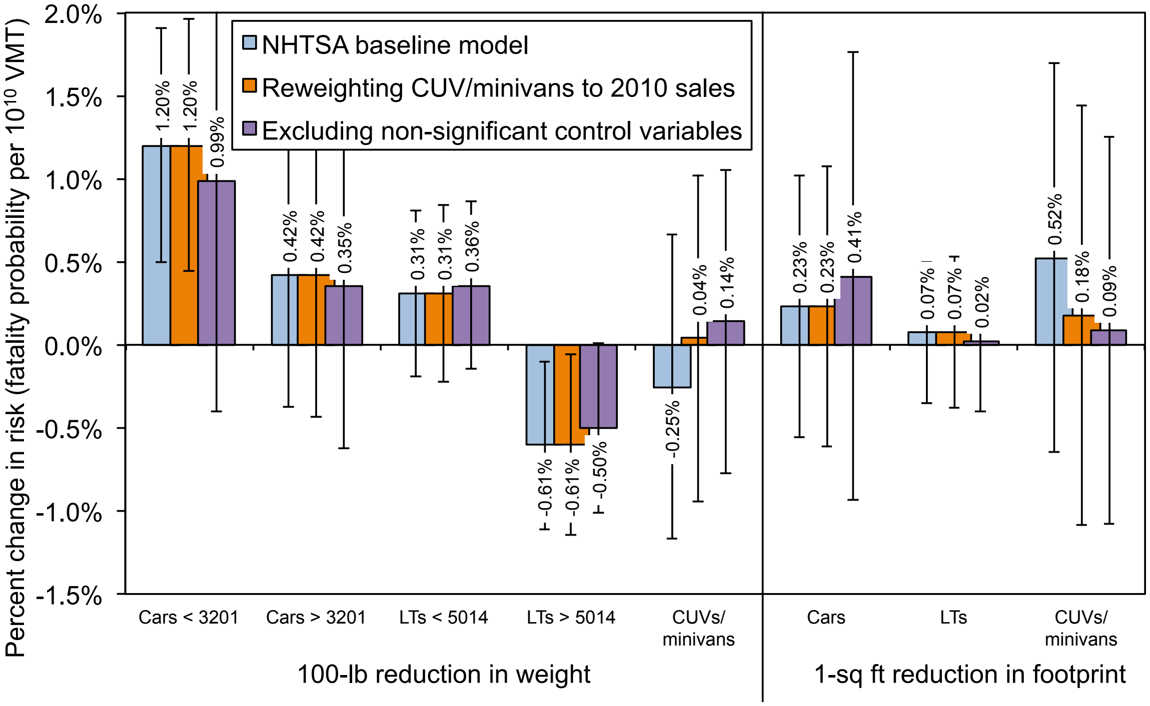
[26] Ideally this adjustment should be updated to reflect 2013 sales; however, comparable sales data for 2013 were not available at the time of the analysis to update this adjustment factor.

Figure 5.14. Estimated effect of mass and footprint reduction on U.S. fatality risk per VMT, after reweighting CUV/minivan fatalities to 2010 sales and excluding non-significant control variables, by vehicle type



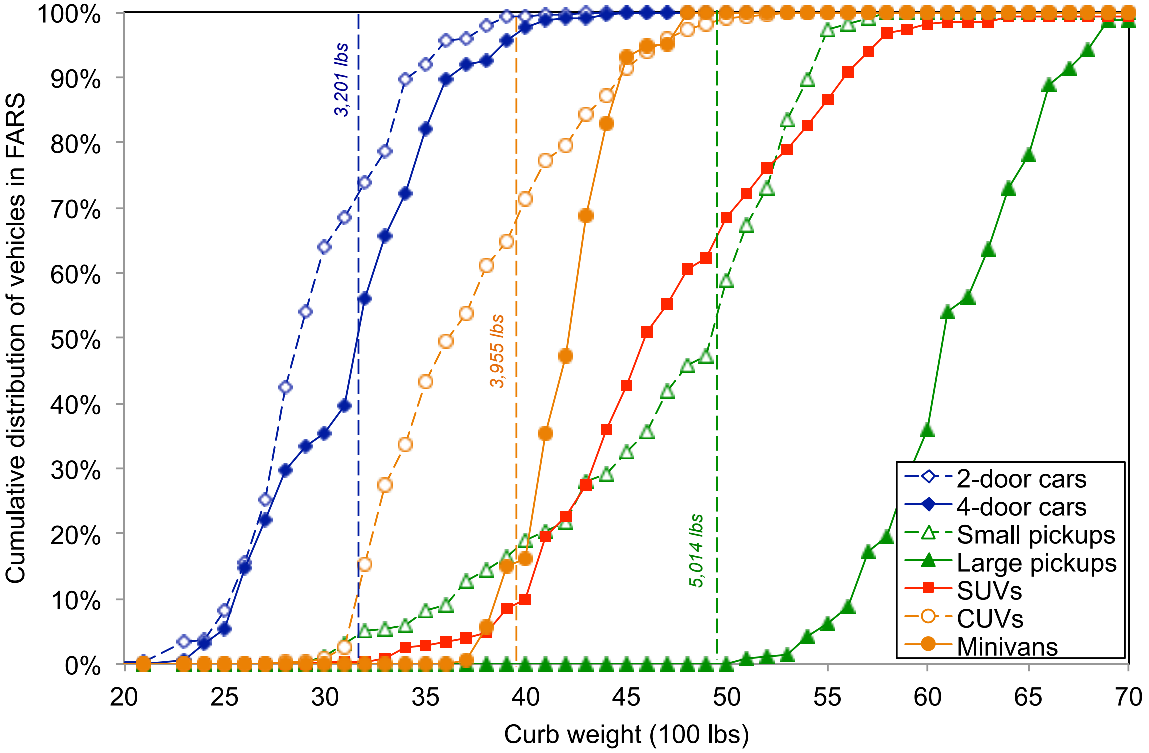
5.4. Effect of new sensitivity cases analyzed

In this section we analyze several additional sensitivity cases not analyzed in the 2012 report.

5.4.1. Sensitivity to how light trucks are classified

Figure 5.15 shows the cumulative distribution of vehicles involved in fatal crashes by curb weight and vehicle type. The median curb weight of the three vehicle groups is shown by vertical dashed lines: 3,201 pounds for passenger cars, 5,014 pounds for light trucks, and 3,955 pounds for CUVs and minivans. Note that, while 4-door cars tend to weigh more than 2-door cars, the difference is small, and that small pickups have a weight distribution similar to SUVs. Minivans tend to be heavier than CUVs, up to 1,000 pounds heavier at the lower end of the weight distribution. Large pickups are substantially heavier than small pickups/SUVs; up to 1,500 pounds heavier at the lower end, and up to 1,200 pounds heavier at the upper end, of the weight distribution. The median curb weight of small pickups/SUVs is only 4,818 pounds, while the median curb weight of large pickups is 6,119 pounds (not shown in figure). Because of the large disparity in curb weight of small pickups/SUVs and large pickups, LBNL ran a sensitivity regression model that treats large pickups as a vehicle class separate from small pickups and truck-based SUVs.

Figure 5.15. Cumulative distribution of vehicle curb weight, by vehicle type



Another factor is that the large pickup category includes pickups with a Gross Vehicle Weight Rating (GVWR) over 10,000 pounds. These vehicles are not covered in the light-duty vehicle standards; rather, they are covered as Class 3/2b trucks in the heavy-duty vehicle standards. Figure 5.16 shows the weight distribution of large pickups split into those with a GVWR less than and greater than 10,000 pounds. The median curb weight of large pickups with a GVWR less than 10,000 pounds is 6,080 pounds, while the median curb weight of large pickups with a GVWR greater than 10,000 pounds is 6,646 pounds. Because pickup trucks rated over 10,000 pounds GVWR are not subject to the light duty vehicle standards, LBNL ran a sensitivity regression model excluding these vehicles.

Figure 5.16. Cumulative distribution of vehicle curb weight, by vehicle type, including large pickups under and over 10,000 GVWR

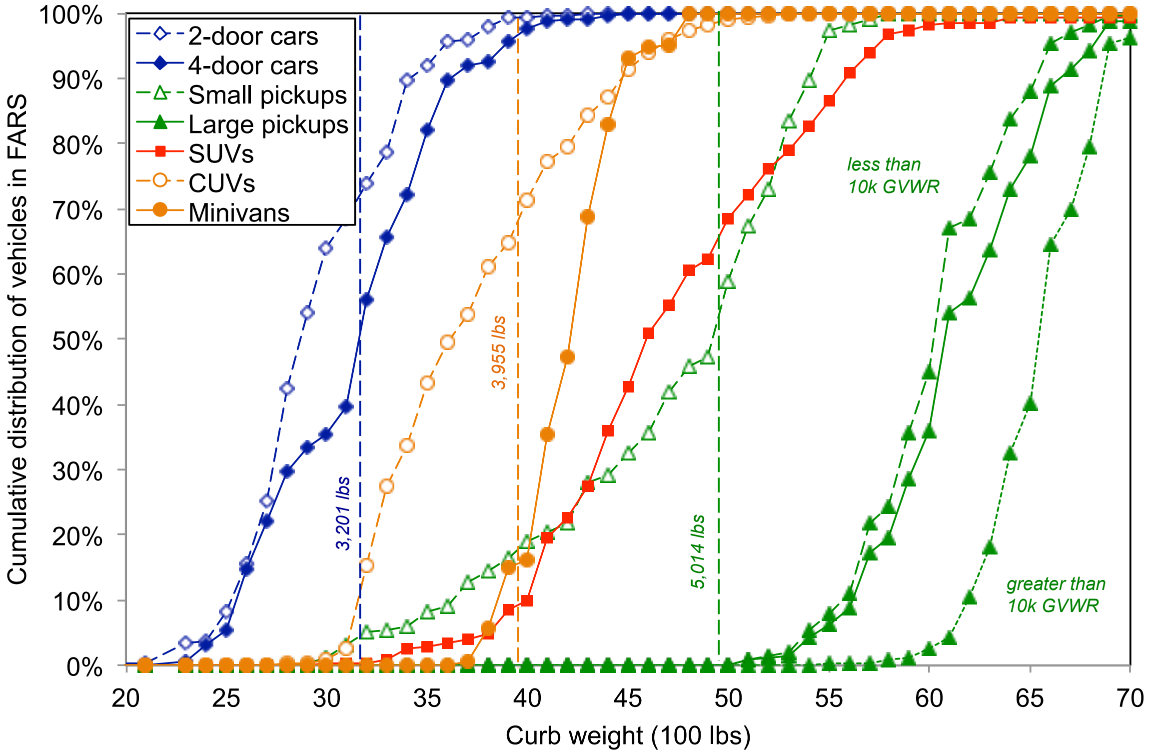


Table 5.7 shows the estimated association of mass reduction with societal fatality risk under the NHTSA baseline regression model and four alternative models that exclude large pickups with GVWR greater than 10,000 pounds and treat large pickups as a separate vehicle class; estimated effects that are statistically significant at the 95% level are shown in red. Model 20 includes large pickups with small pickups and SUVs, but excludes the 4% of large pickups that have GVWR greater than 10,000 pounds. This sensitivity decreases estimated fatality risk in heavier-than-average light trucks from a 0.61% reduction in risk to a 0.83% reduction in risk associated with mass reduction. Models 21 and 22 treat small pickups/SUVs and large pickups as two distinct vehicle classes, with median weights different from those used in NHTSA's baseline model. Mass reduction in heavier-than-average (> 4,818 pounds) small pickups/SUVs (Model 21) is associated with a smaller reduction in risk, 0.45%, than in the baseline model, while mass reduction in heavier-than-average (> 6,119 pounds) large pickups (Model 22) is associated with a 1.74% increase in societal fatality risk. Mass reduction in lighter-than-average (< 6,119 pounds) large pickups (Model 22) is associated with a large 3.1% reduction in societal fatality risk. Model 23, which treats large pickups separately from small pickups/SUVs and excludes large pickups with GVWR greater than 10,000 pounds, results in an even larger 3.5% reduction in societal fatality risk from mass reduction in lighter-than-average (< 6,080 pounds) large pickups. Mass reduction in heavier-than-average (> 6,080 pounds) large pickups is associated with a relatively large 2.1% increase in risk in Model 23.

The results for large pickups in Models 22 and 23 are surprising, in that mass reduction in the lighter large pickups is associated with large decreases in fatality risk, while mass reduction in the heavier large pickups is associated with small increases in fatality risk; one would expect that mass reduction in the heavier large pickups would be associated with even larger decrease in societal fatality risk. In subsequent analyses of the data used in the 2016 studies, LBNL found that using four-, six-, or eight-piece variables for curb weight, rather than the two-piece variable used in the NHTSA baseline regression model, resulted in inconsistent estimates of the effect of mass reduction on societal fatality risk for both cars and light trucks; in other words, mass reduction does not appear to have a consistent relationship with fatality risk across the range of curb weights (Wenzel 2016).

Table 5.7. Estimated effect of mass or footprint reduction on U.S. fatality risk per VMT, under different categorization of large pickups

	Case vehicle type	Baseline	20. Excluding large pickups with GVWR > 10,000 lbs	21. Small pickups/ SUVs separate from large pickups	22. Large pickups separate from small pickups/ SUVs	23. Large PUs separate from small PUs/SUVs excluding GVWR < 10,000 lbs (20 + 22)
Mass reduction	Cars < 3201 lbs	1.20%	1.20%	1.20%	1.20%	1.20%
	Cars ≥ 3201 lbs	0.42%	0.42%	0.42%	0.42%	0.42%
	LTs < median lbs*	0.31%	0.43%	0.23%	-3.07%	-3.52%
	LTs ≥ median lbs*	-0.61%	-0.83%	-0.45%	1.74%	2.11%
	CUV/minivan	-0.25%	-0.25%	-0.25%	-0.25%	-0.25%
Footprint reduction	Cars	0.23%	0.23%	0.23%	0.23%	0.23%
	LTs	0.07%	0.06%	0.32%	-0.19%	-1.43%
	CUV/minivan	0.52%	0.52%	0.52%	0.52%	0.52%

* The median weights used for each alternative regression are 4,992 pounds for Model 20, 4,818 pounds for Model 21, 6,119 pounds for Model 22, and 6,080 pounds for Model 23.
Note: Estimates that are statistically significant at the 95% level are shown in red. Shaded cells indicate instances where alternative model does not affect NHTSA baseline estimate.

5.4.2. Sensitivity to which cars are included

The NHTSA baseline model excludes sporty "muscle" cars,[27] police cars, and AWD cars, under the assumption that these cars are driven more aggressively than conventional cars, and that the driver gender and age variables in the regression model do not adequately account for differences in driver behavior among car models.[28] Sporty, police, and AWD cars account for 10% of the case vehicles involved in fatal crashes in FARS. LBNL investigated the sensitivity of the baseline model to including these three vehicle types in alternative Model 14, discussed above. Including these three vehicle types decreases the association between mass reduction and fatality

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[27] As determined by how they are promoted by their manufacturer. The muscle cars tend to have engines larger than 3 liters, with rated horsepower greater than 200. As of the 2017 database, NHTSA also excluded a small number of Chevrolet Tahoe SUV models used by police departments.

[28] This despite AWD cars having a lower average risk per 10 billion VMT, 73, than that for the average four-door car, 119.

risk from 1.49% to 1.44% for lighter-than-average cars, and increases it from 0.50% to 0.62% for heavier-than-average cars, as shown in Figure 5.13.

The NHTSA 2012 study explains why these vehicles were excluded from the baseline model: *"Police cars and muscle cars have exceptionally high fatality rates, compared to other cars of the same size and mass, because of unusual driving patterns. Given that police and muscle cars are relatively heavy and that, moreover, muscle cars tend to have small footprint (short wheelbase), the regression analyses might attribute the high fatality rates to mass or footprint rather than the unusual driving patterns; see Kahane (2003), pp. 41-42 and 171-173, Kahane (2010), pp. 483-486 and 512-514."* Page 1. *Including these "niche" vehicles, each with its own pattern of crash types and of relationships with mass and footprint, adds some complexity. It might generate coefficients for mass and footprint that to some extent reflect how the vehicle mix varies for different mass-footprint combinations rather than the underlying relationships of mass and footprint with fatality risk.* Page 69.

Table 5.8 compares the estimated effect of mass reduction on risk for cars, under alternative Model 14 (which includes all car models), alternative Model 24 (which includes AWD but not muscle or police cars), alternative Model 25 (which includes muscle and police, but not AWD, cars), the NHTSA baseline model (which excludes the muscle, police, and AWD cars), and alternative Model 26 (which excludes the two high-risk two-door car models Hyundai Tiburon and Scion tC). In Model 14, fatality risk is, on average, 57% lower in AWD cars, but 65% to 70% higher in muscle and police cars, than in four-door cars. Table 5.8 indicates that excluding the risky muscle and police cars in Model 24 reduces the estimated increase in fatality risk associated with mass reduction in lighter-than-average cars, from a 1.21% increase in Model 14 to a 1.05% increase. On the other hand, excluding the relatively safe AWD cars in Model 25 increases the estimated increase in fatality risk associated with mass reduction in lighter-than-average cars, from a 1.21% increase in Model 14 to a 1.37% increase. The baseline model, which excludes the relatively safe AWD cars in addition to the relatively risky muscle and police cars, reduces the estimated increase from a 1.37% increase in Model 25 to a 1.20% increase.

LBNL further analyzed the sensitivity of the baseline model to excluding certain car models. Two two-door car models marketed as "compact sports cars",[29] Hyundai Tiburon and Scion tC, have the highest societal fatality risks per VMT of all two-door cars included in NHTSA's baseline model, 246 and 221 fatalities per 10 billion VMT, compared to a risk of 148 fatalities per 10 billion VMT for the average 2-door car.[30] The risks of these two two-door car models are higher than most of the muscle cars excluded from the NHTSA baseline model; the average risk of muscle cars is only 195 fatalities per 10 billion VMT. Excluding the two high-risk models, which represent less than two percent of the vehicles involved in fatal crashes in FARS, further reduces the estimated increase in fatality risk associated with mass reduction in lighter-than-average cars, from a 1.20% increase in the baseline model to a 1.11% increase, as shown in Model 26. Note that excluding these two high-risk models also reduces the estimated increase in

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[29] Their engines are not powerful enough to classify them as muscle cars: up to 2.5 liters and 200 horsepower.

[30] We did not exclude the Acura RSX, which was discontinued after the 2006 model year, in the current analysis as its fatality risk is only 184 per 10 billion VMT in 2017. There is one other 2-door car model with similar fatality risk, 222 fatalities per 10 billion VMT; however, it is not marketed as a compact sports car, and is less likely to attract particularly risky drivers.

fatality risk associated with mass reduction in heavier-than-average cars, from a 0.42% increase in the baseline model to a 0.25% increase in Model 26.

Alternative Model 27 excludes muscle and police cars, as well as the two high-risk compact sports car models. Excluding these cars from the regression models reduces the increase in fatality risk associated with mass reduction in lighter-than-average cars from a 1.20% increase in the baseline model to a 0.94% increase, while increasing the increase in risk in heavier-than-average cars from a 0.42% increase in the baseline model to a 0.59% increase.

Table 5.8. Estimated effect of mass or footprint reduction on U.S. fatality risk per VMT, after excluding certain car models

	Case vehicle type	14. Include muscle, police, and all-wheel drive cars, and full size vans	24. Exclude muscle and police, but not AWD, cars	25. Exclude AWD, but not muscle and police, cars	Baseline	26. Exclude Hyundai Tiburon, and Scion tC	27. Exclude muscle and police cars, and Tiburon and tC,
Mass reduction	Cars < 3201 lbs	1.21%	1.05%	1.37%	1.20%	1.11%	0.94%
	Cars ≥ 3201 lbs	0.55%	0.83%	0.23%	0.42%	0.25%	0.59%
	LTs < 5014 lbs	0.33%	0.31%	0.31%	0.31%	0.31%	0.31%
	LTs ≥ 5014 lbs	-0.76%	-0.61%	-0.61%	-0.61%	-0.61%	-0.61%
	CUV/minivan	-0.25%	-0.25%	-0.25%	-0.25%	-0.25%	-0.25%
Footprint reduction	Cars	0.16%	0.17%	0.19%	0.23%	0.46%	0.40%
	LTs	0.07%	0.07%	0.07%	0.07%	0.07%	0.07%
	CUV/minivan	0.52%	0.52%	0.52%	0.52%	0.52%	0.52%

Note: Estimates that are statistically significant at the 95% level are shown in red. Shaded cells indicate instances where alternative model does not affect NHTSA baseline estimate.

5.4.3. Sensitivity to two-piece variables for CUV curb weight and for all vehicle footprint

The NHTSA baseline model includes a two-piece variable for curb weight only for cars and light trucks; a single variable for curb weight was used for CUVs/minivans because of the relatively small number of those types of vehicles. Table 5.9 shows the results from using a two-piece variable for curb weight for CUVs/minivans, as well as two-piece variable for footprint for all three vehicle types. Alternative Model 28 indicates that using a two-piece variable for CUV/minivan curb weight, based on their median weight of 3,955 pounds, results in an increase in societal fatalities from mass reduction in lighter-than-average CUVs/minivans (a 0.27% increase) and a larger decrease in heavier-than-average CUVs/minivans (a 0.54% decrease). This model also results in a smaller increase in fatalities from footprint reduction, from a 0.52% increase in the baseline model to a 0.35% increase, as shown in Model 28.

Model 29 in Table 5.9 uses a single variable for CUV/minivan curb weight, but adds two piece-variables for footprint for each of the three vehicle types, based on their median footprint: 45.0 square feet for cars, 56.9 square feet for light trucks, and 49.0 square feet for CUVs/minivans.

Using a two-piece variable for footprint reduces the detrimental effect associated with mass reduction for lighter-than-average cars (from a 1.20% increase in fatality risk to a 0.65% increase), lighter-than-average light trucks (from a 0.31% increase to a 0.07% decrease in fatality risk), and heavier-than-average light trucks (from a 0.61% decrease to a 0.66% decrease), as compared to the NHTSA baseline model. However, the two-piece variable for footprint substantially increases fatality risk associated with mass reduction in heavier-than-average cars (from a 0.42% increase to a 1.12% increase) and slightly increases fatality risk in CUVs/minivans (from a 0.25% decrease to a 0.19% decrease).

Model 30 in Table 5.9 combines the two-piece variable for curb weight for CUVs/minivans from Model 28 with the two-piece variables for footprint for all three vehicle types from Model 29. Model 30 estimates a similar association between mass reduction and fatality risk for CUVs/minivans as Model 28: a 1.25% increase in fatalities for lighter-than-average, and a 0.68% decrease in fatalities for heavier-than-average, CUVs/minivans, as compared to the 0.25% decrease in fatalities for all CUVs/minivans in the NHTSA baseline model.

Table 5.9. Estimated effect of mass or footprint reduction on U.S. fatality risk per VMT, after changing curb weight and footprint variables

	Case vehicle type	Baseline	28. Two-piece variable for CUV weight	29. Two-piece variable for all footprint	30. Two-piece variable for CUV weight, plus two-piece variable for all footprint
Mass reduction	Cars < 3201 lbs	1.20%	1.20%	0.65%	0.65%
	Cars ≥ 3201 lbs	0.42%	0.42%	1.12%	1.12%
	LTs < 5014 lbs	0.31%	0.31%	-0.07%	-0.07%
	LTs ≥ 5014 lbs	-0.61%	-0.61%	-0.66%	-0.66%
	CUVs < 3955 lbs	-0.25%	0.27%	-0.19%	1.25%
	CUVs ≥ 3955 lbs		-0.54%		-0.68%
Footprint reduction	Cars < 45.0 sf	0.23%	0.23%	1.29%	1.29%
	Cars ≥ 45.0 sf			-0.89%	-0.89%
	LTs < 56.9 sf	0.07%	0.07%	0.94%	0.94%
	LTs ≥ 56.9 sf			-0.29%	-0.29%
	CUVs < 49.0 sf	0.52%	0.35%	0.25%	-0.91%
	CUVs ≥ 49.0 sf			0.71%	0.95%

Note: Estimates that are statistically significant at the 95% level are shown in red. Shaded cells indicate instances where alternative model does not affect NHTSA baseline estimate.

5.4.4. Sensitivity to NHTSA VMT weights

In order to estimate the relationship between mass or size reduction on fatality risk per VMT, NHTSA developed a methodology to estimate the annual number of miles driven for every vehicle in the induced exposure database. For its 2016 study, NHTSA developed two mileage accumulation schedules, one for cars and one for light trucks (including CUVs and minivans), based on mileage accumulation rates for each, taken from the 2009 National Household Transportation Survey, as reported in NHTSA's Final Regulatory Impact Analysis for the 2012 rulemaking (NHTSA 2012). The schedules indicate the estimated average annual vehicles miles of travel (VMT) by vehicle age. NHTSA updated these VMT schedules slightly for its 2018 analysis. NHTSA applied these schedules to all vehicles in the thirteen state induced exposure database, based on the age of the vehicle. NHTSA then adjusted the estimated miles by vehicle age for individual vehicle models, based on average odometer data obtained from IHS/Polk. IHS/Polk used the most recent odometer reading for each vehicle reporting for an emissions or safety inspection, or for service at a dealership, over a period of up to 2.5 years,[31] and estimated the average odometer reading by model year for every vehicle model. NHTSA calculated VMT adjustment factors for every vehicle model, by dividing the average odometer reading by model year for each model by the overall average odometer reading by model year for cars and light trucks. NHTSA then applied each of these VMT adjustment factors to the mileage accumulation schedule to estimate the average annual VMT by vehicle year, age, and model.

This methodology assumes that, overall, vehicles of the same age have the same annual VMT, regardless of calendar year. However, the VMT by vehicle age is adjusted by the VMT ratios NHTSA obtained from IHS/Polk odometer readings, by model year; any changes in VMT by model year (or calendar year) of vehicles of a certain age are therefore attributable to differences by model year in the ratio of odometer readings of individual vehicle models to all vehicles in the IHS/Polk odometer database.

Table 5.10 shows the percent change in average annual VMT from 2008 for two-year old vehicles, by vehicle type; these data are derived from the NHTSA public database, by dividing the sum of the VMT weights by the sum of the registration weights, by vehicle type. Table 5.11 shows the same data, obtained from odometer readings of 3 million vehicles reporting for testing in the Texas emission inspection and maintenance (I/M) program.[32] The Texas I/M program requires annual testing of all light-duty vehicles two-years-old or older, in the 17 counties comprising the Houston, Dallas, Austin, and El Paso metropolitan areas. The cumulative changes in average VMT since 2008 in Tables 5.10 and 5.11 are quite different; cases where the Texas data indicate a larger decrease or smaller increase in VMT compared to the national data NHTSA used are shown in green in Table 5.11, whereas cases where the Texas data indicate a larger decrease or smaller increase in VMT compared to the national data NHTSA used are shown in green in Table 5.11. The trends are only similar for two-door cars, with VMT between 2008 and 2012 decreasing a cumulative 6.8% in the national data and 7.5% in the Texas data. The Texas data suggest that VMT decreased over the period for four-door cars, large pickups, SUVs, and CUVs, while the IHS/Polk data suggest that VMT had little change or increased over the period, particularly for small and large pickups (a 6% and 10% increase, respectively, in the national data but a 1% increase and a 3% decrease, respectively, in the Texas data). Similarly, the national data indicate that four-door cars had essentially no change in annual VMT over the

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[31] For its 2016 analysis NHTSA used the average odometer reading by vehicle model from between April 2008 and October 2010, as provided by IHS/Polk; NHTSA did not provide the date range for the updated odometer data provided by IHS/Polk and used in NHTSA's updated 2018 analysis.

[32] Of the 3 million vehicles with more than one odometer reading, only 3% were excluded for having an estimated annual VMT less than zero or greater than 50,000.

period, whereas VMT of four-door cars in Texas decreased 4% between 2008 and 2012. Annual changes in VMT that are larger decreases, or smaller increases, in the Texas data than in the national IHS/Polk data are indicated in green font in the table, while changes in VMT that are smaller decreases, or larger increases, in the Texas data than in the national data are indicated in red font. For the most part, vehicles in Texas showed relatively large annual decreases in VMT between 2008 and 2012, while national vehicles in the IHS/Polk dataset showed smaller decreases, or even increases, in annual VMT between 2008 and 2012.

Table 5.10 Change in average annual VMT since 2008 for two-year-old vehicles, by vehicle type: NHTSA method

Vehicle type	Calendar year				
	2008	2009	2010	2011	2012
2dr car	0.0%	-0.8%	-3.8%	-6.3%	-6.8%
4dr car	0.0%	0.0%	0.6%	-0.1%	0.1%
Sm PU	0.0%	1.4%	1.9%	3.0%	5.5%
Lg PU	0.0%	1.8%	5.7%	1.1%	10.1%
SUV	0.0%	2.9%	0.1%	1.0%	0.9%
CUV	0.0%	-1.3%	-1.4%	-0.7%	-2.3%
Minivan	0.0%	-0.8%	-0.2%	3.3%	2.7%

Table 5.11. Change in average annual VMT since 2008 for two-year-old vehicles, by vehicle type: TX DMV odometer data

Vehicle type	Calendar year				
	2008	2009	2010	2011	2012
2dr car	0.0%	-1.8%	-4.9%	-9.0%	-7.5%
4dr car	0.0%	-2.2%	-2.3%	-4.3%	-4.2%
Sm PU	0.0%	1.7%	-0.6%	-2.2%	1.2%
Lg PU	0.0%	-0.2%	-4.1%	-4.5%	-3.2%
SUV	0.0%	4.7%	1.4%	0.3%	-5.7%
CUV	0.0%	-0.7%	-1.5%	-4.2%	-1.9%
Minivan	0.0%	0.5%	-1.8%	0.1%	1.9%

There are two ways the VMT weights estimated by NHTSA could be incorrect. First, NHTSA applied the same VMT schedule by vehicle age for cars or light trucks for each calendar year. If average VMT varies by calendar year due to economic conditions or gas prices, or if VMT varies substantially by vehicle type, the NHTSA method may misstate average VMT. The second way NHTSA's VMT weights could be incorrect is if the ratios of the average odometer reading for each model relative to the odometer reading for all light-duty vehicles are biased.

NHTSA revised its VMT schedules for its 2018 analysis based on updated vehicle registration data provided by IHS/Polk, which reflect registrations as of December 31, rather than as of July 31 in the 2012 analysis, in each calendar year. Figure 5.17 shows that the VMT schedules NHTSA used have kinks for 7-year-old light trucks (shown in green), and for 8-year-old cars (shown in blue), where average VMT drops substantially from the previous vehicle age. The figure also indicates that the updated VMT schedules for the 2018 analysis (indicated by solid blue and green symbols and lines) are very similar to those NTHSA used in its 2016 analysis (indicated by open symbols and dashed lines). NHTSA has not verified a possible explanation for these kinks in the VMT schedules it used. LBNL ran a sensitivity model where these kinks were removed and the VMT schedules were smoothed, as indicated by the small dashed lines in Figure 5.17.

Figure 5.17. Average vehicle miles traveled by vehicle age and calendar year, NHTSA

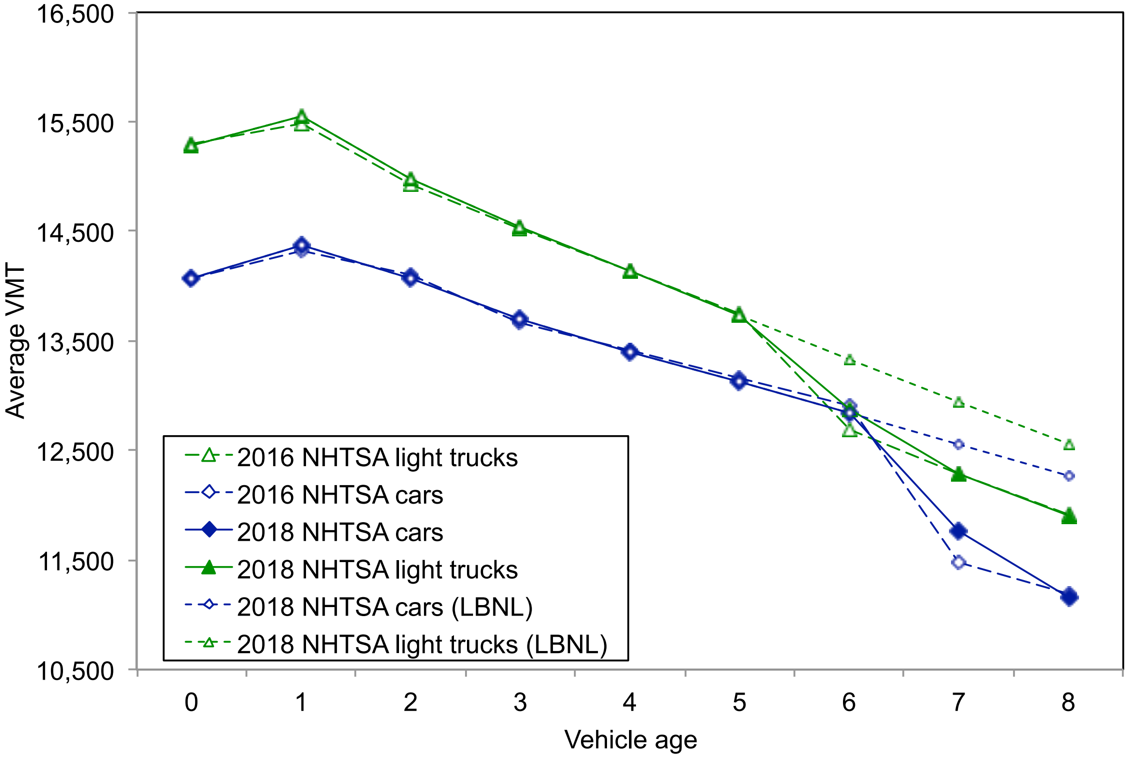


Figure 5.18 shows three VMT schedules from the Texas odometer data, by vehicle type and age: all model year 2004 to 2011 vehicles in years 2006 to 2012, model year 1998 to 2006 vehicles in 2006, and model year 2004 to 2012 vehicles in 2012. Figure 5.18 indicates that the VMT schedules by vehicle age from the Texas odometer data can vary substantially across different model years and calendar years, particularly for vehicles between zero and four years of age. Note that since the Texas emissions inspection program only requires an annual inspection for vehicles two years old and older, the average VMT for vehicles zero to two years of age are estimated on relatively small numbers of vehicles, mostly vehicles that are registered in Texas from another state, and likely are not representative of all young vehicles in the on-road fleet. Figure 5.19 compares the VMT schedules by vehicle age for model year 2004 to 2011 vehicles in 2006 to 2012 in Texas with those NHTSA developed from the NHTS. The VMT schedule for three- to nine-year old cars from the Texas data is very similar to that NHTSA used, although the Texas schedule does not indicated a kink, or reduction, in annual VMT for eight-year old cars as in the NHTSA schedule. For light trucks, the Texas VMT schedule also is similar to the NHTSA schedule, but without the kink for nine-year old light trucks; however, the VMT schedule in Texas is about 600 to 900 miles, or about 6%, higher than the NHTSA VMT schedule for each age of light trucks.

Figure 5.18. Average vehicle miles traveled by vehicle age and calendar year, Texas odometer data

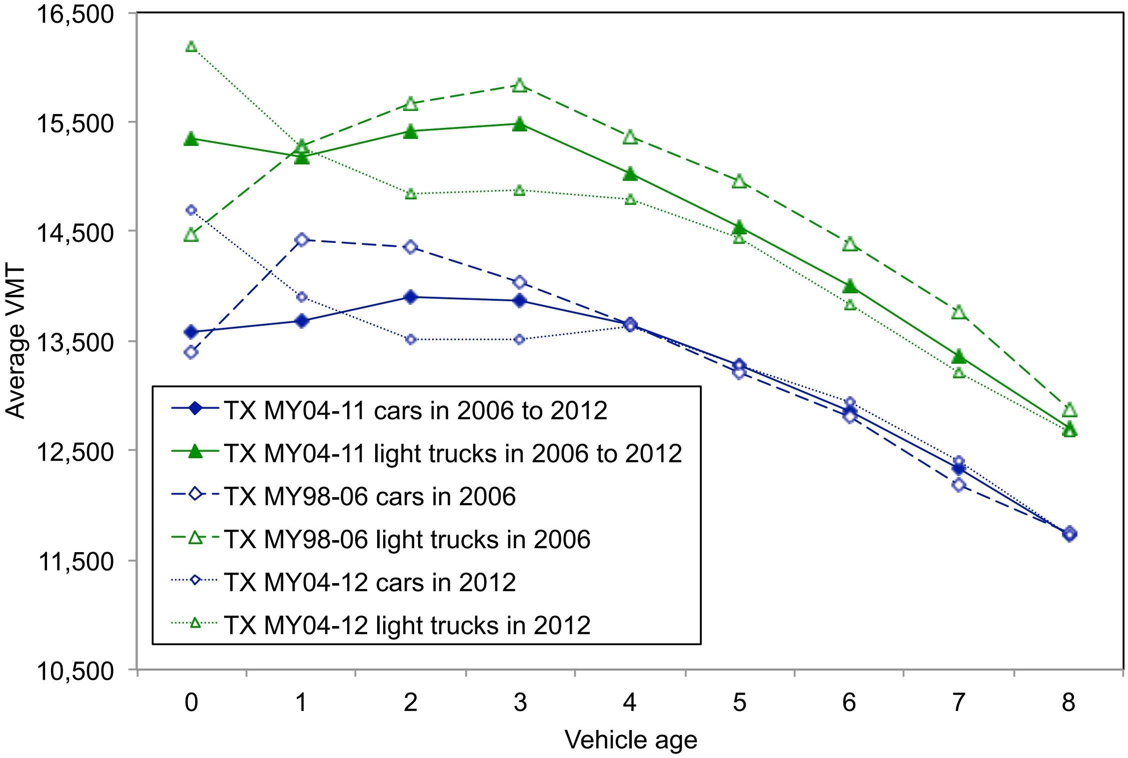
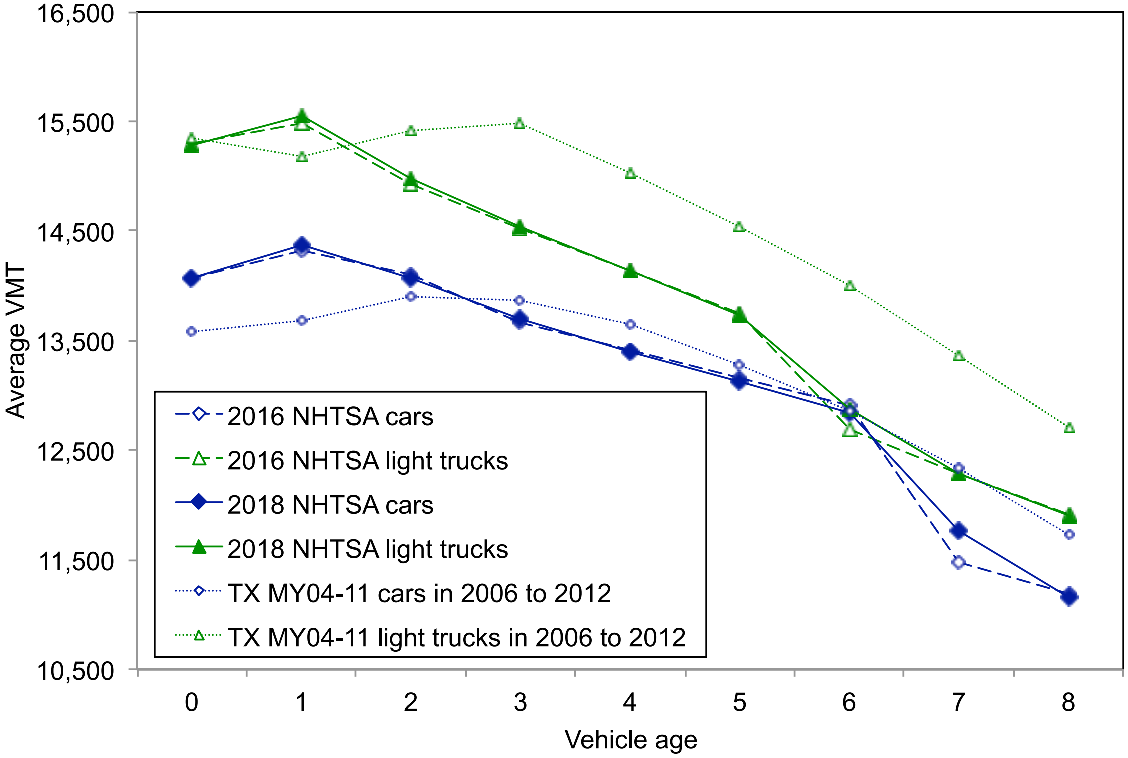


Figure 5.19. Average vehicle miles traveled by vehicle age and calendar year, Texas odometer data



Because vehicles less than two years of age (other than those re-registering in Texas from another state) are exempted from the Texas I/M program, the Texas odometer data cannot be used to estimate a schedule of VMT by vehicle age for the newest vehicles.

Tables 5.12 and 5.13 compare the odometer adjustment ratios NHTSA developed from national IHS/Polk odometer readings with those from the Texas odometer data. The data NHTSA used span a period of up to 2.5 years,[33] while the Texas data are all from January 2014. In contrast to the large differences between the annual VMT estimates used by NHTSA and in the Texas odometer data, the average odometer adjustment ratios are quite similar between the national IHS/Polk data and the Texas odometer data, with relatively large reductions in the odometer ratios for two-door cars (11% nationally and 13% in Texas) and SUVs (4% nationally and 7% in Texas), essentially unchanged odometer ratios for four-door cars in both datasets, and relatively large increases in odometer ratios for small pickups (6% nationally and 4% in Texas) and large pickups (24% nationally and 17% in Texas). The annual changes tend to be greater decreases, or smaller increases, in the Texas data than in the national data, as indicated by the green (vs. red) font in Table 5.13. The only major differences in the odometer adjustment ratios derived from the national and Texas data are for CUVs and minivans, which show decreases in the average odometer adjustment ratios between model years 2004 and 2011 in the national data (a 5% and 1% reduction, respectively) but increases in the average odometer adjustment rations in the Texas data (a 2% and 6% increase, respectively).

Because the change since model year 2004 in the odometer ratios by vehicle model from the national odometer data (Table 5.12) are quite similar to those from the Texas odometer data (Table 5.13), we did not use the Texas odometer data to create different VMT weights by vehicle model.

Table 5.12 Change in average annual odometer adjustment ratio since 2008, by vehicle type and model year (national IHS/Polk odometer averages by year and model used by NHTSA)

Vehicle type	Model year 2004	2005	2006	2007	2008	2009	2010	2011
2dr car	0.0%	-3.2%	-2.1%	-3.2%	-5.3%	-8.5%	-8.5%	-10.6%
4dr car	0.0%	0.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
Sm PU	0.0%	1.0%	2.1%	4.1%	4.1%	5.2%	8.2%	6.2%
Lg PU	0.0%	1.9%	5.8%	7.8%	11.7%	6.8%	16.5%	24.3%
SUV	0.0%	-2.0%	-3.9%	-1.0%	-3.9%	-2.9%	-2.9%	-3.9%
CUV	0.0%	-1.0%	-2.0%	-3.1%	-3.1%	-2.0%	-4.1%	-5.1%
Minivan	0.0%	0.0%	-1.0%	-1.9%	-1.0%	2.9%	1.9%	-1.0%

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[33] For its 2016 analysis NHTSA used the average odometer reading by vehicle model from between April 2008 and October 2010, as provided by IHS/Polk; NHTSA did not provide the date range for the updated odometer data provided by IHS/Polk and used in NHTSA's updated 2018 analysis.

Table 5.13 Change in average annual odometer adjustment ratio since 2008, by vehicle type and model year (Texas odometer data in 2014)

Vehicle type	Model year 2004	2005	2006	2007	2008	2009	2010	2011
2dr car	0.0%	-3.2%	-3.2%	-3.2%	-6.4%	-9.6%	-11.7%	-12.8%
4dr car	0.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
Sm PU	0.0%	1.0%	2.0%	3.0%	3.0%	3.0%	6.0%	4.0%
Lg PU	0.0%	0.8%	2.4%	6.5%	5.7%	4.9%	9.8%	17.1%
SUV	0.0%	-1.0%	-4.0%	0.0%	-3.0%	-2.0%	-7.1%	-7.1%
CUV	0.0%	1.1%	1.1%	0.0%	0.0%	0.0%	2.2%	2.2%
Minivan	0.0%	3.1%	2.1%	2.1%	3.1%	10.3%	16.5%	6.2%

Table 5.14 shows the sensitivity of the NHTSA baseline model to the simple change of removing the kinks in the NHTSA VMT schedules (Model 31), which has little effect on the associations of mass or footprint reduction with societal fatality risk. This is because only 8% of all fatalities in light trucks and CUVs/minivans occur in vehicles older than six years old, and only 3% of all fatalities in cars occur in vehicles older than seven years old.

Table 5.14. Estimated effect of mass or footprint reduction on U.S. fatality risk per VMT, after removing the kinks in the NHTSA VMT schedules by vehicle age

	Case vehicle type	Baseline	31. Remove kinks in NHTSA VMT schedules
Mass reduction	Cars < 3201 lbs	1.20%	1.20%
	Cars ≥ 3201 lbs	0.42%	0.41%
	LTs < 5014 lbs	0.31%	0.31%
	LTs ≥ 5014 lbs	-0.61%	-0.61%
	CUV/minivan	-0.25%	-0.26%
Footprint reduction	Cars	0.23%	0.23%
	LTs	0.07%	0.08%
	CUV/minivan	0.52%	0.53%

Note: Estimates that are statistically significant at the 95% level are shown in red. Shaded cells indicate instances where alternative model does not affect NHTSA baseline estimate.

5.5. Discussion of alternative models

Table 5.15 lists the 31 alternative regression models we estimated, while Table 5.15 summarizes the estimated association of mass or footprint reduction on U.S. societal fatality risk under the NHTSA baseline and each alternative model.

The intent in conducting the alternative regression models shown in Table 5.16 is not to develop a regression model that is "more correct" than the NHTSA baseline model; rather, the intent is to test how sensitive the results from the baseline model are to changes in the data and variables used, as well as to gain an understanding of how accounting for various factors (such as driver alcohol/drug use or driving behavior, or quality of vehicle design) influences the relationship between vehicle mass, size, and societal fatality risk.

Table 5.16 indicates that NHTSA's estimates are sensitive to the definition of risk, and to changes in the data and variables, used in its regression models. For cars < 3,201 pounds, all alternative models estimate that mass reduction is associated with an increase in societal fatality risk, ranging from a 0.26% increase (Model 10) to a 2.34% increase (Model 12). 15 of the 31 alternative models estimate a smaller increase in risk, and 10 estimate a larger increase in risk, than the NHTSA baseline model (the remaining 6 alternative models, shaded in grey in Table ES.1, do not make changes to the regression model for cars). For cars ≥ 3,201 pounds, all but four of the alternative models estimate that mass reduction is associated with an increase in societal fatality risk, ranging from a 0.21% decrease (Model 13) to a 3.10% increase (Model 5). 11 of the 31 alternative models estimate a smaller increase, or a decrease, in risk, and 14 estimate a larger increase in risk, than the NHTSA baseline model (6 alternative models do not make changes to the regression model for cars).

For light trucks < 5,014 pounds, Table 5.16 indicates that all but six of the 29 applicable alternative models estimate that mass reduction is associated with an increase in fatality risk: ranging from a 0.77% decrease in risk (Model 17) to a 1.15% increase in risk (Model 8). 12 of the 29 alternative models estimate a larger increase in risk, and 13 estimate the same, a smaller increase, or a decrease, in risk, than the NHTSA baseline model (6 alternative models do not make changes to the regression model for light trucks). In the two models restricted to analyses of large pickups, trucks < 6,119 pounds (Model 22) and < 6,080 pounds (Model 23), mass reduction is associated with decreases in fatality risk (3.1% and 3.5% decreases in risk, respectively) an order of magnitude larger than the increase estimated in the baseline NHTSA model (0.31% increase). The classification of relatively light (i.e., below the median) trucks in Models 22 and 23 is distinct to the classification of relatively light trucks in the other models.

For light trucks ≥ 5,014 pounds, only two of the 29 applicable alternative models estimate that mass reduction is associated with an increase in fatality risk, and range from a 1.91% decrease in risk (Model 17) to 0.52% increase in risk (Model 8). 15 of the 29 applicable alternative models estimate the same or a larger decrease in risk, and 8 estimate a smaller decrease, or an increase, in risk, than the NHTSA baseline model (6 alternative models do not make changes to the regression model for light trucks). In the two models restricted to analyses of large pickups, trucks ≥ 6,119 pounds (Model 22) and ≥ 6,080 pounds (Model 23), mass reduction is associated with large increases in fatality risk relative to the baseline NHTSA model (1.7% and 2.1% increases in risk, respectively). Again, the classification of relatively heavy (i.e., above the median) trucks in Models 22 and 23 is distinct to the classification of relatively heavy trucks in the other models.

For CUVs/minivans, all but five of the 29 applicable alternative models estimate that mass reduction is associated with a decrease in fatality risk, and range from a 1.00% decrease in risk

(Model 9) to a 0.14% increase in risk (Model 19). 11 of the 31 alternative models estimate a larger decrease in risk, and 9 estimate a smaller decrease, or an increase, in risk, than the NHTSA baseline model (9 alternative models do not make changes to the regression model for CUVs/minivans). In the two models which estimate the effect of mass reduction for lighter- and heavier-than-average CUVs/minivans (Models 28 and 30), mass reduction is associated with increases in fatality risk for lighter-than-average CUVs/minivans (0.27% and 1.25% increases in Models 28 and 30, respectively) but decreases in fatality risk for heavier-than-average CUVs/minivans (0.54% and 0.68% decreases in Models 28 and 30, respectively).

Table 5.15. Description of 31 alternative regression models analyzed in this report

Alternate measure of risk	1.Weighted by current distribution of fatalities (rather than after 100% ESC) 2.Single regression model across all crash types (rather by crash type) 3.Fatal crashes (rather than fatalities) per VMT 4.Fatalities per induced exposure crash (rather than VMT) 5.Fatalities per registered vehicle-year (rather than VMT)
Alternate control variables or data	6.Allow footprint to vary with mass (and vice versa) 7.Account for 14 vehicle manufacturers 8.Account for 14 manufacturers + 5 additional luxury vehicle brands 9.Account for initial vehicle purchase price (based on Polk VIN decoder) 10.Exclude CY variables 11.Exclude crashes with alcohol/drugs 12.Exclude crashes with alcohol/drugs, and drivers with poor driving record 13.Account for median household income 14.Include sports, police, and all-wheel drive cars, and full size vans
Proposed by DRI/ reviewers	15.Use stopped instead of non-culpable vehicles for induced exposure 16.Replace footprint with track width and wheelbase 17.Above two models combined (15 and 16) 18.Reweight CUV/minivans by 2010 sales 19.Exclude non-significant control variables
New alternatives analyzed in this report	20.Exclude LTs over 10k GVWR[1] 21.Small pickups and SUVs[1] 22.Large pickups[1] 23.Above two models combined for large pickups[1] (20 and 22) 24. Include AWD cars, but not muscle or police cars 25. Include muscle and police cars, but not AWD cars 26. Exclude three high-risk car models 27. Include AWD cars, exclude three high-risk car models (24 and 26) 28. Two-piece variable for CUV mass[2] 29. Two-piece variable for PC and LT footprint[3] 30. Two-piece variable for CUV mass, and for all footprint[3] (28 and 29) 31. Remove kinks in NHTSA VMT schedules

[1] The median weights used for Models 20-23 are: 4,992 pounds for Model 20; 4,818 pounds for Model 21; 6,119 pounds for Model 22; and 6,080 pounds for Model 23.

[2] The median weight used for CUVs/minivans in Models 28 and 30 is 3,939 pounds.

[3] The median footprints used for Models 29 and 30 are 44.3 square feet for cars, 56.9 square feet for light trucks, and 49.0 square feet for CUVs/minivans.

Table 5.16. Estimated effect of mass or footprint reduction on U.S. fatalities, baseline and 31 alternative regression models analyzed in this report

Model		Mass reduction					Footprint reduction		
		Cars		Light trucks		CUV/ minivan	Cars	Light trucks	CUV/ minivan
		<3201 lbs	≥3201 lbs	<5014 lbs	≥5014 lbs				
Baseline		1.20%	0.42%	0.31%	-0.61%	-0.25%	0.23%	0.08%	0.52%
Alternate risk definitioin	1	1.06%	0.30%	0.38%	-0.61%	-0.48%	0.47%	0.21%	0.89%
	2	1.05%	0.30%	0.37%	-0.61%	-0.48%	0.47%	0.21%	0.88%
	3	1.40%	0.61%	0.31%	-0.64%	-0.59%	0.26%	0.26%	1.12%
	4	0.36%	0.41%	-0.65%	-0.97%	-0.67%	0.40%	-1.66%	0.91%
	5	1.43%	3.10%	-0.03%	-0.99%	0.22%	-1.75%	-0.41%	-0.69%
Alternate control variables or data	6	1.36%	0.57%	0.40%	-0.57%	0.11%	1.18%	0.11%	0.23%
	7	2.09%	1.59%	1.14%	0.32%	0.00%	-0.13%	-0.82%	0.76%
	8	2.26%	2.74%	1.15%	0.52%	-0.52%	-0.68%	-0.85%	1.38%
	9	1.10%	0.83%	0.05%	-0.83%	-1.00%	0.21%	0.14%	0.52%
	10	0.26%	-0.07%	0.35%	-0.14%	-0.58%	1.03%	-0.02%	0.83%
	11	1.81%	1.13%	0.38%	-0.72%	-0.20%	0.01%	-0.03%	0.41%
	12	2.34%	1.62%	0.54%	-0.51%	-0.47%	0.18%	-0.13%	0.91%
	13	1.01%	-0.21%	0.31%	-0.57%	-0.99%	1.01%	0.10%	1.12%
	14	1.21%	0.55%	0.33%	-0.76%	-0.25%	0.16%	0.07%	0.52%
Suggested by reviewers	15	1.32%	-0.17%	0.21%	-1.55%	-0.08%	0.88%	-0.19%	0.09%
	16	0.66%	0.54%	-0.44%	-0.90%	-0.48%	—	—	—
	17	0.73%	-0.02%	-0.77%	-1.91%	-0.18%	—	—	—
	18	1.20%	0.42%	0.31%	-0.61%	0.04%	0.23%	0.08%	0.18%
	19	0.99%	0.35%	0.36%	-0.50%	0.14%	0.41%	0.02%	0.09%
New alternatives analyzed in this report	20[1]	1.20%	0.42%	0.43%	-0.83%	-0.25%	0.23%	0.06%	0.52%
	21[1]	1.20%	0.42%	0.23%	-0.45%	-0.25%	0.23%	0.32%	0.52%
	22[1]	1.20%	0.42%	-3.07%	1.74%	-0.25%	0.23%	-0.19%	0.52%
	23[1]	1.20%	0.42%	-3.52%	2.11%	-0.25%	0.23%	-1.43%	0.52%
	24	1.05%	0.83%	0.31%	-0.61%	-0.25%	0.17%	0.08%	0.52%
	25	1.37%	0.23%	0.31%	-0.61%	-0.25%	0.19%	0.08%	0.52%
	26	1.11%	0.25%	0.31%	-0.61%	-0.25%	0.46%	0.08%	0.52%
	27	0.94%	0.59%	0.31%	-0.61%	-0.25%	0.40%	0.08%	0.52%
	28[2]	1.20%	0.42%	0.31%	-0.61%	0.27% -0.54%	0.23%	0.08%	0.35%
	29[3]	0.65%	1.12%	-0.07%	-0.66%	-0.19%	1.29% -0.89%	0.94% -0.29%	0.25% 0.71%
	30[2,3]	0.65%	1.12%	-0.07%	-0.66%	1.25% -0.68%	1.29% -0.89%	0.94% -0.29%	-0.91% 0.95%
	31	1.20%	0.41%	0.31%	-0.61%	-0.26%	0.23%	0.08%	0.53%

Red font indicates estimate is statistically significant at 95% confidence interval. Gray shading indicates estimate is not changed from baseline regression model in alternative regression model.

[1] The median weights used for Models 20-23 is: 4,992 pounds for Model 20; 4,818 pounds for Model 21; 6,119 pounds for Model 22; and 6,080 pounds for Model 23.

[2] The two estimates for CUV/minivan mass in Models 28 and 30 are for vehicles under and over the median mass (3,955 pounds).

[3] The two estimates for footprint are for vehicles under and over the median footprint (44.3 square feet for cars, 56.9 square feet for light trucks, and 49.0 square feet for CUVs/minivans).

If the relationship between mass reduction and societal fatality risk is strong, one would expect that the estimated effects from NHTSA's baseline model would be robust to changes in the variables and data used. However this is not the case; the baseline results can be sensitive, especially for cars, to changes in the variables and data used. For instance, accounting for vehicle manufacturer (Model 8), or removing crashes involving alcohol, drugs, or bad drivers (Model 12), substantially increases the detrimental effect of mass reduction in lighter-than-average cars on risk. On the other hand, the DRI measures (using stopped instead of non-culpable vehicles and replacing footprint with wheelbase and track width, Model 17), or including AWD cars but excluding three high-risk sporty compact cars (Model 27), substantially decreases the detrimental effect of mass reduction in lighter-than-average cars on risk.

The differences among the point estimates of the alternative regression models in Table 5.16 are within the uncertainty bounds NHTSA estimated using a jack knife method. However, because the Volpe model NHTSA uses, and the OMEGA model EPA uses, for energy calculations uses the point estimates, and not the uncertainty bounds, using the estimates from one of the alternative models could result in large changes in the estimated change in fatalities from mass reduction. For example, if NHTSA used the estimated relationship between mass reduction for lighter cars and societal fatality risk from Model 17 (0.73% reduction) rather than the estimate from the baseline model (1.20%), the Volpe and OMEGA models would enable manufacturers to make much larger reductions in mass without compromising safety. Therefore we estimated an additional alternative regression model which combines several of the alternative models in Tables 5.15 and 5.16. This model is LBNL's best effort to address the shortcomings of the NHTSA baseline model. The LBNL baseline models include these parameters:

- replaces footprint with track width and wheelbase (Model 15 in Table 5.16) for all vehicle types, to reduce the multicollinearity between vehicle curb weight and footprint for all three vehicle types (as suggested by DRI);
- uses stopped vehicles, rather than non-culpable vehicles, from the thirteen state police-reported crash data as the induced exposure cases (Model 16 in Table 5.16), as suggested by DRI;
- uses the 2010 ratio of CUV to minivan sales (Model 18 in Table 5.16), to account for greater market share of CUVs in the future (as suggested by a peer reviewer of the Preliminary NHTSA 2012 report); and
- replaces the VMT weights provided by NHTSA by removing the kinks in the VMT schedules by vehicle age (Model 31 in Table 5.16).

Table 5.17 compares the results from the DRI measures and the LBNL baseline model with those from the NHTSA baseline model. Under the DRI measures or the LBNL baseline model, mass reduction in cars is associated with much smaller increases, or even decreases, in fatality risk, and mass reduction in light trucks is associated with much larger decreases in fatality risk, while mass reduction in CUVs and minivans is associated with smaller decreases in fatality risk, than in the NHTSA baseline model.

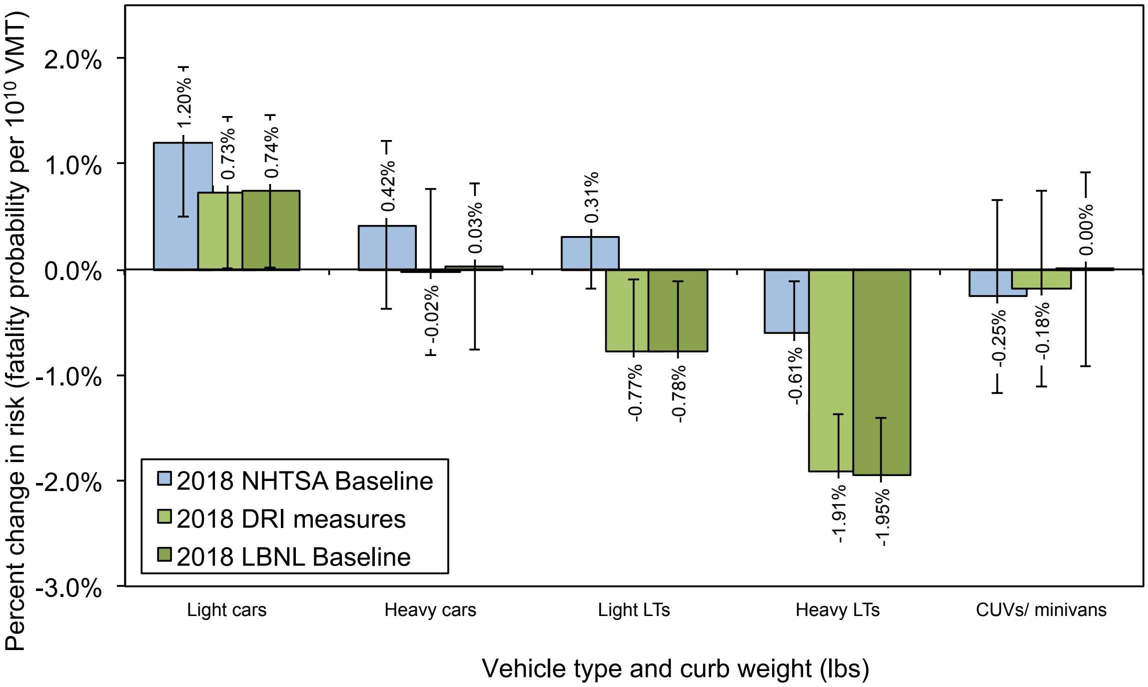
Figure 5.20 compares the estimated relationships from the 2018 NHTSA baseline model with the two DRI measures and the LBNL baseline model. The two DRI measures substantially reduce the estimated detrimental effect of mass reduction in cars, with mass reduction in heavier cars now associated with a very small decrease in societal fatality risk. The two DRI measures change the estimated increase in fatality risk to an estimated decrease in risk in lighter light trucks, and substantially increase the estimated beneficial effect of mass reduction in heavier light trucks. On the other hand, the DRI measures estimate a slightly smaller beneficial effect from mass reduction in CUVs/minivans from the NHTSA baseline model. Compared to the DRI measures, the LBNL baseline model has little effect on the relationship between mass reduction and fatality risk in cars, but slightly increases the safety benefit from mass reduction in light trucks and essentially eliminates the small safety benefit from mass reduction in CUVs/minivans.

Table. 5.17. Estimated effect of mass or footprint reduction on U.S. fatality risk per VMT, under NHTSA and LBNL baseline models

Variable	Case vehicle type	NHTSA Baseline	DRI measures	LBNL Baseline
Mass reduction	Cars < 3201 lbs	1.20%	0.73%	0.74%
	Cars ≥ 3201 lbs	0.42%	-0.02%	0.03%
	LTs < 5014 lbs	0.31%	-0.77%	-0.78%
	LTs ≥ 5014 lbs	-0.61%	-1.91%	-1.95%
	CUV/ minivan	-0.25%	-0.18%	0.00%
Footprint reduction	Cars	0.23%	—	—
	LTs	0.07%	—	—
	CUV/ minivan	0.52%	—	—
Track width reduction	Cars	—	5.90%	5.86%
	LTs	—	1.81%	1.84%
	CUV/ minivan	—	0.87%	0.74%
Wheel base reduction	Cars	—	-1.15%	-1.14%
	LTs	—	-0.08%	-0.07%
	CUV/ minivan	—	-0.20%	-0.31%

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

Figure 5.20. Estimated effect of mass reduction on U.S. fatality risk per VMT by vehicle type, NHTSA baseline, DRI measures, and LBNL baseline



6. Fleetwide scenarios of mass reduction

In its 2012 report NHTSA simulated the effect of four fleetwide mass reduction scenarios on the change in annual fatalities (Section 3.6). NHTSA estimated that the most aggressive of these scenarios (reducing mass 5.2% in heavier light trucks and 2.6% in all other vehicles types except lighter cars) would result in a small reduction in societal fatalities.

LBNL replicated the methodology NHTSA used in 2012 to simulate the four fleetwide mass reduction scenarios, and updated the analysis for the four scenarios as well as analyzed two additional scenarios. Table 6.1 shows the estimated annual change in fatalities from six different fleetwide mass reduction scenarios. The six scenarios are:

- Scenario 1: 100-lb reduction in all vehicles;
- Scenario 2: proportionate 2.73% mass reduction in all vehicles;
- Scenario 3: mass reduction of 5.45% in heavier light trucks, 2.73% in all other vehicle types except lighter cars, whose mass is kept constant;
- Scenario 4: the safety-neutral scenario developed by NHTSA in their 2016 report (Puckett and Kindelberger 2016);
- Scenario 5: reduce mass of lighter- and heavier-than-average light trucks to the median mass of lighter- and heavier-than-average cars;
- Scenario 6: mass reduction estimated in 2015 NRC committee report; the NRC committee report estimated that manufacturers would reduce the mass of small cars by 5%, midsize cars 10%, large cars 15%, and light trucks, CUVs, and minivans 20%; LBNL translated

this into mass reductions of 5% for lighter-than-average cars, and 12.5% for heavier-than-average cars;

- Scenario 7: mass reduction in 2021, as estimated by EPA OMEGA model in 2016 Technical Assessment Rreport (TAR; 0.0% for small cars, 4.4% for large cars, 6.3% for small light trucks, 4.7% for large light trucks, and 6.7% for CUVs/minivans);
- Scenario 8: mass reduction in 2021, as estimated by EPA OMEGA model in 2016 TAR (0.0% for small cars, 6.1% for large cars, 8.0% for small light trucks, 5.7% for large light trucks, and 10.6% for CUVs/minivans).

The top section of Table 6.1 shows the percentage mass reduction applied to each vehicle type under each scenario. The middle section of the table shows the change in annual fatalities by case vehicle type, and by crash type. The bottom section of the table shows the change in annual fatalities based on the relationship between vehicle mass and fatality risk from the 2012 and 2016 NHTSA reports.

Table 6.1 indicates that the estimated change in fatalities (in absolute terms or fraction of total fatalities) under each scenario is comparable to those in the 2012 analysis, but not as beneficial as those in the 2016 analysis. For example, an across the board 100-lb reduction in mass would result in only an estimated 87 additional annual fatalities, compared with an estimated 157 additional annual fatalities based on the 2012 analysis, and 91 additional annual fatalities based on the 2016 analysis. Of particular note are the results from Scenario 6, the mass reductions recommended by the 2015 NRC committee report. Under this scenario mass reduction would result in a 141 increase in fatalities, compared with a 224 increase in fatalities in the 2012 analysis, but a 344 decrease in annual fatalities in the 2016 analysis. This is achieved by offsetting relatively large percentage reductions in mass from the heavier vehicles (light trucks and CUVs/minivans) with smaller percentage reductions in mass from the lighter vehicles (cars).

The last two columns of Table 6.1 show the estimated change in fatalities from the mass reductions EPA estimated in the Technical Assessment Report using its OMEGA model. These scenarios assume less than one percent mass reduction in the lightest cars, with progressively larger mass reductions in heavier vehicles, with slight increases in fatalities (29 and 40 additional fatalities in Scenarios 7 and 8, respectively).

Table 6.2 compares the estimated change in annual fatalities using the relationships between mass reduction and fatality risk estimated by the NHTSA baseline model, the DRI measures, and the LBNL baseline model. All of the scenarios in Table 6.2 estimate a net decrease in fatalities associated with mass reduction using the DRI measures or the LBNL baseline model, from 61 to 1,750 lives saved using the DRI measures, to 39 to 1,737 lives saved using the LBNL baseline model.

Table 6.1. Estimated annual change in fatalities from six different fleetwide mass reduction scenarios, using coefficients estimated by NHTSA baseline model

Vehicle/ crash type	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Mass reductions								
Lgt car	3.61%	2.80%	0.00%	1.78%	0.0%	5.0%	0.0%	0.0%
Hvy car	2.88%	2.80%	2.80%	2.63%	0.0%	12.5%	4.4%	6.1%
Lgt LT	2.25%	2.80%	2.80%	2.67%	37.7%	20.0%	6.3%	8.0%
Hvy LT	1.80%	2.80%	5.60%	3.23%	37.5%	20.0%	4.7%	5.7%
CUV/Minivan	2.53%	2.80%	2.80%	2.61%	0.0%	20.0%	6.7%	10.6%
Change in fatalities from 2018 baseline, by case vehicle type								
Lgt car	65	51	0	32	0	91	0	0
Hvy car	26	25	25	24	0	113	40	55
Lgt LT	10	12	12	12	166	88	28	35
Hvy LT	-11	-17	-34	-19	-225	-120	-28	-34
CUV/Minivan	-4	-4	-4	-4	0	-31	-10	-16
Total	87	67	0	44	-59	141	29	40
Pct change	0.35%	0.27%	0.00%	0.18%	-0.24%	0.57%	0.12%	0.16%
Change in fatalities from 2018 baseline, by crash type								
1: Rollover	-29	-25	-17	-21	31	-94	-30	-43
2: w/object	-19	-15	-7	-13	97	-39	-22	-30
3: w/ped	-6	-12	-27	-16	89	-165	-66	-108
4: w/HDT	56	56	48	50	123	281	84	121
5: w/lgt car	-7	-12	-25	-13	-245	-80	-8	-5
6: w/hvy car	34	27	9	20	-81	77	21	33
7: w/lgt LT	1	-1	-8	-3	-56	-27	-7	-9
8: w/hvy LT	54	55	50	49	126	281	86	124
9: Other	3	-5	-24	-9	-142	-93	-30	-41
Total	87	67	0	44	-59	141	29	40
Pct change	0.35%	0.27%	0.00%	0.18%	-0.24%	0.57%	0.12%	0.16%
2012 change in fatalities from 2012 baseline (LBNL 2012)								
Total	157	108	-8	0	-150	224	—	—
Pct change	0.56%	0.39%	-0.03%	0.00%	-0.54%	0.80%	—	—
2016 change in fatalities from 2016 baseline (LBNL 2016)								
Total	91	36	-93	0	-776	-344	-149	-203
Pct change	0.29%	0.12%	-0.30%	0.00%	-2.49%	-1.10%	-0.48%	-0.65%

Table 6.2. Estimated annual change in fatalities from six different fleetwide mass reduction scenarios, using coefficients estimated by NHTSA baseline, DRI measures, and LBNL baseline models

Coefficients used	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
NHTSA	87	65	0	44	-60	140	29	40
DRI	-61	-112	-248	-137	-1715	-920	-242	-300
LBNL	-39	-87	-225	-114	-1737	-740	-181	-202

7. Conclusions

This 2018 update confirms the findings of the 2012 and 2016 NHTSA analyses regarding mass reduction while holding footprint constant: mass reduction in cars and lighter-than-average light trucks is likely to lead to small increases, while mass reduction in heavier-than-average light trucks and CUVs/minivans is likely to lead to small decreases, in societal fatality risk per VMT. Therefore policies to disproportionately reduce the mass of heavier light trucks and CUVs/minivans relative to the mass of cars and lighter light trucks can be used to reduce fuel consumption and CO_2 emissions without compromising, or perhaps even improving, safety.

As in the 2012 and 2016 studies, mass reduction while holding footprint constant is estimated to have a larger detrimental impact on societal fatality risk in lighter-than-average cars (1.20% increase) than in heavier-than-average cars (0.42% increase), and a detrimental impact in lighter-than-average light trucks (0.31% increase) but a beneficial impact in heavier-than-average light trucks (0.71% decrease). The 2018 update suggests that mass reduction in CUVs/minivans is now associated with a smaller (0.25%) decrease in societal fatality risk than in either the 2012 or 2016 study (a 0.38% and 0.99% decrease, respectively). Although the estimated effects on lighter cars, heavier light trucks, and CUVs/minivans are statistically significant at the 95% confidence level based on the standard errors output by the regression models, the more involved jack knife method NHTSA used to estimate uncertainty indicates that all three are only statistically significant at the 90% confidence level.

The 2018 update also confirms many of the other findings from the 2012 and 2016 studies. The estimated effect of mass or footprint reduction on risk is relatively small compared with other vehicle attributes, driver characteristics, and, in particular, crash circumstances such as driving at night, on high-speed roads, in rural counties, or in a high-fatality state. And an analysis by vehicle model suggests that, even after accounting for other differences in vehicle safety characteristics, driver age and gender, and crash circumstances, there is a wide range in risk for vehicles of a given mass.

LBNL analyzed 31 alternative regression models to test the sensitivity of the NHTSA baseline regression results to changes in the measure of risk, and the data and control variables used in the regression models. Treating large pickups as a vehicle category independent of small pickups and SUVs results in much larger decreases in societal fatality risk from mass reduction of the lighter large pickups than from the heavier large pickups (Models 22 and 23 in Table 5.16). This result suggests that there is no consistent relationship between mass reduction and societal fatality risk across the range in vehicle masses, even within a given vehicle type. The NHTSA baseline model, which excludes muscle, police, and AWD cars, is quite sensitive to which types of cars are included; including AWD cars, but excluding three additional "sporty" cars that do not qualify as "muscle" cars, reduces the association of mass reduction in lighter cars from a 1.20% increase to only a 0.94% increase in societal fatality risk (Model 27 in Table 5.16). Using a two-piece variable for footprint, as the NHTSA baseline model does for curb weight, reduces the detrimental effect of mass reduction in lighter cars but increases it in heavier cars, and increases the beneficial effect of mass reduction in pickups.

The intent in conducting the 31 alternative regression models is not to develop a regression model that is “more correct” than the NHTSA baseline model; rather, the intent is to test how sensitive the results from the baseline model are to changes in the data and variables used, as well as to gain an understanding of how accounting for various factors (such as driver alcohol/drug use or driving behavior, or quality of vehicle design) influences the relationship between vehicle mass, size, and societal fatality risk. If the relationship between mass reduction and societal fatality risk is strong, one would expect that the estimated effects from NHTSA’s baseline model would be robust to changes in the variables and data used. While the ranges of estimates from the alternative models tend to fall within the confidence bounds NHTSA estimated for the baseline model, the individual point estimates vary substantially depending on the particular alternative model used. As a result we estimated the effect of a plausible alternative to the NHTSA baseline model, which we call the LBNL baseline model. This alternative baseline model is LBNL’s best effort to address the shortcomings of the NHTSA baseline model, and includes the two DRI measures (Model 17 in Table 5.16), adjusts the weights for CUVs/minivans to reflect the recent increase in CUV sales (Model 18 in Table 5.16), and corrects the kink for older vehicles in the schedule of VMT by vehicle age that NHTSA uses (Model 31 in Table 5.16). The LBNL baseline model results in substantially less detrimental or more beneficial effects from mass reduction in cars and light trucks, but less beneficial effects from mass reduction in CUVs/minivans, relative to the NHTSA baseline model.

When we recreated the technique NHTSA used in its 2012 and 2016 studies to estimate the effect of different mass reduction scenarios on fatalities across the fleet, we found that the degree of mass reduction estimated by EPA’s OMEGA model[34] would result in a small net increase of 50 fatalities (or 0.2%) using the coefficients estimated by the NHTSA baseline model. If the coefficients from the DRI or LBNL baseline regression models are used, the result would be a net decrease in fatalities, with over 300 lives saved. Therefore we recommend that the agencies consider running the Volpe and OMEGA modeling systems under at least one sensitivity case that calls for more aggressive mass reduction than estimated by the NHTSA baseline model.

The 2012 and 2016 NHTSA studies concluded that the estimated effect of mass reduction while maintaining footprint on societal U.S. fatality risk is small, and statistically non-significant for all but the lightest cars. Nothing in this update to the 2012 and 2018 reports runs counter to the conclusions from 2012: mass reduction, particularly if concentrated in heavier light trucks and CUVs/minivans, can be introduced to improve fuel economy and reduce greenhouse gas emissions without compromising the overall safety of vehicle occupants and other road users. In addition, the estimated effect of mass reduction in cars, particularly lighter-than-average cars, is steadily decreasing over time.

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[34] Mass reductions of 0.9% for lighter-than-average cars, 7.3% for heavier-than-average cars, 9.1% and 9.2% for lighter and heavier light trucks, respectively, and 11.2% for CUVs and minivans by model year 2025.

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Appendix A. Detailed comparison of data from the 2012, 2016, and 2018 analyses

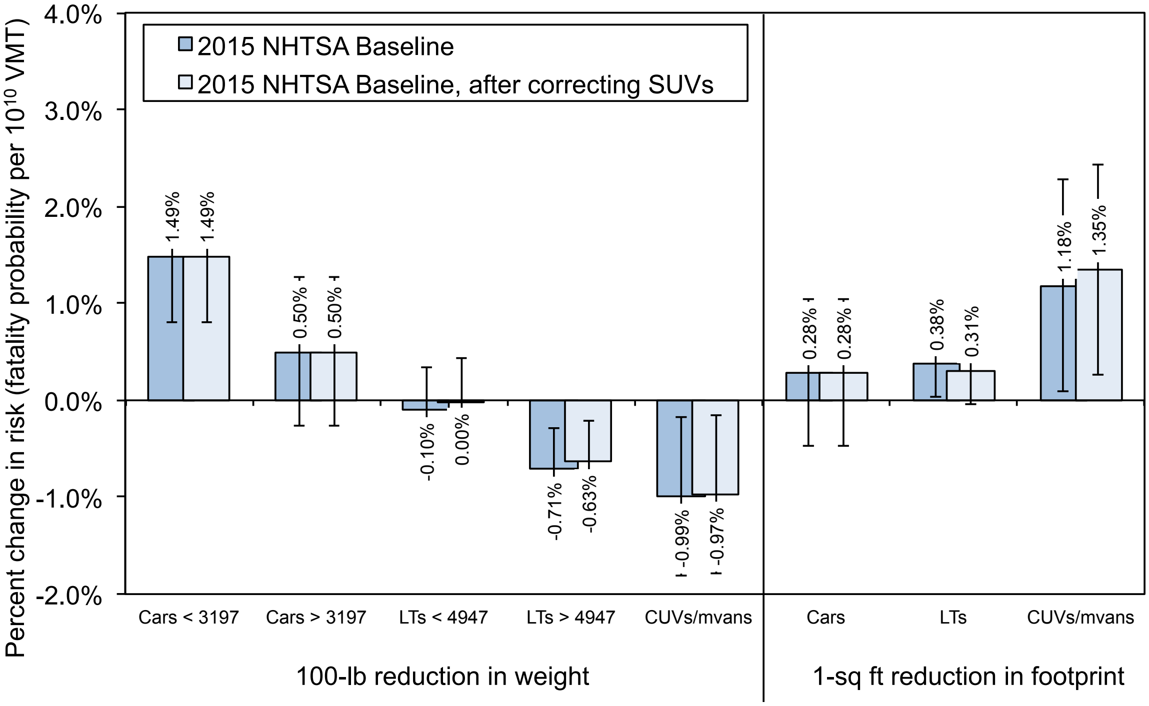
This appendix investigates several possible causes of the fluctuation in the estimated change in fatality risk from mass reduction in lighter-than-average light trucks and CUVs/minivans over the three analyses:

- mischaracterization of several CUV models as SUVs in 2016;
- changes in risk per VMT, curb weight, footprint, VMT weights, or registration weights of specific models;
- models with missing exposure record (and therefore VMT weights);
- changes in VMT weights for specific vehicle models; and
- fatality risk in models not included in both 2016 and 2018 analyses.

A.1. Mischaracterization of several CUV models as SUVs in 2016

In its 2016 analysis NHTSA mischaracterized 12 CUV models as SUVs: Dodge Journey, Ford Flex, Lincoln MKT, Cadillac SRX, VW Tiguan, Nissan Cube, Honda Accord Crosstour, Mercedes GLK350, Subaru Forester, Toyota Venza, Infiniti FX35, and Lexus RX330). These models accounted for only 202 case vehicles, and 238 total fatalities; however, as indicated in Figure A.1, mischaracterizing them slightly under-estimated the relationship between mass reduction and risk in lighter-than-average light trucks (a 0.10% decrease rather than no change) and in CUVs/minivans (a 0.99% decrease rather than a 0.97% decrease). Mischaracterizing the CUV models had virtually no effect on the estimated effect of mass reduction on CUVs/minivans.

Figure A.1. Estimated effect of reduction in mass or footprint on risk, by vehicle type and analysis year



A.2. Comparison of specific models

Figures A.2 and A.3 compare the fatality risk per VMT by vehicle type and model between the 2012 and 2016 analyses (Figure A.2) and between the 2016 and 2018 analyses (Figure A.3). 237 models with at least 100 fatalities, or 10 billion VMT, in at least one analysis year are included; these models represent over 86% of all fatalities and VMT. In general there is lower correlation between the risks per VMT in 2012 vs. 2016 (R^2 by vehicle type ranging from 0.47 to 0.89) than in 2016 vs. 2018 (R^2 by vehicle type ranging from 0.70 to 0.97); this is likely because only 38% of the fatal crashes in FARS are included in both the 2012 and 2016 analyses, while 82% of the fatal crashes in FARS are included in both the 2016 and 2018 analyses. Note that for most vehicle types in Figure A.2 the slope of the correlations between the 2012 and 2016 analyses are very similar; the exception is for large pickups, which have a relatively low risk per VMT in 2016 than in 2012, compared to the other vehicle types.

Figure A.3 indicates that four small pickup models (Toyota Tundra Access cab 4x4, Ford Ranger, Dodge Ram 1500 Quad cab, and Dodge Ram 1500) have substantially lower risk per VMT in 2018 than in 2016, relative to other small pickup models; for example, the Tundra has a risk of 107 fatalities per 10 billion VMT in 2018, but a risk of 184 fatalities per 10 billion VMT in 2016. Similarly, the Subaru Outback CUV has substantially lower risk in 2018 than in 2016 (58 vs. 150 fatalities per 10 billion VMT). These outlier models bring down the R^2 of the correlations to 0.70 for CUVs and 0.76 for small pickups. The four small pickup models account for about 10% of fatalities and VMT of all small pickups, while the one CUV model accounts for only 2% of fatalities and VMT of all CUVs. However, Figure A.4 indicates that the four models that have substantially lower risk per VMT in 2018 than in 2016 are balanced by four other models that have substantially higher risk per VMT in 2018 than in 2016, relative to all other small pickups.

Figure A.2. Comparison of societal fatality risk per VMT by vehicle type and model, 2012 vs. 2016

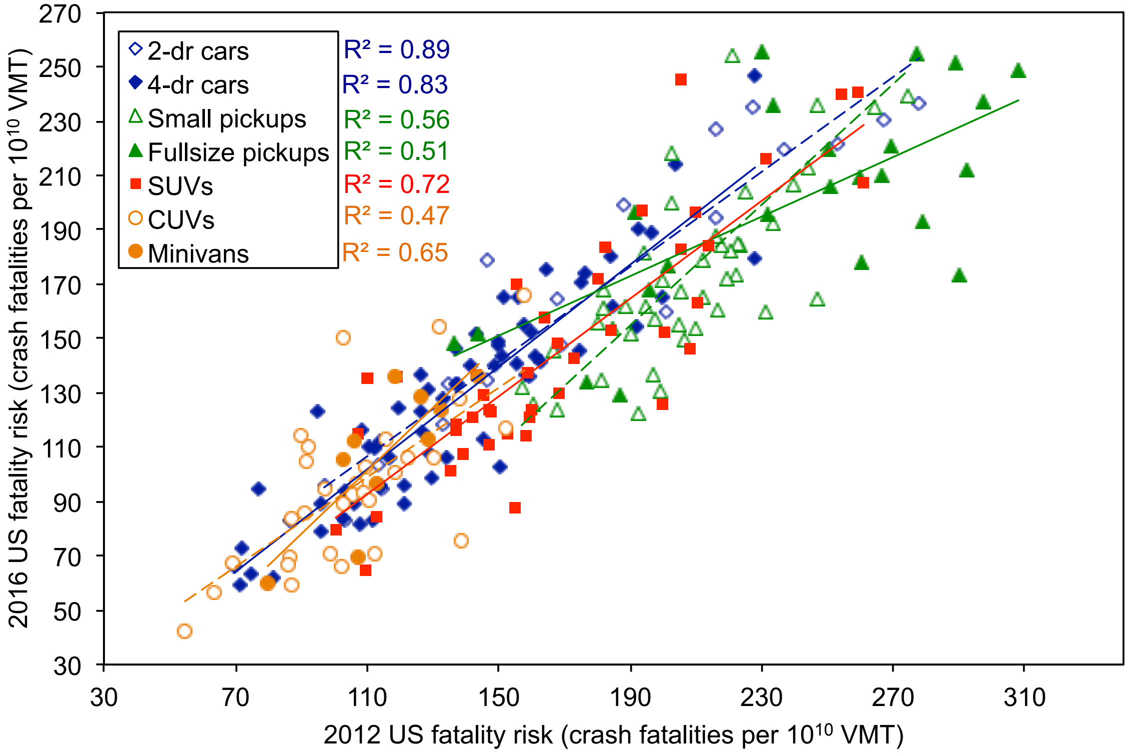


Figure A.3. Comparison of societal fatality risk per VMT by vehicle type and model, 2016 vs. 2018

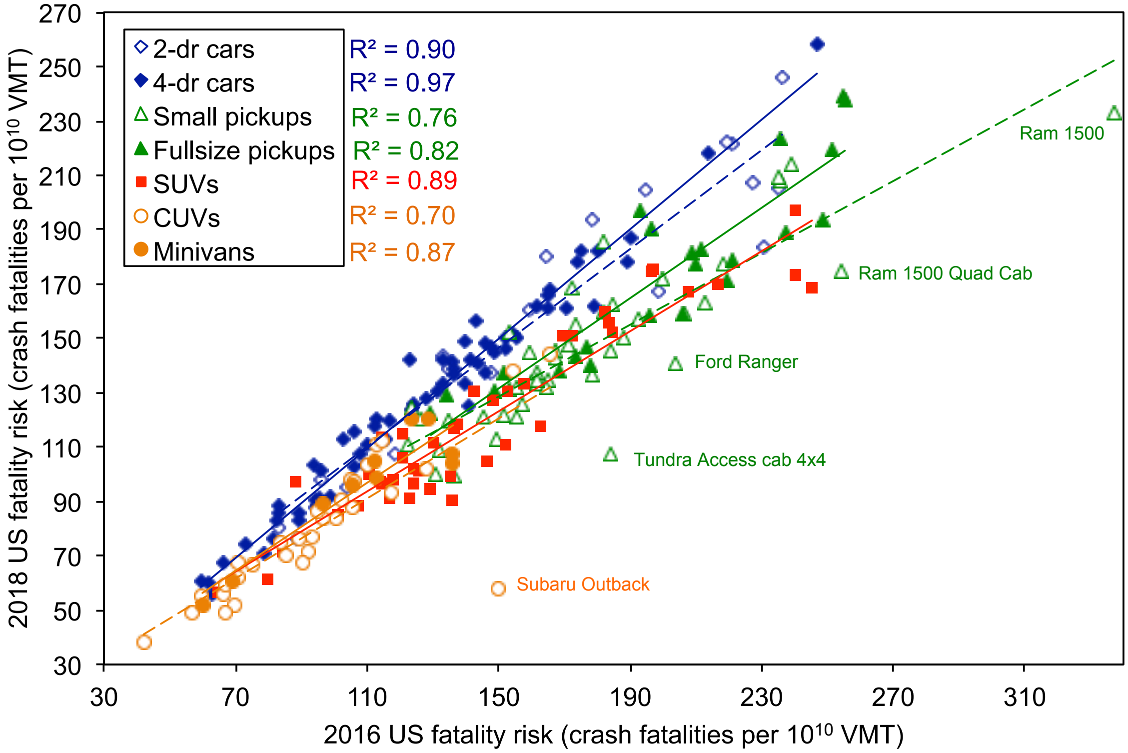


Figure A.4. Comparison of societal fatality risk per VMT by small pickup model, 2012 vs. 2016

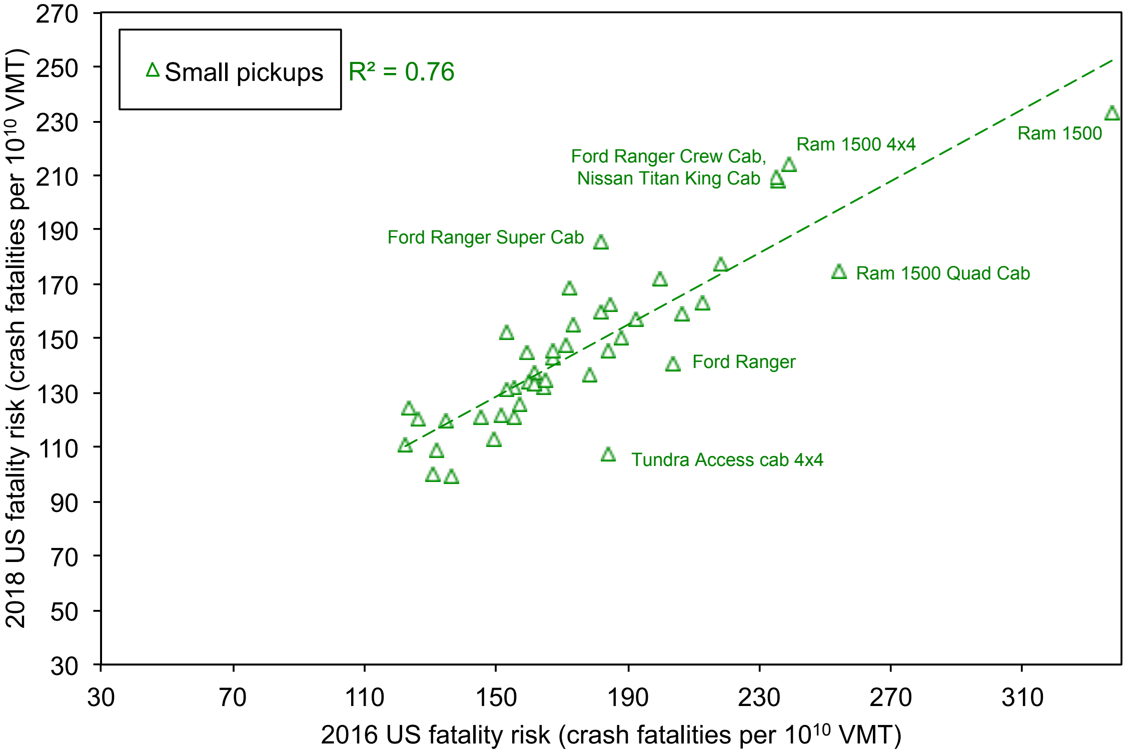
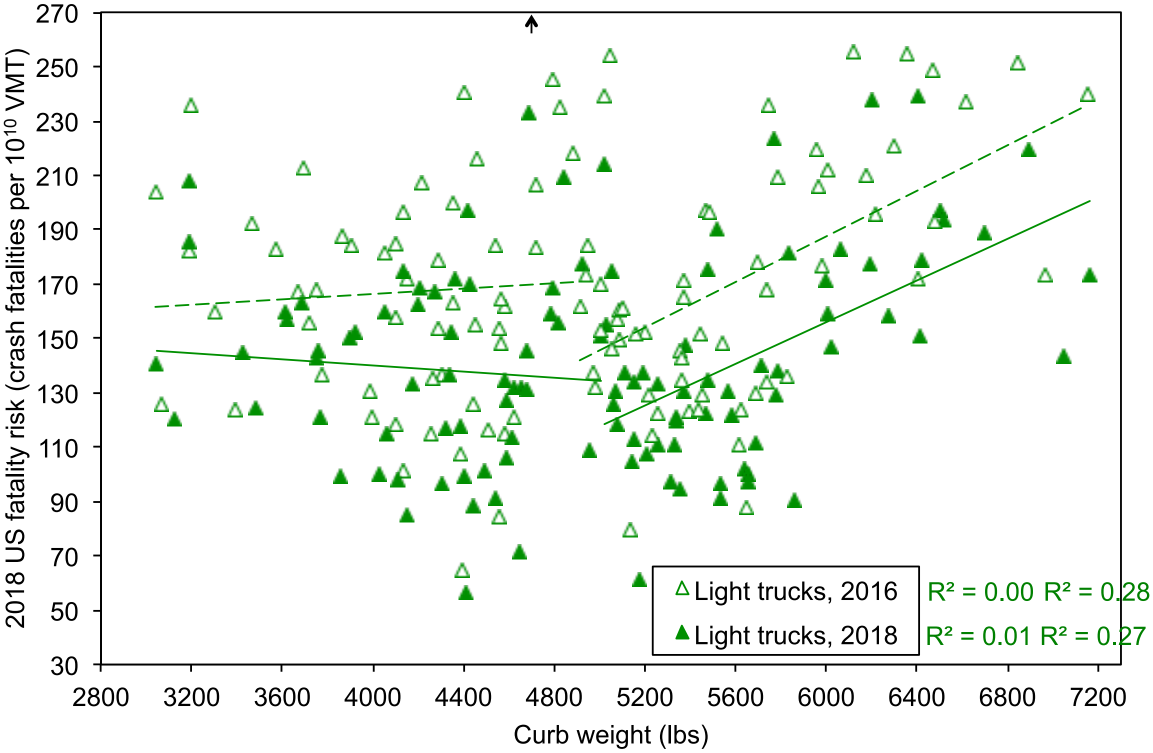


Figure A.5 shows risk by curb weight for all light trucks (small pickups, large pickups, and SUVs) by vehicle model, in the 2016 and 2018 analyses. The four trend lines show the linear correlations between curb weight and fatality risk below and above the median mass of all light trucks (4,947 lbs in 2016, 5,014 in 2018). In three out of the four cases, an increase in curb weight is associated with an increase in societal fatality risk, on average; i.e. mass reduction on average is associated with a decrease in risk. The exception is lighter-than-average light trucks in the 2018 analysis, where mass reduction on average is associated with an increase in risk; these results agree with those shown in Figure 2.9 in the body of the report. Note that one of the light truck models in the 2016 analysis has risk substantially higher than the scale shown in Figure A.5 (Dodge Ram 1500 pickup, 337 fatalities per 10 billion VMT, 4,690 lbs), as indicated by the arrow in the figure.

Figure A.5. Societal fatality risk per VMT by curb weight, small pickups and SUVs by model and weight bin, 2016 vs. 2018



Figures A.6 through A.8 compare average curb weight, footprint, and annual vehicle miles of travel by vehicle type and model for 237 vehicle models, from the 2016 and 2018 analyses. Figure A.6 shows that average curb weight is highly correlated for all vehicle models; for the most part average footprint is also highly correlated (Figure A.7), although three Toyota Tundra models had substantially different footprint in 2016 and 2018: Tundra Access Cab (59.9 square feet in 2016, 62.4 square feet in 2018), Tundra Access cab 4x4 (61.1 in 2016, 64.3 in 2018), and Tundra Double Cab (68.6 in 2016, 66.8 in 2018). Two fullsize pickup models had large enough differences in footprint to skew the correlation line, and reduce the R^2 to 0.14: Ford F-350 Crew Cab (64.7 in 2016, 73.7 in 2018) and Ford F-350 4x4 Super Cab (74.6 in 2016, 66.9 in 2018). Figure A.8 indicates that, with the exception of the Ford Taurus and the Subaru Outback, the VMT weights NHTSA developed by model are quite consistent between the 2016 and 2018 analyses.

Figure A.9 shows the percent change in vehicle registrations and VMT from 2016 to 2018, by vehicle type and model. Three of the four small pickup models shown in Figure A.3 had larger changes in registrations and VMT than other models, and are labeled in Figure A.9 (the Subaru Outback had an over 220% increase in registrations and VMT between the 2018 and 2016 analyses, and is not shown in the figure). The fourth small pickup model shown in Figure A.3, Ford Ranger, had a large reduction in fatalities over the three analysis periods: 737 fatalities in the 2012 analysis, but only 399 in 2016 and 267 in 2018. The distribution of fatalities across the nine crash types was similar across all three analysis periods. Registrations and VMT of the

Ford Ranger declined nearly 40%, and fatality risk 9%, between 2012 and 2016, but only 3% to 5% between 2016 and 2018, when fatalities declined 31%.

Figure A.6. Average curb weight by vehicle type and model, 2016 vs. 2018

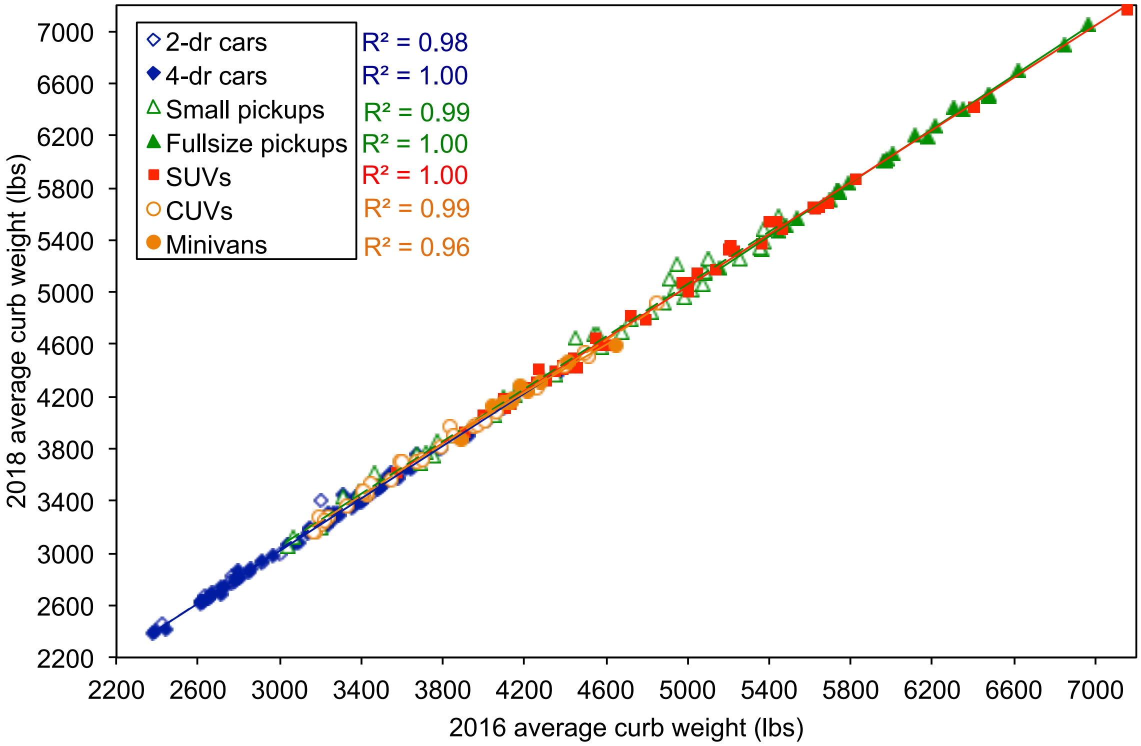


Figure A.7. Average footprint by vehicle type and model, 2016 vs. 2018

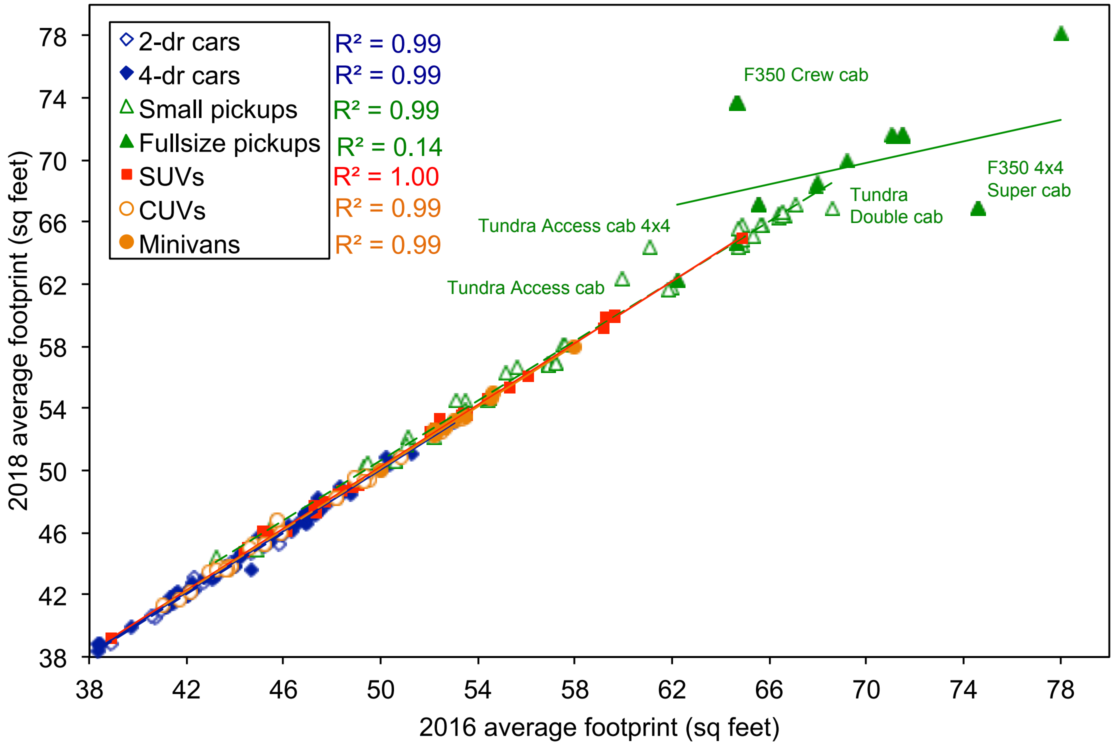


Figure A.8. Vehicle miles of travel by vehicle type and model, 2016 vs. 2018

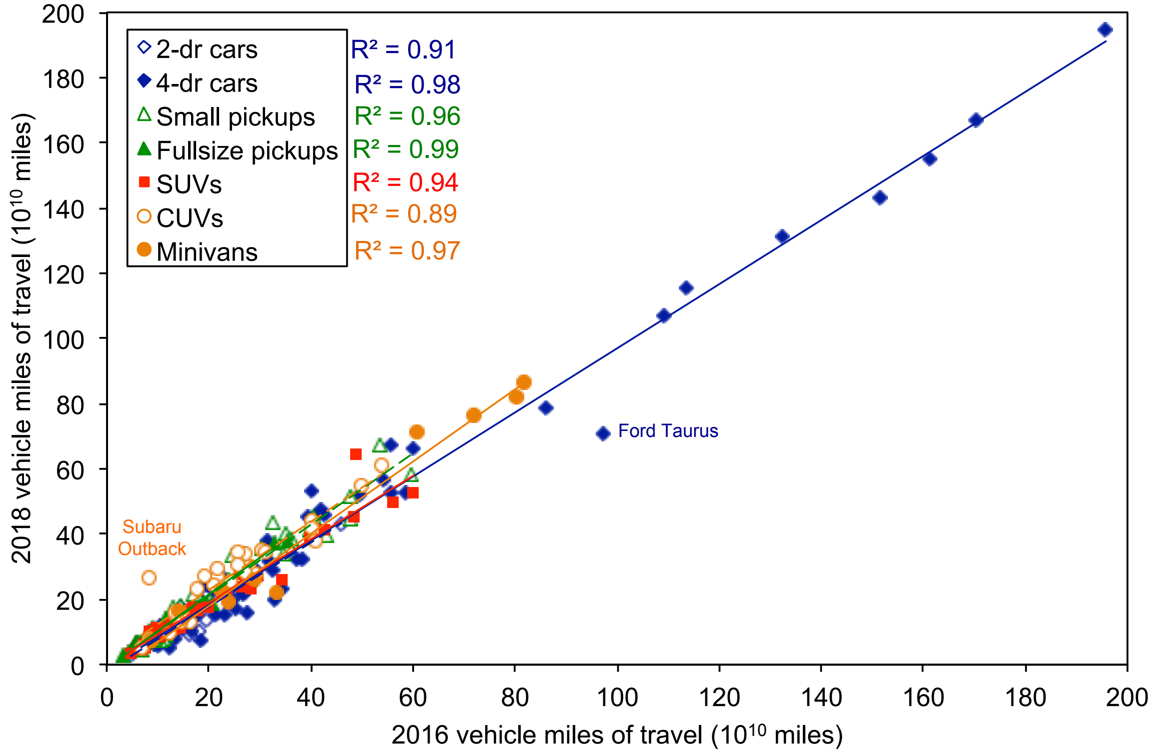
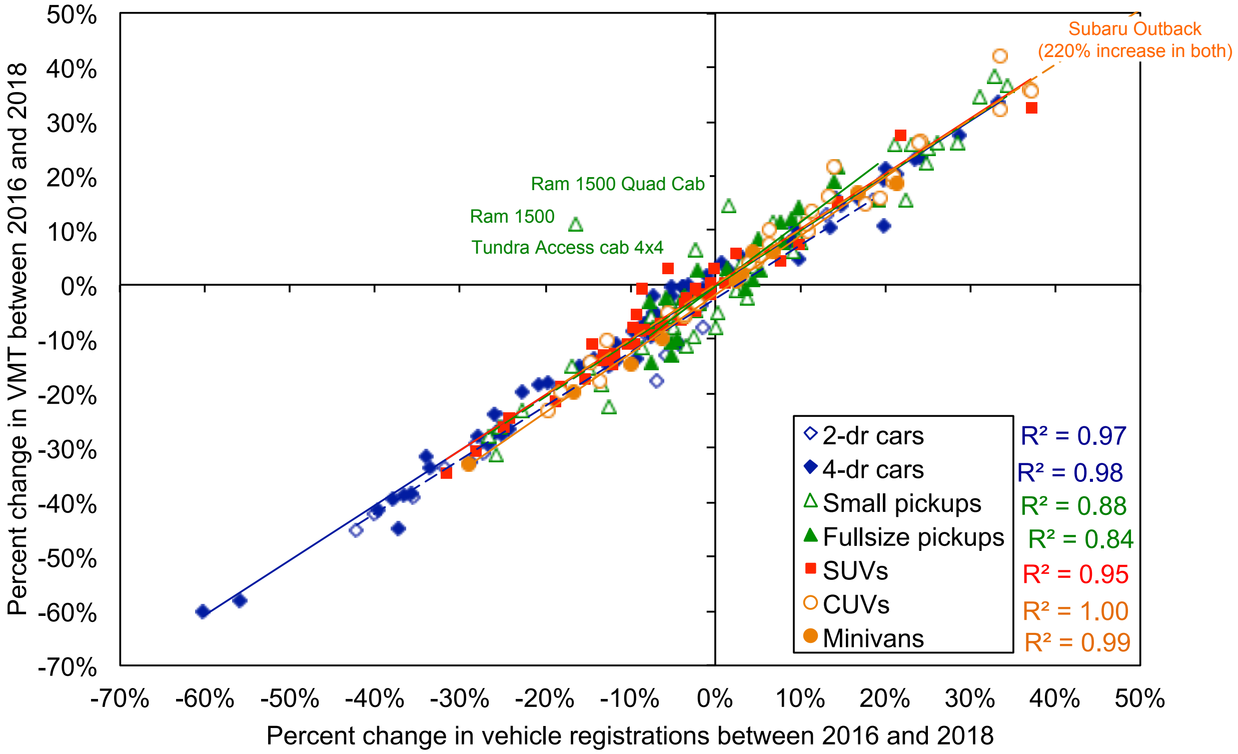


Figure A.9. Percent change in vehicle registrations and VMT between 2016 and 2018, by vehicle type and model



A.3. Models with missing exposure record (and therefore VMT weights)

Recall that in Figure A.3 the Subaru Outback CUV has substantially lower risk in 2018 than in 2016. The reason is that there are 13 fatalities, but no induced exposure record or VMT weights, for the MY07 Outback in the database NHTSA provided, and that the VMT weights for the MY05 and MY06 Outback in the 2016 database (1.1 and 0.3 billion VMT) are much lower than in the 2018 database (6.8 and 4.6 billion VMT); this is also indicated in Figure A.8. Replacing the VMT weights in the 2016 data base for those model years with the weights from the 2018 database reduces the fatality risk per VMT for the Outback from 150 to 58, identical to the risk per VMT in the 2018 database. In addition to the MY07 Outback, there is one other model, the MY10 Elantra, that has an appreciable number of fatalities (33) but no induced exposure record in the 2016 NHTSA database. Other than the Outback and the Elantra in the 2016 database, there are a handful of MY-model combinations in both the 2016 database (five) and the 2018 database (four) that have a single fatality but no induced exposure record; because of the very small number of fatalities involved, these are unlikely to affect the estimated coefficients from the regression models.

A.4. Changes in VMT weights for specific vehicle models

NHTSA developed VMT weights for each vehicle based on two components: 1) a VMT schedule by vehicle age and type (cars vs. light trucks), from analysis of the 2009 National Household Travel Survey (NHTS); and 2) an adjustment factor by vehicle model, from a database of odometer readings provided by Polk. Figure A.10 compares the VMT schedules for cars and light trucks from the 2016 and 2018 analyses; the 2018 VMT schedules are nearly identical to those used in the 2016 analysis.

NHTSA's VMT adjustment factor by vehicle model varies by model year, but not by calendar year within a given model year. For its 2018 analysis, NHTSA used an updated database of odometer readings from Polk to construct adjustment factors by vehicle model. Figures A.11 and A.12 compare the VMT adjustment factors for individual vehicle models used in the 2016 and 2018 analyses, for model year 2004 (Figure A.11) and model year 2009 (Figure A.12) vehicles. Figure A.13 indicates that, for the most part, the adjustment factors used for vehicle models in the 2018 analysis are quite similar to those used in the 2016 analysis, for 2004 vehicles, with only a few models deviating; for example, Dodge Ram 1500 pickups were driven 63% fewer miles than the average truck of the same age in the 2016 database, but Dodge Ram 1500 pickups were driven only 12% fewer miles than the average truck of the same age in the 2018 database. The agreement between the two databases is strongest for car, CUV, and minivan models (over 0.90 R^2), and weakest for pickups and SUVs (less than 0.60 R^2). Figure A.12 indicates that the agreement is slightly worse for 2009 vehicles than for 2004 models, especially for cars and small pickups.

Figure A.10. VMT schedules by vehicle age NHTSA used in the 2016 and 2018 analyses

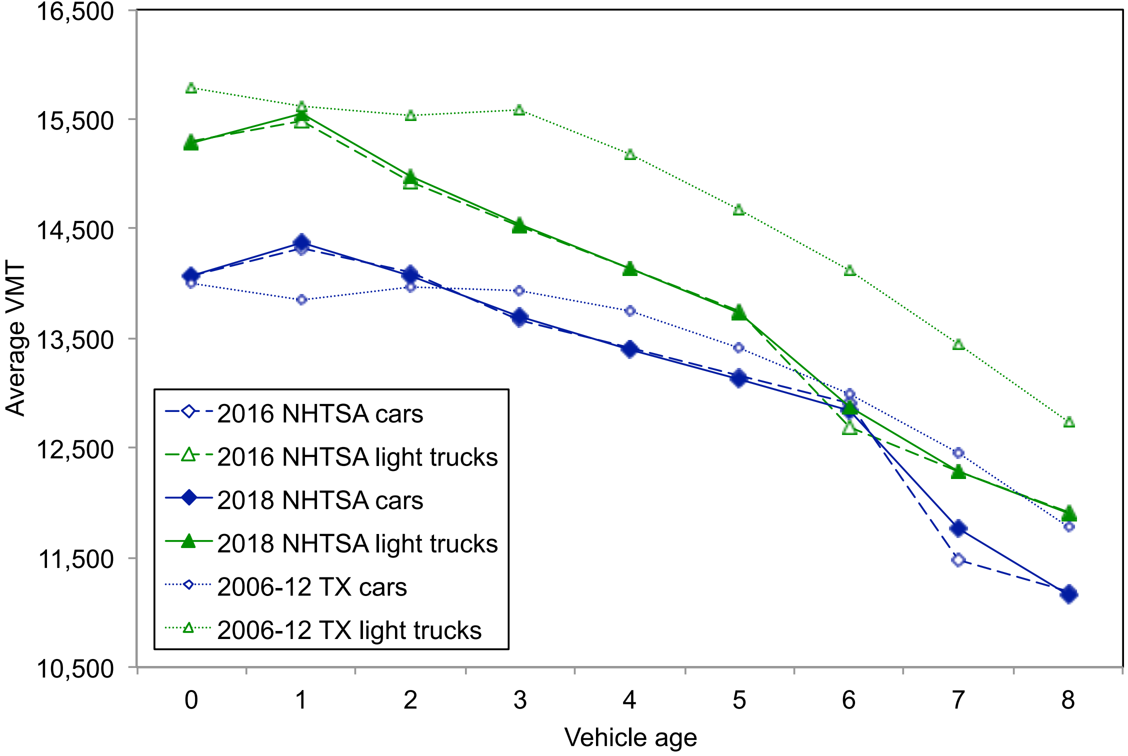


Figure A.11. VMT adjustment factors for model year 2004 vehicle models, in 2016 and 2018 analyses

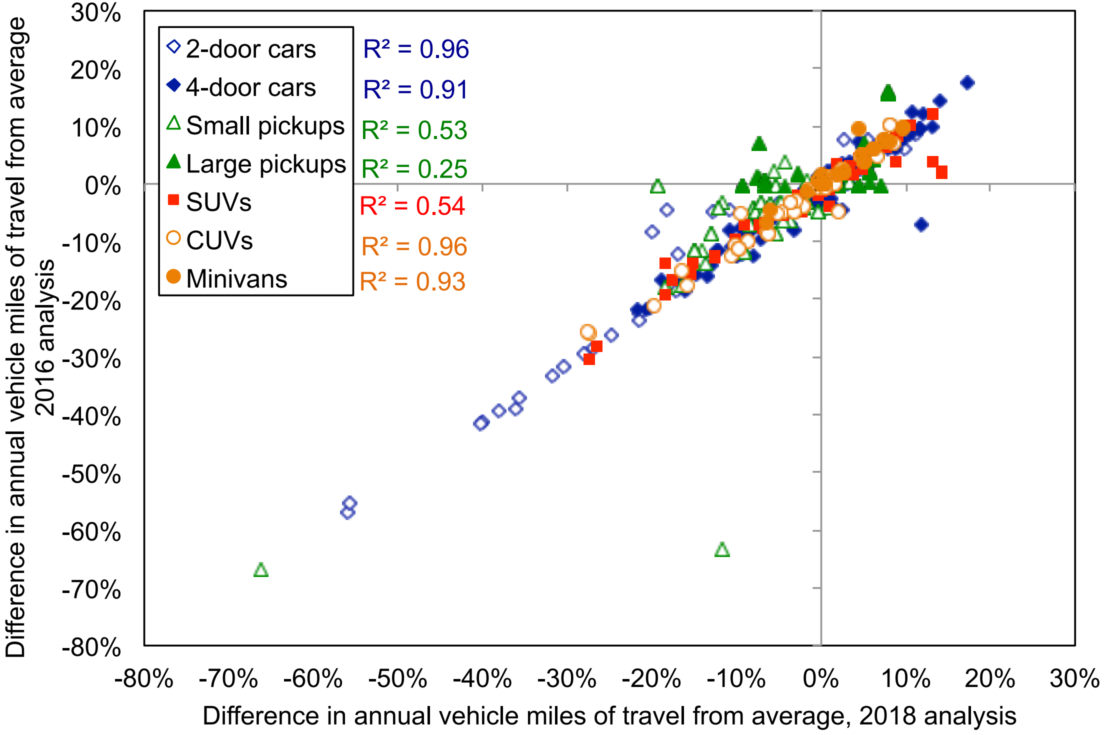


Figure A.12. VMT adjustment factors for model year 2009 vehicle models, in 2016 and 2018 analyses

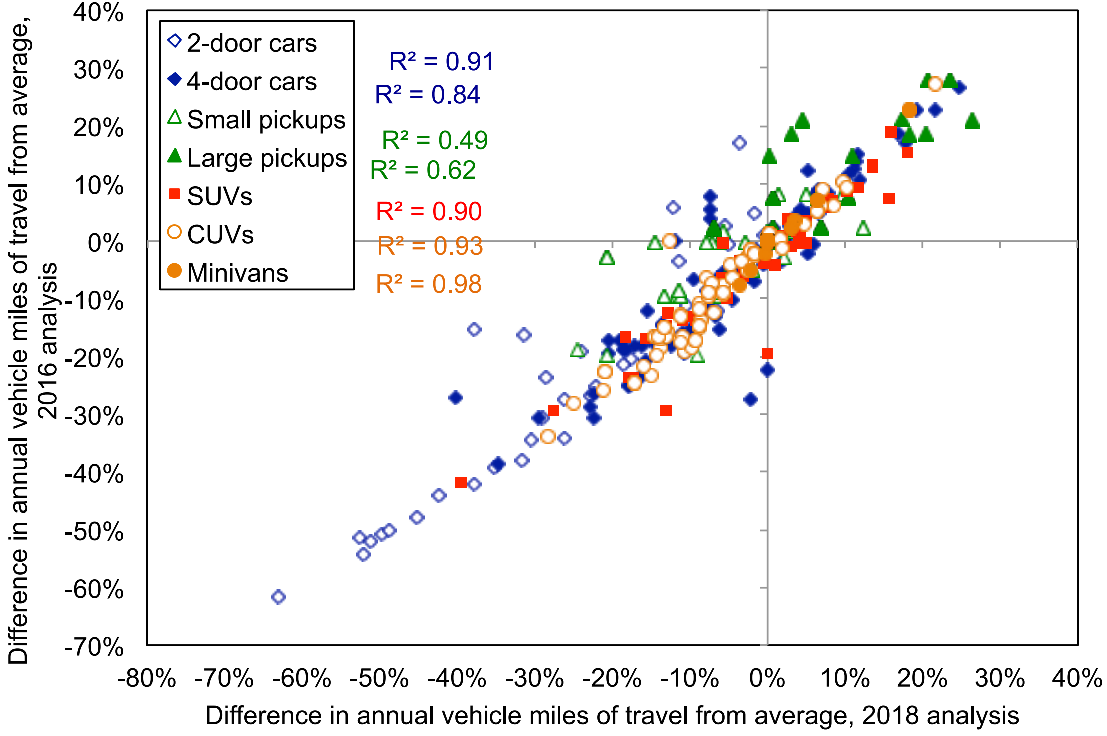


Figure A.10 also compares the VMT schedules developed by NHTSA from the NHTS data with average VMT calculated using annual odometer readings on nearly every vehicle registered in the state of Texas between 2006 and 2012. Note that the shape of the schedules are different, with VMT fairly consistent for vehicles up to three years of age in Texas, but steadily declining after one year of age in the Polk data. After three years of age the VMT schedules for cars are quite similar from the Polk and Texas odometer data; the VMT trends for older trucks also are similar, but trucks of a given age are driven about 500 more miles per year in Texas than in the U.S. as a whole.

LBNL used the Texas VMT schedules shown in Figure A.10 to calculate the VMT adjustment factor by vehicle model and age in the Texas odometer data. Figures A.13 and A.14 compare the Texas and NHTSA 2018 VMT adjustment factors for model year 2007 and 2008 vehicles; the adjustment factors from Texas are for three-year-old vehicles. The correlations between the NHTSA and Texas VMT adjustment factors (Figures A.13 and A.14) tend to be substantially lower than between the adjustment factors NHTSA used in their 2016 and 2018 analyses (Figures A.11 and A.12). Figures A.13 and A.14 indicate that the correlations between the Texas and NHTSA VMT adjustment factors are particularly low for pickups, with R^2 under 0.50; in particular, large pickups tend to have much higher VMT adjustment factors (vehicle model VMT relative to average light truck VMT) in Texas than in the 2018 NHTSA analysis.

Figure A.13. VMT adjustment factors for model year 2007 vehicle models, in 2018 NHTSA analysis and from Texas odometer readings for three-year-old vehicles

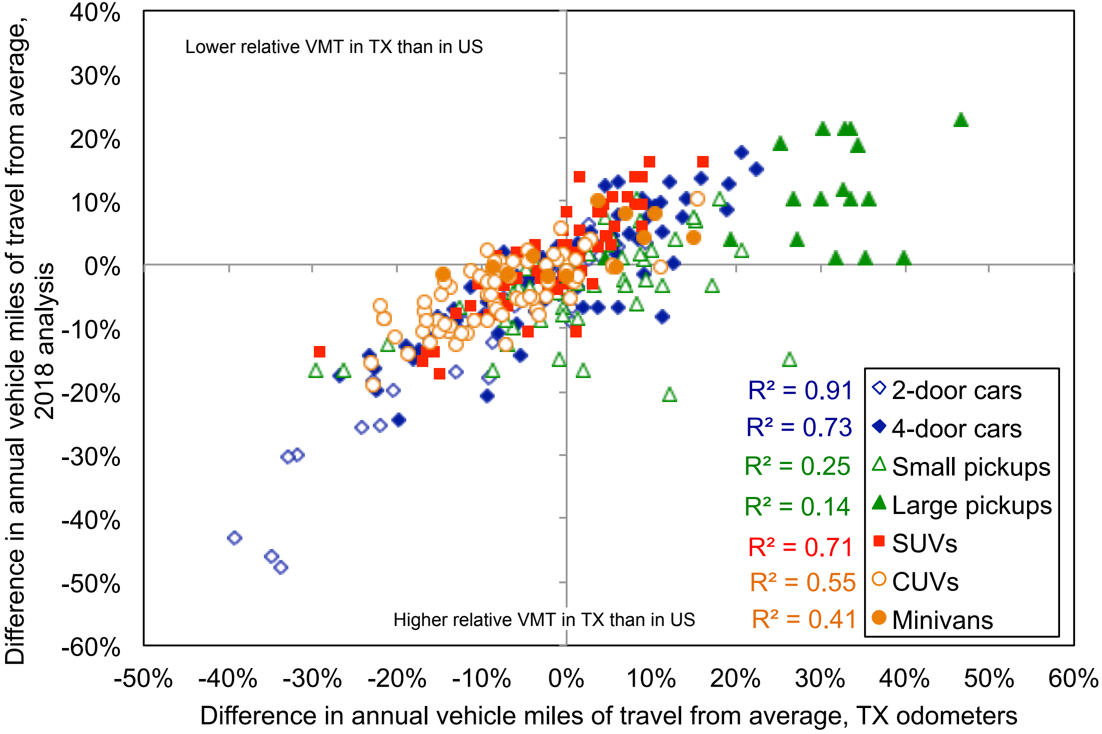
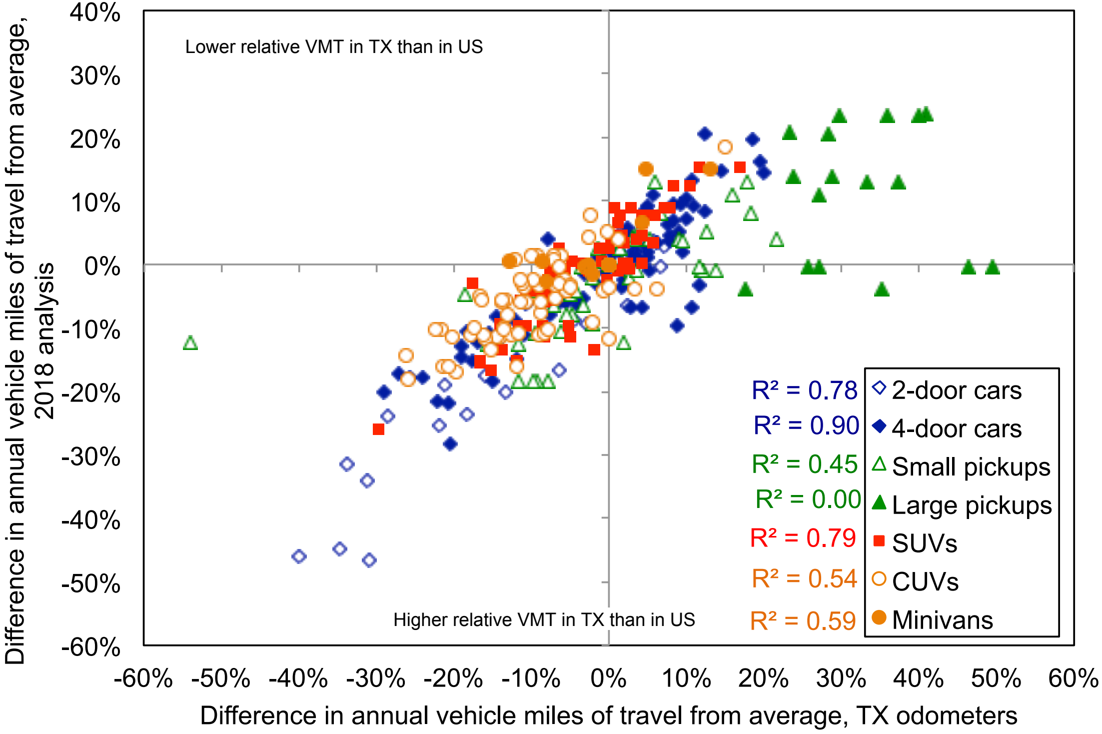


Figure A.14. VMT adjustment factors for model year 2008 vehicle models, in 2018 NHTSA analysis and from Texas odometer readings for three-year-old vehicles



A.5. Fatality risk in models not included in both 2016 and 2018 analyses

Table A.1 compares the number of fatal crashes, by the model year of the case vehicle and calendar year, for the three analyses conducted in 2012, 2016, and 2018. The model year and calendar year combinations for each analysis are outlined in the table. Of the 106,618 case vehicles in the 2012 analysis, 40,275, or 38%, are also included in the 2016 analysis; on the other hand, of the 80,920 case vehicles included in the 2016 analysis (shown in red and green font), 59,082, or 73%, are also included in the 2018 analysis (shown in green font), while 13,534 new case vehicles from model year 2011 or in calendar year 2012 are included in the 2018 analysis (shown in blue font).

Of the 40,395 small pickup/SUV case vehicles included in the 2012 analysis, 14,058, or 35%, are also included in the 2016 analysis; of the 27,290 small pickup/SUV case vehicles included in the 2016 analysis, 18,886, or 69%, are also included in the 2018 analysis, while 3,983 new small pickup/SUV case vehicles from model year 2011 or in calendar year 2012 are included in the 2018 analysis.

Table A.1. Fatal crashes in case vehicles, by vehicle model year and calendar year

Model year	Calendar year										
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
2000	3080	3115	3189	3068	3013	2895	2513	-	-	-	-
2001	2934	2824	2946	2887	2963	2728	2314	-	-	-	-
2002	2258	2964	2786	2882	2820	2749	2451	-	-	-	-
2003	0	2198	2700	2737	2645	2735	2491	2216	2176	2138	-
2004	0	0	2066	2633	2656	2503	2390	2267	2147	2189	2276
2005	0	0	0	2067	2586	2504	2244	2175	2076	2017	2088
2006	0	0	0	0	1857	2359	2139	1933	1950	1842	1879
2007	0	0	0	0	0	1683	2046	1819	1830	1708	1827
2008	0	0	0	0	0	0	1291	1573	1480	1516	1598
2009	0	0	0	0	0	0	0	708	923	941	896
2010	0	0	0	0	0	0	0	0	806	924	1007
2011	0	0	0	0	0	0	0	0	0	869	1094

Table A.2 shows the distribution of the case vehicle data for lighter-than-average light trucks and CUVs/minivans that were used in either the 2016 or 2018 analysis, but not in both; i.e. vehicles from model year 2003 or in calendar year 2005 in the 2016 analysis, and vehicles from model year 2011 or in calendar year 2012 in the 2018 analysis. The table groups these vehicles into vehicle models that were included only in the 2016 or 2018 analysis, in the top portion of the table; models that were included in both the 2016 and 2018 analyses, in the middle portion of the table; and all models in the bottom portion of the table. The fatalities shown in Table A.2 represent 27% of all 80,920 fatalities included in the 2016 analysis, and 19% of all 72,616 fatalities included in the 2018 analysis.

While only 4% of fatalities in the earliest year of the 2016 analysis were not included in 2018 (either because they were discontinued in MY04 or their mass increased to above the median curb weight; such as F-150 Crew Cab, Dodge Durango 4x4, and 2-door Ford Explorer), about 14% of the fatalities in the latest year of data from the 2018 analysis were in new light truck models not included in the 2016 analysis because they were not introduced until MY11 (such as four-door Jeep Wrangler, Honda Ridgeline, Dodge Nitro, and others); on the other hand, 32% of the CUV fatalities in the latest year of data from the 2018 analysis were in models not included in the 2016 analysis that were introduced in MY11 or later (such as Chevrolet HHR, Buick Enclave/GMC Acadia/Chevrolet Traverse, Ford Edge/Lincoln MKX/Mazda CX-9, Nissan Rogue, and Pontiac Torrent/GMC Terrain, and others). Because a larger fraction of CUVs were replaced in the 2018 analysis than light trucks, we might expect a larger change from 2016 to 2018 analysis in the estimated relationship between mass reduction and risk in results for CUVs/minivans than for light trucks. The last column of Table A.2 indicates that the new light truck models included in the 2018 analysis have about the same change in risk as the light truck models included in both analyses, about 20% to 30% lower risk in the 2018 analysis as in the 2016 analysis. However, the CUV models included in the 2018 analysis have a 13% higher fatality risk than the CUV models from the 2016 analysis that they “replaced”.

Table A.2. Fatalities and risk for light trucks and CUVs/minivans not included in both 2016 and 2018 analyses

	2016 analysis			2018 analysis			Change in fatality risk from 2016
Vehicle type	Fatalities	Fatality risk per 10^{10} VMT	Fraction of all fatalities	Fatalities	Fatality risk per 10^{10} VMT	Fraction of all fatalities	
Models in 2016 (MY03 in 2005) or 2018 (MY11 in 2012) analysis only							
Sm PUs	133	177	4%	179	135	15%	-24%
SUVs	157	159	5%	175	106	13%	-33%
CUVs	16	61	1%	630	69	32%	13%
Minivans	22	113	2%	5	38	1%	-66%
Models in both 2016 and 2018 analyses							
Sm PUs	3,015	204	96%	978	127	85%	-38%
SUVs	3,257	171	95%	1,148	125	87%	-27%
CUVs	1,765	110	99%	1,334	72	68%	-35%
Minivans	1,247	112	98%	672	84	99%	-25%
All models							
Sm PUs	3,148	203	100%	1,157	128	100%	-37%
SUVs	3,414	171	100%	1,323	122	100%	-28%
CUVs	1,781	109	100%	1,964	71	100%	-35%
Minivans	1,269	112	100%	677	83	100%	-26%

Table A.3 compares the fatality risk per VMT for all vehicles included in both the 2016 and 2018 analyses (i.e. model years 2004 through 2010, in calendar years 2006 through 2011), by vehicle type. For the vehicles that were included in both analyses, fatality risk increased 2% between the 2016 and 2018 analyses for cars, and decreased 11% for light trucks and 9% for CUVs/minivans. Since the number of fatalities, and presumably vehicle mass, in the FARS cases did not change between the 2016 and 2018 analyses, the changes in fatality risk per VMT are likely due to the different VMT weights NHTSA developed for the 2018 analysis.

Table A.3. Fatalities and risk for vehicles included in both 2016 and 2018 analyses, by vehicle type

	2016 analysis		2018 analysis		
Vehicle type	Fatalities	Fatality risk per 10^{10} VMT	Fatalities	Fatality risk per 10^{10} VMT	Change in fatality risk from 2016
2-dr cars	4,267	146	4,269	149	2%
4-dr cars	27,128	114	27,138	116	2%
Sm pickups	11,584	158	11,490	140	-12%
Lg pickups	4,512	197	4,509	176	-10%
SUVs	9,908	122	9,671	110	-10%
CUVs	6,807	83	7,105	75	-9%
Minivans	3,189	90	3,176	83	-8%
All	67,395	120	67,358	114	-5%