LBNL-2001092

An Analysis of the Relationship between Casualty Risk Per Crash and Vehicle Mass and Footprint for Model Year 2003-2010 Light-Duty Vehicles

Preliminary report prepared for the Office of Energy Efficiency and Renewable Energy,
U.S. Department of Energy

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January 2018

This work was supported by the Vehicle Technologies Office,
Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy
under Contract No. DE-AC02-05CH11231.

Acknowledgements

We would like to thank those who reviewed earlier drafts of this report, and provided helpful comments and insights: Tom White, Office of Energy Policy and Systems Analysis, U.S. Department of Energy; Chi Li, Office of Transportation and Air Quality, U.S. Environmental Protection Agency; John Kindelberger, National Highway Transportation Safety Administration, U.S. Department of Transportation; Sean Puckett, Volpe Transportation Center; and Sydny Fujita, Lawrence Berkeley National Laboratory.

The report was funded by Carol Schutte of the Vehicle Technologies Program in the Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy. We are grateful for her support of this research.

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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; these analyses are referred to as LBNL Phase 1 analysis. In addition, LBNL has conducted additional analysis of the relationship between mass and the two components of risk per VMT, crash frequency (crashes per VMT) and risk once a crash has occurred (risk per crash); these analyses are referred to as LBNL Phase 2 analysis.

NHTSA recently completed a logistic regression analysis updating its earlier studies of the relationship between vehicle mass and U.S. fatality risk per vehicle mile of travel (VMT; Kahane 2003, Kahane 2010, Kahane 2012, Puckett and Kindelberger 2016). The new study updates the 2012 analysis using NHTSA's Fatality Analysis Reporting System (FARS) data from 2005 to 2011 for model year 2003 to 2010. In a companion Phase 1 report (Wenzel 2016c), we use the updated databases NHTSA has created to replicate their findings on the relationship between vehicle weight, size (actually footprint, or vehicle wheelbase times track width), and U.S. societal fatality risk per VMT. Societal fatality risk considers fatalities in both the case vehicle and any crash partner, including pedestrians, cyclists, and heavy-duty vehicles. The data are examined in slightly different ways, to get a deeper understanding of the relationship between reductions in vehicle mass and footprint, and overall safety. This report compares the logistic regression results of the 2016 NHTSA analysis of U.S. societal fatality risk per VMT with an analysis of 13-state fatality risk and casualty risk per crash, updating our previous Phase 2 analysis conducted in 2012 (Wenzel 2012b).

Our Phase 2 analysis differs from the NHTSA and LBNL Phase 1 analyses in two respects: first, it analyzes risk per crash, using data on all police-reported crashes from thirteen states, rather than risk per estimated VMT; and second, it analyzes casualty (fatality plus serious injury) risk,

as opposed to just fatality risk. There are several good reasons to investigate the effect of mass and footprint reduction on casualty risk per crash. First, risk per VMT, includes two effects that influence whether a person is killed or seriously injured in a crash: how well a vehicle can be, or actually is, driven (based on its handling, acceleration, and braking capabilities) to avoid being involved in a serious crash (crash avoidance), and, once a serious crash has occurred, how well a vehicle protects its occupants from fatality or serious injury (crashworthiness) as well as the occupants of any crash partner (compatibility). By encompassing both of these aspects of vehicle design, risk per VMT gives a complete picture of how vehicle design can promote, or reduce, road user safety. On the other hand, risk per crash isolates the second of these two safety effects, crashworthiness/compatibility, by examining the effect of mass and footprint reduction on how well a vehicle protects its occupants once a crash occurs.

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

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

Table ES.1 summarizes the results of our analysis of the effect of vehicle mass or footprint reduction on the two components of risk per VMT, crash frequency (number of crashes per VMT) and crashworthiness/compatibility (risk per crash), for both fatality and casualty risk, using data from 13 states. 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. Estimated effect of mass or footprint reduction on two components of 13- state fatality and casualty risk per VMT: crash frequency (crashes per VMT) and crashworthiness/compatibility (risk per crash)

Variable	Case vehicle type	A. NHTSA U.S. fatalities per VMT	B. 13-state crashes per VMT	C. 13-state fatalities per crash	D. 13-state fatalities per VMT	E. 13-state crashes per VMT	F. 13-state casualties per crash	G. 13-state casualties per VMT
Mass reduction	Cars < 3197 lbs	1.49%	1.60%	-0.74%	1.13%	1.60%	-0.84%	1.22%
	Cars > 3197 lbs	0.50%	2.33%	-0.32%	1.76%	2.33%	-0.26%	2.18%
	LTs < 4947 lbs	-0.10%	0.36%	-0.77%	-0.06%	0.36%	-0.27%	0.43%
	LTs > 4947 lbs	-0.71%	1.31%	-1.43%	-0.06%	1.31%	-0.49%	0.46%
	CUV/ minivan	-0.99%	2.59%	-2.12%	-0.49%	2.59%	-0.44%	1.25%
Footprint reduction	Cars	0.28%	-0.95%	-0.03%	-0.61%	-0.95%	0.51%	-0.32%
	LTs	0.38%	1.63%	0.10%	1.29%	1.63%	-0.17%	1.19%
	CUV/ minivan	1.18%	-2.31%	0.87%	0.16%	-2.31%	0.48%	-0.51%

Based on NHTSA's estimation of uncertainty using a jack knife method, none of the estimates of mass reduction in Column A are statistically significant at the 95% confidence level.
Estimates that are statistically significant at the 95% level are shown in red.

Table ES.1 indicates that for cars and light trucks, the effects from the two components, crash frequency and crashworthiness/compatibility, roughly add together to result in the overall effect on fatality risk per VMT. For example, the models estimate that a 100-lb mass reduction in heavier-than-average light trucks is associated with a 1.31% increase in crash frequency (column B), while lower mass is associated with a 1.43% decrease in the number of fatalities per crash (column C); the net effect is a 0.06% decrease in the risk of fatality per VMT (column D), which is roughly the sum of the crash frequency and crashworthiness/compatibility effects (1.31% - 1.43% = - 0.12%). For many of the other four types of vehicles, the relationship is different; for example, for example, mass reduction in lighter-than-average cars is associated with a 1.60% increase in crash frequency, but a 0.74% decrease in the number of fatalities per crash; however, the net result, an estimated 1.13% increase in the number of fatalities per VMT, is more than the sum of the two components (1.60% - 0.74% = 0.86%). Solving the three equations (crashes per VMT, risk per crash, and risk per VMT) simultaneously, as Dynamic Research, Inc. (DRI) has done (Van Auken and Zellner 2013), forces the estimates for the first two-stages of the regression (crashes per VMT and risk per crash) to equal that of the third state of the regression (risk per VMT).

The regression results in Table ES.1 estimate that mass reduction is associated with increased crash frequency (columns B and E) in all five vehicle types, with larger estimated increases in crossover utility vehicles (CUVs)/minivans and heavier-than-average cars. On the other hand, mass reduction is associated with decreases in both fatality risk per crash (column C) and casualty risk per crash (column F) in all vehicle types; these estimated reductions are statistically significant for fatality risk per crash in CUVs/minivans and heavier-than-average light trucks, and for casualty risk per crash in lighter cars, CUVs/minivans, and heavier-than-average light trucks. For all but lighter cars, mass reduction is associated with a larger decrease in fatality risk per crash than in casualty risk per crash, especially for heavier light trucks (-1.43% vs. -0.49%) and CUVs/minivans (-2.12% vs. -0.44%). As a result, mass reduction is estimated to have a more beneficial effect on fatality risk per VMT (column D) than on casualty risk per VMT (column G), for all five types of vehicles. Footprint reduction is associated with an increase in crash frequency (columns B and E) only for light trucks, but with decreases in crash frequency for cars and CUVs/minivans; footprint reduction does not have a statistically-significant effect on fatality risk per crash (column C), and an increase in casualty risk per crash (column F) for cars. For light trucks, lower footprint is associated with a statistically significant increase in both fatality risk per VMT (column D) and casualty risk per VMT (column G).

It is unclear why lower vehicle mass is associated with higher crash frequency, but lower risk per crash, in the regression models. It is possible that including variables that more accurately account for important differences among vehicles and driver behavior would reverse this relationship. For example, adding vehicle purchase price substantially reduces the estimated increase in crash frequency associated with mass reduction for all types of vehicles (Table 3.1 in Section 3). On the other hand, it is also possible that over thirty years of improvements in vehicle design to achieve high crash test ratings have enabled manufacturers to design vehicles to mitigate some of the safety penalty of low mass vehicles.

The estimated effects for 13-state fatality risk per VMT (column D) are similar to the effects NHTSA estimated for U.S. fatality risk per VMT (column A), with mass reduction associated with increases in fatality risk per VMT in cars, and decreases in light trucks and CUVs/minivans, in both the U.S. and 13-state analyses.

Table ES.2 compares the results for casualty risk from the 2012 and current analyses. For the most part, the results from the current analysis show the same general trends as the 2012 analysis: mass reduction is associated with statistically-significant increases in crash frequency, small decreases in casualties per crash, and on net statistically-significant increases in casualty risk per VMT, for all five types of vehicles.

Table ES.2. Comparison of 2012 and 2017 estimates of effect of mass or footprint reduction on 13-state crash frequency (crashes per VMT), crashworthiness/compatibility (risk per crash), and casualty risk per VMT

Variable	Case vehicle type	A. 2017 NHTSA U.S. fatalities per VMT	2012 analysis			2017 analysis		
			E. 13-state crashes per VMT	F. 13-state casualties per crash	G. 13-state casualties per VMT	E. 13-state crashes per VMT	F. 13-state casualties per crash	G. 13-state casualties per VMT
Mass reduction	Cars < 3197 lbs	1.49%	2.00%	0.09%	1.86%	1.60%	-0.84%	1.22%
	Cars > 3197 lbs	0.50%	1.50%	-0.77%	0.73%	2.33%	-0.26%	2.18%
	LTs < 4947 lbs	-0.10%	1.44%	-0.11%	1.55%	0.36%	-0.27%	0.43%
	LTs > 4947 lbs	-0.71%	0.94%	-0.62%	-0.04%	1.31%	-0.49%	0.46%
	CUV/ minivan	-0.99%	0.95%	-0.16%	0.10%	2.59%	-0.44%	1.25%
Footprint reduction	Cars	0.28%	0.64%	0.23%	1.54%	-0.95%	0.51%	-0.32%
	LTs	0.38%	1.04%	-0.25%	0.94%	1.63%	-0.17%	1.19%
	CUV/ minivan	1.18%	-0.55%	0.56%	1.54%	-2.31%	0.48%	-0.51%

Based on NHTSA's estimation of uncertainty using a jack knife method, none of the estimates of mass reduction in Column A are statistically significant at the 95% confidence level.
Estimates that are statistically significant at the 95% level are shown in red.

The estimated effect of reductions in vehicle mass and footprint shown in Table ES.2 all have a much lower effect on risk than most of the additional control variables included in the regression models. The estimated effects of vehicle type, other vehicle attributes, such as side airbags, antilock braking systems (ABS), electronic stability control (ESC), and all-wheel drive (AWD), or male drivers on fatality or casualty risk per VMT are nearly an order of magnitude larger than those estimated for lower mass or footprint, while driving at night, on rural or high-speed roads, are estimated to have an effect several hundred times that of vehicle mass or footprint reduction. For example, a 100-lb reduction in the mass of a lighter-than-average car is associated with an increase in casualty risk per crash of only 1.2%, while installing ABS would reduce risk by 20%. Therefore, the regression estimates suggest that, in theory, the mass of a lighter car could be reduced by as much as 1,600 pounds while adding ABS, without increasing casualty risk per crash. Similarly, the estimated effect of mass or footprint reduction on fatality or casualty risk per crash also is much lower than many of the control variables used.

The estimated effects of the control variables are fairly consistent, for both fatality and casualty risk per crash or per VMT (presented in Tables 2.6 through 2.8 in Section 2.3). In some cases, these relationships on the two components of risk per VMT, crash frequency and risk per crash, are as expected; for example, ABS and ESC in cars are estimated to reduce crash frequency more than risk per crash, while AWD in light trucks and CUVs/minivans is estimated to increase crash frequency more than risk per crash. Two-door cars and the side airbag variables in cars have a larger effect on risk given a crash than on crash frequency; two-door cars increase risks per crash, while side airbags decrease risks per crash. The driver age variables estimate that crash frequency consistently increases for the youngest and oldest drivers, and that risk per crash consistently increases for the two oldest groups of drivers (over 50 years old). All of these results are expected.

On the other hand, there are several unexpected results: bumper height compatibility measures in light trucks, and some types of side airbags in cars and CUVs/minivans, are associated with decreases in risk once a crash has occurred, as expected, but are also associated with decreases in crash frequency. Crash prevention technologies ESC and ABS are associated with decreases in crash frequency, as expected, but are also associated with decreases in risk once a crash has occurred, especially in first-event rollovers and crashes with a stationary object; while male drivers, young drivers, and driving at night, in a rural county, or on a high-speed road, are all associated with increases in crash frequency as expected, but are also associated with risk once a crash has occurred. AWD is associated with an increase in both crash frequency, in light trucks and CUVs/minivans, as well as fatality risk in light trucks once a crash has occurred. These unexpected results suggest that important control variables are not being included in the regression models. For example, crashes involving male drivers, in trucks equipped with AWD, or that occur at night on rural or high-speed roads, may not be more frequent but rather more severe than other crashes, and thus lead to greater fatality or casualty risk. And drivers who select vehicles with certain safety features may tend to drive more carefully, resulting in vehicle safety features designed to improve crashworthiness or compatibility, such as side airbags, being also associated with lower crash frequency.

As mentioned above, the baseline model continues to find that mass reduction is associated with increases in crash frequency, which is unexpected, as smaller and lighter vehicles are assumed to be more nimble, have shorter braking distances, and better able to avoid a crash than larger and heavier vehicles. It is possible that including variables that more accurately account for important differences among vehicles and driver behavior would reverse this relationship. We conducted several sensitivity analyses to see if they changed this unexpected relationship (described in Section 3.1). We added five control variables, both individually and together, to the baseline regression model: vehicle model initial purchase price; average income of households owning particular vehicle models; average bad driver rating by vehicle model; fraction of drivers reported to be using alcohol or drugs; and fraction of drivers not using restraints. We also ran a sensitivity including 15 dummy variables for vehicle makes. For the most part, including the additional variables does not change the general results of the baseline regression model: that mass reduction is associated with an increase in crash frequency in all three types of vehicles, while footprint reduction is associated with an decrease in crash frequency in cars and CUVs/minivans, but with an increase in crash frequency in light trucks. These results suggest that other, more subtle, differences in vehicles and their drivers may account for the unexpected finding that lighter vehicles have higher crash frequencies than heavier vehicles.

We further investigated the unexpected results for many of the control variables in the baseline regression models (described in Section 3.2). Based on recommendations by Kahane, we re-ran the regression models including only severe crashes, in an attempt to control for crash severity. We defined a severe crash as one in which at least one of the vehicles involved were reported as either "disabled" or towed from the scene of the crash.[1] In some cases, excluding the non-severe crashes reduces the unexpected results from the baseline model; however, in none of the estimates does excluding the non-severe crashes change the sign on the estimated coefficient to the expected direction. We therefore conclude that not accounting for crash severity in the

[1] Because Washington does not report either of these measures of crash severity, all crashes in Washington were excluded from this particular analysis.

baseline model is not the reason why many control variables have unexpected associations with crash frequency or risk per crash.

As with our analysis of U.S. fatalities per VMT, this report concludes that the estimated effect of mass reduction on casualty risk per crash is small, and is overwhelmed by other control variables, such as vehicle type, specific safety technologies, and crash conditions such as whether the crash occurred at night, in a rural county, or on a high-speed road. We do not believe that casualty risk per crash is necessarily a better metric than fatality risk per VMT for evaluating the effect of mass or footprint reduction on risk; rather, it provides a different perspective in assessing the benefits or drawbacks of mass and footprint reduction on safety in vehicles. However, it does allow the risk per VMT to be separated into its two components, crash frequency and risk per crash. Our analysis indicates that much of the estimated detrimental effect of mass or footprint reduction on risk can be attributed to the tendency for crash frequency, rather than crashworthiness/compatibility (risk once a crash has occurred), to increase as vehicle mass or footprint decreases. Including other variables to account for differences among vehicle models and their drivers does not change this fundamental result. In addition, accounting for crash severity does not change the unexpected results for many of the control variables used in the baseline regression models. These results suggest that other, more subtle, differences in vehicles and their drivers may account for lighter vehicles having higher crash frequencies than heavier vehicles. On the other hand, it is also possible that over thirty years of improvements in vehicle design to achieve high crash test ratings have enabled manufacturers to design vehicles to mitigate some of the safety penalty of low mass vehicles.

As in our analysis of U.S. fatalities per VMT, we stress two important caveats of these results. First, although the purpose of these analyses is to estimate the effect of vehicle mass reduction on societal risk, this is not exactly what the regression models are estimating. Rather, they are estimating the recent historical relationship between mass and risk, after accounting for most measurable differences between vehicles, drivers, and crash times and locations. In essence, the regression models are comparing the risk of a 2600-lb Dodge Neon with that of a 2500-lb Honda Civic, after attempting to account for all other differences between the two vehicles. The models are not estimating the effect of literally removing 100 lbs from the Neon, leaving everything else unchanged.

In addition, the analyses are based on the relationship of vehicle mass and footprint on risk for recent vehicle designs (model year 2003 to 2010). These relationships may or may not continue into the future as manufacturers utilize new vehicle designs and incorporate new technologies, such as more extensive use of strong lightweight materials and specific safety technologies. Therefore, throughout this report we use the phrase "the estimated effect of mass (or footprint) reduction on risk" as shorthand for "the estimated change in risk as a function of its relationship to mass (or footprint) for vehicle models of recent design."

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1. Introduction

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; these analyses are referred to as LBNL Phase 1 analysis. In addition, LBNL has conducted additional analysis of the relationship between mass and the two components of risk per VMT, crash frequency (crashes per VMT) and risk once a crash has occurred (risk per crash); these analyses are referred to as LBNL Phase 2 analysis.

NHTSA recently completed a logistic regression analysis updating its 2003, 2010, and 2012 studies of the relationship between vehicle mass and U.S. fatality risk per vehicle mile of travel (Puckett and Kindelberger 2016). The new study updates the 2012 analysis by using FARS data for 2005 to 2011 involving model year 2003 to 2010 vehicles. In a companion report (Wenzel, 2016c), we use the updated databases NHTSA has created to replicate their findings on the relationship between vehicle weight, size (actually footprint, or vehicle wheelbase times track width), and U.S. fatality risk per VMT, for model year 2003 to 2010 light-duty vehicles involved in fatal crashes between 2005 and 2011. The data are examined in slightly different ways, to get a deeper understanding of the relationship between reductions in vehicle mass and footprint, and overall safety.

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

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

Second, estimating risk on a per crash basis requires using data on police-reported crashes from states. Although NHTSA generates a national sample of police-reported crashes, the National Automotive Sampling System, General Estimates System (NASS GES), that can be used to estimate per crash risks on a national basis, the database is relatively small and may be biased towards crashes that occur in relatively urban areas. Only sixteen states currently record the vehicle identification number (VIN) of all vehicles involved in police-reported crashes, which is necessary to determine the model year, make, and model of each vehicle, in order to assign its correct curb weight, footprint, type, and installed safety features (such as side airbags, ABS, ESC, and all-wheel drive). The sixteen states that report VIN information represent about one-third of the country, so estimating fatality risk per crash from these sixteen states increases the statistical uncertainty of the analysis, relative to that from estimating fatality risk per VMT using all U.S. fatalities.[2] Extending the analysis to casualties (fatalities plus serious/incapacitating injuries) reduces the statistical uncertainty of analyzing just fatalities per crash. In addition, a serious incapacitating injury can be just as traumatic to the victim and her family, and costly from an economic perspective, as a fatality. Limiting the analysis to the risk of fatality, which is an extremely rare event, ignores the effect vehicle design may have on reducing the large number of incapacitating injuries that occur each year on the nation's roadways.

In an earlier report LBNL compared fatality risk per vehicle registration-year and casualty risk per crash, using the same database of all police-reported crashes in five states (Wenzel, 2012a). For the most part, the trend in casualty risk by vehicle type is quite similar to that of fatality risk, when vehicle registration-years are used as the measure of exposure, although casualty risks are substantially lower than fatality risks for sports cars and for pickups. The trend in casualty risk by vehicle type is similar regardless of whether vehicle registration years or police-reported crashes are used as the measure of exposure. Casualty risks for subcompact and compact cars are relatively lower per crash than per vehicle, while casualty risks for large and import luxury

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

cars, minivans, large SUVs, and pickups are relatively higher per crash than per vehicle. We accounted for miles driven by vehicle make and model using odometer readings from vehicle emission inspection and maintenance programs in four of the five states. For most vehicle types, adjusting casualty risk per vehicle registration-year for miles driven has little to no effect (although the adjustment does substantially increase casualty risk for sports cars, which are driven many fewer miles than other vehicles, by 30%, and slightly reduces casualty risk for fullsize vans and ¾-ton pickups, which are driven more miles than the average vehicle).

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

The section below summarizes the expected relationships between vehicle mass, size and fatality risk. In Section 2 we reproduce the logistic regression models NHTSA used in its analysis of U.S. fatality risk per VMT, and compare the estimated effect of mass and footprint reduction on U.S. fatality risk per VMT, 13-state fatality risk per crash, and 13-state casualty risk per crash. Section 3 examines in more detail the multi-collinearity between vehicle mass and footprint, and methods to address that multi-collinearity when assessing their effect on casualty risk per crash. In Section 4 we examine the relationship between vehicle mass and casualty risk per crash by vehicle model, before and after accounting for the differences in driver characteristics, crash locations, and other vehicle attributes included in the NHTSA regression models. In Section 5 we test alternative specifications of the regression models, in order to examine the sensitivity of our results to different model specifications, and using additional data.

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

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

2. 13-State Fatality and Casualty Risk Per Crash

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 thirteen states; NHTSA refers to this subset of vehicles as "induced exposure" cases. The induced exposure cases provide information on driver and crash characteristics for vehicles that are not involved in fatal crashes, as in the FARS data. NHTSA developed weighting factors to scale the induced exposure vehicles up to national level vehicle registrations. NHTSA then multiplied the vehicle registration-years by annual vehicle miles traveled (VMT) factors it developed by vehicle type and age, from odometer data provided by RL Polk. For more details on NHTSA's data and methodology, refer to (Puckett and Kindelberger 2016).

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

2.1. Data and Methods

For its analysis NHTSA used FARS data on fatal crashes, and police-reported crash data from 13 states, for MY03 to MY10 light-duty vehicles between calendar years 2005 and 2011. NHTSA used a subset of non-culpable vehicles in two-vehicle crashes as a measure of what it calls "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 VMT.

NHTSA compiled a database of the following vehicle attributes, by model year, make and model: curb weight and footprint (wheelbase times track width), as well as the presence of all-wheel drive and automated braking systems. NHTSA added several new variables for new safety technologies and designs: electronic stability controls (ESC), four types of side airbags, and two methods to comply with the voluntary manufacturer agreement to better align light truck bumpers to make them more compatible with other types of vehicles (BLOCKER1 and BLOCKER2).

NHTSA ran a separate logistic regression model for each of three vehicle types (passenger cars, composed of two- and four-door cars; light trucks, composed 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 (3,157 pounds), and a pickup or truck-based SUV lighter or heavier than average (4,303 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. We followed NHTSA's convention of excluding these vehicles from our analyses; we test the sensitivity of the estimates to excluding these vehicles in Section 5.5.

Table 2.1 shows the control variables NHTSA used in its regression models for each of the case vehicle types. For cars and trucks, NHTSA uses two variables (UNDRWT00, OVERWT00) for vehicle weight, allowing the effect of weight on risk to vary for lighter and heavier cars and trucks. The determination of the two weight classes is based on the average weight for each vehicle type: 3,197 pounds for cars and 4,947 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 2012 analysis, for the current analysis NHTSA includes the control variable ROLLCURT airbags only in the regression models for rollover crashes involving cars or CUVs/minivans; regression models of pedestrian crashes do not include any control variables for airbags; and the control variables for CURTAIN, COMBO, and TORSO airbags are included in regression models for all other crashes involving cars or CUVs/minivans. No airbag variables were included in the regression models for light trucks.

Rather than reporting coefficients for the variables of interest (curb weight and footprint) from a single regression model across all crash types, NHTSA reports a weighted average of the coefficients from the nine regression models run for each of the nine crash types. NHTSA uses a "baseline" distribution of fatalities across the crash types, to represent the expected distribution of fatalities in the 2017 to 2025 timeframe of the new CAFE and GHG emission standards. Similar to the 2003 study, NHTSA derives the baseline fatalities from MY04-09 vehicles in crashes between 2004 and 2008. NHTSA then adjusts this baseline distribution downward to account for the assumption that all vehicles in the 2017-2025 timeframe will have ESC installed. The assumptions used for this adjustment are taken from a NHTSA analysis that found that ESC reduces fatal rollovers by 56% in cars and 74% in light trucks; fixed-object impacts by 47% in cars and 45% in light trucks; and other non-pedestrian crashes by 8% in both cars and light trucks.[3] These assumptions treat crossover SUVs and minivans as light trucks rather than cars. This "post-ESC" distribution of fatalities by crash type is then multiplied by the regression coefficients for each crash type to create the weighted average effect of each control variable on risk. Table 2.2 shows the baseline distribution of fatalities, by case vehicle type and crash type, which are used to create the overall coefficient estimates weighted by the results from the regressions for each crash type.

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

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

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

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

C: continuous variable

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

D: dummy variable, coded as either 1 or 0

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

Table 2.2 and Figure 2.1 compare the distribution of light-duty vehicle crashes in the U.S. from the NHTSA 2016 report with those from the 13 states. Note that there are higher fractions of “other” crashes (that is, crashes involving more than two vehicles, or for which not all information was available) in the 13-state data; for example, 22% of U.S. fatal car crash involvements in FARS are in the “other” category, while 29% of fatality crash involvements, and

31% of casualty crash involvements, in the thirteen states are in the "other" category. The distributions of vehicles involved in crashes in Figure 2.1 exclude the "other" crash category, so that the fractions of all other types of crashes equal 100% for each vehicle type.

Table 2.2. Fatal and casualty crash involvements for model year 2003 to 2010 light-duty vehicles in 2005 to 2011, by vehicle type

	Fatal crash involvements (FARS)			Fatal crash involvements (13 states)			Casualty crash involvements (13 states)		
Crash type	Cars	LTVs	CUVs/ minivans	Cars	LTVs	CUVs/ minivans	Cars	LTVs	CUVs/ minivans
1: Rollovers	1,929	3,567	503	441	714	141	2,996	3,819	773
2: w/object	7,237	5,055	1,421	1,661	1,117	328	11,303	7,171	2,289
3: Ped etc.	5,692	5,222	2,253	1,791	1,460	714	10,166	6,601	3,652
4: w/HDT	2,438	1,618	673	736	430	218	3,532	1,878	992
5: w/lgt car	3,181	3,857	1,242	908	997	359	12,547	8,306	4,260
6: w/hvy car	3,567	3,333	1,120	846	718	261	10,566	6,294	3,320
7: w/lgt LT	2,261	1,912	572	877	677	252	10,943	6,685	3,301
8: w/hvy LT	2,555	1,462	636	752	350	212	6,953	3,474	2,164
9: Other	8,000	6,625	2,865	3,437	2,409	1,085	30,675	18,865	10,381
Total	36,860	32,651	11,285	11,449	8,872	3,570	99,681	63,093	31,132
1: Rollovers	5.2%	10.9%	4.5%	3.9%	8.0%	3.9%	3.0%	6.1%	2.5%
2: w/object	19.6%	15.5%	12.6%	14.5%	12.6%	9.2%	11.3%	11.4%	7.4%
3: Ped etc.	15.4%	16.0%	20.0%	15.6%	16.5%	20.0%	10.2%	10.5%	11.7%
4: w/HDT	6.6%	5.0%	6.0%	6.4%	4.8%	6.1%	3.5%	3.0%	3.2%
5: w/lgt car	8.6%	11.8%	11.0%	7.9%	11.2%	10.1%	12.6%	13.2%	13.7%
6: w/hvy car	9.7%	10.2%	9.9%	7.4%	8.1%	7.3%	10.6%	10.0%	10.7%
7: w/lgt LT	6.1%	5.9%	5.1%	7.7%	7.6%	7.1%	11.0%	10.6%	10.6%
8: w/hvy LT	6.9%	4.5%	5.6%	6.6%	3.9%	5.9%	7.0%	5.5%	7.0%
9: Other	21.7%	20.3%	25.4%	30.0%	27.2%	30.4%	30.8%	29.9%	33.3%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Figure 2.1 shows the same data as Table 2.2 but the percentages are calculated excluding "other" crashes. Figure 2.1 indicates that there is a smaller portion of fatal car crashes with stationary objects, heavy cars, and rollover crashes in the thirteen states (20.7%, 10.6%, and 5.5%, respectively) than in the entire U.S. (25.1%, 12.4%, and 6.7%, respectively). On the other hand, there are more fatal car crashes in crashes with pedestrians/pedalcycles, light cars, light and heavy light-duty trucks, and heavy-duty trucks in the thirteen states (22.4%, 11.3%, 10.9%, 9.4%, and 9.2%, respectively) than in the U.S. (19.7%, 11.0%, 7.8%, 8.9%, and 8.4%, respectively). For the most part these trends hold for light trucks and CUVs/minivans as well.

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

The distributions of fatal and casualty crashes involving cars in the thirteen states are quite similar to those involving CUVs and minivans; however, CUVs and minivans tend to be involved in fewer crashes with stationary objects (13.2% of all fatal crashes) than cars (20.7% of all fatal crashes). Light trucks tend to have more fatal/casualty crashes in rollovers and crashes with lighter cars (11.0% and 15.4% of all fatal crashes, respectively) than cars do (5.5%, and 11.3% of all fatal crashes, respectively), but relatively fewer crashes with stationary objects (17.3%, vs. 20.7% for cars) and heavier light trucks (5.4%, vs. 9.4% for cars).

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

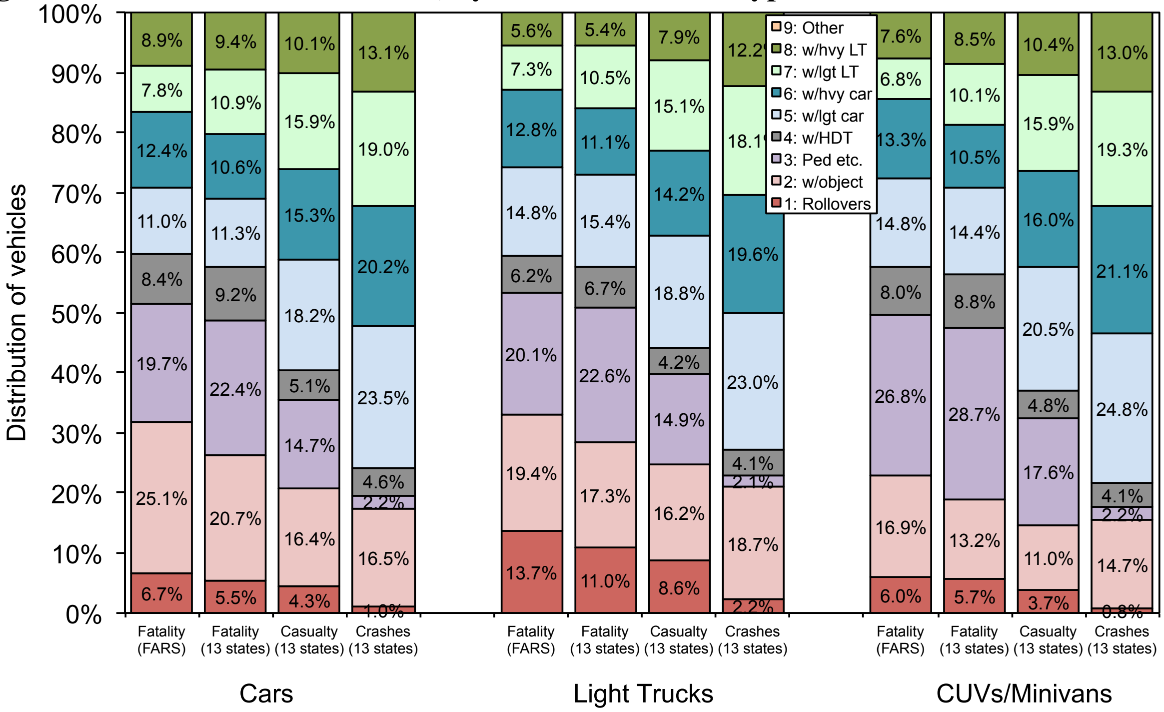


Figure 2.1 also shows the distribution of all police-reported crashes from the 13 states. There are many fewer overall crashes involving pedestrians/cyclists and first-event rollovers than casualty crashes; the fraction of all crashes vs. casualty crashes is greater for all other crash types.

Note in Table 2.2 that there are many fewer fatal crash involvements in the thirteen states (e.g., 11,449 cars) than in the U.S. FARS (36,860 cars). Extending the analysis to include incapacitating injuries substantially increases the number of casualty crash involvements in the thirteen states (to 99,681 cars). The focus of this report is on the estimated effect of mass and footprint reduction on casualty risk using data from the thirteen states, although we do compare the effect on fatality risk in the next section.

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

However, it was necessary to diverge from the NHTSA analysis in several respects. First, as discussed above, in analyzing the relationship between vehicle mass and U.S. fatality risk per VMT, NHTSA used all U.S. fatalities from FARS, and a subset of non-culpable vehicles in two-vehicle crashes from police-reported crash data from the thirteen states to assign driver and environment control variables to national vehicle registration years (from Polk). NHTSA selected non-culpable vehicles in two-vehicle crashes to determine induced exposure crash involvements. Each of these vehicles was assigned a weight representing the national registration-years for each particular year, make and model. NHTSA developed other weights for total VMT based on a database of vehicle odometer readings by vehicle year, make and model, also obtained from Polk. For a more thorough discussion of how NHTSA derived the vehicle and VMT weighting factors, refer to Sections 2.3 through 2.6 of (Puckett and Kindelberger 2016).

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

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

- "Muscle" cars, police cars, and all-wheel drive cars; all Ford Crown Victorias[4]; and fullsize passenger and cargo vans.
- Vehicles whose reported model year did not match the model year decoded from the VIN.
- Vehicles whose model year was not reported in the state crash data (with the exception of all crash records from Washington, which NHTSA included in their analysis of induced exposure crashes).

2.2. Accounting for the State in Which the Crash Occurred

In its regression models of U.S. fatality risk per VMT, NHTSA included the control variable HIFAT_ST, which identifies states with high fatality rates per million vehicle-years. We

[4] NHTSA excluded all 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.

investigated the effect of replacing this single control variable with two variables, for states with high and with low fatality risks per crash, as well as with 12 control variables for each state used in the analysis except Florida.

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

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

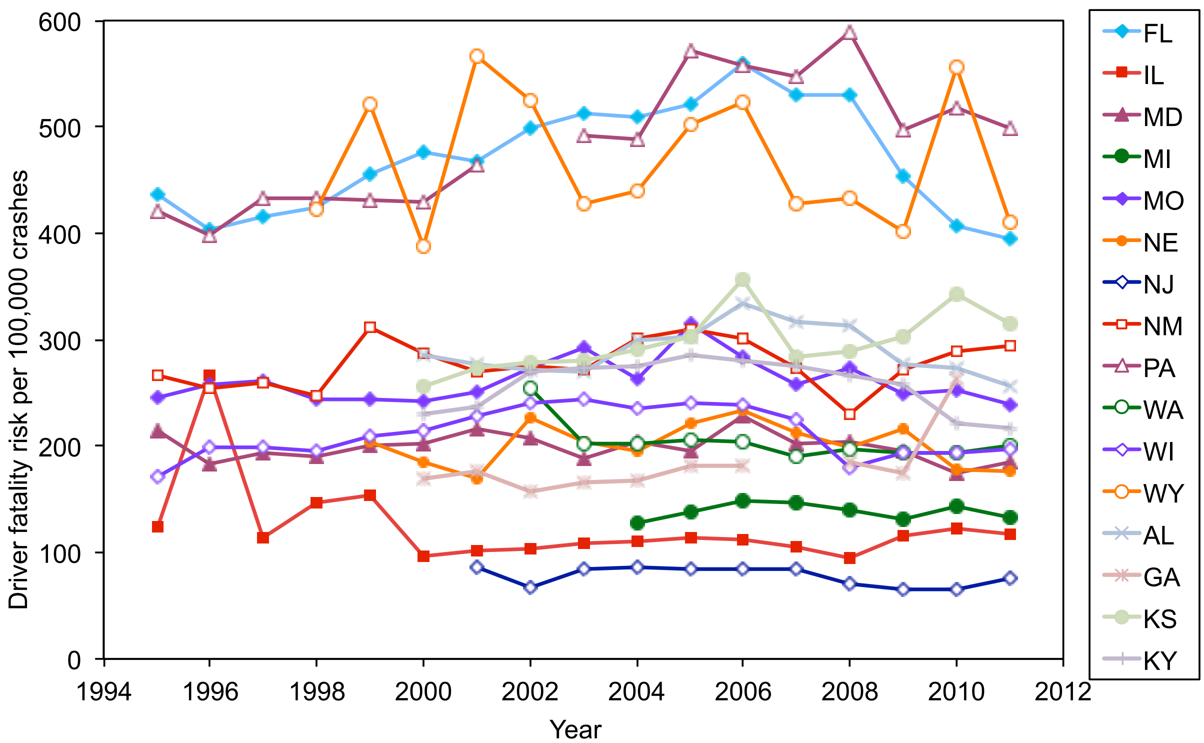
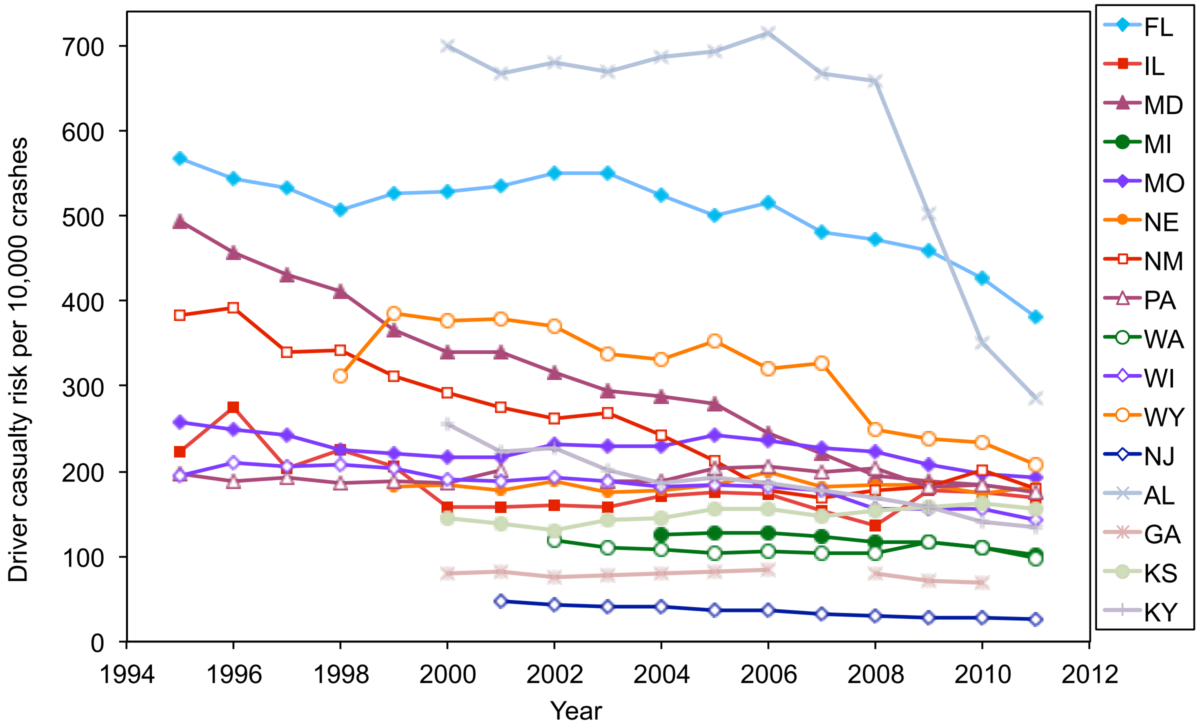
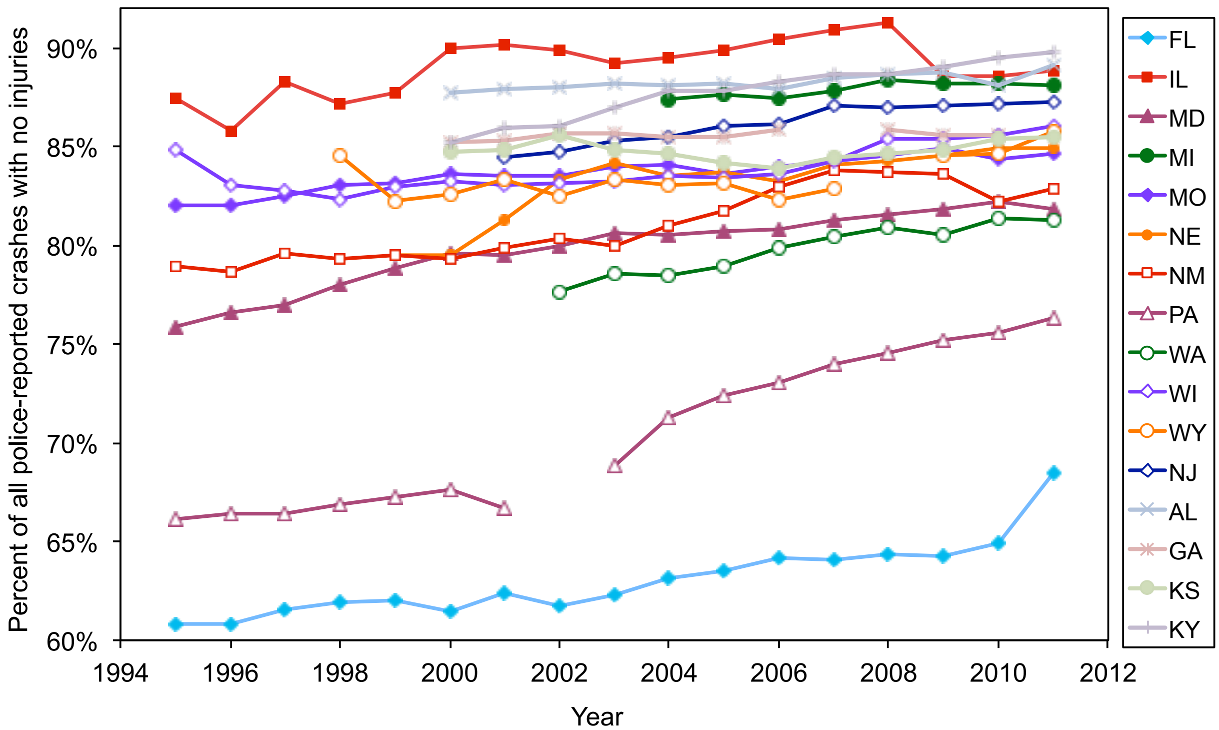


Figure 2.3. Driver casualty risk per 10,000 crashes in 16 states



The relatively high or low risks shown for some states in Figures 2.2 and 2.3 do not necessarily reflect more dangerous driving conditions in those states; rather, they reflect either different definitions of "incapacitating", "serious", or "major" injuries, or different reporting requirements or reporting bias in those states. For example, Pennsylvania is unique in that it reports "moderate" injuries in addition to "major" and "minor" injury; as a result, there are relatively few "major" injuries reported in Pennsylvania, which increases its casualty risk per crash relative to other states. In Florida, there is no property damage threshold over which a crash is required to be included in the state crash database; in most other states crashes resulting in property damage in excess of $500 must be reported. In Figure 2.4, only 60% to 70% of all crashes in the Florida database are non-injury crashes, whereas 80% to 90% of the crashes in most other states are non-injury crashes. As a result, risks per crash are higher in Florida than in almost any other state. Note that the fraction of non-injury crashes in Illinois declined from 91% in 2008 to 89% in 2009, when the reporting threshold increased from $500 to $1,500 if all parties in the crash were insured.

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



Based on Figures 2.2 through 2.4, we replaced the HIFAT_ST variable NHTSA used for analysis of U.S. fatalities per VMT with 12 variables identifying each state except Florida for our analysis of fatality and casualty risks per crash.

2.3. Effect of Mass and Footprint Reduction on Fatality and Casualty Risk Per Crash

All of the regression coefficients presented in the NHTSA 2016 report, 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 reduction in vehicle mass or footprint; we use the same convention throughout this report).[5]

Figure 2.5 presents the regression coefficients of the effect of reductions in mass and footprint on U.S. fatality risk per ten billion VMT, from the NHTSA 2016 analysis (in light blue). The

[5] The output from the SAS LOGIST procedure reflects the percent change in the log-odds of casualty (or fatality) per crash for a one-unit increase in the explanatory variable. In 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 casualty is small; however it substantially increases the percent change for explanatory variables that have a large effect on the log-odds of casualty (such as the crash location variables). For example, the casualty risk per crash from a lighter-than-average car involved in a rollover crash has a 1.54 times higher log-odds of casualty if it occurs in a rural county; after conversion, this crash has a 366 percent higher probability of casualty if it occurs in a rural county (EXP(1.54) - 1 = 3.66).

coefficients for each of the nine crash types are weighted by the distribution of fatal crashes after adjustment for full ESC penetration, based on NHTSA's method of using data only on the newest vehicles, model years 2007 to 2010 in calendar years 2007 to 2011. Figure 2.5 indicates that mass reduction is associated with an increase in U.S. societal[6] fatality risk per VMT of about one percent for cars, while mass reduction is associated with a slight reduction in fatality risk for lighter-than-average light trucks, and about a one percent reduction in fatality risk for the heavier light trucks and CUV/minivans (shown in light blue columns). The 95% confidence intervals in the figure indicate that the changes in risk for lighter cars, heavier light-duty trucks, and CUVs/minivans 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% confidence level; however, the estimates for increases in risk associated with mass reduction in lighter-than-average cars, and decreases in risk associated with mass reduction in heavier-than-average light trucks and CUVs/minivans, are statistically significant at the 90% confidence interval.

Figure 2.5 compares the estimated effect of mass and footprint reduction on U.S. fatalities per billion VMT (from NHTSA 2016, in blue) with that on 13-state fatality risk (in red), and 13-state casualty risk (in green), per police-reported crash. The effect for each of the nine crash types is weighted by the expected distribution of 13-state fatalities, casualties, or crashes (for fatality risk, casualty risk, or crash frequency, respectively) in 2016, after full adoption of ESC, just as in the NHTSA 2016 report. Note that a different post-ESC distribution is used for fatality risk, casualty risk, and crash frequency, as indicated by the different distributions in Figure 2.1 above. Lower mass in all five vehicle types, while holding footprint constant, is associated with a consistent reduction in state fatality risk per crash; only the estimated reductions for heavier light trucks and CUVs/minivans are statistically significant. Smaller footprint in cars and light trucks is associated with essentially no change, while smaller footprint in CUVs/minivans is associated with an increase, in fatality risk per crash; however, all three estimated effects are not statistically significant.

The estimated effects for 13-state fatality risk per crash (shown in red) in Figure 2.5 are quite different from the effects NHTSA estimated for U.S. fatality risk per VMT (shown in blue), especially for cars; mass reduction in cars is associated with increases in U.S. fatality risk per VMT, but decreases in 13-state fatality risk per crash. And mass reduction in light trucks and CUVs/minivans is associated with larger decreases in 13-state fatality risk per crash than in U.S. fatality risk per VMT.

Figure 2.5 indicates that lower mass in cars is associated with nearly identical reductions in fatality and casualty risk per crash; however, lower mass in light trucks and CUVs/minivans is associated with smaller reductions in casualty risk per crash than in fatality risk per crash; the

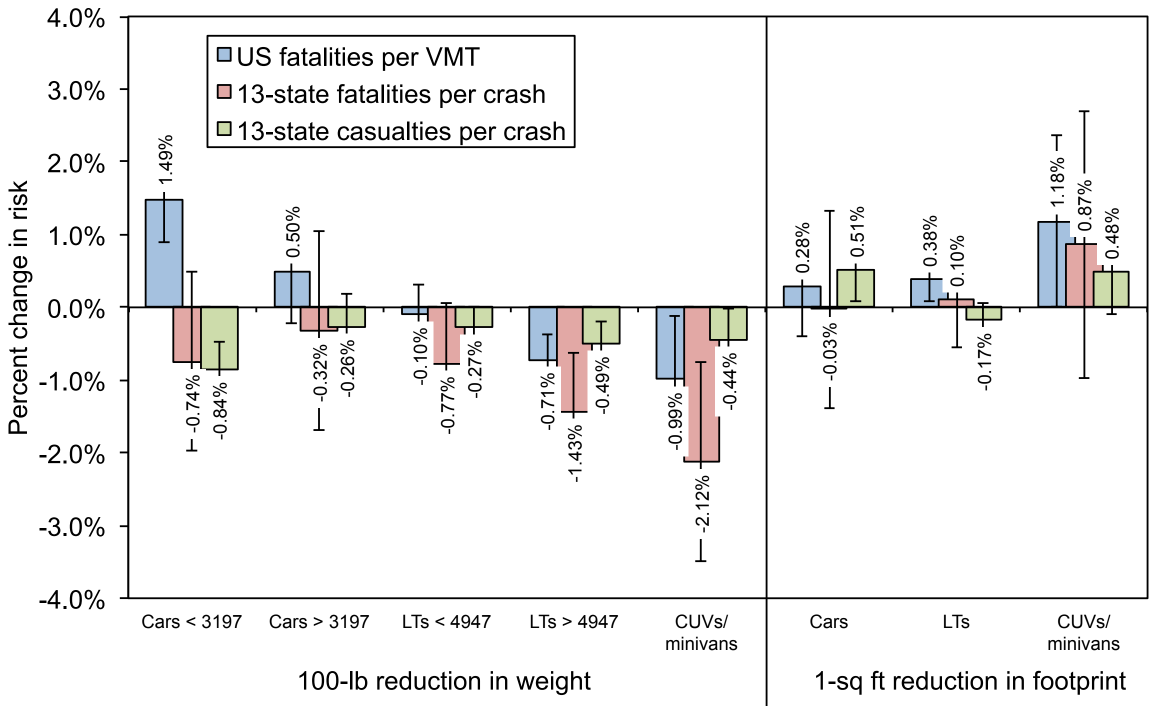
[6] All of the fatality risks reported in the 2016 NHTSA report are societal fatality risk, that is fatalities to all vehicle occupants and non-occupants involved in the crash are included. Unless specified otherwise, all risks in this report also are societal risk.

estimates for casualty risk per crash for light trucks and CUVs/minivans are comparable to those for U.S. fatality risk per VMT. Smaller footprint is associated with a larger increase in casualty risk than in fatality risk per crash for cars; a small decrease in casualty risk, but a small increase in fatality risk, per crash for light trucks; and a smaller increase in casualty risk than in fatality risk per crash for CUVs/minivans.

The different results for fatality risk per VMT versus per crash could be attributed to at least three factors.

- First, as discussed above, the estimated effect of mass reduction on fatality risk per VMT is the combined effect of a vehicle's crash avoidance and its crashworthiness/compatibility; the ability of a vehicle to avoid a crash altogether, and the extent to which a vehicle protects its occupants, as well as the occupants of any crash partners, once a serious crash occurs. The net detrimental effect of mass reduction on fatality risk per VMT for cars and lighter light-duty trucks may be the result of a large detrimental effect of mass reduction on these vehicles' crash avoidance, combined with a smaller, beneficial effect of mass reduction on crashworthiness/compatibility. We address this possibility below.

Figure 2.5. Estimated effect of mass or footprint reduction on three types of risk, by vehicle type



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

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

Figure 2.6 shows the same data as Figure 2.5, but for 13-state fatality and casualty risk per VMT, not per crash, using the VMT weights developed by NHTSA using national registration data and induced exposure crashes in the thirteen states. Comparing Figure 2.6 with Figure 2.5, one sees that the estimated effects of mass and footprint reduction in cars on risk per VMT are quite a bit more detrimental than the estimated effects on risk per crash; mass reduction in lighter cars is associated with a 0.74% reduction in fatality risk per crash but a 1.13% increase in fatality risk per VMT, and a 0.84% reduction in casualty risk per crash but a 1.22% increase in casualty risk per VMT, while mass reduction in heavier cars is associated with a 0.32% reduction in fatality risk per crash but a 1.76% increase in fatality risk per VMT, and a 0.26% reduction in casualty risk per crash but a 2.18% increase in casualty risk per VMT. Mass reduction for all vehicle types is associated with substantially more detrimental (or substantially less beneficial) risk per VMT than risk per crash.

Figure 2.6. Estimated effect of mass or footprint reduction on three types of risk per VMT, by vehicle type

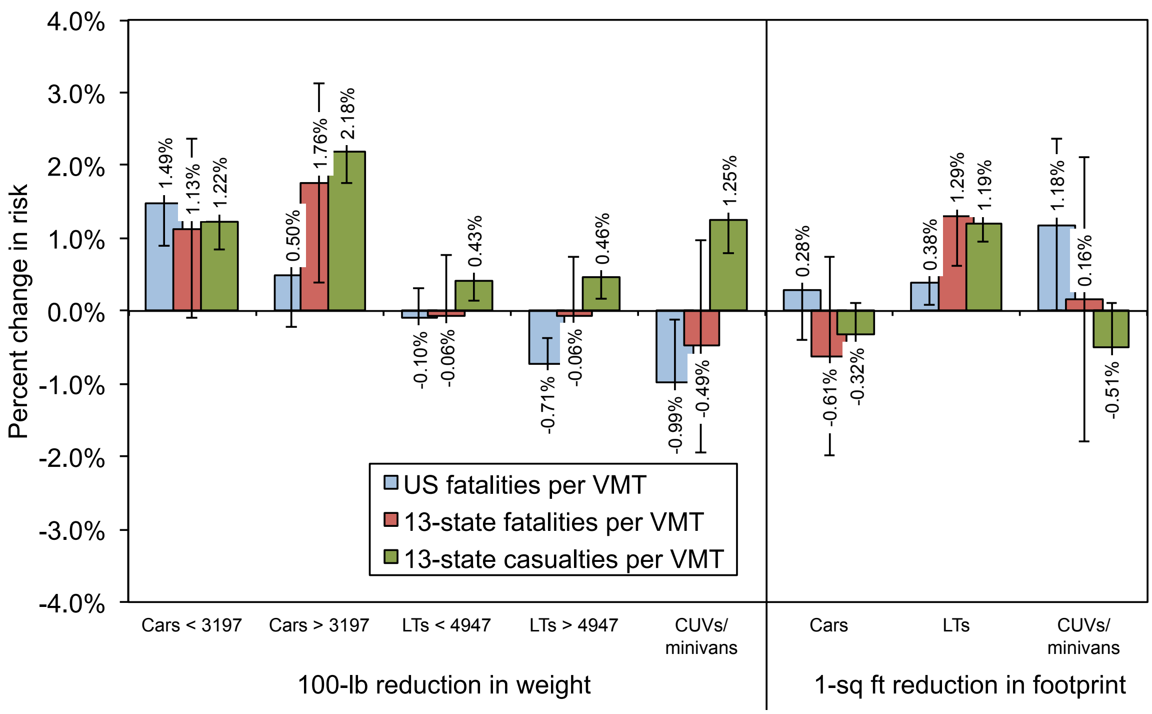


Figure 2.6 also indicates that the estimated effects of mass reduction on fatality risk per VMT from the 13-state data (shown in red) are comparable to NHTSA's estimated effects on national fatality risk per VMT (shown in blue) for only lighter-than-average cars and lighter-than-average light trucks. Mass reduction in heavier-than-average cars is associated with a 0.50% increase in fatality risk using the U.S. data but a 1.76% increase in fatality risk using the 13-state data, while mass reduction in heavier-than-average light trucks and CUVs/minivans is associated with a much smaller decrease in fatality risk per VMT using the 13-state data (0.06% decrease for

heavier light trucks, 0.49% decrease for CUVs/minivans) than using the U.S. data (0.71% decrease for light trucks, 0.99% decrease for CUVs/minivans).

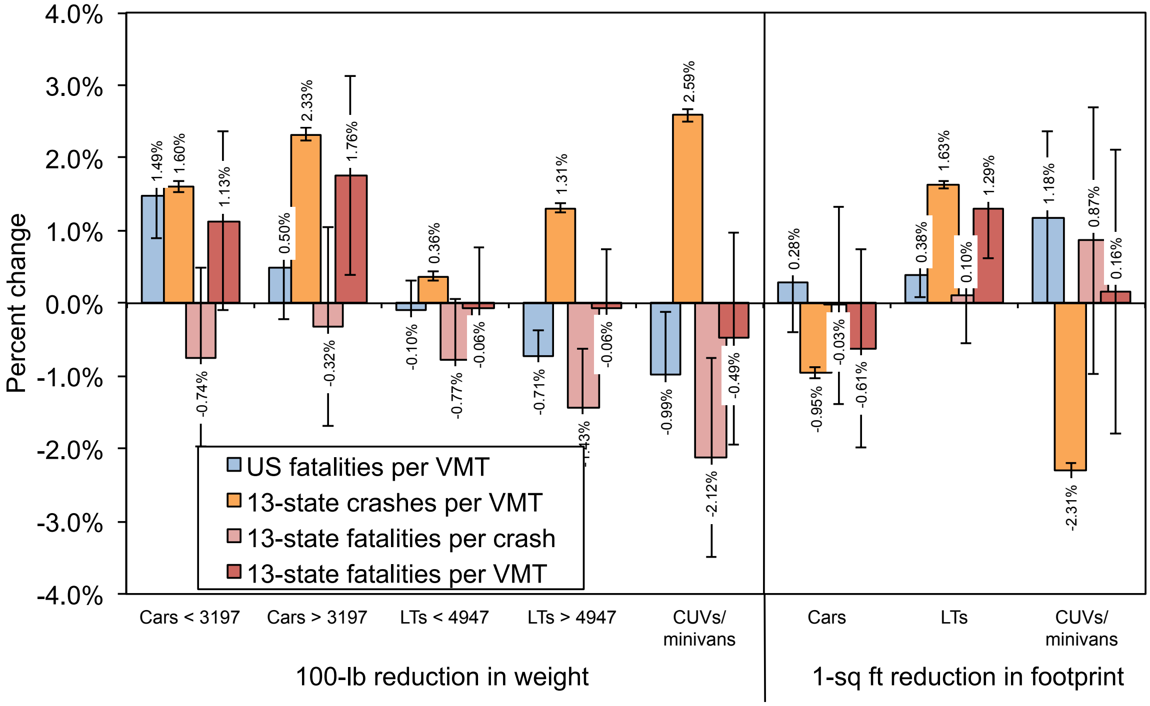
The estimated effects on casualty risk per VMT from the thirteen states (shown in green) are comparable to the estimated effects on U.S. fatality risk per VMT (shown in blue) only for lighter-than-average cars, and are consistently positive for all five types of vehicles.

The improved similarity in the U.S. and 13-state fatality risks expressed in terms of VMT exposure in Figure 2.6 (compared to the 13-state fatality risks per crash) suggests that the large differences between U.S. fatality risk per VMT and 13-state fatality risk per crash in Figure 2.5 are more the result of changing the measure of exposure from per VMT to per crash, and less because the relationships between mass and footprint reductions and risk in the thirteen states are different from those relationships in the entire U.S. (the second possible explanation for the differences in fatality risk per VMT vs. per crash, summarized above).

Figure 2.7 compares the estimated effect of mass and footprint reduction on the two components of risk, the number of crashes per VMT (crash frequency, the inverse of crash avoidance, shown in orange) and the fatality risk per crash (crashworthiness/compatibility, shown in light red), with the estimated effect on fatality risk per VMT (shown in dark red), from the 13-state crash data. The estimates in Figure 2.7 for crash frequency and crashworthiness/compatibility were obtained using the same regression models, with the dependent variable changed from fatalities per VMT to crashes per VMT (for crash frequency) or fatalities per crash (for crashworthiness/compatibility). For all five vehicle types, mass reduction is associated with an increase in crash frequency, but a decrease in fatality risk per crash; the effects from the two components roughly add together to result in the overall estimated effect on fatality risk per VMT. For example, the models estimate that a 100-lb mass reduction in heavier-than-average light trucks is associated with a 1.31% increase in crash frequency (column B), while lower mass is associated with a 1.43% decrease in the number of fatalities per crash (column C); the net effect is a 0.06% decrease in the risk of fatality per VMT (column D), which is roughly the sum of the crash frequency and crashworthiness/compatibility effects (1.31% - 1.43% = - 0.12%). For many of the other four types of vehicles, the relationship is different; for example, for example, mass reduction in lighter-than-average cars is associated with a 1.60% increase in crash frequency, but a 0.74% decrease in the number of fatalities per crash; however, the net result, an estimated 1.13% increase in the number of fatalities per VMT, is more than the sum of the two components (1.60% - 0.74% = 0.86%).[7] In its previous studies DRI solved the three equations, crashes per VMT, fatalities per crash, and fatalities per VMT, simultaneously, which forces the estimated effects on fatalities per VMT to equal the sum of the estimated effects on crashes per VMT and fatalities per crash.

[7] One possible reason the sum of the estimated effect of crash frequency and risk per crash does not equal the estimated effect of risk per VMT for each vehicle type is that each measure is weighted using a different distribution after full penetration of ESC into the on-road fleet; crash frequency is weighted by the estimated distribution of all crashes, fatality risk by the estimated distribution of fatalities, and casualty risk by the estimated distribution of casualties, after full penetration of ESC. However, using the same distributions to estimate the weighted effect for crash frequency, risk per crash, and risk per VMT does not consistently bring the three estimates closer to agreement (crash frequency + risk per crash = risk per VMT).

Figure 2.7. Estimated effect of mass or footprint reduction on crashes per VMT (vehicle crash frequency), fatalities per crash (vehicle crashworthiness/compatibility), and fatalities per VMT, by vehicle type



For cars and light trucks, mass reduction is associated with larger increases in crash frequency as the mass of the case vehicle increases; i.e., mass reduction in heavier-than-average cars and light trucks is associated with a larger increase in crash frequency than mass reduction in lighter-than-average cars and light trucks. For light trucks and CUVs/minivans, mass reduction is associated with progressively larger increases in crash frequency, which are offset by progressively larger decreases in fatality risk per crash, resulting in relatively small reductions in fatality risk per VMT.

Figure 2.7 indicates that a smaller footprint in light trucks is associated with a large increase in crash frequency and a small increase in fatality risk per crash, while smaller footprint in cars and CUVs/minivans is associated with decreases in crash frequency, essentially no change in fatality risk per crash for cars, and a relatively large increase in fatality risk per crash for CUVs/minivans. Figure 2.8 shows similar estimates for the two components of casualty risk per VMT; the estimates for crash frequency (orange columns) in Figure 2.8 are identical to those in Figure 2.7.

It is unclear why lower vehicle mass is associated with higher crash frequency, but lower risk per crash, for all five vehicle types in the regression models. It is possible that including variables that more accurately account for important differences among vehicles and driver behavior would reverse this relationship. We examine what effect adding a variable to account for driver behavior, a measure of household income, to the regression models has on the estimated relationship between increased crash frequency for lighter vehicles, in Section 4. On the other hand, it is also possible that over thirty years of improvements in vehicle design to achieve high crash test ratings have enabled manufacturers to design vehicles to mitigate some of the safety penalty of low mass vehicles.

Figure 2.8. Estimated effect of mass or footprint reduction on crashes per VMT (vehicle crash frequency), casualties per crash (vehicle crashworthiness/compatibility), and casualties per VMT, by vehicle type

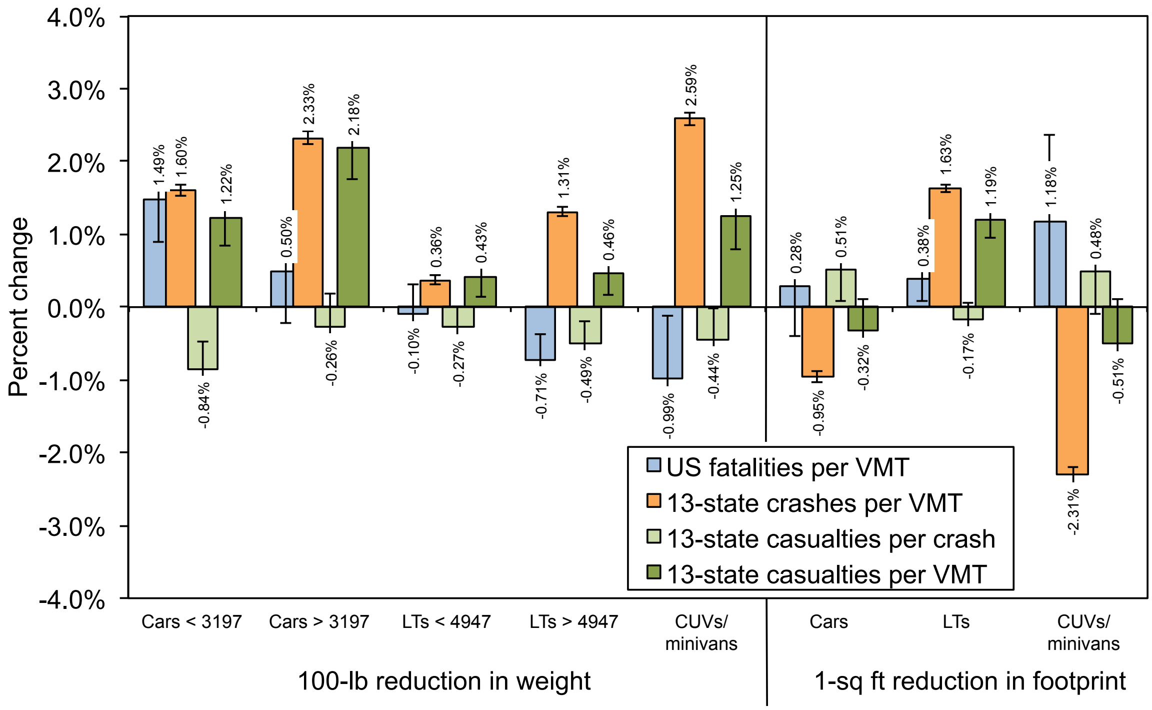


Table 2.3 compares the estimated effects of the NHTSA baseline regression model for fatalities per VMT with the results from the 13 states, from Figures 2.5 to 2.8. Table 2.4 compares the results for casualty risk from the 2012 and current analyses. For the most part, the results from the current analysis show the same general trends as the 2012 analysis: mass reduction is associated with statistically-significant increases in crash frequency, small decreases in casualties per crash, and on net statistically-significant increases in casualty risk per VMT, for all five types of vehicles.

Table 2.3. Estimated effect of mass or footprint reduction on two components of 13- state fatality and casualty risk per VMT: crash frequency (crashes per VMT) and crashworthiness/compatibility (risk per crash)

Variable	Case vehicle type	A. NHTSA U.S. fatalities per VMT	B. 13-state crashes per VMT	C. 13-state fatalities per crash	D. 13-state fatalities per VMT	E. 13-state crashes per VMT	F. 13-state casualties per crash	G. 13-state casualties per VMT
Mass reduction	Cars < 3197 lbs	1.49%	1.60%	-0.74%	1.13%	1.60%	-0.84%	1.22%
	Cars > 3197 lbs	0.50%	2.33%	-0.32%	1.76%	2.33%	-0.26%	2.18%
	LTs < 4947 lbs	-0.10%	0.36%	-0.77%	-0.06%	0.36%	-0.27%	0.43%
	LTs > 4947 lbs	-0.71%	1.31%	-1.43%	-0.06%	1.31%	-0.49%	0.46%
	CUV/ minivan	-0.99%	2.59%	-2.12%	-0.49%	2.59%	-0.44%	1.25%
Footprint reduction	Cars	0.28%	-0.95%	-0.03%	-0.61%	-0.95%	0.51%	-0.32%
	LTs	0.38%	1.63%	0.10%	1.29%	1.63%	-0.17%	1.19%
	CUV/ minivan	1.18%	-2.31%	0.87%	0.16%	-2.31%	0.48%	-0.51%

Based on NHTSA's estimation of uncertainty using a jack knife method, none of the estimates of mass reduction in Column A are statistically significant at the 95% confidence level.
Estimates that are statistically significant at the 95% level are shown in red.

Table 2.4. Comparison of 2012 and 2017 estimates of effect of mass or footprint reduction on 13-state crash frequency (crashes per VMT), crashworthiness/compatibility (risk per crash), and and casualty risk per VMT:

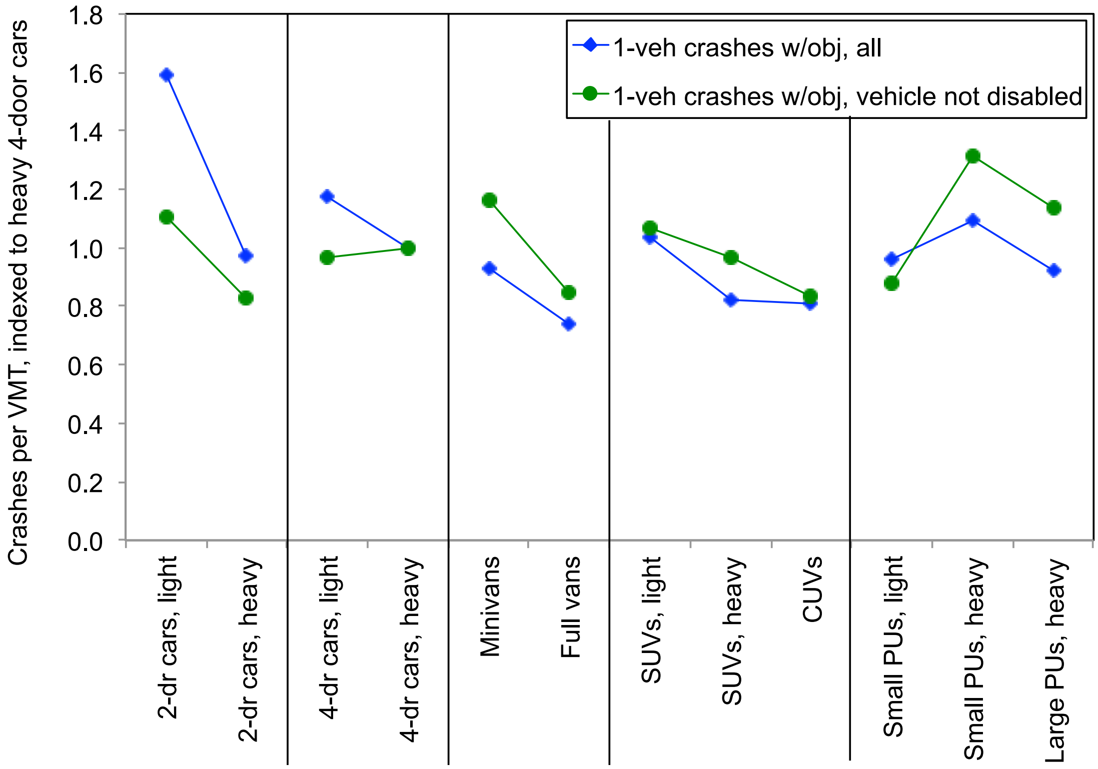
Variable	Case vehicle type	A. 2017 NHTSA U.S. fatalities per VMT	2012 analysis			2017 analysis		
			E. 13-state crashes per VMT	F. 13-state casualties per crash	G. 13-state casualties per VMT	E. 13-state crashes per VMT	F. 13-state casualties per crash	G. 13-state casualties per VMT
Mass reduction	Cars < median	1.49%	2.00%	0.09%	1.86%	1.60%	-0.84%	1.22%
	Cars > median	0.50%	1.50%	-0.77%	0.73%	2.33%	-0.26%	2.18%
	LTs < median	-0.10%	1.44%	-0.11%	1.55%	0.36%	-0.27%	0.43%
	LTs > median	-0.71%	0.94%	-0.62%	-0.04%	1.31%	-0.49%	0.46%
	CUV/ minivan	-0.99%	0.95%	-0.16%	0.10%	2.59%	-0.44%	1.25%
Footprint reduction	Cars	0.28%	0.64%	0.23%	1.54%	-0.95%	0.51%	-0.32%
	LTs	0.38%	1.04%	-0.25%	0.94%	1.63%	-0.17%	1.19%
	CUV/ minivan	1.18%	-0.55%	0.56%	1.54%	-2.31%	0.48%	-0.51%

Based on NHTSA's estimation of uncertainty using a jack knife method, none of the estimates of mass reduction in Column A are statistically significant at the 95% confidence level.
Estimates that are statistically significant at the 95% level are shown in red.

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

We suspect that one-vehicle, non-rollover, low-severity crashes by pickup trucks are under-reported in the state crash data. Two-vehicle crashes are more likely to be reported, because two parties are involved, while rollover and injury crashes are more likely to be reported because they tend to be more severe. If pickup truck owners were not reporting one-vehicle low-severity crashes, we would expect the crash rate per estimated VMT for pickup trucks in one-vehicle low-severity crashes to be lower relative to that of pickup trucks in all crashes. Figure 2.9 compares the crash frequency per VMT of all crashes and low-severity crashes, for one-vehicle, non-rollover crashes with a stationary object, from the updated 13-state database of police-reported crashes. "Low-severity" crashes are one-vehicle crashes in which the vehicle was not disabled or damaged enough to be towed from the crash scene. Crash rates for each type of crash are indexed to that for heavy four-door cars. For the most part the relative crash frequencies are quite similar for all crashes (in blue) and for non-injury crashes (in green), for all types of vehicles.

Figure 2.9. Frequency of one-vehicle crashes with an object per VMT, by crash severity and vehicle type



Two-door cars, lighter four-door cars, and possibly lighter small pickups, have a lower crash frequency for low-severity crashes (in green) than for all crashes (in blue), suggesting that there may be a reporting bias for low-severity crashes involving these types of vehicles. On the other hand, heavier small pickups and large pickups have higher crash frequency for low-severity crashes than for all crashes. This suggests that pickup truck owners are not under-reporting the type of crash least likely to be reported, one-vehicle, low-severity crashes, in the state crash databases.

Another type of bias in the state crash data is inaccurate reporting of injury outcomes by police officers at the scene of a crash. Using detailed NASS CDS records, in which a crash investigator tracks hospital records of victims in a small sample of police-reported crashes, Farmer (2003) found that 41% of injuries that police responders coded as “serious” or “incapacitating” received Modified Abbreviated Injury Scale (MAIS) ratings of “minor injury” by health care professionals. An updated analysis using NASS CDS from 2000 to 2008 found that 59% of injuries police reported as “incapacitating” received eventual MAIS ratings of “minor” or “no injury”; 39% of injuries eventually receiving MAIS “serious” rating, and 27% that received a MAIS “severe” or “critical” rating, were initially coded as non-incapacitating injuries by the initial police responder.[8] The possibility that these injury reporting errors are not consistent across states is another reason to include a control variable for the state in which the crash occurred.

Recall that the risks and crashes per VMT in Figures 2.6 through 2.8 and Table 2.3 use the VMT weights developed by NHTSA using national registration data and induced exposure crashes in the thirteen states. To more accurately calculate fatality risk per VMT for the thirteen states, we need to obtain vehicle registration data, by calendar year, and vehicle model year and model, for the thirteen states, and develop new VMT weights to represent total VMT in the thirteen states, as opposed to the national VMT weights NHTSA used in their analysis and here.

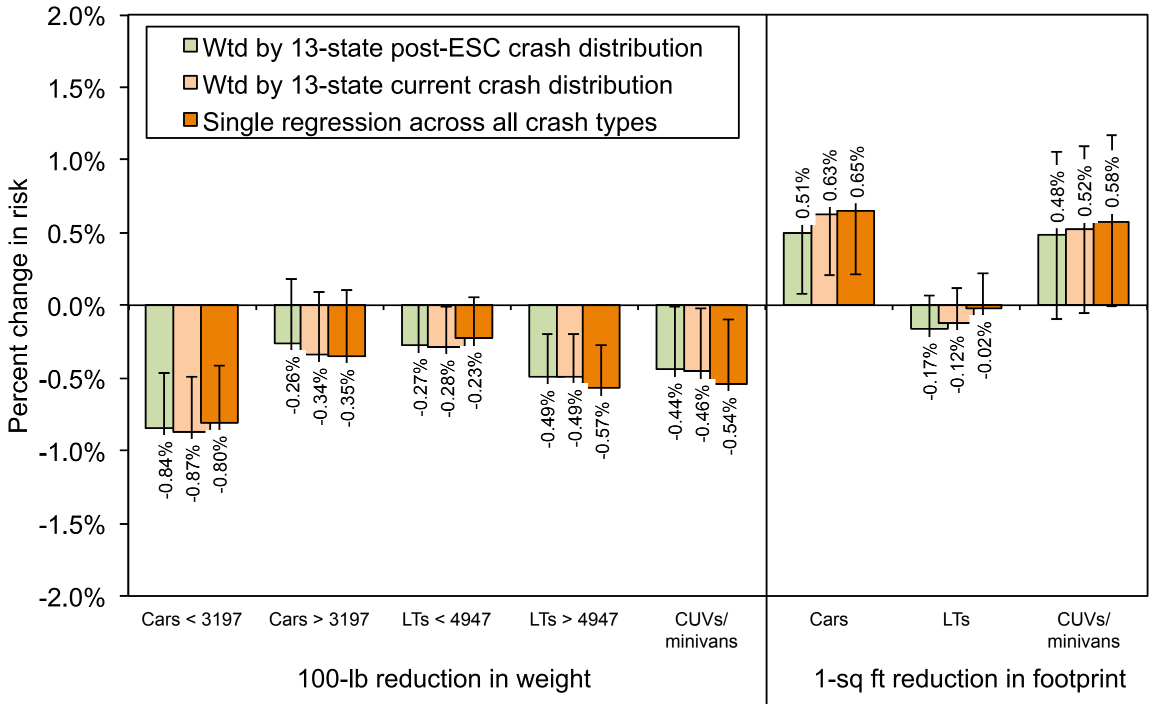
Figure 2.10 compares the estimated effect of mass or footprint reduction on 13-state casualty risk per crash, after accounting for full adoption of ESC by 2017 (in green, from Figure 2.5) with the results from the nine regression models by crash type weighted by the current distribution of crashes casualties (light orange). Assuming full penetration of ESC in the on-road fleet (going from the light orange to green columns in the figure) slightly reduces the estimated decrease in casualty risk per crash from mass reduction in cars, particularly in heavier-than-average cars (from a 0.34% decrease to a 0.26% decrease). Accounting for the change in the distribution of crashes after full ESC penetration slightly reduces the estimated detrimental effect of footprint reduction in cars and light trucks, particularly in cars (from an estimated 0.63% increase to an estimated 0.51% increase in risk).

Estimates from a single regression model across all nine crash types are also shown in Figure 2.10 (in dark orange). The estimated effects of mass reduction on casualty risk per crash using a

[8] The percentages are calculated using the national weights assigned to each crash in the NASS CDS sample. Using unweighted data, 41% of injuries reported as “incapacitating” by initial police responders received an eventual MAIS rating of “minor” or “no injury”, and 16% of injuries eventually receiving MAIS “serious” rating, and 10% receiving a MAIS “severe” or “critical” rating, were initially coded as non-incapacitating by the initial police responder.

single regression model are less beneficial than when the estimated effects by crash type are weighted by the current distribution of crashes (in light orange) for lighter-than-average cars and light trucks, and are more beneficial for heavier-than-average cars and light trucks and CUVs/minivans. The estimated effect of footprint reduction using a single regression model rather than weighted by the current distribution of crashes is less beneficial/more detrimental for all three types of vehicles.

Figure 2.10. Estimated effect of mass or footprint reduction on 13-state casualty risk per crash by vehicle type, across all crash types and weighted average effect in each type of crash



Figures 2.11 through 2.13 and Table 2.5 show the estimated effect of changes in mass or footprint on casualty risk per crash, by type of crash. Figure 2.11 indicates that the largest estimated effects from mass reduction in cars are in rollovers (estimated 2.1% decrease in risk for lighter cars, estimated 6.7% decrease in risk for heavier cars). Smaller footprint in cars is associated with a large increase in casualty risk in rollovers (7.1%), and in crashes with objects and with a lighter light truck (estimated 2.1% increase in risk for each). Because full ESC adoption is expected to substantially reduce the number of rollovers and crashes with objects, and footprint reduction is estimated to substantially increase casualty risk in these types of crashes, removing many of these types of crashes by 2017 will reduce the estimated overall detrimental effect of footprint reduction in cars on casualty risk per crash (from a 0.63% increase to a 0.51% increase as shown in Figure 2.10).

Figure 2.11. Estimated effect of mass or footprint reduction on 13-state casualty risk per crash in cars, by type of crash

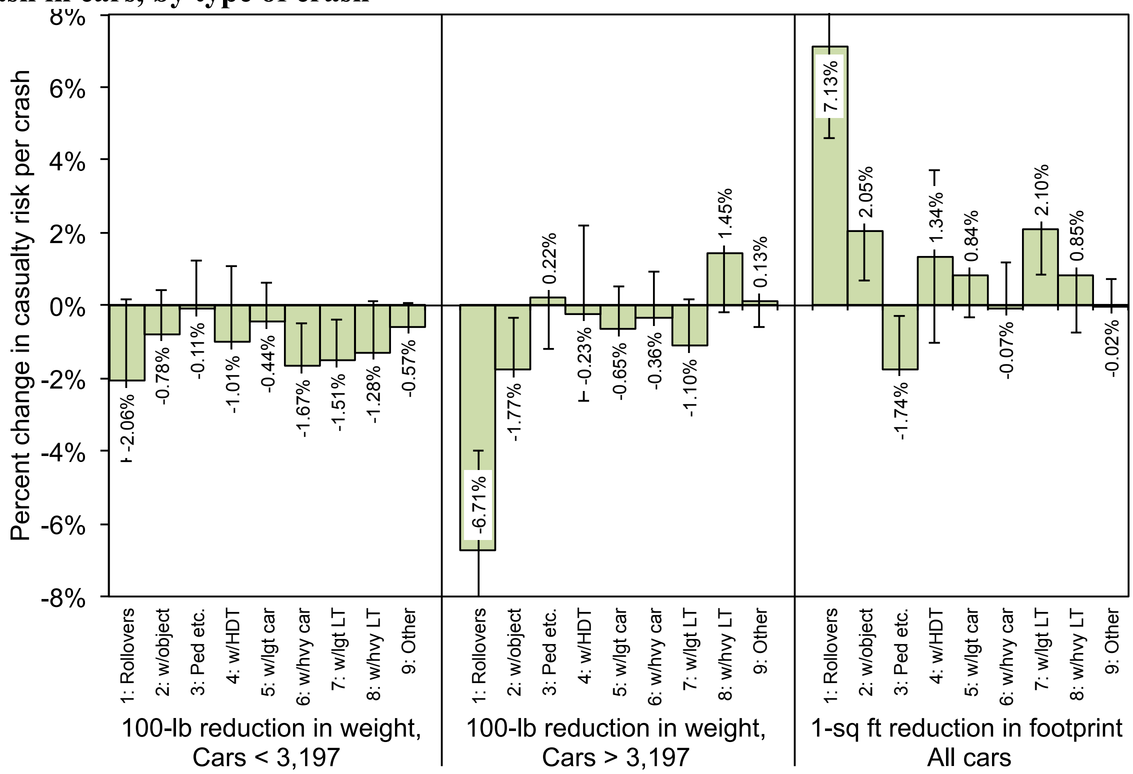


Figure 2.12 shows the estimated effect of mass and footprint reductions on risk in light trucks, by type of crash. In general, although relatively small, more of the estimated effects of mass or footprint reduction on risk tend to be statistically significant for light trucks than for cars. Mass reduction in lighter-than-average light trucks is associated with relatively large increases in casualty risk per crash in rollovers (1.4%) and crashes with heavy trucks (2.0%), heavier cars (0.9%) and heavier light trucks (1.2%), while mass reduction is associated with a large (1.7%) decrease in casualty risk per crash in crashes with a stationary object. While mass reduction in lighter light trucks is associated with an increase in casualty risk per crash, mass reduction in heavier light trucks is associated with a relatively large (1.6%) decrease in risk in rollovers. As discussed in Section 1.1, once it has rolled over, a lighter vehicle applies less force on its roof than a heavier vehicle. We see the same estimated beneficial effect of mass reduction in casualty rollover risk in CUVs/minivans, in (2.9% decrease, Figure 2.13). As with cars, footprint reduction is associated with increases in risk in rollovers and crashes with objects (by 0.4% and 1.9%, respectively) in light-duty trucks, and to an even greater extent (by 5.5% and 3.7%, respectively) in CUVs/minivans. The large estimated detrimental effects of reducing CUV/minivan footprint on casualty risk in rollovers and crashes with objects account for the decrease in the effect of footprint reduction on risk after removing many of these types of crashes in Figure 2.10 (from a 0.52% increase in risk per crash to a 0.48% increase after accounting for full ESC penetration). Mass reduction in lighter-than-average light trucks and CUVs/minivans is associated with statistically significant increases in casualty risk in crashes with heavy-duty trucks (2.0% and 4.2% increases, respectively).

Figure 2.12. Estimated effect of mass or footprint reduction on 13-state casualty risk per crash in light trucks, by type of crash

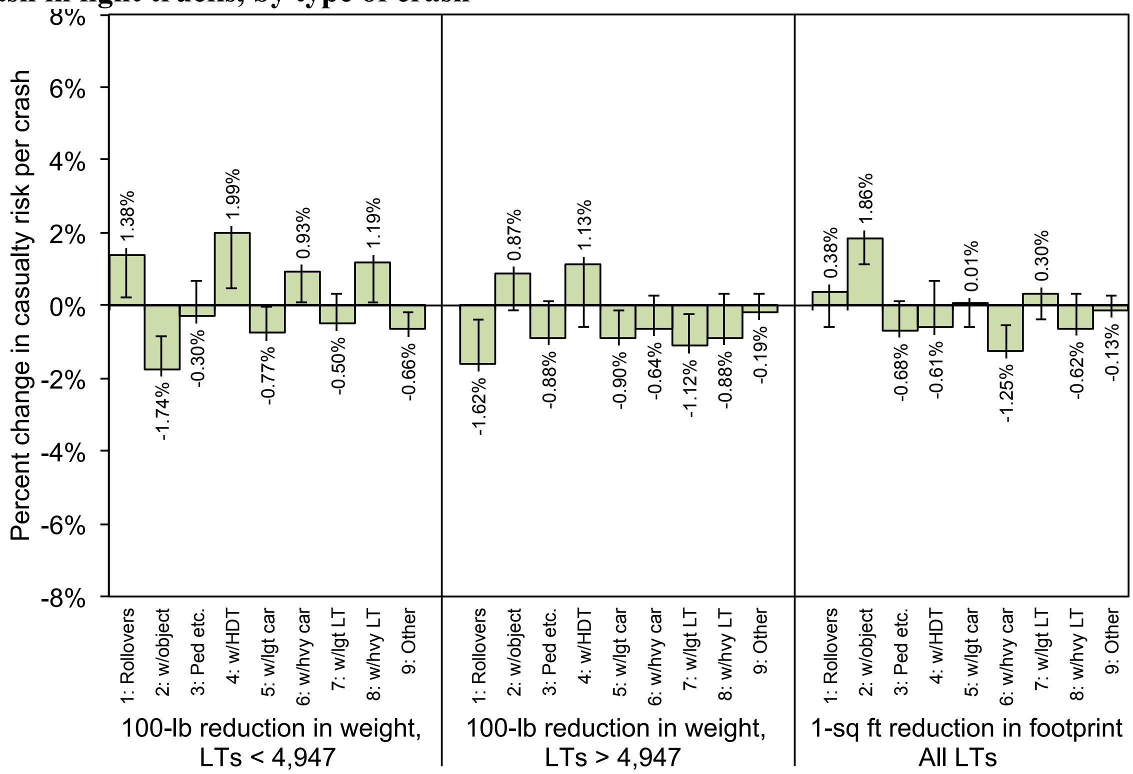


Figure 2.13. Estimated effect of mass or footprint reduction on 13-state casualty risk per crash in CUVs/minivans, by type of crash

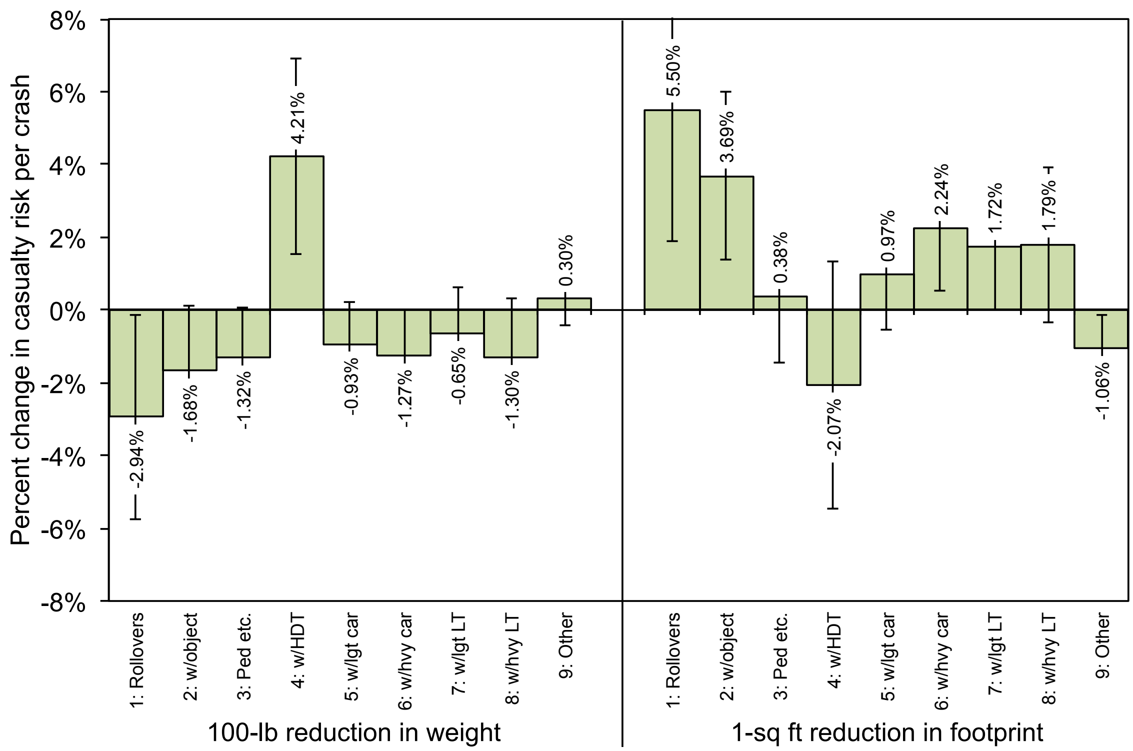


Table 2.5. Estimated effect of mass or footprint reduction on 13-state casualty risk per crash, by type of crash

Type of crash	Mass reduction Cars < 3197 lbs	Cars > 3197 lbs	LTs < 4947 lbs	LTs > 4947 lbs	CUVs/ minivans	Footprint reduction Cars	LTs	CUVs/ minivans
1: Rollovers	-2.06%	-6.71%	1.38%	-1.62%	-2.94%	7.13%	0.38%	5.50%
2: w/object	-0.78%	-1.77%	-1.74%	0.87%	-1.68%	2.05%	1.86%	3.69%
3: Ped etc.	-0.11%	0.22%	-0.30%	-0.88%	-1.32%	-1.74%	-0.68%	0.38%
4: w/HDT	-1.01%	-0.23%	1.99%	1.13%	4.21%	1.34%	-0.61%	-2.07%
5: w/lgt car	-0.44%	-0.65%	-0.77%	-0.90%	-0.93%	0.84%	0.01%	0.97%
6: w/hvy car	-1.67%	-0.36%	0.93%	-0.64%	-1.27%	-0.07%	-1.25%	2.24%
7: w/lgt LT	-1.51%	-1.10%	-0.50%	-1.12%	-0.65%	2.10%	0.30%	1.72%
8: w/hvy LT	-1.28%	1.45%	1.19%	-0.88%	-1.30%	0.85%	-0.62%	1.79%
9: Other	-0.57%	0.13%	-0.66%	-0.19%	0.30%	-0.02%	-0.13%	-1.06%
All	-0.84%	-0.26%	-0.27%	-0.49%	-0.44%	0.51%	-0.17%	0.48%

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

Table 2.6 compares the estimated effect of changes in the other vehicle, driver, and crash control variables on U.S. fatality risk with 13-state fatality and casualty risk per VMT, by vehicle type. In general, the estimates for the control variables on the three types of risk per VMT are similar. Two-door cars are associated with higher risk than four-door sedans, and SUVs with higher risk than pickups, for each type of risk; however, while minivans are associated with (13%) lower U.S. fatality risk per VMT than CUVs, they are associated with (5%) higher 13-state casualty risk per VMT than CUVs. The side airbag variables do not show a consistent relationship across the three types of risk, with the exception of torso side airbags which are consistently associated with a decrease in risk for cars and CUVs/minivans. ABS in cars and CUVs/minivans, and ESC in all three vehicle types, are also consistently associated with a decrease in both types of risk per VMT. AWD in light trucks and CUVs/minivans is associated with a 21% decrease in U.S. fatality risk per VMT, but is associated with increases in 13-state fatality risk, and to a lesser extent casualty risk, per VMT. Each additional year of vehicle age is consistently estimated to increase risk by about 3% to 7%, while a brand new vehicle is estimated to increase risk by up to 14%, presumably because the driver is unfamiliar with its controls, handling, and/or braking capabilities. The estimated effect of a male driver on risk generally is highest for U.S. fatality risk, followed by 13-state fatality risk and 13-state casualty risk, and generally is higher in cars and CUVs/minivans than in light trucks. For each type of risk, the youngest and oldest drivers have higher risk than other drivers, for all three vehicle types. The estimated effects of driving at night, on high-speed or rural roads are consistently high for all three types of risk, but tend to be lowest for 13-state casualty risk per VMT. In general the calendar year variables are estimated to have a decreasing effect on all three types of risk over time.

Note that the four vehicle variables of interest, UNDRWT, OVERWT, LBS100 and FOOTPRINT, all have a much lower effect on risk than almost all of the control variables in Table 2.6. The estimated effects of vehicle type, other vehicle attributes (such as side airbags, ABS, ESC, or AWD), or male drivers on risk per VMT are nearly an order of magnitude larger than those estimated for lower mass or footprint, while driving at night, on rural or high-speed roads, are estimated to have an effect several hundred times that of vehicle mass or footprint reduction. For example, a 100-lb reduction in the mass of a lighter-than-average car is associated with an increase in casualty risk per crash of only 1.2%, while installing ABS would reduce risk by 20%. Therefore, the regression estimates suggest that, in theory, the mass of a lighter car could be reduced by as much as 1,600 pounds while adding ABS, without increasing casualty risk per crash.

Table 2.7 compares the estimated effect of changes in the other vehicle, driver, and crash control variables on 13-state fatality or casualty risk per crash. While 2-door cars are associated with increased fatality risk per VMT (16%) or per crash (15%), this effect disappears in terms of casualty risk per crash. SUVs are associated with an increase in U.S. fatality risk per VMT (11%), but have little effect on fatality or casualty risk per crash; conversely, heavy-duty pickups have little effect on U.S. fatality risk per VMT, but are associated with increased fatality or casualty risk per crash (20% and 4% increases, respectively), while minivans are associated with a 13% decrease in U.S. fatality risk per VMT, but a 9% increase in casualty risk per crash. The ROLLCURT, CURTAIN, and COMBO side airbag variables do not show a consistent relationship across the three types of risk; however, the estimated beneficial effects of torso side airbags, ABS, and ESC are similar among the three types of risk, with the exception of torso side airbags in fatality risk per crash in CUVs/minivans. While AWD in light trucks and CUVs/minivans is associated with a 21% reduction in U.S. fatality risk per VMT, it has little effect in terms of fatality or casualty risk per crash, and even increases fatality risk per crash 7% in light trucks. Vehicle age and brand new vehicles are associated mostly with increased risk under the three measures of risk. The driver age and gender variables have a smaller estimated effect on fatality risk per crash, and a much smaller estimated effect on casualty risk per crash, than on U.S. fatality risk per VMT; this suggest that much of the driver effect on risk contributes to the occurrence of a serious crash, and not the crashworthiness/compatibility of the vehicle once a crash has occurred. Nevertheless, risk is estimated to be higher for the oldest drivers, even in terms of casualty risk per crash. Likewise, driving at night, on rural or high-speed roads, has a bigger effect on U.S. fatality risk per VMT than on 13-state fatality or casualty risk per crash. Even so, these three variables are estimated to substantially increase the likelihood of fatality or casualty once a crash occurs. As in Table 2.6, the calendar year variables are estimated to have a decreasing effect on all three types of risk over time.

As in Table 2.6, the four vehicle variables of interest, UNDRWT, OVERWT, LBS100, and FOOTPRINT, all have a much lower estimated effect on risk than almost all of the control variables. For instance, a one square foot reduction in footprint for an underweight car is expected to increase casualty risk per crash by only 0.5%, while installing ABS would reduce risk by 5.5%. Therefore, the regression estimates suggest that, in theory, the footprint of a lighter car could be reduced by as much as 10 square feet while adding ABS, without increasing casualty risk per crash.

As discussed above, the NHTSA regression of U.S. fatality risk per VMT included a variable for high-fatality states; our regression models for fatality and casualty risk per crash include twelve variables for each state in the database. The bottom of Tables 2.6 and 2.7 show the estimated effect of each of the state control variables on fatality or casualty risk per VMT or per crash,

Table 2.6. Estimated effect of variables on U.S. fatality risk, 13-state fatality risk, and 13-state casualty risk per VMT

	U.S. fatality risk per VMT			13-state fatality risk per VMT			13-state casualty risk per VMT		
Variable	Cars	LTs	CUVs	Cars	LTs	CUVs	Cars	LTs	CUVs
UNDERWT	1.49%	-0.10%	—	1.13%	-0.06%	—	1.22%	0.43%	—
OVERWT	0.50%	-0.71%	—	1.76%	-0.06%	—	2.18%	0.46%	—
LBS100	—	—	-0.99%	—	—	-0.49%	—	—	1.25%
FOOTPRINT	0.28%	0.38%	1.18%	-0.61%	1.29%	0.16%	-0.32%	1.19%	-0.51%
TWODOOR	16.2%		—	25.8%	—	—	9.7%	—	—
SUV	—	10.7%	—	—	6.50%	—	—	8.65%	—
HD_PKP	—	1.5%	—	—	9.90%	—	—	-5.47%	—
BLOCKER1	—	-3.28%	—	—	0.32%	—	—	2.78%	—
BLOCKER2	—	0.34%	—	—	-5.25%	—	—	-2.09%	—
MINIVAN	—	—	-12.6%	—	—	-2.39%	—	—	4.81%
ROLLCURT	-2.31%	—	-1.17%	0.32%	—	-0.41%	0.51%	—	-0.45%
CURTAIN	-1.78%	—	2.81%	5.29%	—	-4.73%	0.35%	—	1.21%
COMBO	1.13%	—	-4.85%	4.67%	—	-3.28%	8.63%	—	2.22%
TORSO	-7.08%	—	-5.47%	-17.6%	—	-3.63%	-13.5%	—	-12.9%
ABS	-15.2%	—	-16.2%	-16.4%	—	-33.1%	-19.9%	—	-25.3%
ESC	-8.50%	-22.8%	-17.6%	-9.81%	-28.5%	-27.7%	-11.6%	-24.5%	-10.7%
AWD	—	-20.8%	-20.6%	—	25.5%	3.26%	—	17.2%	0.79%
VEHAGE	2.98%	4.89%	7.31%	3.85%	6.42%	4.45%	2.68%	5.46%	5.03%
BRANDNEW	9.58%	1.37%	13.9%	9.14%	11.4%	3.22%	7.86%	2.41%	-3.58%
DRVMALE	40.1%	24.8%	28.1%	28.9%	18.5%	26.8%	6.17%	-2.46%	8.32%
M14_30	4.65%	3.52%	2.99%	5.78%	4.61%	4.35%	4.30%	3.89%	4.55%
M30_50	1.15%	1.58%	1.50%	0.90%	0.64%	0.69%	0.45%	0.44%	-0.04%
M50_70	1.97%	1.87%	2.02%	3.13%	2.30%	2.70%	1.03%	1.36%	1.24%
M70_96	7.01%	6.80%	6.53%	7.84%	7.61%	7.51%	5.74%	5.36%	5.02%
F14_30	2.61%	3.28%	3.08%	4.05%	1.62%	3.28%	3.45%	3.11%	3.84%
F30_50	0.27%	0.74%	-0.25%	-0.85%	0.29%	-0.32%	-0.36%	-0.04%	-0.29%
F50_70	2.98%	3.85%	2.89%	3.12%	3.54%	3.44%	1.39%	1.75%	1.84%
F70_96	7.92%	3.75%	7.48%	9.29%	-0.64%	7.96%	5.83%	4.40%	5.07%
NITE	117%	109%	104%	111%	111%	102%	42.9%	52.8%	41.0%
RURAL	122%	116%	122%	77.1%	69.3%	73.6%	41.7%	41.2%	37.3%
SPDLIM55	127%	127%	125%	142%	140%	143%	88.3%	89.9%	87.9%
CY2005	22.5%	30.8%	30.9%	24.5%	34.0%	26.2%	21.7%	32.1%	19.2%
CY2006	22.5%	23.6%	23.5%	24.1%	25.1%	13.3%	14.9%	24.4%	15.3%
CY2007	20.9%	25.0%	20.7%	21.1%	18.8%	8.44%	10.9%	17.3%	13.1%
CY2008	7.50%	11.8%	6.66%	9.72%	14.9%	3.89%	3.75%	9.10%	4.78%
CY2010	-2.45%	-2.69%	-3.43%	-2.92%	-8.96%	-5.46%	-10.0%	-10.5%	-2.00%
CY2011	-3.99%	-9.44%	-13.4%	-4.84%	-6.70%	-6.01%	-12.5%	-23.3%	-13.9%
HIFAT_ST	25.1%	23.6%	25.5%	—	—	—	—	—	—
AL	—	—	—	-8.28%	-34.9%	-10.4%	71.5%	42.5%	61.5%
KS	—	—	—	-29.0%	-18.8%	-4.91%	-80.6%	-63.9%	-37.5%
KY	—	—	—	-10.4%	-15.4%	-8.27%	-34.0%	-41.8%	-25.0%
MD	—	—	—	-34.9%	-69.6%	-59.2%	-40.1%	-51.4%	-47.5%
MI	—	—	—	-70.8%	-85.9%	-50.7%	-89.3%	-85.8%	-85.6%
MO	—	—	—	-17.6%	-40.6%	-20.9%	-36.0%	-49.0%	-41.0%
NE	—	—	—	-53.1%	-50.4%	-88.0%	-41.5%	-38.4%	-44.2%
NJ	—	—	—	-42.5%	-60.3%	-57.7%	-177%	-169%	-192%
PA	—	—	—	-41.2%	-35.5%	-23.1%	-168%	-135%	-153%
WA	—	—	—	-76.4%	-50.5%	-44.1%	-143%	-114%	-114%
WI	—	—	—	-53.7%	-64.6%	-48.0%	-80.8%	-76.7%	-78.9%
WY	—	—	—	-32.2%	-63.9%	-26.3%	-68.9%	-83.5%	-50.9%

* Values in red are statistically significant at the 95% level.

Table 2.7. Estimated effect of variables on U.S. fatality risk per VMT, and 13-state fatality risk and 13-state casualty risk per crash

	U.S. fatality risk per VMT			13-state fatality risk per crash			13-state casualty risk per crash		
Variable	Cars	LTs	CUVs	Cars	LTs	CUVs	Cars	LTs	CUVs
UNDERWT	1.49%	-0.10%	—	-0.74%	-0.77%	—	-0.84%	-0.27%	—
OVERWT	0.50%	-0.71%	—	-0.32%	-1.43%	—	-0.26%	-0.49%	—
LBS100	—	—	-0.99%	—	—	-2.12%	—	—	-0.44%
FOOTPRINT	0.28%	0.38%	1.18%	-0.03%	0.10%	0.87%	0.51%	-0.17%	0.48%
TWODOOR	16.2%		—	14.7%	—	—	-1.26%	—	—
SUV	—	10.7%	—	—	-1.34%	—	—	1.49%	—
HD	—	1.5%	—	—	20.4%	—	—	4.24%	—
BLOCKER1	—	-3.28%	—	—	-0.89%	—	—	0.29%	—
BLOCKER2	—	0.34%	—	—	-5.41%	—	—	-2.62%	—
MINIVAN	—	—	-12.6%	—	—	-0.58%	—	—	8.51%
ROLLCURT	-2.31%	—	-1.17%	0.20%	—	-0.43%	0.34%	—	-0.45%
CURTAIN	-1.78%	—	2.81%	2.17%	—	-10.06%	-3.06%	—	-2.38%
COMBO	1.13%	—	-4.85%	-0.91%	—	1.51%	2.34%	—	8.33%
TORSO	-7.08%	—	-5.47%	-11.2%	—	3.57%	-6.69%	—	-5.66%
ABS	-15.2%	—	-16.2%	-1.57%	—	-11.8%	-5.54%	—	-4.75%
ESC	-8.50%	-22.8%	-17.6%	-1.40%	-10.3%	-18.6%	-7.09%	-9.59%	-6.56%
AWD	—	-20.8%	-20.6%	—	7.29%	-0.50%	—	0.51%	-0.43%
VEHAGE	2.98%	4.89%	7.31%	2.35%	2.58%	1.02%	0.79%	1.53%	1.10%
BRANDNEW	9.58%	1.37%	13.9%	3.08%	11.9%	5.12%	2.70%	3.56%	-2.60%
DRVMALE	40.1%	24.8%	28.1%	21.8%	22.3%	22.8%	-0.79%	-0.07%	4.54%
M14_30	4.65%	3.52%	2.99%	1.84%	1.25%	-0.04%	0.43%	0.47%	0.28%
M30_50	1.15%	1.58%	1.50%	0.18%	-0.20%	0.22%	-0.15%	-0.24%	-0.39%
M50_70	1.97%	1.87%	2.02%	3.45%	2.20%	2.54%	1.26%	1.22%	1.15%
M70_96	7.01%	6.80%	6.53%	4.28%	4.09%	4.53%	2.17%	1.89%	1.93%
F14_30	2.61%	3.28%	3.08%	0.97%	-1.49%	0.12%	0.38%	-0.16%	0.56%
F30_50	0.27%	0.74%	-0.25%	-1.22%	0.06%	-0.57%	-0.68%	-0.22%	-0.44%
F50_70	2.98%	3.85%	2.89%	2.71%	2.95%	2.73%	0.89%	1.14%	1.19%
F70_96	7.92%	3.75%	7.48%	5.36%	-4.16%	4.11%	1.90%	0.83%	1.33%
NITE	117%	109%	104%	81.9%	68.4%	68.3%	23.5%	20.8%	17.4%
RURAL	122%	116%	122%	53.7%	43.8%	49.2%	30.1%	26.7%	23.2%
SPDLIM55	127%	127%	125%	104%	107%	113%	55.5%	63.9%	63.4%
CY2005	22.5%	30.8%	30.9%	25.9%	27.4%	29.2%	19.1%	24.1%	17.2%
CY2006	22.5%	23.6%	23.5%	24.9%	20.2%	16.7%	14.3%	19.0%	17.3%
CY2007	20.9%	25.0%	20.7%	18.8%	12.0%	8.80%	7.82%	11.3%	11.5%
CY2008	7.50%	11.8%	6.66%	10.1%	10.8%	5.83%	4.47%	7.90%	6.20%
CY2010	-2.45%	-2.69%	-3.43%	-4.88%	-7.40%	-4.69%	-11.3%	-9.75%	-1.88%
CY2011	-3.99%	-9.44%	-13.4%	-16.0%	-6.63%	-11.1%	-20.8%	-23.0%	-17.3%
HIFAT_ST	25.1%	23.6%	25.5%	—	—	—	—	—	—
AL	—	—	—	-103%	-111%	-112%	-24.2%	-36.2%	-40.6%
KS	—	—	—	-124%	-133%	-131%	-161%	-167%	-146%
KY	—	—	—	-129%	-133%	-153%	-156%	-169%	-173%
MD	—	—	—	-55.0%	-80.6%	-73.8%	-58.2%	-61.3%	-58.2%
MI	—	—	—	-199%	-224%	-187%	-203%	-211%	-206%
MO	—	—	—	-109%	-119%	-116%	-127%	-131%	-136%
NE	—	—	—	-155%	-156%	-201%	-134%	-140%	-145%
NJ	—	—	—	-146%	-172%	-168%	-281%	-283%	-304%
PA	—	—	—	-27.5%	-40.2%	-22.5%	-154%	-143%	-154%
WA	—	—	—	-125%	-127%	-129%	-194%	-190%	-201%
WI	—	—	—	-124%	-148%	-125%	-144%	-155%	-149%
WY	—	—	—	-164%	-169%	-172%	-188%	-182%	-176%

* Values in red are statistically significant at the 95% level.

relative to the risks in Florida, by vehicle type. Note that the model predicts a 24% to 41% lower casualty risk per crash in Alabama than in Florida (in Table 2.7), while Figure 2.3 above indicates that Alabama has a roughly 25% higher actual casualty risk per crash than Florida (at least through 2009). This discrepancy may be explained by the regression model also accounting for where crashes occurred in each state: over half of all police-reported crashes in Alabama occurred on roads in rural areas, which tend to have higher risks than crashes in urban areas, whereas only 15% of all crashes in Florida were in rural areas. After accounting for the greater amount of driving in dangerous rural areas in Alabama, the regression model indicates that driving in Alabama is actually 24% to 41% safer in terms of casualties per crash, depending on the type of vehicle, than driving in Florida. Similarly, the regression model predicts that a vehicle has a roughly 180% lower casualty risk per crash in Wyoming than in Florida, while Figure 2.3 above indicates that the actual casualty risk per crash in Wyoming is only about 40% lower than that in Florida. All driving in Wyoming is in rural areas.

Certain vehicle technologies, such as ABS and ESC, should reduce crash frequency, while others, such as side airbags in cars and CUVs/minivans, and supplementary frontal bumpers (BLOCKER1) or greater bumper overlap (BLOCKER2) on light trucks, should reduce fatality or casualty risk once a crash has occurred. And one might expect that, all else held equal, mass reduction would reduce braking distance, and footprint (or more specifically wheelbase) reduction would improve maneuverability, both of which would result in reduced crash frequency. On the other hand, one might expect that the added mass of AWD might increase braking distance, and thus increase crash frequency, while perhaps decreasing risk per crash in the subject vehicle but perhaps increasing societal risk per crash. One might expect that male, and young, drivers might be associated with higher crash frequency because they are more likely to be risky drivers, and that female, and elderly, drivers might be associated with higher risk per crash because they are, on average, less robust than male or young drivers. Finally, it is expected that the variables for crash circumstances, driving at night, in a rural county, or on a high-speed road, are all associated with increases in crash frequency, but not necessarily fatality or casualty risk once a crash has occurred.

Table 2.8 shows the estimated effect of the vehicle, driver, and calendar year control variables on the two components of fatality risk per VMT: crashes per VMT (or crash frequency) and fatality and casualty risk per crash. Variables with estimates in the expected direction are highlighted in green, whereas estimates in the unexpected direction are highlighted in yellow; only estimates that are statistically significant, which are shown in red font, are highlighted.

Two-door cars are associated with an increase in both crash frequency and fatality (but not casualty) risk per crash. One might expect that two-door cars, that are smaller and lighter than four-door cars, would be associated with lower crash frequency because of their maneuverability and shorter braking distances; however, these vehicles may not have the crash avoidance technologies included in four-door cars. It is not clear why two-door cars have higher fatality risk per crash independent of their mass and footprint. SUVs are associated with higher crash frequency, but little difference in terms of risk per crash, relative to pickups. On the other hand, heavy-duty pickups are associated with decreased crash frequency, but increased societal fatality and casualty risk per crash independent of their mass and footprint, which is expected given their stiff frontal structures and relatively high bumpers. Greater bumper overlap (BLOCKER2) in light trucks is associated with large decreases in casualty risks per crash, as expected, but supplemental front bumpers (BLOCKER1) are not; however both bumper overlap compliance measures also are associated with large decreases in crash frequency, which are unexpected. Minivans are associated with a lower crash frequency than CUVs, which may be due to more careful drivers, but a higher casualty risk per crash than CUVs, which is unexpected.

Three of the four side airbag variables in both cars and CUVs/minivans are associated with significant changes in crash frequency, which is unexpected. Torso side airbags are associated with decreases in fatality and casualty risk per crash in cars, and casualty risk per crash in CUVs/minivans, and curtain side airbags with decreased casualty risk per crash in cars, as expected. However, rollover curtain side airbags in cars, and combination side airbags in cars and CUVs/minivans, are associated with significant increases in casualty risk per crash, which is unexpected. ABS and ESC in all three vehicle types is associated with a decrease in crash frequency, as expected, but also decreases in casualty risk per crash, which is unexpected. AWD in light trucks and CUVs is associated with increased crash frequency, perhaps because drivers of AWD vehicles tend to be more risky than those of two-wheel drive light trucks and CUVs; however, AWD in light trucks is associated with an increase in fatality risk per crash, which is unexpected.

As expected, male drivers are associated with an increase in crash frequency in cars and CUVs/minivans, but an unexpected decrease in crash frequency in light trucks; male drivers are associated with large increases in fatality risk per crash in all three types of vehicles, and casualty risks per crash in CUVs/minivans, all of which are unexpected. A possible explanation is that male drivers are not involved in more crashes than female drivers, but that the crashes they are involved in are more severe. As expected, the driver age variables estimate that crash frequency is highest for the youngest and oldest drivers across all three types of vehicles, and that risk per crash is highest for the two oldest groups of drivers (over 50 years old), with the exception of female drivers over 70 years old in light trucks. However, the youngest drivers in cars, young males in light trucks, and young females in CUVs/minivans, are all associated with increased fatality and casualty risk per crash, which is unexpected given their ability to better withstand crash forces relative to older drivers. As expected the crash circumstance variables are all associated with large increases in crash frequency for each type of vehicle; however, they also are all associated with unexpected large increases in risk per crash, especially fatality risk per crash. Again, the crashes that occur under these conditions may be more severe than other crashes, and thus lead to greater fatality or casualty risk once a crash has occurred.

As summarized above, Florida and Pennsylvania substantially under-report non-injury crashes; after accounting for other control variables, all of the states have a higher crash frequency than Florida, except Pennsylvania. Kentucky and New Jersey have the highest crash frequencies for all three types of vehicles; Pennsylvania, Maryland, and Wisconsin have the lowest crash frequency. Wyoming has a low crash frequency for light trucks (41%), but relatively high crash frequencies for cars and CUVs/minivans (over 80%), while Washington has a low crash frequency for cars (37%) but relatively high crash frequencies of light trucks and

Table 2.8. Estimated effect of variables on crashes per VMT, fatalities per crash, and casualties per crash, using data from 13 states

Variable	Cars			Light trucks			CUVs/minivans		
	Crash/ VMT	Fatality/ crash	Casualty/ crash	Crash/ VMT	Fatality/ crash	Casualty/ crash	Crash/ VMT	Fatality/ crash	Casualty/ crash
UNDERWT	1.60%	-0.74%	-0.84%	0.36%	-0.77%	-0.27%	—	—	—
OVERWT	2.33%	-0.32%	-0.26%	1.31%	-1.43%	-0.49%	—	—	—
LBS100	—	—	—	—	—	—	2.59%	-2.12%	-0.44%
FOOTPRINT	-0.95%	-0.03%	0.51%	1.63%	0.10%	-0.17%	-2.31%	0.87%	0.48%
TWODOOR	6.48%	14.7%	-1.26%	—	—	—	—	—	—
SUV	—	—	—	7.06%	-1.34%	1.49%	—	—	—
HD	—	—	—	-2.28%	20.4%	4.24%	—	—	—
BLOCKER1	—	—	—	-3.72%	-0.89%	0.29%	—	—	—
BLOCKER2	—	—	—	-7.01%	-5.41%	-2.62%	—	—	—
MINIVAN	—	—	—	—	—	—	-2.66%	-0.58%	8.51%
ROLLCURT	0.00%	0.20%	0.34%	—	—	—	-0.08%	-0.43%	-0.45%
CURTAIN	3.43%	2.17%	-3.06%	—	—	—	2.29%	-10.06%	-2.38%
COMBO	7.49%	-0.91%	2.34%	—	—	—	-5.92%	1.51%	8.33%
TORSO	-7.14%	-11.2%	-6.69%	—	—	—	-8.59%	3.57%	-5.66%
ABS	-14.2%	-1.57%	-5.54%	—	—	—	-14.4%	-11.8%	-4.75%
ESC	-8.80%	-1.40%	-7.09%	-11.3%	-10.3%	-9.59%	-5.59%	-18.6%	-6.56%
AWD	—	—	—	36.3%	7.29%	0.51%	13.6%	-0.50%	-0.43%
VEHAGE	0.93%	2.35%	0.79%	1.87%	2.58%	1.53%	1.61%	1.02%	1.10%
BRANDNEW	3.44%	3.08%	2.70%	-0.23%	11.9%	3.56%	-1.13%	5.12%	-2.60%
DRVMALE	5.49%	21.8%	-0.79%	-3.28%	22.3%	-0.07%	1.97%	22.8%	4.54%
M14_30	4.10%	1.84%	0.43%	3.93%	1.25%	0.47%	4.74%	-0.04%	0.28%
M30_50	0.51%	0.18%	-0.15%	0.49%	-0.20%	-0.24%	0.23%	0.22%	-0.39%
M50_70	-0.01%	3.45%	1.26%	0.35%	2.20%	1.22%	0.38%	2.54%	1.15%
M70_96	3.60%	4.28%	2.17%	3.79%	4.09%	1.89%	3.15%	4.53%	1.93%
F14_30	3.36%	0.97%	0.38%	3.72%	-1.49%	-0.16%	3.59%	0.12%	0.56%
F30_50	0.26%	-1.22%	-0.68%	0.09%	0.06%	-0.22%	0.11%	-0.57%	-0.44%
F50_70	0.62%	2.71%	0.89%	0.95%	2.95%	1.14%	0.90%	2.73%	1.19%
F70_96	4.00%	5.36%	1.90%	3.05%	-4.16%	0.83%	3.85%	4.11%	1.33%
NITE	20.2%	81.9%	23.5%	28.6%	68.4%	20.8%	19.9%	68.3%	17.4%
RURAL	10.6%	53.7%	30.1%	15.0%	43.8%	26.7%	13.51%	49.2%	23.2%
SPDLIM55	33.1%	104%	55.5%	25.1%	107%	63.9%	19.2%	113%	63.4%
CY2005	-0.12%	25.9%	19.1%	3.13%	27.4%	24.1%	-4.34%	29.2%	17.2%
CY2006	0.14%	24.9%	14.3%	2.11%	20.2%	19.0%	-5.65%	16.7%	17.3%
CY2007	2.80%	18.8%	7.82%	4.96%	12.0%	11.3%	-1.06%	8.80%	11.5%
CY2008	-0.27%	10.1%	4.47%	1.32%	10.8%	7.90%	-1.93%	5.83%	6.20%
CY2010	2.82%	-4.88%	-11.3%	0.42%	-7.40%	-9.75%	2.14%	-4.69%	-1.88%
CY2011	7.04%	-16.0%	-20.8%	0.46%	-6.63%	-23.0%	4.63%	-11.1%	-17.3%
AL	95.1%	-103%	-24.2%	79.7%	-111%	-36.2%	104%	-112%	-40.6%
KS	56.1%	-124%	-161%	60.3%	-133%	-167%	81.7%	-131%	-146%
KY	114%	-129%	-156%	113%	-133%	-169%	141%	-153%	-173%
MD	14.4%	-55.0%	-58.2%	1.46%	-80.6%	-61.3%	6.19%	-73.8%	-58.2%
MI	94.9%	-199%	-203%	92.2%	-224%	-211%	102%	-187%	-206%
MO	83.7%	-109%	-127%	64.0%	-119%	-131%	88.0%	-116%	-136%
NE	80.8%	-155%	-134%	74.3%	-156%	-140%	86.6%	-201%	-145%
NJ	100%	-146%	-281%	101%	-172%	-283%	110%	-168%	-304%
PA	-22.5%	-27.5%	-154%	-13.6%	-40.2%	-143%	-7.2%	-22.5%	-154%
WA	37.3%	-125%	-194%	53.8%	-127%	-190%	73.4%	-129%	-201%
WI	46.5%	-124%	-144%	45.8%	-148%	-155%	54.5%	-125%	-149%
WY	84.3%	-164%	-188%	41.4%	-169%	-182%	79.9%	-172%	-176%

* Values in red are statistically significant at the 95% level.

CUVs/minivans (over 50%). All states have a lower fatality or casualty risk per crash than Florida, for each type of vehicle. Pennsylvania has a much higher fatality risk relative to its casualty risk per crash (the estimate for fatality risk is much higher, i.e. less negative relative to Florida) than the estimate for casualty risk), while Alabama has a much lower fatality risk relative to its casualty risk per crash (the fatality risk estimate is much lower, i.e. more negative relative to Florida).

In summary, the strong and consistent relationship in Tables 2.6 through 2.8 between the control variables for vehicle attributes, driver gender and age, crash circumstances, and crash frequency and risk, is encouraging. However, the tables show several unexpected results:

- Bumper height compatibility measures in light trucks, and some types of side airbags in cars and CUVs/minivans, are associated with decreases in crash frequency.
- AWD is associated with an increase in crash frequency.
- ESC and ABS are associated with decreases in risk once a crash has occurred.
- AWD, male drivers, young drivers, and driving at night, in a rural county, or on a high-speed road are all associated with increases in risk once a crash has occurred.

In some cases these unexpected results apply to all three vehicle types, in other cases to only one or two of the three vehicle types. These unexpected results suggest that the regression models may not fully account for all the variables that influence crash frequency or risk per crash. In particular, they may not account for why risky or unskilled drivers select certain vehicle types, or even particular makes and models. Not accounting for these associations may be biasing the relationships the models estimate between vehicle mass or footprint and crash frequency and risk per crash.

3. Sensitivity of Results for Crash Frequency and Risk Per Crash

Figures 2.7 and 2.8 above indicate that mass reduction is associated with increases in crash frequency but decreases in fatality (Figure 2.7) and casualty (Figure 2.8) risk per crash, for all types of vehicles except lighter-than-average light trucks. These results are unexpected: one would expect that lighter vehicles, with better maneuverability and shorter braking distances, would have lower crash frequency than heavier vehicles; and that heavier (or larger) vehicles would have lower risk once a crash has occurred than lighter vehicles. In this section we examine the sensitivity of the results on crash frequency to adding several additional explanatory variables to the baseline NHTSA regression model, and to restricting the analysis only to severe crashes.

3.1. Estimated Effect of Accounting for Other Vehicle and Driver Characteristics on Crash Frequency

In its 2012 Phase 2 report LBNL also found that mass reduction was associated with increases in crash frequency, for all five types of vehicles. In a later report LBNL conducted several additional regression analyses that added five additional control variables to see if they would change the relationship between vehicle mass and crash frequency in the NHTSA baseline model

(Wenzel 2016a). This section recreates these analyses, using the updated 13-state crash data through 2011.[9]

Table 3.1 shows the estimated effect of seven alternative regression models that test the sensitivity of the relationship between mass or footprint reduction and crash frequency to additional vehicle or driver variables. Coefficients shown in red font are statistically significant, based on the Chi-square value output by the logistic regression models.

Alternative Model 1 includes the initial purchase price, in thousands of dollars, by vehicle model, as derived from the Polk VIN decoder; this information was available for about 97% of the vehicles in the state crash databases. Table 3.2 indicates that average initial purchase price varies from just over $20,000 for four-door cars to over $32,000 for large pickups, SUVs, and all-wheel drive cars. Including initial purchase price lowers the detrimental effect of mass reduction on crash frequency, particularly for heavier-than-average cars (from a 2.3% increase in crash frequency to a 0.8% increase in crash frequency); for lighter-than-average light trucks, the association of mass reduction changes from a slight (0.36%) increase in crash frequency to a slight (0.56%) decrease in crash frequency after adding vehicle price. The bottom panel in the table indicates that crash frequency is slightly reduced (0.3 to 1.4%) for every additional $1,000 in the initial purchase price of a particular vehicle model.

Alternative Model 2 includes the average income of households that own a particular model of vehicle. The data are derived from California vehicle registration data, based on the median income in the zip code in which individual vehicles are registered, averaged over all vehicles of a given model. This information was available for about 98% of the vehicles in the state crash databases. Table 3.2 indicates that average household income ranges from just over $49,000 for pickups to over $60,000 for all-wheel drive cars (police cars, which are owned by government agencies located in predominantly urban zip codes, have an average "household" income of only $39,000). Model 2 suggests that including average household income by vehicle model has little effect on the estimated relationship between vehicle mass or footprint reduction and crash frequency, and that an increase in household income is associated with a (0.3% to 1.7%) decrease in crash frequency.

[9] Previously LBNL also examined the results of three vehicle braking and handling tests conducted by Consumer Reports: the maximum speed achieved during the avoidance maneuver test, acceleration time from 45 to 60 mph, and dry braking distance. When these three test results are added to the LBNL baseline regression model of crash frequency in cars, none were associated with the expected effect on crash frequency; in other words, an increase in maximum maneuver speed, the time to reach 60 miles per hour, or braking distance on dry pavement in cars, either separately or combined, was associated with a decrease in the likelihood of a crash, of any type or with a stationary object. LBNL did not update this analysis because the Consumer Reports test results could be matched to vehicle models representing only 40% of all cars, 22% of all CUVs and minivans, and essentially none of all light trucks.

Table 3.1. Effect of mass and footprint reduction on crash frequency, under alternative regression model specifications

Variable	Case vehicle type	NHTSA baseline model (crashes per VMT)	1. Including initial vehicle purchase price ($000s)	2. Including median household income ($000s)	3. Including 15 variables for vehicle manufacturer	4. Including average "bad driver" rating	5. Including whether driver was using alcohol or drugs	6. Including whether driver was properly using restraint	7. Including all additional variables
Mass reduction	Cars < 3106	1.60%	0.99%	1.55%	2.91%	1.66%	1.60%	1.67%	2.36%
	Cars > 3106	2.33%	0.82%	1.66%	3.84%	2.56%	2.34%	2.40%	3.23%
	LTs < 4594	0.36%	-0.56%	0.37%	1.32%	-0.20%	0.27%	0.37%	0.05%
	LTs > 4594	1.31%	0.01%	1.19%	2.36%	0.89%	1.21%	1.27%	1.00%
	CUV/mvan	2.59%	2.29%	2.07%	3.90%	2.62%	2.62%	2.57%	4.36%
Footprint reduction	Cars	-0.95%	-0.75%	-0.23%	-1.87%	-1.00%	-0.89%	-0.98%	-1.33%
	LTs	1.63%	1.50%	1.66%	0.67%	1.81%	1.66%	1.62%	0.83%
	CUV/mvan	-2.31%	-2.27%	-1.79%	-3.81%	-2.32%	-2.33%	-0.08%	-3.74%
Initial purchase price	Cars	—	-0.70%	—	—	—	—	—	-0.01%
	LTs	—	-1.39%	—	—	—	—	—	-0.99%
	CUV/mvan	—	-0.28%	—	—	—	—	—	0.73%
Average household income	Cars	—	—	-1.70%	—	—	—	—	-0.83%
	LTs	—	—	-0.31%	—	—	—	—	0.66%
	CUV/mvan	—	—	-1.24%	—	—	—	—	-0.74%
Bad driver rating	Cars	—	—	—	—	6.38%	—	—	3.37%
	LTs	—	—	—	—	-7.74%	—	—	-8.19%
	CUV/mvan	—	—	—	—	2.37%	—	—	-4.08%
Driver alcohol or drug use	Cars	—	—	—	—	—	251%	—	243%
	LTs	—	—	—	—	—	245%	—	236%
	CUV/mvan	—	—	—	—	—	236%	—	225%
Driver properly restrained	Cars	—	—	—	—	—	—	-21.3%	-9.95%
	LTs	—	—	—	—	—	—	-29.0%	-16.6%
	CUV/mvan	—	—	—	—	—	—	-24.7%	-11.8%

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

Alternative Model 3 includes dummy variables for 15 vehicle makes; accounting for vehicle make makes mass reduction more detrimental, and footprint reduction more beneficial/less detrimental, in terms of crash frequency, for all vehicle types.

Table 3.2. Average vehicle and driver characteristics, by vehicle type

Vehicle type	Average initial purchase price	Average household income	Average bad driver rating	Percent drivers using alcohol or drugs	Percent drivers not using restraints
2-dr cars	$21,048	$52,454	2.61	3.07%	2.85%
4-dr cars	$20,855	$51,421	1.69	1.85%	2.22%
Sporty cars	$28,575	$54,360	4.90	4.46%	3.07%
Police cars	$25,849	$38,795	1.13	0.27%	5.00%
AWD cars	$34,455	$60,362	1.91	1.98%	1.28%
Sm pickups	$27,023	$49,315	3.56	3.08%	3.34%
Lg pickups	$32,677	$49,363	4.64	3.01%	4.14%
SUVs	$32,409	$53,866	1.69	1.75%	1.93%
CUVs	$26,925	$55,682	0.85	1.30%	1.57%
Minivans	$26,390	$53,593	0.62	0.66%	1.53%
Full vans	$26,382	$51,425	1.34	0.90%	2.20%
All	$24,840	$52,293	1.85	1.91%	2.27%

NHTSA baseline regression model and alternative models exclude the vehicle types shown in red.

The average "bad driver" rating by vehicle model is added to alternative Model 4. In its 2003 report NHTSA created a "bad driver" rating variable based on whether alcohol or drugs were involved in the current crash, whether the driver had a valid license or was accused of reckless driving in the current crash, or whether the driver had a moving violation within the last three years. Table 3.2 shows that sporty cars have the highest average bad driver rating, 4.9, followed by large and small pickups (4.6 and 3.6, respectively), while minivans and CUVs have an average bad driver rating of less than 0.9. In terms of individual vehicle models with over 100 fatalities or 10 billion VMT, the bad driver rating varies from 0.2 for Lexus RX330 to 6.4 for Nissan Titan King Cab.

We assigned the average bad driver rating to each vehicle model in the state crash cases, and included the variable in the regression models (the LBNL 2012 and 2016 reports excluded FARS cases where drivers were suspected of alcohol or drug use, or were otherwise "bad" drivers). We only included the bad driver rating for vehicle models that had at least 50 individual vehicles in the FARS data, which accounted for about 99% of all the vehicles in the crash data and induced exposure data. Table 3.1 indicates that adding the bad driver rating variable does not substantively change the estimated relationship between mass or footprint reduction and crash frequency, although mass reduction in lighter light trucks is associated with a small decrease in crash frequency after including the bad driver rating. An increase in the bad driver rating is associated with increases in crash frequency for cars and CUVs/minivans, but a reduction in crash frequency in light trucks.

Alternative Models 5 and 6 account for whether the drivers in the state crash data cases were suspected of using alcohol or drugs, or were not wearing safety restraints, respectively, at the time of the crash. These data were reported for about 92% to 95% of the crash cases, and about 88% to 94% of the induced exposure crash cases used to estimate vehicle miles of travel, depending on vehicle type. There are very few case vehicles whose driver was suspected of using alcohol or drugs, or was not wearing a safety restraint. Only 1.91% of drivers in all crashes, and only 0.19% of drivers in the induced exposure cases, were suspected of using alcohol or drugs, and only 2.27% of drivers in all crashes, and only 2.87% of drivers in the induced exposure cases, were not wearing their restraints. Table 3.2 indicates that suspected alcohol/drug use was highest in sporty cars (4.5%), followed by two-door cars and pickups (over 3%), and lowest in police cars (0.27%) and minivans (0.66%); drivers in sporty cars, police cars, and pickups were most likely not to use restraints (over 3%), while drivers in minivans, SUVs, CUVs, and all-wheel drive cars were least likely not to use restraints (under 2%).

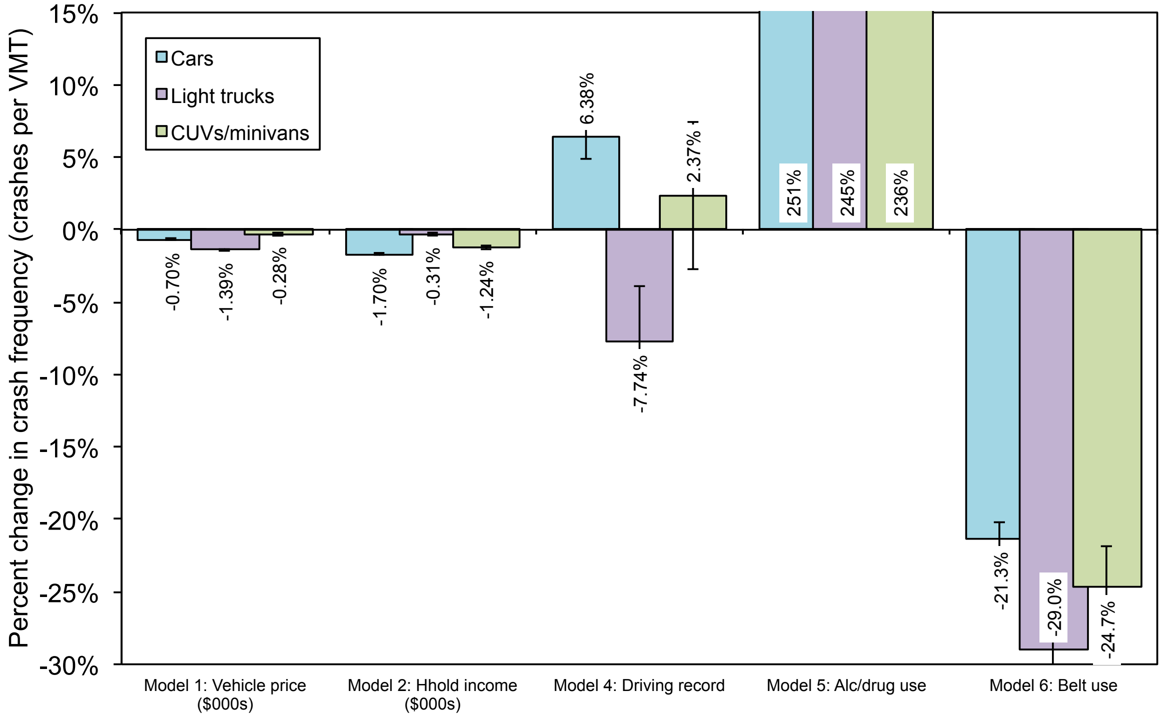
The last rows of Table 3.1 indicate that crash frequency increases dramatically (over 200%) if the driver was using alcohol or drugs, and decrease substantially (over 20%) if the driver was properly using his or her restraint. Adding either of these variables to the regression models has little effect on the estimated relationship between mass or footprint reduction on crash frequency, with one exception: adding restraint use changes the estimated effect of footprint reduction in CUVs/minivans from a large (2.3%) decrease in crash frequency in the NHTSA baseline model to a small (0.08%) decrease in crash frequency.

Alternative Model 7 includes all of the additional variables (initial vehicle purchase price, average household income, 15 vehicle makes, average bad driver rating, driver alcohol/drug use, and driver restraint use) in one regression model. Including all of the variables reduces the number of crash cases by 12% to 14%, and the induced exposure cases by 14% to 18%, depending on vehicle type. Including all of the additional variables in Model 7 reduces the estimated effect of mass or footprint reduction on crash frequency in many cases (especially mass reduction in lighter light trucks, which goes from a 0.36% increase to a 0.05% increase in crash frequency), in every one of the eight cases the sign of the coefficient is the same as in the NHTSA baseline model.

For the most part, the estimated effect of the five additional vehicle and driver variables on crash frequency is similar when all five variables are included in the Model 7 as when only one of the five is included. However, there are some exceptions: initial vehicle purchase price gets very small for cars in Model 7 (from a 0.70% decrease in crash frequency to in Model 1 to 0.01% decrease in crash frequency in Model 7), and changes sign for CUVs/minivans (from a 0.28% decrease to a 0.73% increase in crash frequency); average household income changes sign for light trucks (from a 0.31% decrease to a 0.66% increase in crash frequency); and bad driver rating changes sign for CUVs/minivans (from a 2.4% increase in crash frequency to a 4.1% decrease in crash frequency). The association of driver restraint use with crash frequency decreases substantially when the other variables are added to the regression models, from a 21% to 29% reduction in crash frequency to a 10% to 17% reduction in crash frequency, depending on vehicle type.

Figure 3.1 shows graphically the estimated effect of adding each of the five additional variables listed in the bottom panel of Table 3.1 on the change in crash frequency estimated in the baseline model, by vehicle type. Again, Figure 3.1 suggests that increasing vehicle price, household income, and driver seat belt use are each consistently associated with a reduction in crash frequency, while driver alcohol/drug use is associated with a very large increase in crash frequency, in all three vehicle types. A poor driving record is associated with an increase in crash frequency in cars and CUVs/minivans, but a decrease in crash frequency in light trucks.

Figure 3.1. Estimated effect of individually adding five additional variables on the change in crash frequency estimated in baseline model, by vehicle type



Figures 3.2 through 3.4 graphically show the estimated effect of adding the five additional variables listed in the top panel of Table 3.1, individually and cumulatively, on the estimated effect of mass or footprint reduction on crash frequency, for cars, light trucks, and CUVs/minivans, respectively. The last columns in the figure ("All 5 + Makes") represent the estimated effect of Model 7 shown in Table 3.1 (adding all five of the additional variables, as well as 15 vehicle manufacturer variables).

For the most part, including the five additional variables, as well as the dummy variables for vehicle makes, either individually or including all in the same regression model, does not change the general results of the baseline NHTSA regression model: that mass reduction is associated with an increase in crash frequency in all three types of vehicles, while footprint reduction is associated with an decrease in crash frequency in cars and CUVs/minivans, but with an increase in crash frequency in light trucks. The results for lighter-than-average light trucks is least stable under these alternative models, mostly because lighter light trucks are associated with only a small increase in crash frequency under the baseline model. The alternative regression model with the biggest effect is Model 3, which adds dummy variables for 15 vehicle makes, and substantially increases the estimated increase in crash frequency from mass reduction in the baseline model for all five vehicle types. These results suggest that other, more subtle, differences in vehicles and their drivers may account for the unexpected finding that lighter vehicles have higher crash frequencies than heavier vehicles.

Figure 3.2. Estimated effect of adding five additional variables on the estimated change in mass or footprint reduction on crash frequency, cars

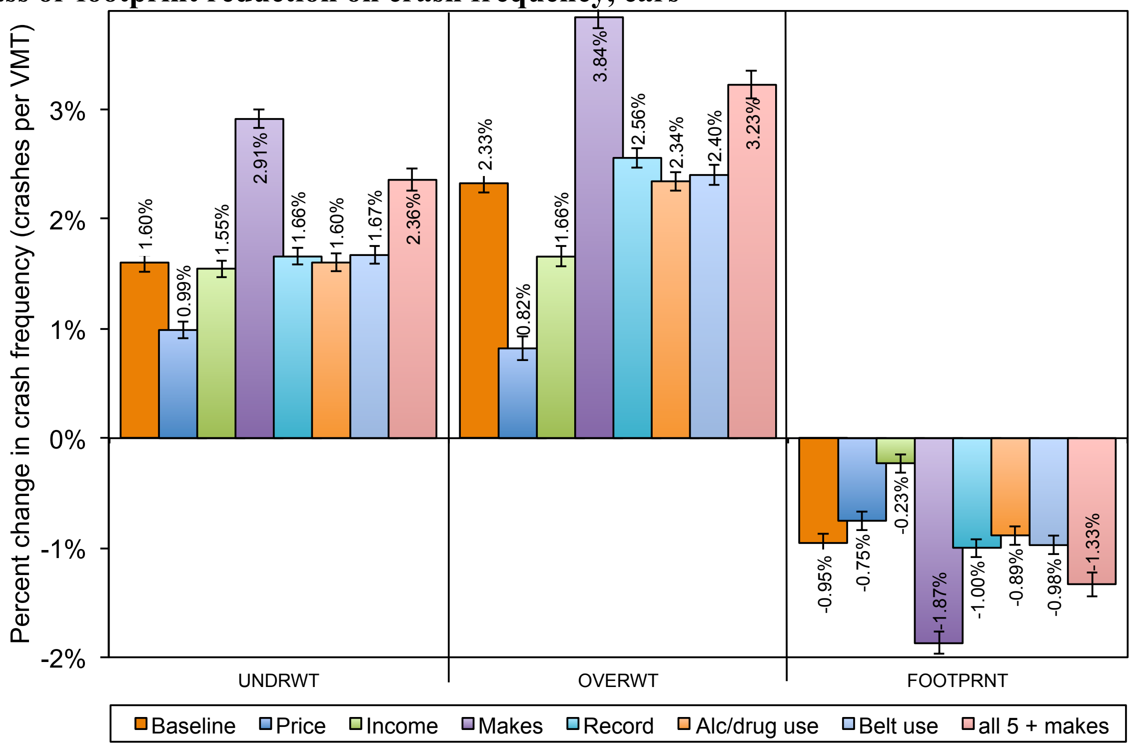


Figure 3.3. Estimated effect of adding five additional variables on the estimated change in mass or footprint reduction on crash frequency, light trucks

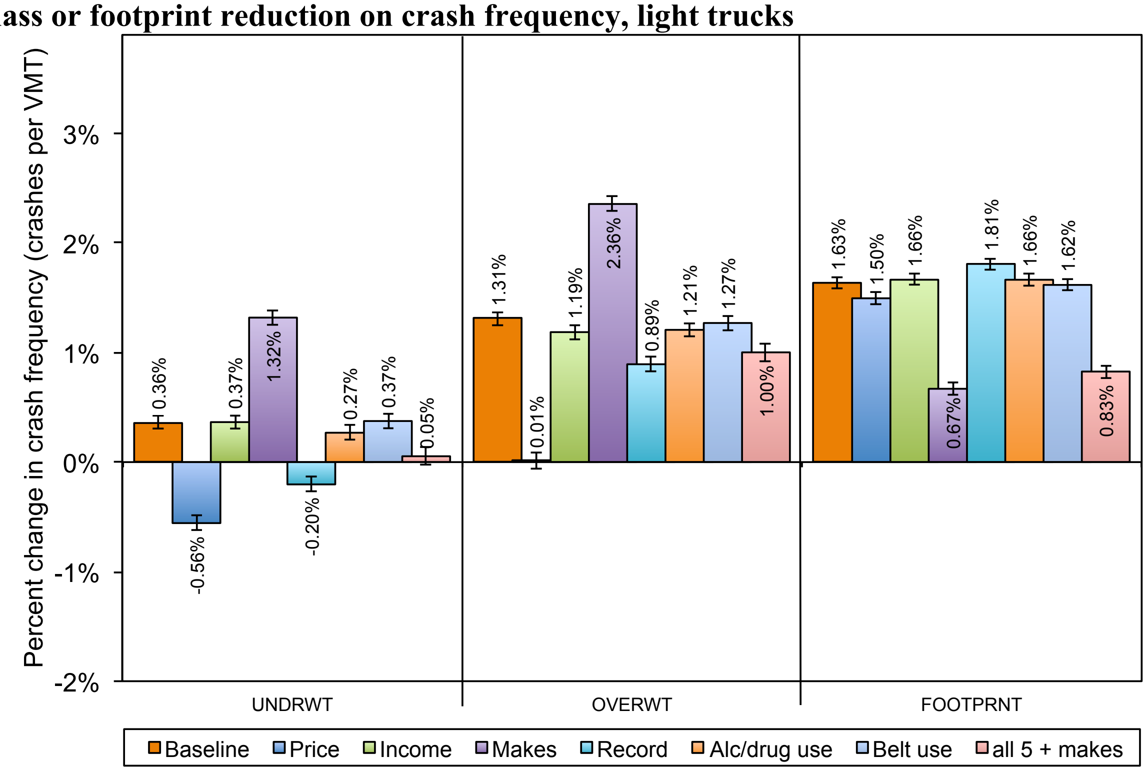


Figure 3.4. Estimated effect of adding five additional variables on the estimated change in mass or footprint reduction on crash frequency, CUVs/minivans

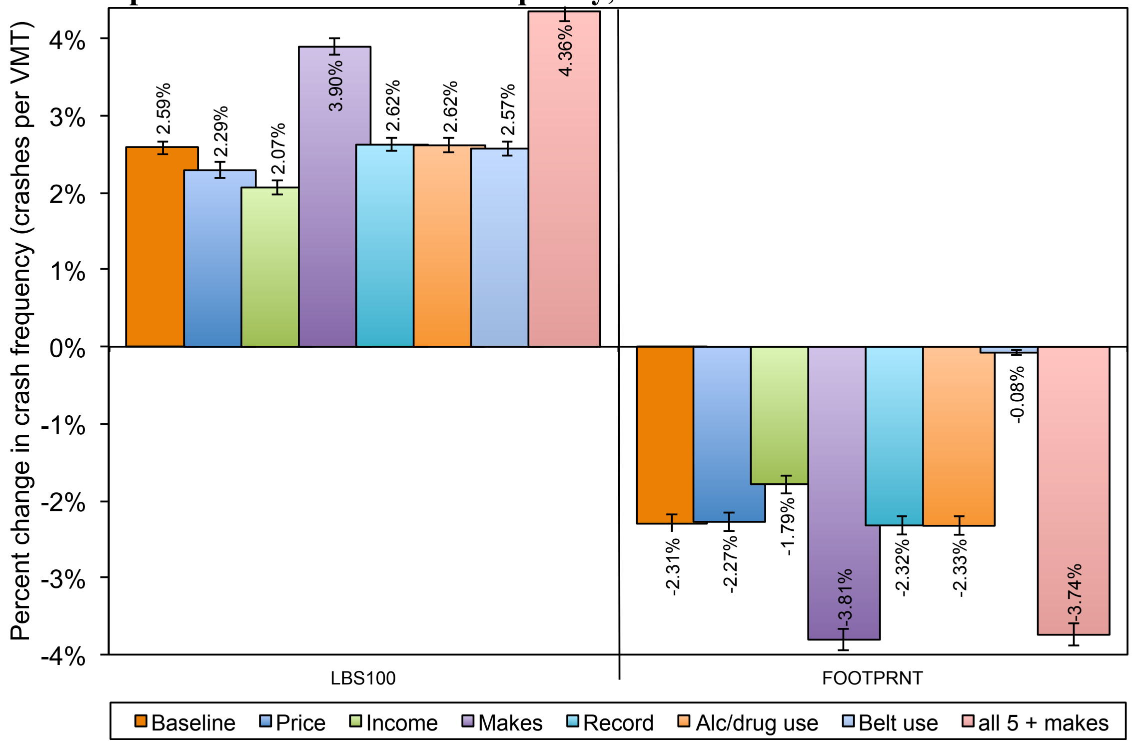


Table 3.3 compares all of the control variables estimated by the baseline model with those estimated by Model 7. For the most part the estimated coefficients of the other control variables under Model 7 are comparable to those from the baseline regression model; however, there are some differences. SUVs are associated with a 7.1% increase in crash frequency, and heavy-duty pickups a 2.3% decrease in crash frequency, under the baseline model; but neither are associated with a change in crash frequency in Model 7. The light truck compatibility measures (BLOCKER1 and BLOCKER2) both are associated with larger decreases in crash frequency in Model 7 (6.7% and 13.6% decreases, respectively) than in the baseline model (3.7% and 7.0% decreases, respectively). Torso side airbags are associated with large decreases in crash frequency for both cars and CUVs/minivans under the baseline model, but a 2.9% increase in crash frequency for CUVs/minivans in Model 7. ABS is associated with a 14% decrease in crash frequency for cars in the baseline model, but only a 5% decrease in Model 7, while ESC is associated with smaller decreases in crash frequency in Model 7 (1% to 5%, depending on vehicle type) than in the baseline model (65 to 11%). And in Model 7 AWD is associated with a smaller increase in crash frequency (from a 36% increase to a 25% increase) for light trucks, but a slightly larger increase (from a 14% increase to a 20% increase) for CUVs/minivans, than in the baseline model.

Table 3.3. Estimated effect of variables on 13-state crash frequency per VMT, by vehicle type

Variable	NHTSA baseline			Including additional vehicle and driver variables		
	Cars	LTs	CUVs	Cars	LTs	CUVs
UNDERWT	1.60%	0.36%	—	2.36%	0.05%	—
OVERWT	2.33%	1.31%	—	3.23%	1.00%	—
LBS100	—	—	2.59%	—	—	4.36%
FOOTPRINT	-0.95%	1.63%	-2.31%	-1.33%	0.83%	-3.74%
TWODOOR	6.48%	—	—	2.79%	—	—
SUV	—	7.06%	—	—	-0.14%	—
HD	—	-2.28%	—	—	-0.73%	—
BLOCKER1	—	-3.72%	—	—	-6.67%	—
BLOCKER2	—	-7.01%	—	—	-13.6%	—
MINIVAN	—	—	-2.66%	—	—	-4.82%
ROLLCURT	0.00%	—	-0.08%	-0.10%	—	-0.08%
CURTAIN	3.43%	—	2.29%	1.66%	—	-0.52%
COMBO	7.49%	—	-5.92%	5.00%	—	-6.21%
TORSO	-7.14%	—	-8.59%	-1.18%	—	2.92%
ABS	-14.2%	—	-14.4%	-5.34%	—	-15.9%
ESC	-8.8%	-11.3%	-5.59%	-4.59%	-1.74%	-1.26%
AWD	—	36.3%	13.6%	—	24.9%	19.5%
VEHAGE	0.93%	1.87%	1.61%	0.80%	2.79%	2.25%
BRANDNEW	3.44%	-0.23%	-1.13%	2.63%	-2.16%	-1.47%
DRVMALE	5.49%	-3.28%	1.97%	4.94%	-3.91%	1.51%
M14_30	4.10%	3.93%	4.74%	4.25%	3.90%	4.76%
M30_50	0.51%	0.49%	0.23%	0.27%	0.37%	0.13%
M50_70	-0.01%	0.35%	0.38%	0.01%	0.38%	0.38%
M70_96	3.60%	3.79%	3.15%	3.57%	3.85%	3.19%
F14_30	3.36%	3.72%	3.59%	3.30%	3.62%	3.53%
F30_50	0.26%	0.09%	0.11%	0.15%	0.01%	0.06%
F50_70	0.62%	0.95%	0.90%	0.69%	0.95%	0.89%
F70_96	4.00%	3.05%	3.85%	3.99%	3.01%	4.14%
NITE	20.2%	28.6%	19.9%	13.3%	19.1%	14.7%
RURAL	10.6%	15.0%	13.5%	10.1%	16.5%	13.5%
SPDLIM55	33.1%	25.1%	19.2%	34.1%	26.9%	19.9%
CY2005	-0.12%	3.13%	-4.34%	2.39%	9.50%	1.14%
CY2006	0.14%	2.11%	-5.65%	-0.08%	5.11%	-2.71%
CY2007	2.80%	4.96%	-1.06%	2.67%	6.04%	0.82%
CY2008	-0.27%	1.32%	-1.93%	-0.76%	2.13%	-1.91%
CY2010	2.82%	0.42%	2.14%	1.63%	-1.28%	0.57%
CY2011	7.04%	0.46%	4.63%	8.12%	-1.21%	3.72%
AL	95.1%	79.7%	104%	96.3%	84.9%	104%
KS	56.1%	60.3%	81.7%	57.1%	63.4%	81.8%
KY	114%	113%	141%	115%	117%	142%
MD	14.4%	1.46%	6.19%	20.0%	8.77%	9.41%
MI	94.9%	92.2%	102%	92.5%	90.7%	99.3%
MO	83.7%	64.0%	88.0%	84.3%	65.1%	87.7%
NE	80.8%	74.3%	86.6%	85.2%	79.9%	93.0%
NJ	100%	101%	110%	108%	108%	115%
PA	-22.5%	-13.6%	-7.25%	-26.4%	-20.9%	-10.9%
WA	37.3%	53.8%	73.4%	49.8%	71.0%	85.6%
WI	46.5%	45.8%	54.5%	38.7%	37.3%	47.0%
WY	84.3%	41.4%	79.9%	76.4%	33.6%	73.1%

The 15 dummy variables for vehicle makes show some interesting results. Toyota and BMW cars are associated with the lowest crash frequency (over 12% lower crash frequency than GM cars), while Kia and Hyundai cars have the highest crash frequency (over 6% higher than GM cars). Subaru and Volvo SUVs have the lowest crash frequency of all light trucks (over 40% lower than GM trucks), while Chrysler, Mitsubishi, and Kia light trucks have the highest (over 15% higher than GM trucks). Among CUVs/minivans, Volvo and Nissan models have the lowest crash frequency (over 12% lower than GM models), and Mitsubishi, Kia and Mazda have the highest (over 18% higher than GM models).

Table 3.4. Estimated effect of vehicle manufacturer variables on 13-state crash frequency per VMT, by vehicle type

	NHTSA baseline			Including additional vehicle and driver variables		
Variable	Cars	LTs	CUVs	Cars	LTs	CUVs
CHRYS	—	—	—	-0.26%	27.8%	14.2%
FORD	—	—	—	-0.60%	13.1%	6.05%
TOYOTA	—	—	—	-12.9%	-26.6%	-8.24%
HONDA	—	—	—	-7.86%	-27.9%	-8.56%
NISSAN	—	—	—	-16.0%	-11.1%	-12.3%
HYUNDAI	—	—	—	6.95%	-13.9%	21.6%
MITSU	—	—	—	2.73%	15.1%	19.8%
VW	—	—	—	-7.80%	-30.2%	9.52%
KIA	—	—	—	6.11%	15.1%	34.2%
MAZDA	—	—	—	2.37%	-1.73%	18.7%
BMW	—	—	—	-14.7%	0.00%	3.34%
SUBARU	—	—	—	0.00%	-48.5%	-3.67%
MBZ	—	—	—	-4.29%	-15.0%	-3.44%
VOLVO	—	—	—	-6.41%	-46.7%	-23.8%
OTHER	—	—	—	-5.34%	14.4%	-0.31%
PRICE000	—	—	—	-0.01%	-0.99%	0.73%
INC000	—	—	—	-0.83%	0.66%	-0.74%
BAD_DRV	—	—	—	3.37%	-8.19%	-4.08%
ALC_DRUG	—	—	—	243%	236%	225%
RESTUSE	—	—	—	-9.95%	-16.6%	-11.8%

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

3.2. Accounting for Crash Severity

In his 2012 report Kahane suggested two possible explanations for the unexpected results from the 2012 LBNL Phase 2 report: that the analysis did not account for the severity of the crash, and possible bias in the crashes reported to police in different states, with less severe crashes being under-reported for certain vehicle types (Kahane 2012). The full text from Kahane 2012 is included in the Appendix. (In his preliminary 2011 report Kahane speculated that owners of heavier vehicles such as SUVs and pickups would be less likely to report minor crashes than owners of lighter passenger cars, because the heavier vehicles would sustain less damage in a two-vehicle crash; however this suggestion was removed from the final report. It would seem just as likely that owners of vehicles that are un- or under-insured would refrain from reporting a minor crash; their vehicles are likely to be inexpensive passenger cars rather than heavier and more expensive pickups or SUVs.)

This section analyzes the first of Kahane's explanations for the unexpected result of mass reduction being associated with decreased risk per crash: that the regression models do not account for the severity of the crash. Previously we did a similar analysis using the 2012 LBNL Phase 2 results (Wenzel 2016b).

Of the 13 states whose police-reported crash data were used, seven report the severity of the damage sustained by the subject vehicle, two report whether the vehicle had to be towed from the crash scene, and three report both. Because Washington does not report either of these measures of crash severity, all crashes in Washington had to be excluded from this particular analysis. For the seven states that report crash damage severity, vehicles that were described as "disabled" were included, while vehicles with functional, none, or unknown damage were excluded. 95% of crashes involving a casualty occurred in states other than Washington; of these crashes, 42% were severe crashes. 98% of casualties occurred in states other than Washington; of these casualties, 84% occurred in severe crashes.

As noted above, ABS and ESC should reduce crash frequency, while side airbags in cars and CUVs/minivans, and supplementary frontal bumpers (BLOCKER1) or greater bumper overlap (BLOCKER2) on light trucks, should reduce casualty risk once a crash has occurred. And one might expect that, all else held equal, mass reduction would reduce braking distance, and footprint reduction (or more specifically wheelbase) would improve maneuverability, both of which would result in reduced crash frequency. On the other hand, one might expect that the added mass of AWD might increase braking distance, and thus increase crash frequency, while decreasing risk per crash in the subject vehicle but perhaps increasing societal risk per crash.

Table 3.1 compares the estimates for all variables for the crash frequency and casualty risk per crash regression models, under two regression models: the "Base" estimates are from the NHTSA baseline model (Table 2.7 above), while the "Ex NS" estimates are from a model which includes only vehicles in crashes in which at least one involved vehicle was so disabled from the crash that it had to be towed from the crash scene (i.e. excludes non-severe crashes, labeled "Ex NS" in the table). Because Washington does not report a measure of crash severity, it also is excluded in the "Ex NS" results. Values in red are statistically significant at the 95% level; the estimates shaded green are in the expected direction, and those shaded yellow are in the opposite direction.

In some cases, excluding the non-severe crashes in the "Ex NS" model reduces the unexpected results from the baseline model; however, in none of the estimates does excluding the non-severe crashes change the sign on the estimated coefficient to the expected direction. We conclude that not accounting for crash severity in the baseline model is not the reason why many control variables have unexpected associations with crash frequency or risk per crash.

Table 3.5. Estimated effect on crash frequency (crashes per mile traveled) and casualty risk per crash, from NHTSA baseline ("Base") and after excluding non-severe crashes and all crashes in Washington ("Ex NS")

	Crash frequency (crashes per VMT)						Casualties per crash					
	Cars		Light Trucks		CUVs/minivans		Cars		Light Trucks		CUVs/minivans	
Variable	Base	Ex NS	Base	Ex NS	Base	Ex NS	Base	Ex NS	Base	Ex NS	Base	Ex NS
UNDRWT00	1.60%	1.42%	0.36%	0.65%	—	—	-0.84%	-0.87%	-0.27%	-0.62%	—	—
OVERWT00	2.33%	2.05%	1.31%	1.49%	—	—	-0.26%	0.05%	-0.49%	-0.63%	—	—
LBS100	—	—	—	—	2.59%	2.23%	—	—	—	—	-0.44%	-0.18%
FOOTPRNT	-0.95%	0.16%	1.63%	1.51%	-2.31%	-1.56%	0.51%	-0.30%	-0.17%	-0.15%	0.48%	0.35%
TWODOOR	6.48%	7.89%	—	—	—	—	-1.26%	-1.16%	—	—	—	—
SUV	—	—	7.06%	9.39%	—	—	—	—	1.49%	0.38%	—	—
HDPU	—	—	-2.28%	-2.61%	—	—	—	—	4.24%	5.37%	—	—
BLOCKER1	—	—	-3.72%	-1.33%	—	—	—	—	0.29%	-0.80%	—	—
BLOCKER2	—	—	-7.01%	-5.73%	—	—	—	—	-2.62%	-3.43%	—	—
MINIVAN	—	—	—	—	-2.66%	-8.82%	—	—	—	—	8.51%	18.1%
ROLLCURT	0.00%	0.07%	—	—	-0.08%	-0.18%	0.34%	0.42%	—	—	-0.45%	-0.48%
CURTAIN	3.43%	2.98%	—	—	2.29%	4.88%	-3.06%	-3.66%	—	—	-2.38%	-4.83%
COMBO	7.49%	8.49%	—	—	-5.92%	-8.74%	2.34%	0.50%	—	—	8.33%	13.0%
TORSO	-7.14%	-6.97%	—	—	-8.59%	-10.7%	-6.69%	-7.17%	—	—	-5.66%	-4.07%
ABS	-14.2%	-15.5%	—	—	-14.4%	-17.6%	-5.54%	-3.87%	—	—	-4.75%	-1.02%
ESC	-8.80%	-11.7%	-11.3%	-18.3%	-5.59%	-10.9%	-7.09%	-5.74%	-9.59%	-5.56%	-6.56%	-0.79%
AWD	—	—	36.3%	30.9%	13.6%	13.0%	—	—	0.51%	0.03%	-0.43%	-2.11%
VEHAGE	0.93%	1.62%	1.87%	3.34%	1.61%	2.78%	0.79%	0.04%	1.53%	0.46%	1.10%	0.57%
BRANDNEW	3.44%	4.65%	-0.23%	0.51%	-1.13%	-1.96%	2.70%	2.82%	3.56%	4.85%	-2.60%	-1.96%
DRVMALE	5.49%	10.7%	-3.28%	-0.35%	1.97%	5.47%	-0.79%	-5.62%	-0.07%	-1.98%	4.54%	1.58%
M14_30	4.10%	5.15%	3.93%	4.55%	4.74%	5.73%	0.43%	-0.72%	0.47%	-0.44%	0.28%	-1.22%
M30_50	0.51%	0.94%	0.49%	0.76%	0.23%	0.53%	-0.15%	-0.43%	-0.24%	-0.52%	-0.39%	-0.60%
M50_70	-0.01%	0.01%	0.35%	0.31%	0.38%	0.50%	1.26%	1.18%	1.22%	1.16%	1.15%	1.05%
M70_96	3.60%	4.54%	3.79%	4.32%	3.15%	3.97%	2.17%	1.39%	1.89%	1.46%	1.93%	1.20%
F14_30	3.36%	4.58%	3.72%	4.73%	3.59%	4.66%	0.38%	-0.63%	-0.16%	-1.28%	0.56%	-0.81%
F30_50	0.26%	0.47%	0.09%	0.14%	0.11%	0.25%	-0.68%	-0.93%	-0.22%	-0.24%	-0.44%	-0.52%
F50_70	0.62%	0.93%	0.95%	0.91%	0.90%	1.11%	0.89%	0.61%	1.14%	1.22%	1.19%	0.87%
F70_96	4.00%	4.87%	3.05%	3.56%	3.85%	4.61%	1.90%	1.11%	0.83%	0.32%	1.33%	0.40%
NITE	20.2%	32.0%	28.6%	35.9%	19.9%	26.8%	23.5%	15.3%	20.8%	12.5%	17.4%	13.3%
RURAL	10.6%	15.1%	15.0%	12.8%	13.5%	13.3%	30.1%	28.7%	26.7%	26.4%	23.2%	22.7%
SPDLIM55	33.1%	60.0%	25.1%	53.1%	19.2%	44.7%	55.5%	42.6%	63.9%	50.5%	63.4%	54.5%
CY2005	-0.12%	-6.09%	3.13%	3.25%	-4.34%	-8.00%	19.1%	22.3%	24.1%	25.4%	17.2%	20.6%
CY2006	0.14%	-2.28%	2.11%	4.46%	-5.65%	-4.83%	14.3%	15.9%	19.0%	19.3%	17.3%	18.0%
CY2007	2.80%	0.49%	4.96%	6.50%	-1.06%	-1.93%	7.82%	9.22%	11.3%	11.8%	11.55%	12.7%
CY2008	-0.27%	-1.60%	1.32%	1.78%	-1.93%	-2.17%	4.47%	4.85%	7.90%	7.29%	6.20%	6.36%
CY2010	2.82%	2.30%	0.42%	-0.92%	2.14%	1.42%	-11.3%	-12.0%	-9.75%	-10.3%	-1.88%	-2.26%
CY2011	7.04%	9.9%	0.46%	1.08%	4.63%	6.43%	-20.8%	-25.7%	-23.0%	-26.6%	-17.3%	-22.7%
AL	95.1%	43.1%	79.7%	25.2%	104%	43.6%	-24.2%	37.8%	-36.2%	29.6%	-40.6%	28.3%
KS	56.1%	14.4%	60.3%	13.4%	81.7%	35.6%	-161%	-107%	-167%	-106%	-146%	-90.9%
KY	114%	40.5%	113.0%	31.3%	141%	55.7%	-156%	-89.5%	-169%	-95.6%	-173%	-101%
MD	14.4%	14.0%	1.46%	-3.76%	6.2%	6.63%	-58.2%	-62.9%	-61.3%	-63.2%	-58.2%	-64.7%
MI	94.9%	32.0%	92.2%	21.5%	102%	36.8%	-203%	-138%	-211%	-137%	-206%	-138%
MO	83.7%	33.0%	64.0%	10.6%	88.0%	29.5%	-127%	-77.4%	-131%	-78.1%	-136%	-81.0%
NE	80.8%	10.3%	74.3%	0.61%	86.6%	9.25%	-134%	-60.3%	-140%	-65.9%	-145%	-71.6%
NJ	100%	53.2%	101%	44.2%	110%	50.5%	-281%	-237%	-283%	-233%	-304%	-252%
PA	-22.5%	-1.22%	-13.6%	5.63%	-7.2%	10.8%	-154%	-174%	-143%	-161%	-154%	-177%
WA	37.3%	—	53.8%	—	73.4%	—	-194%	—	-190%	—	-201%	—
WI	46.5%	6.46%	45.8%	-3.57%	54.5%	4.6%	-144%	-99.1%	-155%	-105%	-149%	-99.2%
WY	84.3%	28.7%	41.4%	-20.0%	79.9%	17.2%	-188%	-120%	-182%	-122%	-176%	-105%

* Values in red are statistically significant at the 95% level. Estimates shaded green are in the expected direction, those shaded yellow are in the opposite direction.

4. Conclusions

This report confirms the findings of the 2012 LBNL Phase 2 analysis regarding the relationship between mass or footprint reduction on the two components of casualty risk per VMT, crash frequency and casualty risk per crash. Mass reduction continues to be associated with increases in crash frequency in all five vehicle types, especially lighter-than-average cars and light-duty trucks, while mass reduction is associated with decreases in both fatality risk and casualty risk per crash in all vehicle types, especially in CUVs/minivans and for casualty risk per crash in lighter-than-average cars. Footprint reduction is associated with an increase in crash frequency only for light trucks, and with decreases in crash frequency for cars and CUVs/minivans; footprint reduction does not have a statistically-significant effect on fatality risk per crash, and an increase in casualty risk per crash for cars.

We conducted several sensitivity analyses to see if adding additional variables, both individually and together, to the baseline regression model reverses the unexpected relationship between mass reduction and increased crash frequency. For the most part, including these additional variables does not change the general results of the baseline regression model. It remains unclear why lower vehicle mass is associated with higher crash frequency, but lower risk per crash; it is possible that other, more subtle, differences in vehicles and their drivers may account for these unexpected findings. On the other hand, it is also possible that over thirty years of improvements in vehicle design to achieve high crash test ratings have enabled manufacturers to design vehicles to mitigate some of the safety penalty of low mass vehicles.

The estimated effects of the control variables accounting for other vehicle, driver, and crash circumstance variables are fairly consistent, for both fatality and casualty risk per crash or per VMT. In many cases, however, there are several unexpected results: bumper height compatibility measures in light trucks, and some types of side airbags in cars and CUVs/minivans, are associated with decreases in crash frequency; AWD is associated with an increase in crash frequency; ESC and ABS are associated with decreases in risk once a crash has occurred; and AWD, male drivers, young drivers, and driving at night, in a rural county, or on a high-speed road, are all associated with increases in risk once a crash has occurred. These unexpected results suggest that important control variables are not being included in the regression models.

We investigated these unexpected results by re-running the regression models including only severe crashes, in an attempt to control for crash severity. In some cases, excluding the non-severe crashes reduces the unexpected results from the baseline model; however, in none of the estimates does excluding the non-severe crashes change the sign on the estimated coefficient to the expected direction. We therefore conclude that not accounting for crash severity in the baseline model is not the reason why many control variables have unexpected associations with crash frequency or risk per crash.

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Appendix A: Discussion of Crash Frequency and Risk Per Crash Results in Kahane 2012

Below is the discussion of DRI's estimates of crash frequency and risk per crash included in Kahane 2012.

> For passenger cars and truck-based LTVs, overall and for many of the individual crash types, these analyses tend to show that (1) mass reduction lowers F/A *[i.e. risk per crash]*, but (2) increases A/VMT *[i.e. crash frequency]*.
>
> The analyses appear to be computationally valid. The sum of the F/A and the A/VMT coefficients is usually close to the baseline coefficients in NHTSA's analysis.
>
> However, in most of their tables, Van Auken and Zellner label the column of F/A coefficients as the "effect of mass reduction on **crashworthiness** and crash compatibility" and the A/VMT coefficients as its "effect on **crash avoidance**." In other words, the tables say mass reduction benefits crashworthiness and harms crash avoidance. NHTSA believes these are not accurate characterizations of the coefficients and they lead, in turn, to misunderstandings. Specifically, the ICCT in their public comment argue that the observed benefit to crashworthiness and harm to crash avoidance is counterintuitive and may be evidence of a flaw in the baseline analysis, such as a need for additional or different control variables.
>
> NHTSA believes the metric of fatalities per reported crash (F/A) does not measure just crashworthiness but also certain important aspects of crash avoidance, namely the severity of a crash. In addition, it could be influenced by how often crashes are reported or not reported.
>
> Conceptually, crashworthiness is the likelihood that an occupant will survive, given an impact to a vehicle that in turn results in a particular physical insult to the occupant. It is quite appropriate for the regression analyses to control for driver age and gender, because it is known that, given the same physical insult, a person is more likely to die with each year that he or she gets older. Furthermore, from young adulthood up to middle age, a female is more likely to die from the same physical insult as a male of the same age. Crash-data analyses have shown increases in fatality risk of 2 to 4 percent for each year that a person gets older. Young adult females are 20 to 30 percent more vulnerable than males of the same age; that differences decreases over time and eventually reverses by late middle age, but averaging across all ages, females are still 5 to 20 percent more vulnerable than males of the same age.
>
> In other words, if these F/A regressions truly modeled crashworthiness, the analyses of the crash types where most fatalities are in the case vehicle (rollover, fixed-object, heavy-truck, and the various types of collisions where the other vehicle is heavier) should have coefficients like -0.03 for M14_30, F14_30, M30_50, and F30_50, each of which measure how many years the driver is younger than 30 or 50, respectively. They should have coefficients like +0.03 for M50_70, F50_70, M70_96, and F70_96, which measure how many years the driver is older than 50 or 70. They should have a coefficient like -

0.10 for DRVMALE, because a male is less vulnerable than a female. In crashes where the fatalities are uncommon in the case vehicle (hitting a pedestrian or a much lighter vehicle), the coefficients should all be close to zero, because the age or gender of the driver will not affect how the pedestrian reacts to a physical insult.
Instead, the regressions rather consistently estimate positive or near-zero coefficients for M14_30, F14_30, M30_50, and F30_50 and positive coefficients for DRVMALE. They say F/A decreases as the occupant ages up to age 50 and F/A is lower for females than males.

A more blatant example: on purely crashworthiness considerations, whether it is light or dark outside ought to have little effect on the risk of death from a given physical insult, except perhaps to the extent it affects EMS arrival. But NITE is consistently associated with an extraordinary increase in F/A.

Of course, it is obvious what is going on. These crash data have no measure of crash severity, such as delta v. M14_30, F14_30, M30_50, F30_50, DRVMALE, and NITE all act as surrogates for crash severity. They not only indicate crashworthiness (ability to survive a physical insult) but also, and in some cases primarily, crash avoidance – namely, the ability of age 30-50 drivers, females, and daytime drivers to stay out of situations that lead to fatal crashes, while having their share of fender-benders. Driving at night, on the other hand, is a way to avoid fender-benders characteristic of rush-hour traffic and thereby increases F/A.

Just as many of the control variables in the F/A regressions measure effects of crash avoidance in addition to (and sometimes in place of) crashworthiness, by the same token, there is no particular reason that the coefficients for UNDRWT00, OVERWT00, and FOOTPRNT measure the effects of crashworthiness exclusively and not also crash avoidance. Control variables such as M14_30, F14_30, M30_50, F30_50, DRVMALE, NITE, and also SPDLIM55 and RURAL may account for much of the effect of crash severity on risk per reported crash, but it is unknown exactly how much.

A salient feature of NHTSA's approach, where the numerator is fatalities and the denominator VMT, is to take crash-reporting rates out of the formula for calculating risk. A fatality is a fatality and a mile of travel is a mile of travel – unlike contact events that may or may not be police-reported, depending on the vehicle, the driver, the locality, or the circumstances of the moment. These analyses of F/A and A/VMT appear to be computationally valid, but NHTSA doubts they truly measure the "effect of mass reduction on crashworthiness" and "effect of mass reduction on crash avoidance."