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Author
Wenzel, Tom

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The Effect of Recent Trends in Vehicle Design on U.S. Societal Fatality Risk per Vehicle Mile Traveled, and Their Projected Future Relationship with Vehicle Mass

Tom Wenzel, Lawrence Berkeley National Laboratory
1 Cyclotron Road, 90R2000
Berkeley, CA 94720
Phone: 510-486-5753
Fax: 510-486-6996
TPWenzel@lbl.gov

Abstract

The National Highway Traffic Safety Administration (NHTSA) recently updated its 2003 and 2010 logistic regression analyses of the effect of a reduction in light-duty vehicle mass on US fatality risk per vehicle mile travelled (VMT). The current NHTSA analysis is the most thorough investigation of this issue to date. LBNL's assessment of the analysis indicates that the estimated effect of mass reduction on risk is smaller than in the previous studies, and statistically non-significant for all but the lightest cars.

The effect three recent trends in vehicle designs and technologies have on societal fatality risk per VMT are estimated, and whether these changes might affect the relationship between vehicle mass and fatality risk in the future. Side airbags are found to reduce fatality risk in cars, but not necessarily light trucks or CUVs/minivans, struck in the side by another light-duty vehicle; reducing the number of fatalities in cars struck in the side is predicted to reduce the estimated detrimental effect of footprint reduction, but increase the detrimental effect of mass reduction, in cars on societal fatality risk. Better alignment of light truck bumpers with those of other vehicles appears to result in a statistically significant reduction in risk imposed on car occupants; however, reducing this type of fatality will likely have little impact on the estimated effect of mass or footprint reduction on risk. Finally, shifting light truck drivers into safer, car-based vehicles, such as sedans, CUVs, and minivans, would result in larger reductions in societal fatalities than expected from even substantial reductions in the masses of light trucks. A strategy of shifting drivers from truck-based to car-based vehicles would reduce fuel use and greenhouse gas emissions, while improving societal safety.

Keywords: Fatality risk, logistic regression, vehicle mass, vehicle footprint, side airbags, ESC, compatibility

Introduction

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. Reducing vehicle mass is perhaps the easiest and least expensive method to improve fuel economy and reduce green house gas emissions. For this reason the new 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.

The National Highway Traffic Safety Administration (NHTSA) recently completed an update of its 2003 and 2010 studies of the relationship between vehicle mass and US fatality risk per vehicle mile traveled, in support of the upcoming joint rulemaking on new fuel economy and greenhouse gas emission standards for new vehicles sold in 2017 to 2025 (NHTSA 2012). LBNL used the same data and methods to replicate NHTSA's analysis, examined the effect of changing the data and control variables used in their regression models, and analyzed the relationship between mass reduction and risk by vehicle model (Wenzel 2012).

For its baseline analysis NHTSA assumed that all new vehicles will have electronic stability controls (ESC) installed by 2017, which will reduce the fraction of fatalities in rollovers and crashes with stationary objects, and thus will increase the estimated detrimental overall effect of mass reduction, but decrease the estimated detrimental overall effect of footprint reduction, on US societal fatality risk per vehicle mile traveled (VMT). However, other recent trends that are likely to continue through 2017, such as the installation of side airbags, better alignment of light truck bumpers with those of other vehicles, and the shift in market share from truck-based pickups and SUVs to car-based minivans and crossover utility vehicles (CUVs) may also affect the distribution of crashes in that year. This paper summarizes our analysis of the effect of recent trends in vehicle design on US societal fatality risk per VMT, and its relationship with vehicle mass.

Several recent studies have estimated the relationship between mass and risk: (Broughton 1996a, 1996b, 1996c, 2008, 2012; Toy and Hammitt 2003; Evans 2004a and 2004b; Kim et al. 2006; Fredette et al. 2008; Martin and Lenguerrand 2008; Tolouei and Titheridge 2009; Eyges and Padmanaaban 2009). A discussion of these analyses and a comparison with the main conclusions of the NHTSA 2012 analysis is included in a companion paper (Wenzel, submitted). In addition, several have evaluated the effectiveness that new technologies ESC (Farmer 2006; Sivinski 2011), side airbags (Kahane 2007; McCartt and Kyrychenko 2007), and compatibility measures (Baker et al. 2008; Ossiander et al. 2013) have in reducing fatality risk. However, none of these studies have evaluated whether widespread introduction of these technologies are expected to change the current relationship between vehicle mass and fatality risk per vehicle-mile traveled (VMT).

Data and methods

Information on all US traffic fatalities in crashes involving model year 2000 to 2007 light-duty vehicles that occurred between 2002 and 2008, from the Fatality Analysis Reporting System (FARS) were used in the regression analyses. Fatalities include those in both the case vehicles and any of their crash partners, including medium- and heavy-duty vehicles, motorcycles, bicyclists, and pedestrians. NHTSA ran separate regression models run for each of three types of vehicles (passenger cars, light-duty trucks, and car-based crossover utility vehicles, or CUVs, and minivans), and for each of nine types of crashes (first-event rollovers; crashes with stationary objects, motorcycles/bicycles/pedestrians, heavy-duty vehicles, and four categories of other light-duty vehicles; and all other crashes, most involving three or more vehicles) for a total of 27 regression models. Crashes with another light-duty vehicle were categorized into four additional types based on the type and weight of the crash partner: a car, CUV or minivan lighter or heavier than average (1,398 kg), and a pickup or truck-based SUV lighter or heavier than average (1,882 kg). NHTSA excluded case vehicles that were considered "sporty" cars, cars used primarily for police use, cars with all-wheel drive, and fullsize vans from its initial analysis.

NHTSA created an "induced exposure file", using a subset of non-culpable vehicles involved in two-vehicle crashes from police-reported crash data from thirteen states, to represent crashes that did not lead to a fatality. These thirteen states (AL, FL, KS, KY, MD, MI, MO, NE, NJ, PA, WA, WI and WY) were selected because they provide the first 12 digits of the 17-digit vehicle identification number (VIN) which can be decoded to determine the model year and model of each vehicle. These records provide distributions of a random sample 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). NHTSA then gave each induced exposure record a weighting factor, so that each represents a number of national vehicle registrations of a particular model year, make and model; the sum of the weighting factors equals the number of vehicles registered in the country. Each record was also given an annual vehicle miles traveled (VMT) weighting factor, based on vehicle year, make/model, and age, using odometer data provided by R.L. Polk. NHTSA's databases of fatal crashes, and of induced-exposure crashes used to develop national vehicle registration and annual miles traveled weights, are available for download at: ftp://ftp.nhtsa.dot.gov/CAFE/; for more details on NHTSA's data and methodology, refer to NHTSA 2012.

NHTSA combined the databases of fatal crashes and induced exposure cases, in order to estimate the likelihood that a given vehicle/driver combination driven over a certain number of miles results in a crash fatality. The analysis involved running a logistic regression model with total crash fatalities as the dependent variable for each of the nine crash types and the three vehicle types, for a total of 27 regressions. Because all fatalities in the crash were used, the risks reflect societal risk, rather than just the risk to the occupants of the case vehicle. The induced exposure cases were weighted by the number of vehicle registrations and the annual mileage, so that the models are estimating the effect of changes in the control variables on US societal fatalities per vehicle mile traveled (VMT).

NHTSA compiled a database of curb weight and footprint, as well as other vehicle attributes, by model year, make and model. For cars and trucks, two variables (UNDRWT00, OVERWT00) were used for vehicle weight, allowing the effect of weight on risk to vary for lighter- and heavier-than-average vehicles. The determination of the two weight classes is based on the average weight for model year 2000 to 2007 versions of each vehicle type: 1,433 kg for cars and 2,247 kg for light-duty trucks. Because there are fewer CUVs and minivans in the database, a single variable, LBS100, was used for CUV/minivan weight.

Table 1 lists the control variables NHTSA used in its regression analyses. Control variables were used for two door cars, truck-based SUVs, heavy-duty (i.e. 3/4- and 1-ton rated) pickups, and minivans. Several new variables are added for new safety technologies and designs that

Table 1. Control variables used in regression models, by type of case vehicle

Type	Control variable	Description	Cars	Light trucks	CUVs/ minivans.
Vehicle variables	UNDRWT00	Lbs (in hundreds) less than average curb weight (all negative values)	C	C	—
	OVERWT00	Lbs (in hundreds) more than average curb weight (all positive values)	C	C	—
	LBS100	Lbs curb weight (in hundreds)	—	—	C
	FOOTPRINT	Wheelbase times track width, in sq feet	C	C	C
	TWODOOR	Two-door car	D	—	—
	SUV	Truck-based SUV	—	D	—
	HD_PKP	Heavy-duty pickup (200/300 series)	—	D	—
	BLOCKER1	Option 1 compatibility (bumper overlap)	—	D	—
	BLOCKER2	Option 2 compatibility ("blocker beam")	—	D	—
	MINIVAN	Minivan	—	—	D
	ROLLCURT#	Curtain airbag that deploys in rollovers	C #	—	C #
	CURTAIN #	Curtain side airbag	C #	—	C #
	COMBO #	Combo curtain/torso side airbag	C #	—	C #
	TORSO #	Torso side airbag	C #	—	C #
	ABS	Automated braking system	C #	—	C #
	ESC	Electronic stability control	C #	C #	C #
	AWD	All-wheel drive	—	C #	C #
	VEHAGE	Vehicle age	D	D	D
	BRANDNEW	Vehicle age = 0	C	C	C
Driver variables	DRVMALE	Driver is male	C	C	C
	M14_30	Number of years male driver is	C	C	C
	M30_50	younger than 50 years old	C	C	C
	M50_70	Number of years male driver is	C	C	C
	M70_96	older than 50 years old	C	C	C
	F14_30	Number of years female driver is	C	C	C
	F30_50	younger than 50 years old	C	C	C
	F50_70	Number of years female driver is	D	D	D
	F70_96	older than 50 years old	D	D	D
Crash variables	NITE	Crash occurred at night	D	D	D
	RURAL	Crash occurred in rural county (<250 population / square mile)	D	D	D
	SPDLIM55	Crash occurred on a roadway with speed limit of 55 mph or higher	C	C	C
	HIFAT_ST	Crash occurred in a high fatality risk state (25 Southern and Mountain states, plus KS and MO)	D	D	D
	CY2002	Crash occurred in 2002	D	D	D
	CY2003	Crash occurred in 2003	D	D	D
	CY2004	Crash occurred in 2004	D	D	D
	CY2005	Crash occurred in 2005	D	D	D
	CY2007	Crash occurred in 2007	D	D	D
	CY2008	Crash occurred in 2008	D	D	D

C: continuous variable

C #: for some vehicles 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

CURTAIN, COMBO, and TORSO airbags are included in regression models for all non-rollover crashes involving cars or CUVs/minivans, except motorcycle/bicycle/pedestrian crashes. A single variable for ROLLCURT airbags replaces the CURTAIN, COMBO, and TORSO variables in the regression for rollovers.

were not included in previous studies: electronic stability controls (ESC), four types of side airbags (ROLLCURT, CURTAIN, COMBO, TORSO),[1] 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, BLOCKER2). Vehicles with automated braking systems (ABS) and all-wheel drive (AWD) were identified, as was the vehicle age and whether the vehicle was brand new (i.e. vehicle age of zero). Eight variables for driver age were used, in addition to whether the driver was male. To account for crash conditions, control variables for whether the crash occurred at night, in a rural county, on a roadway with a speed limit of 55 miles per hour or greater, or in a state that has a relatively high fatality rate per VMT, as well as the calendar year in which the crash occurs, were included. As noted in Table 1, not all control variables were used in the regression models for each type of vehicle or crash.

Rather than reporting coefficients for the variables of interest (curb weight and footprint) from a single regression model across all crash types, NHTSA reported a weighted average of the coefficients from the nine regression models run for each of the nine crash types. NHTSA used 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. NHTSA derived the baseline fatalities from MY04-09 vehicles in crashes between 2004 and 2008. NHTSA then adjusted this baseline distribution of fatalities 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 (Sivinski 2011). These assumptions treated CUVs and minivans as light trucks rather than cars. This "post-ESC" distribution of fatalities by crash type was then multiplied by the regression coefficients for each crash type to create the weighted average effect of each control variable on risk.

LBNL used the data and methods described above to recreate the NHTSA results. All of the regression coefficients presented in the NHTSA 2012 report are the direct output from the SAS LOGIST procedure (with the exception of those for the mass and footprint variables UNDRWT00, OVERWT00, LBS100, and FOOTPRNT, which NHTSA multiplies by -1 so that they reflect the effect of a <u>decrease</u> in vehicle mass or footprint; the same convention is used here). The output from the SAS LOGIST procedure reflects the percent change in the <u>log-odds</u> of fatality per billion VMT for a one-unit increase in the explanatory variable. In order to obtain the <u>percent change in the probability</u> of fatality, the SAS outputs need to be converted from log-space to linear space, and from odds to probabilities. The equation $e^x - 1$, where x is the logistic regression coefficient from the SAS output, is used to make this conversion. This conversion has no effect on the output regression coefficients when the change in the log-odds of fatality is small; however it substantially increases the percent change for explanatory variables that have a large effect on the log-odds of fatality (such as the crash location variables). For example, the

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[1] The control variable ROLLCURT airbags is included 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 are included in the regression models for light trucks.

fatality risk from a rollover crash involving a car has a 2.20 times higher log-odds of fatality if it occurs in a rural county; after conversion, this crash has a 802 percent higher probability of fatality if it occurs in a rural county (EXP(2.20) - 1 = 8.02). The 95% confidence intervals reported here are calculated the same way, using the standard error of the log-odds output by the SAS LOGIST procedure.

The main results of the NHTSA and LBNL 2012 analyses on the relationship between vehicle mass or footprint and US societal fatality risk per VMT are summarized in a companion paper (Wenzel submitted).

ESC is expected to reduce fatalities in all types of crashes, but particularly in rollovers and crashes with stationary objects; however, side airbags are expected to reduce fatalities when a vehicle is struck in the side, while compatibility measures are expected to reduce fatalities in both frontal and side-impact crashes. For the analysis of the expected effect of full adoption of side airbags and compatibility measures, LBNL ran separate regression models where the dependent variable is the risk of fatality to the occupants in the struck vehicle only. Fatalities to occupants of the case vehicle are identified in the NHTSA dataset by the DEATHS variable, as opposed to the FATALS variable (which identifies all of the fatalities in the crash, including those in any crash partner vehicle). Regression models were run for three configurations of crashes with another light-duty vehicle: when the case vehicle struck another vehicle head-on, when it was struck in the side (either driver or passenger side), and all other two-vehicle crashes (case vehicle struck in the rear, or case vehicle striking another vehicle in the side or rear). The crash configuration was determined using the IMPACT1 variable in FARS,[2] which is the clock position of the initial impact, for both vehicles in a two-vehicle crash. Clock positions of 11, 12, or 1 were considered a frontal impact; of 2 through 4, or 8 through 10, a side impact (with no distinction between near- or far-side crashes relative to the driver); and 5 though 7 a rear impact.

Results

As discussed above, NHTSA estimated the change in fatalities in 2017-2025 after assuming full market penetration of electronic stability control (ESC) in new vehicles. As shown in Figure 1, manufacturers began installing ESC as a standard feature in model year 2005; by 2007 half of 2007 CUVs and minivans, a third of 2007 light trucks, but less than 5% of cars have ESC. As NHTSA has required ESC on all light-duty vehicles by 2012, there likely has been a quick increase in the market penetration of ESC in new vehicles, including cars, between 2007 and 2012. There are other trends in vehicle technologies, in addition to ESC, that may affect baseline fatalities in 2017 through 2025. Side airbags are becoming standard equipment on most vehicles, and manufacturers are taking measures to improve light truck compatibility with other vehicles in frontal crashes. And in recent years there has been a market shift from truck-based SUVs to

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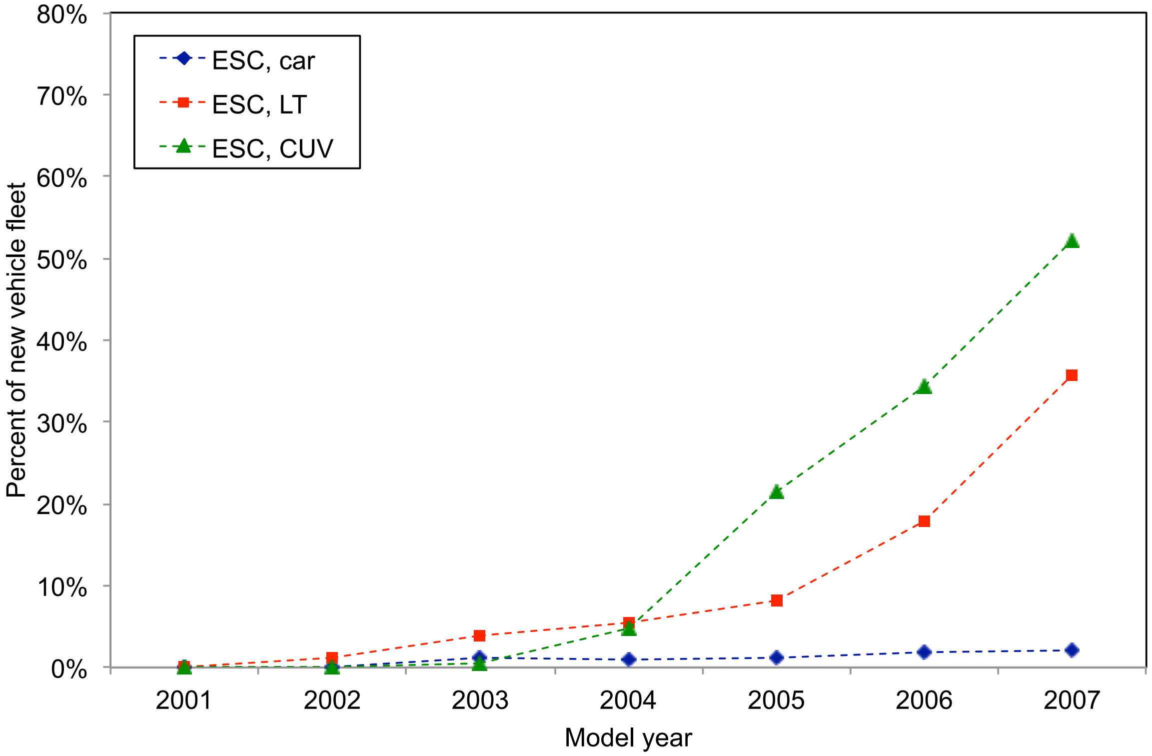
[2] The IMPACT1 variable is not included in NHTSA's public dataset. This variable was added to the public dataset by matching records in the public dataset with original FARS records, by CY, state, and crash case number.

Figure 1. Market penetration of ESC, by vehicle type and model year



car-based CUVs. In this section the influence these trends, if they continue, may have on the effect of mass reduction on risk in the 2017-2025 timeframe is analyzed.

A recent NHTSA study estimated 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 estimates treated crossover SUVs and minivans as light trucks rather than cars.) Figure 2 compares these recent results, shown in red, with the estimated effect of ESC installation on fatality risk from NHTSA's regression models in the 2012 analysis, by vehicle and crash type. The figure indicates that the current analysis gives comparable estimates for ESC effectiveness for cars in rollovers, light trucks in rollovers and crashes with objects, and CUVs/minivans in crashes with objects. However, the current analysis estimates a lower ESC effectiveness for car crashes with objects, and CUV/minivan rollovers, than the Sivinski study. On the other hand, the current study estimates substantially higher ESC effectiveness in reducing risk in crashes with other vehicles in many cases.

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[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.

Figure 2. Estimated effect of ESC on US societal fatality risk per VMT, by vehicle type and crash type

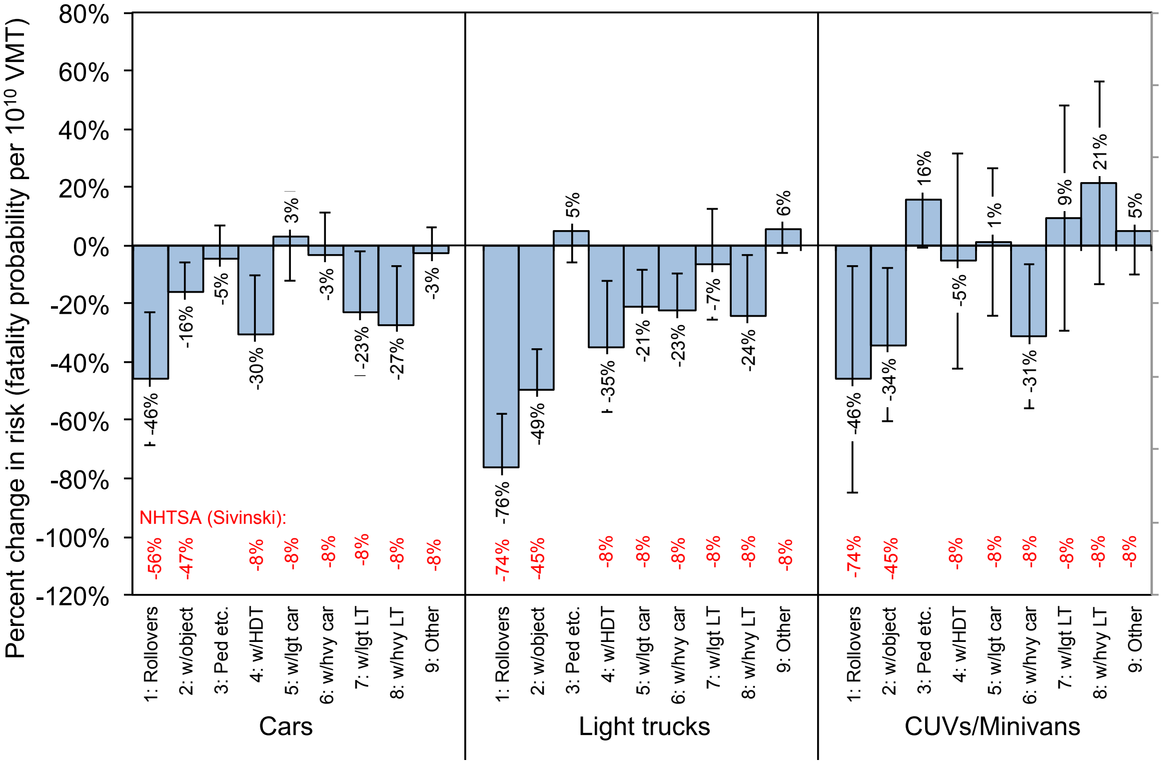


Table 2 shows the estimated effect of a 45-kg reduction in mass, or a 0.09-m^2 reduction in footprint, on risk, by vehicle and crash type, from the NHTSA 2012 and LBNL 2012a studies. For cars, mass reduction is associated with an increase in risk in all crash types except rollovers and crashes with stationary objects; mass reduction in CUVs and minivans is also associated with large and statistically significant reductions in risk in rollovers and crashes with stationary objects. A possible explanation for why mass reduction reduces risk in rollovers is that once a vehicle rolls over, a lighter vehicle applies less force on its roof than a heavier vehicle. And if additional mass is sufficient to knock down a stationary object such as a small tree or pole, it can protect occupants in a one-vehicle crash; however, additional mass will increase the kinetic crash energy, and likely increase occupant risk if the object is immovable. The estimated effect of mass or footprint reduction on overall fatality risk is shown in the next-to-last row of the table. Because NHTSA assumes that by 2017 ESC will have eliminated many of the fatalities in rollovers and crashes with stationary objects, and these are the only types of crashes in which mass reduction reduces risk, NHTSA's weighted regression estimates for 2017-2025 show a larger increase in overall risk for cars (a 1.55% and 0.51% increase for lighter- and heavier-than-average cars, respectively; last row of Table 2) than the estimates based on the current distribution of fatalities (a 1.27% and 0.37% increase for lighter- and heavier-than-average cars, respectively). For CUVs and minivans, full adoption of ESC is estimated to reduce the small overall benefit in fatality risk from mass reduction (from a 0.70% reduction to a 0.38% reduction in risk). On the other hand, footprint reduction is associated with the largest risk increases in rollovers and crashes with stationary objects, so removing fatalities in these types of crashes will reduce the estimated overall detrimental effects of footprint reduction. For example, footprint reduction in cars increases risk by 7.76% in rollovers and 3.93% in crashes with a stationary object; full adoption of ESC reduces the detrimental effect of footprint reduction in cars from a 2.16% overall increase in risk to a 1.87% overall increase in risk.

Table 2. Estimated effect of a 45-kg reduction in mass or a 0.09-m^2 reduction in footprint on US societal fatality risk, by vehicle and crash type

	Effect of 45-kg reduction in mass					Effect of 0.09-m^2 reduction in footprint		
Crash type	Cars < 1433 kg	Cars > 1433 kg	LTs < 2247 kg	LTs > 2247 kg	CUV/ minivan	Cars	LTs	CUV/ minivan
Rollover	-1.85%	-2.93%	0.65%	-1.29%*	-7.27%*	7.76%*	1.18%*	10.94%*
w/stationary object	-0.46%	-1.30%	-1.40%*	0.76%	-3.68%*	3.93%*	1.97%*	7.39%*
w/cycles, pedestrians	2.01%*	-0.14%	1.06%	-0.05%	-1.58%	0.91%	-1.25%*	0.37%
w/heavy-duty truck	2.24%	0.39%	1.61%	0.32%	1.92%	2.92%*	0.75%	4.56%
w/light car	0.75%	0.26%	-0.09%	-0.92%*	-0.09%	0.23%	-0.21%	-0.79%
w/heavy car	0.48%	1.61%	-0.71%	-1.38%*	1.67%	0.49%	0.31%	-2.21%
w/light light truck	1.17%	0.53%	-0.63%	-0.97%	3.75%	3.88%*	1.00%	-4.13%
w/heavy light truck	5.88%*	2.32%	4.36%*	0.53%	-0.93%	1.75%	-1.70%*	3.73%
Others	1.93%*	1.16%	0.73%	-0.11%	-0.40%	1.13%	-0.44%	2.68%*
All, current disn	1.27%*	0.37%	0.42%*	-0.36%*	-0.70%	2.16%*	0.14%	2.25%*
All, 2017 disn#	1.55%*	0.51%	0.52%*	-0.34%*	-0.38%	1.87%*	-0.07%	1.72%*

* statistically significant at the 95% level.

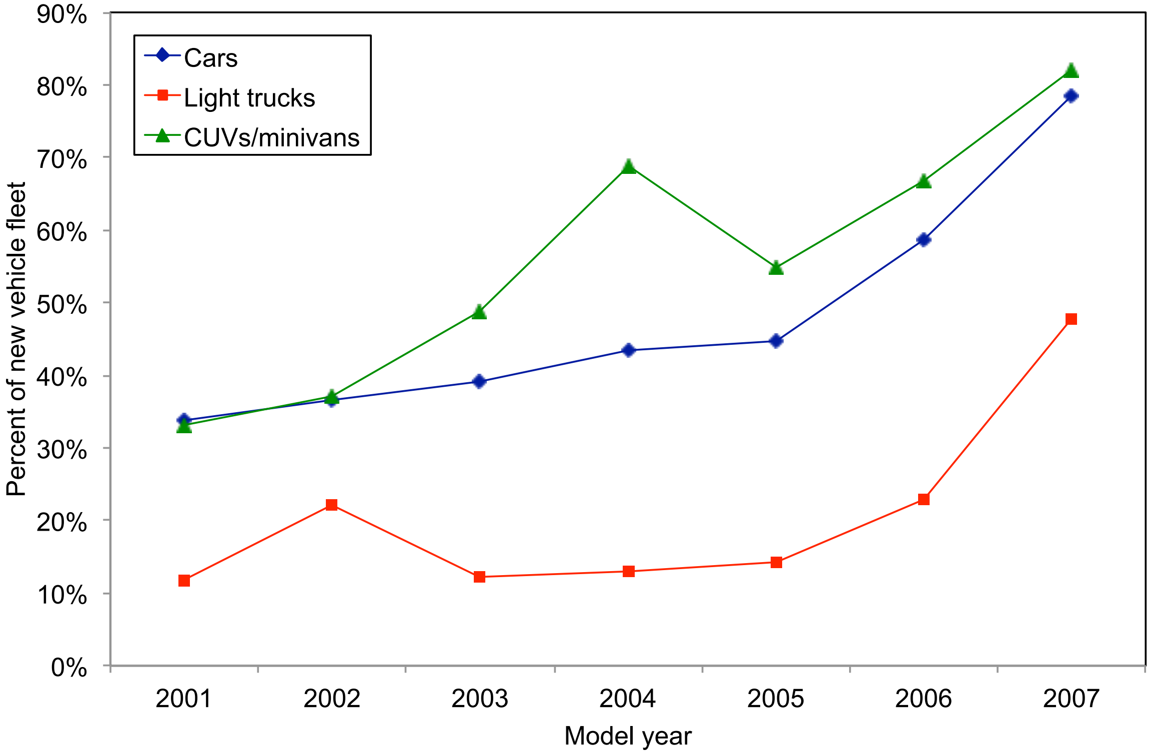
\# coefficients for each crash type reweighted after removing avoided fatal crashes due to full adoption of ESC, based on Sivinski estimate of ESC effectiveness by crash type shown in Figure 2

Side airbags

Figure 3 shows the recent trend in the market penetration of side airbags in new vehicles. The data in Figure 3 are only for vehicles coded in the NHTSA database as having zero or 100% of a particular airbag technology; because side airbag technologies are optional equipment on many models, particularly light trucks, NHTSA used the fraction of vehicles of these models that had the technology installed. The data in Figure 3 account for 80% to 90% of all cars, 60% to 100% of all light trucks, and 77% to 86% of all CUVs/minivans, depending on the model year. Because many models are coded as having both side curtain and side torso airbags, the figure shows the fraction of new vehicles that have any type of side airbag technology installed.

About one third of model year 2001 cars and CUVs/minivans had any type of side airbag; this fraction has grown to about 80% as of model year 2007. Light trucks are less likely to come equipped with any type of side airbag; 12% of 2001 light trucks came equipped with side airbags, rising to nearly 50% of 2007 light trucks. Figure 3 indicates that side airbags have been available for a longer period than ESC, and by model year 2007 were more prevalent than ESC for all three types of vehicles (compared with Figure 1).

Figure 3. Market penetration of side impact airbags, by vehicle type and model year



Side airbags should reduce fatality risk in crashes when another vehicle strikes the case vehicle in the side, by minimizing occupant contact with the interior near and far sides of the cabin, and perhaps with any components of the striking vehicle that intrude into the cabin (curtain side airbags are designed to also deploy in rollovers and severe frontal crashes). A recent analysis (McCartt and Kyrychenko 2007) found that, regardless of striking vehicle type, cars struck in the side had a 37 percent lower fatality risk when equipped with head-protecting side airbags, and a 26 percent lower fatality risk when equipped with torso-only side airbags. For SUVs, head-protecting side airbags reduced fatality risk 52 percent, while torso-only airbags reduced risk by 30 percent. There were insufficient data to estimate the effectiveness of side airbags in reducing fatality risk in pickups and minivans.

Table 3 shows the result of a regression model that combines the NHTSA side airbag variables CURTAIN, TORSO, and COMBO into a single SIDEAB variable. The table shows the estimated effect any side airbag technology has on the risk of fatality to the occupants in the struck vehicle only when struck in the side (either driver or passenger side), by struck and striking vehicle type. Table 3 suggests that the presence of any type of side airbag is estimated to reduce fatality risk in cars by 35% and 40% when struck in the side by another car, and by 21% and 24% when struck in the side by a light truck. Side airbag technology is slightly more beneficial to car occupants when struck by another car than when struck by a light truck. The benefits do not appear to be affected by the mass of the striking vehicle; in other words, when a car is struck in the side by another car, the protective effect of side airbags is nearly the same regardless of the mass of the striking car. And when a car is struck in the side by a light truck, the protective effect of side airbags is unaffected by the mass of the striking light truck.

Table 3. Estimated effect of any type of side air bag on 2002 to 2008 US fatality risk in model year 2000 to 2007 vehicles struck in the side, by struck and striking vehicle type

	Vehicle struck in the side		
Striking vehicle	Car	Light truck	CUV/minivan
Car < 1,398 kg	-40%* (+/- 24%)	12% (+/- 60%)	-44% (+/- 83%)
Car > 1,398 kg	-35%* (+/- 16%)	-17% (+/- 49%)	4% (+/- 42%)
Light truck < 1,882 kg	-24%* (+/- 17%)	-9% (+/- 57%)	-4% (+/- 45%)
Light truck > 1,882 kg	-21%* (+/- 14%)	-18% (+/- 43%)	-11% (+/- 32%)

* effect is statistically significant at the 95% confidence level (95% confidence interval shown in parentheses)

Side air bags in light trucks and CUVs/minivans are not estimated to have a consistent effect on risk to occupants when struck in the side by a car; side airbags in CUVs are associated with a large reduction in risk when struck in the side by a lighter-than-average car, but the estimate is not statistically-significant, perhaps because of the relatively small number of fatalities in this type of crash. Both light trucks and CUVs/minivans show a statistically insignificant reduction in risk when struck in the side by a light truck.

Table 4 shows the estimated effect of mass reduction on US fatality risk in struck vehicles, in crashes between two light-duty vehicles, by striking and struck vehicle type, for three crash configurations: front-to-front crashes, crashes where the case vehicle is struck in the driver or passenger side, and all other crash configurations. The first two columns of the table indicate that mass reduction in a struck car is associated with a larger increase in risk in side impact crashes than in other crash configurations in only one case: when a lighter-than-average car is struck by a lighter-than-average light-duty truck. In all other cases, the detrimental effect of mass reduction on risk is estimated to be greater in either frontal crashes or other crashes with another light-duty vehicle, than when a car is struck in the side. On the other hand, mass reduction is associated with a larger increase in risk in side impact crashes than frontal or other crashes for both light trucks (6 out of 8 combinations in columns three and four) and CUVs/minivans (3 out of 4 combinations in the last column).

Although Table 3 indicates that full adoption of side airbags will reduce the number of fatalities in cars struck in the side, Table 4 suggests that side airbags will only reduce the influence of mass reduction on risk when a lighter-than-average car is struck by a lighter-than-average light truck. In crashes with other crash partners, the reduction of side impact fatalities will tend to increase the overall estimated effect of mass reduction on risk in cars in two-vehicle crashes.

When a CUV/minivan is struck in the side by a heavy car or light truck, the estimated effect of mass reduction, although large and statistically significant, is only slightly larger than when a CUV/minivan is involved in a frontal or other crash, as shown in Table 4. Therefore it appears that a reduction in the number fatalities in crashes where a CUV/minivan is struck in the side would slightly reduce the detrimental effect of mass reduction in CUVs and minivans. However, it is not clear the extent to which side airbags will reduce fatalities when CUVs/minivans are struck in the side, as none of the effects shown in Table 1 for CUVs/minivans are statistically significant.

Table 4. Estimated effect of a 45-kg reduction in mass on 2002 to 2008 US fatality risk in struck model year 2000 to 2007 vehicles, by striking and struck vehicle type, and crash configuration

		Estimated effect of a 45-kg reduction in mass in the struck vehicle, by struck vehicle type				
Striking vehicle		Light car (<1,409 kg)	Heavy car (>1,409 kg)	Light LT (<2,084 kg)	Heavy LT (>2,084 kg)	CUV
Light car	Front-front	7.26%**	4.78%	5.29%**	-3.41%	3.51%
	Front-side	5.40%**	-2.33%	8.83%**	2.30%	2.21%
	Other	7.76%*	7.84%	1.02%	0.74%	3.18%
Heavy car	Front-front	8.52%**	3.53%	2.21%	0.63%	11.06%**
	Front-side	1.44%	5.75%**	6.98%**	0.58%	11.51%**
	Other	5.71%*	7.21%*	-2.18%	0.31%	7.69%
Light LT	Front-front	2.02%	2.96%	3.65%*	3.48%	10.00%**
	Front-side	3.23%	-0.30%	7.93%**	6.88%**	12.11%**
	Other	-2.03%	-1.37%	-1.02%	7.13%**	8.34%
Heavy LT	Front-front	7.74%**	1.57%	6.45%**	5.75%**	0.18%
	Front-side	6.84%**	4.66%**	6.74%**	7.75%**	3.96%
	Other	5.93%*	6.28%	1.89%	-3.17%	-4.60%

** effect is statistically significant at the 95% confidence level

* effect is statistically significant at the 90% confidence level

Note: instances where the estimated increase in risk is greater when the subject vehicle is struck in the side rather than in the front or rear are indicated in red. Definitions of "light" and "heavy" are based on the average mass of all striking or struck vehicles.

Interestingly, columns three and four of Table 4 suggest that the estimated detrimental effect of mass reduction on risk to light-duty truck occupants is, for the most part, substantially greater when a light truck is struck in the side, than in a frontal or other crash. In other words, increased mass appears to have a larger beneficial safety effect for light trucks hit in the side than for cars or CUVs/minivans hit in the side. This is likely because the relatively high door sills of light trucks provide some protection from intrusion of the target vehicle into the occupant compartment; casualties in side impact crashes in light trucks are therefore mostly the effect of changes in momentum, which can be mitigated by increasing the mass of the struck light truck. Door sills of cars and CUVs/minivans are relatively low, and do not provide as much protection from intrusion of the striking vehicle; therefore, increasing the mass of cars and CUVs/minivans has little safety benefit in crashes where they are struck in the side, regardless of the striking vehicle type. Although mass reduction is estimated to be detrimental to light trucks when they are struck in the side, Table 3 suggests that there is no statistically significant benefit of side airbags in preventing fatalities in light-duty trucks when struck in the side.

Table 5 shows the estimated effect of footprint reduction on fatality risk in struck vehicles, by striking and struck vehicle type and crash configuration. The table indicates that footprint reduction is associated with a larger increase in side-impact risk than in a frontal or other crash configuration, for cars when struck in the side by another car (regardless of the weight of the striking car), and when a CUV is struck in the side by a lighter-than-average car. This suggests that additional footprint is more protective in side impact than other crashes, for cars and in some cases for CUVs. Therefore, reducing the number of side impact fatal crashes, by greater adoption of side airbags, should reduce the estimated effect of footprint reduction in cars. Although Table 5 indicates that footprint reduction is estimated to increase risk in CUVs and minivans when they are struck in the side by lighter-than-average cars, Table 3 suggests that there is no statistically significant benefit of side airbags in preventing fatalities in CUVs and minivans when struck in the side (although the relatively large protective effect of side airbags when a CUV or minivan is struck in the side by a lighter-than-average car in Table 1 might become statistically-significant with a larger sample size).

Table 5. Estimated effect of a 0.09-m^2 reduction in footprint on 2002 to 2008 US fatality risk in struck model year 2000 to 2007 vehicles, by striking and struck vehicle type, and crash configuration

		Estimated effect of a 0.09-m^2 reduction in footprint in the struck vehicle, by struck vehicle type		
Striking vehicle		Car	Light truck	CUV
Light car	Front-front	1.86%	2.72%	4.39%
	Front-side	6.91%**	-1.84%	5.97%
	Other	-8.42%*	1.54%	1.12%
Heavy car	Front-front	-1.32%	3.05%*	-9.49%**
	Front-side	3.48%	0.51%	-5.89%**
	Other	-1.22%	3.80%**	0.72%
Light LT	Front-front	6.57%**	2.65%	-13.13%**
	Front-side	4.56%*	-0.67%	-7.92%**
	Other	7.01%	1.94%	-5.47%
Heavy LT	Front-front	0.55%	-2.66%**	3.63%
	Front-side	1.09%	-1.75%	1.32%
	Other	4.82%	2.34%	5.58%

** effect is statistically significant at the 95% confidence level

* effect is statistically significant at the 90% confidence level

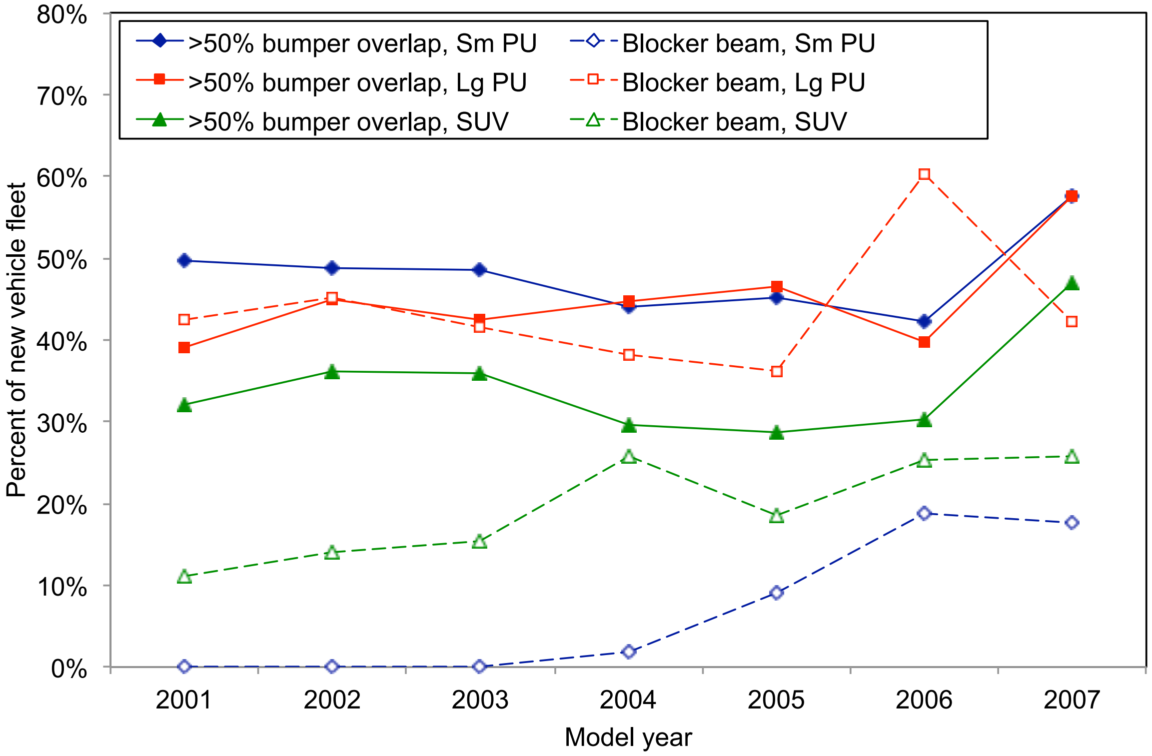
Note: instances where the estimated increase in risk is greater when the subject vehicle is struck in the side rather than in the front or rear are indicated in red.

The analysis suggests that full adoption of side airbags will reduce fatality risk in cars struck in the side by another light-duty vehicle, which should reduce the estimated detrimental effect of footprint reduction in cars. However, it appears that fewer fatalities in cars struck in the side will, if anything, slightly increase the estimated detrimental effect of mass reduction in cars. It is not clear whether full adoption of side airbags will reduce fatality risk when light-duty trucks and CUVs/minivans are struck in the side, and what effect this change in the distribution of fatal crashes will have on the estimated effect of mass or footprint reduction on risk.

Measures to increase light truck compatibility

In 2003 manufacturers made a voluntary commitment to reduce the aggressivity of light trucks in crashes with other vehicles, by incorporating one of two designs in their new vehicles by model year 2010. The first is improving the overlap of light truck bumpers with those of other vehicles. The second is adding a secondary energy-absorbing structure (known as a "blocker beam") behind and below the bumper, so that it engages the bumper of the other vehicle. Figure 4 indicates that about 30% to 50% of MY01 light trucks already met the increased bumper overlap guidelines, depending on truck type; this percent has held fairly constant, but increased substantially in MY07. Fewer small pickups and SUVs used the blocker beam technology than bumper overlap in MY01, but use of the blocker beam has increased in the last few years, particularly in smaller pickup trucks.

Figure 4. Market penetration of compatibility measures in light trucks, by light truck type and model year



The Insurance Institute for Highway Safety estimated the effect of either one of the light-truck compatibility measures on US fatality risk in struck cars (Baker et al. 2008). The analysis compared risk per registered vehicle-year for vehicle models before and after they adopted one of the voluntary compatibility measures. They found that the measures installed in light trucks reduced fatality risk imposed on belted car occupants in front-to-front crashes by 16% for SUVs, and by 20% for pickup trucks. In crashes where a light truck struck a car in the driver side, the measures reduced fatality risk imposed on car occupants by 30% for SUVs and by 10% for pickups. Ossiander et al. (2013) combined each fatal crash from FARS with a matched police-reported crash from GES to estimate the effect of the two compatibility measures on fatality risk per crash, after accounting for several vehicle, driver, and crash variables, including the mass of the case vehicle and its crash partner. They found that combined the compatibility measures reduced fatality risk by 32% in cars struck in the side by a light truck, but had no effect on risk in cars in frontal crashes with a light truck; they found no significant difference in risk between the two compatibility measures.

The estimated effects of the two measures to improve light truck compatibility on risk to occupants of the crash partner vehicle, by crash partner vehicle type and crash configuration, from the current analysis are shown in Table 6. The figure indicates that greater bumper overlap is associated with a 1% to 11% reduction in fatality risk in the crash partner in a frontal crash, depending on the crash partner vehicle type; however, none of these reductions are statistically significant. On the other hand, greater bumper overlap is estimated to reduce fatalities in both lighter and heavier cars struck in the side by a light truck, by a statistically-significant 15% (and has only a statistically insignificant 3% reduction in fatalities when a light truck strikes another light truck in the side). The blocker beam technology tends to reduce fatality risk in cars struck in either the front or the side by a light truck, but none of the reductions are statistically significant.

Although Table 6 suggests that better alignment of light truck bumpers with those of other vehicles appears to result in a statistically significant reduction in risk imposed on car occupants, the effect of lower car mass on risk to car occupants when struck in the side by light trucks is not consistently higher than in other types of two vehicle crashes, as shown in Table 4 above. Therefore, by reducing the number of fatalities in crashes where light trucks strike cars in the side, full adoption of measures to improve light truck compatibility will likely have little impact on the estimated effect of car mass reduction on risk. Similarly, smaller footprint in cars is not associated with a larger increase in fatality risk when a car is struck in the side by a light truck than in other crash configurations, as shown in Table 5. Therefore, full adoption of bumper overlap in light-duty trucks, which is estimated to substantially reduce fatalities in cars struck in the side by light trucks, will likely result in little change in the estimated detrimental effect of smaller car footprint on societal fatality risk.

Table 6. Estimated effect of compatibility measures on 2002 to 2008 US fatality risk imposed by model year 2000 to 2007 light trucks on other light-duty vehicles, by crash partner vehicle type and crash configuration

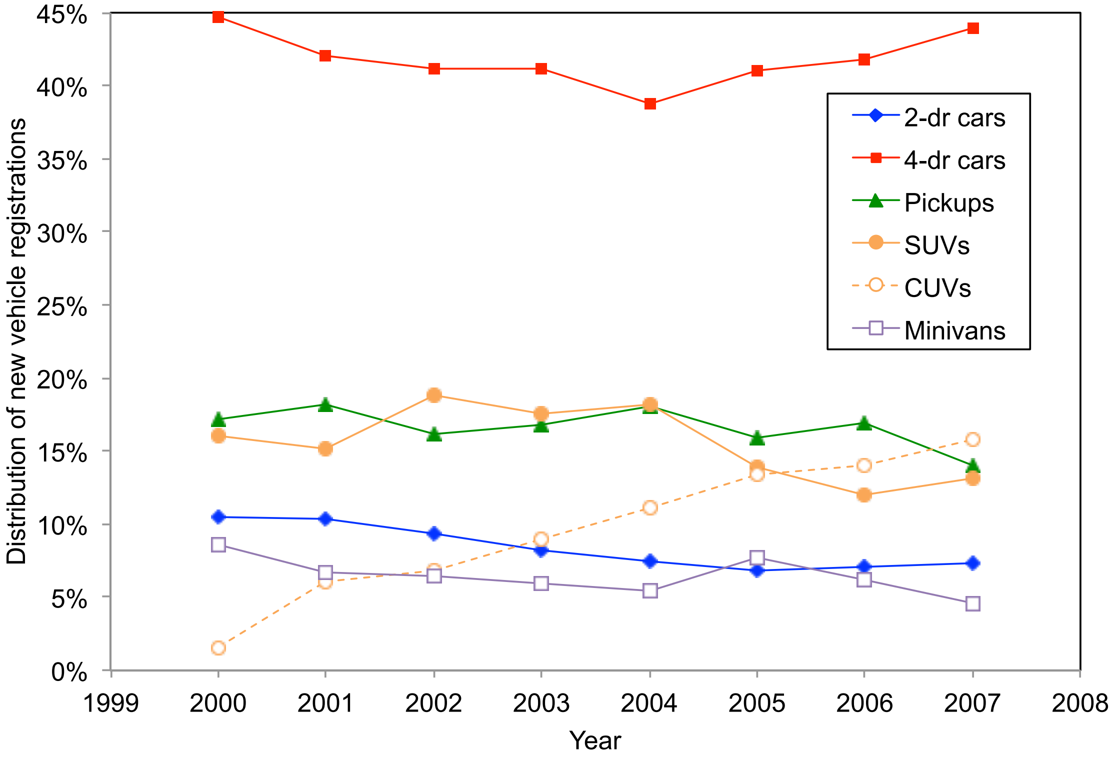
Struck vehicle		Compatibility measure BLOCKER1 (>50% bumper overlap)	 BLOCKER2 (blocker beam)
Light car	Front-front	-6.4% (+/- 10.4%)	-10.3% (+/- 15.2%)
	Front-side	-15.2%* (+/- 9.2%)	-4.8% (+/- 12.6%)
Heavy car	Front-front	-0.9% (+/- 11.5%)	-2.7% (+/- 16.4%)
	Front-side	-15.7%* (+/- 10.5%)	-3.2% (+/- 14.1%)
Light LT	Front-front	-1.7% (+/- 15.2%)	8.1% (+/- 21.5%)
	Front-side	-3.2% (+/- 19.6%)	1.8% (+/- 27.2%)
Heavy LT	Front-front	-11.3% (+/- 20.3%)	10.2% (+/- 26.5%)
	Front-side	-2.9% (+/- 28.3%)	-4.6% (+/- 37.9%)

* effect is statistically significant at the 95% confidence level (95% confidence interval shown in parentheses)

Sales shift from SUVs and other light trucks to car-based CUVs and minivans

Figure 5 shows the rapid growth in market share of CUVs, from nearly zero in model year 2000 to over 15% of all new model year 2007 vehicle registrations (from Table 1-3 in the NHTSA 2012 report). At the same time the share of minivans decreased from 9% to 5%, and 2-door cars from 11% to 5%. Between model years 2001 and 2004 the advent of CUVs appears to have taken market share from 4-door cars (from 45% to 39%), while after MY04 the market share of SUVs and pickups declined (from a combined 36% to 26%). It is likely that the share of SUVs, and perhaps pickups, will decline further if gas prices remain high, as consumers continue to switch to more fuel-efficient cars and car-based CUVs.

Figure 5. US registrations of new vehicles, by vehicle type and year



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

Using the results by crash type over all vehicle types, a 45-kg reduction in vehicle mass is associated with a statistically significant 0.31% increase in fatality risk, while a 0.09-square meter reduction in footprint is associated with a statistically non-significant 0.05% increase in risk. Table 7 shows fatality risk per VMT by vehicle type relative to that in a four-door sedan, using the regression models by crash type over all vehicle types. Compared to four-door sedans of the same mass and footprint, for a driver of the same age and gender, and for equal values on the other control variables such as urbanization and time of day, sports cars (52%), police cars (43%), SUVs (39%), fullsize vans (36%), heavy-duty pickups (36%), and other pickup trucks (22%) have much higher risk than four-door sedans. Two-door sedans (16%) and CUVs (11%) have higher risk, while all-wheel drive cars and minivans have about the same risk as four-door sedans, after accounting for all differences in vehicles, drivers, and crash times and locations using the control variables listed in Table 1.

Table 7. 2002 to 2008 US societal fatality risks relative to that of model year 2000 to 2007 4-door sedans, and average driver characteristics and crash times and locations, by vehicle type

	Fatality risk relative to 4-door sedan		Driver characteristics			Crash times and location characteristics			
Vehicle type	Accounting for all variables in Table 1	Accounting for driver and crash variables only	DRVMALE	AGE14_30	AGE70_96	NITE	RURAL	SPDLIM55	HIFAT_ST
2-dr cars	16.4%	16.5%	41%	55%	1.9%	22%	18%	15%	38%
4-dr sedans	—	—	42%	34%	7.2%	18%	19%	15%	39%
Sports cars	51.1%	48.3%	57%	46%	1.4%	23%	19%	16%	49%
Police cars	43.4%	34.3%	90%	31%	0.3%	38%	21%	13%	41%
AWD cars	-1.8%	-21.1%	48%	25%	4.6%	16%	14%	16%	20%
Small pickups	21.8%	6.8%	83%	26%	3.7%	16%	31%	20%	51%
Large pickups*	35.2%	3.5%	91%	20%	1.9%	13%	39%	26%	49%
SUVs	39.3%	15.5%	47%	26%	1.8%	18%	21%	17%	43%
CUVs	10.8%	-3.2%	37%	21%	3.2%	16%	16%	17%	35%
Minivans	-2.0%	-9.3%	39%	13%	5.8%	14%	22%	16%	34%
Fullsize vans	35.9%	21.1%	85%	21%	2.0%	11%	16%	19%	35%
All	—	—	51%	30%	4.7%	17%	21%	17%	41%

* Large pickups are 200- or 300-series, rated ¾- or 1-ton capacity

Note: most risky driver and crash characteristics shown in red, least risky shown in green.

However, much of the additional risk in, say, pickups relative to four-door sedans is due to who drives these vehicles and where they are driven. Table 7 also shows the average driver (percent male, under age 30, and over age 70) and crash (at night, on rural roads, on high-speed roads, and in high fatality states) characteristics by vehicle type, for the induced-exposure cases weighted by national vehicle registration-year and miles traveled weights. Pickups have the highest fractions of male drivers, and are driven the most on rural, high-speed roads in high-fatality states. Therefore fatality risks by vehicle type need to account for driver and crash variables before estimating the effect of shifting the distribution from light trucks to other vehicle types. The second column in Table 7 shows the risk by vehicle type relative to that of a four-door sedan, after accounting only for the driver and crash variables (that is, not accounting for any differences in vehicles other than mass and footprint). Accounting for how and where vehicles are driven reduces the risk of light trucks relative to that of four-door sedans, so that the heavy-duty pickups have essentially the same risk as four-door sedans.

To simulate the effect of drivers switching from a relatively high-risk vehicle such as a light truck, to a lower risk vehicle such as a four-door sedan, the risk per ten billion VMT of light truck drivers in a four-door sedan needs to be analyzed. Table 8 shows estimated risks for each vehicle type, after accounting for all vehicle, driver, and crash time/location control variables used in NHTSA's preferred regression model (first column), and after moving the average driver of the case vehicle into one of four types of safer vehicles (next four columns). For example, heavy-duty pickups have a risk of 166 fatalities per ten billion VMT; if all the heavy-duty pickup drivers, who are overwhelmingly male and mostly drive on high-speed roads in rural counties in high-risk states, were to instead drive four-door sedans, their risk would be 161 fatalities per ten billion VMT (still much higher than that of the typical car driver, 96). The incremental effect of heavy-duty pickup owners driving at the same times in the same locations, but in a car instead of a heavy-duty pickup, is only 5 fatalities per ten billion VMT (166 – 161), and not the difference between the risk of the average driver of a heavy-duty pickup and that of the average driver of a four-door sedan (70 fatalities per ten billion VMT, or 166 – 96). The initial risks of light truck drivers are shown in green in Table 8; the risks if those drivers instead drove a four-door sedan, all-wheel drive car, CUV, or minivan are shown in red in the table. The difference between the risks in green and the risks in red in Table 8 is used to simulate the effect of a fraction of drivers replacing their light trucks with safer cars, CUVs, and minivans. Note that the adjusted risks in Table 8 only account for the difference in risk associated with driver age and gender, and the crash circumstances shown in Table 7. If there are other differences among drivers who select certain vehicle types, these differences are not accounted for in the adjusted risks in Table 8.

Table 8. Actual 2002 to 2008 US societal fatality risk per billion VMT, and risk adjusted to the average driver and crash time/location in a four-door sedan, all-wheel-drive car, CUV, and minivan, by vehicle type

		Adjusted risk after moving the average driver and crash location/time of the case vehicle into a:				Average annual for MY01-07 vehicles between 2004 and 2008	
Case vehicle type	Actual risk per 10 billion VMT	4-door sedan	AWD car	CUV	Minivan	Fatalities	VMT (billion)
2-dr cars	117	101	79	97	91	5,195	446
4-dr sedans	96	96	76	93	87	26,001	2,749
Sports cars	168	114	90	110	103	1,528	93
Police cars	174	129	102	125	117	644	39
AWD cars	62	78	62	76	71	737	120
Small pickups	142	133	105	129	121	12,326	897
HD pickups	166	161	127	156	146	4,344	276
SUVs	109	95	75	92	86	12,439	1,159
CUVs	72	74	59	72	67	4,111	578
Minivans	79	87	69	84	79	3,583	462
Fullsize vans	108	89	70	86	81	1,421	141
Total	—	—	—	—	—	72,329	6,961

In its 2003 report, NHTSA estimated the effect of a change in the mix of vehicle types on the number of fatalities (Section 5.7, page 220). A similar estimate is conducted here, based on the updated data on US fatalities and estimated vehicle miles traveled. The last two columns of Table 8 show the average number of annual fatalities, and annual VMT (in billions), in crashes involving case light-duty vehicles from model years 2000 through 2007, for the last five years of data available (between 2004 and 2008); the number of fatalities has been adjusted to account for full use of ESC by 2017. To avoid double-counting, the number of total fatalities in each crash is divided by the number of case vehicles involved in each crash, so that the total number of fatalities in a given crash are evenly allocated to each of the case vehicles involved in the crash.

Table 8 can be used to estimate how the number of fatalities involving model year 2000 to 2007 vehicles would be changed by shifting VMT among the vehicle types, while maintaining the average driver and crash time/location characteristics of the original vehicle types. For example, moving SUV drivers into CUVs, while maintaining the driver characteristics and driving times and locations of the SUVs, would reduce the fatality risk from 109 to 92 fatalities per ten billion VMT. Table 9 shows the results from three scenarios of shifting market share: replacing 10% of SUVs with CUVs, replacing 10% of small pickups with CUVs, and replacing 10% of large SUVs with SUVs. The last scenario shown in Table 9 simulates an aggressive shift in vehicle market share: replacing 80% of SUVs (50% with CUVs, 20% with minivans, and 10% with AWD cars); replacing 80% of small pickups (60% with CUVs, and 20% with four-door cars); and replacing 50% of large pickups (25% with CUVs and 25% with minivans). This aggressive shift in market share would reduce fatalities in crashes involving model year 2000 to 2007 vehicles by 2,411, resulting in a 3.3% reduction in fatalities.

Table 9. Estimated change in annual 2002 to 2008 fatalities in crashes involving model year 2000 to 2007 vehicles, from four scenarios of shifts among vehicle types

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

Although the reductions in fatalities from shifting light truck drivers into safer, car-based vehicles are small in percentage terms, they are larger than the mass reduction scenarios NHTSA simulated in its 2012 report (Section 3.6, Table 3-8). The four mass reduction scenarios NHTSA simulated, including the effect of reducing mass of all vehicles by 45 kg, all result in less than a 0.5% change in fatalities. Even an aggressive mass reduction scenario, in which the mass of lighter and heavier light trucks are reduced 613 and 849 kg, respectively, to the average mass of lighter and heavier cars, would reduce fatalities by only 0.5%. Therefore, shifts in market share from more dangerous vehicles such as light trucks to safer car-based vehicles would result in much larger reductions in fatalities than the small changes in fatalities expected from even substantial reductions in the masses of light trucks.

Conclusions

For its estimate of baseline fatalities in the 2017 to 2025 timeframe of the new fuel economy/greenhouse gas emission standards, NHTSA assumes that all new vehicles will have ESC installed by 2017. This will reduce the fraction of fatalities in rollovers and crashes with stationary objects, and thus will increase the estimated detrimental overall effect of mass reduction, but decrease the estimated detrimental overall effect of footprint reduction, on risk. However, other recent trends that are likely to continue through 2017 may also affect the distribution of crashes in that year. For example, side airbags in cars, and lower bumpers in light trucks, will likely reduce the fraction of car fatalities in side-impact crashes. It appears that mass reduction in cars has less of an estimated detrimental effect on risk when cars are struck in the side than when they are involved in frontal or rear-end crashes, so any future reduction in fatalities in car side impact crashes will not necessarily influence the relationship between car mass and risk. On the other hand, footprint reduction in cars is associated with a much larger increase in risk in side impact than other crashes with another car; therefore, it is predicted that full adoption of side airbags in cars should reduce the estimated detrimental effect of car footprint reduction on societal fatality risk, at least in crashes with another car. Footprint reduction in cars is not associated with higher risk when struck in the side, rather than the front or rear, by a light truck; therefore, improved compatibility measures in light trucks will likely result in little change in the relationship between car footprint and societal fatality risk in cars. It is not clear whether full adoption of side airbags or compatibility measures for light trucks will reduce fatality risk when light-duty trucks or CUVs/minivans are struck in the side; therefore full adoption of these technologies likely will result in little change in the estimated effect of mass or footprint reduction in light trucks or CUVs/minivans on societal fatality risk.

This paper assumes that the technical effectiveness of ESC, side airbags, and compatibility measures in model year 2000 to 2007 vehicles will be continued in future vehicle designs. The effectiveness of these technologies may vary among manufacturers or model year, or even among models of the same manufacturer. These features tend to be first introduced in more expensive models; it is possible that less-effective versions of these technologies may be installed at a later date in less-expensive vehicle models, thereby reducing their effectiveness fleetwide.

Finally, in part because of high gas prices and the poor economy, households have been purchasing smaller and lighter vehicles in the last decade. For example, the explosion of CUVs appears to have led to a reduction in the market share of minivans, cars, and in recent years (model year 2005 to 2007) SUVs and pickups. It is likely that these trends would continue, even in the absence of stronger fuel economy and greenhouse gas emission standards. Any future market shifts from SUVs or pickups to cars or car-based CUVs and minivans will result in much larger reductions in fatality risk than the relatively small increases in risk expected from mass or footprint reduction. For example, it is estimated that a large-scale shift in the market share of pickups and SUVs to CUVs, minivans, and cars will reduce overall fatalities by over 3%. It appears that policies that encourage drivers to shift from truck-based pickups, SUVs, and full size vans into car-based vehicles would reduce fuel use and greenhouse gas emissions, while increasing societal safety.

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