Characteristics of rear-end crashes involving passenger vehicles with automatic emergency braking*

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ABSTRACT

Objectives: Automatic emergency braking (AEB) is a proven effective countermeasure for preventing front-to-rear crashes, but it has not yet fully lived up to its estimated potential. This study identified the types of rear-end crashes in which striking vehicles with AEB are overrepresented to determine if the system is more effective in some situations than others, so that additional opportunities for increasing AEB effectiveness might be explored.

Methods: Rear-end crash involvements were extracted from 23 U.S. states during 2009–2016 for striking passenger vehicles with and without AEB among models where the system was optional. Logistic regression was used to examine the odds that rear-end crashes with various characteristics involved a striking vehicle with AEB, controlling for driver and vehicle features.

Results: Striking vehicles were significantly more likely to have AEB in crashes where the striking vehicle was turning relative to when it was moving straight (OR=2.35, 95% CI 1.76, 3.13); when the struck vehicle was turning (OR=1.66, 95% CI 1.25, 2.21) or changing lanes (OR=2.05, 95% CI 1.13, 3.72) relative to when it was slowing or stopped; when the struck vehicle was not a passenger vehicle or was a special use vehicle relative to a car (OR=1.61, 95% CI 1.01, 2.55); on snowy or icy roads relative to dry roads (OR=1.83, 95% CI 1.16, 2.86); or on roads with speed limits of 70+ mph relative to those with 40–45 mph speed limits (OR=1.49, 95% CI 1.10, 2.03). Overall, 25.3% of crashes where the striking vehicle had AEB had at least one of these overrepresented characteristics, compared with 15.9% of strikes by vehicles without AEB.

Conclusions: The typical rear-end crash occurs when two passenger vehicles are proceeding in line, on dry road, and at lower speeds. Because atypical crash circumstances are overrepresented among the rear-end crashes by striking vehicles with AEB, it appears that the system is doing a better job of preventing the more typical crash scenario. Consumer information testing programs of AEB use a test configuration that models the typical rear-end crash type. Testing programs promoting good AEB performance in crash circumstances where vehicles with AEB are overrepresented could guide future development of AEB systems that perform well in these additional rear-end collision scenarios.

Keywords: crash avoidance; collision warning; autonomous emergency braking; AEB testing

INTRODUCTION

About one third of crashes reported to police in the United States in 2016 were rear-end crashes (Insurance Institute for Highway Safety [IIHS] 2018). It has been estimated that forward collision warning systems, which warn drivers when a rear-end crash may be imminent, and automatic emergency braking (AEB), which may brake automatically if drivers do not respond to the potential collision, could potentially prevent up to 70% of front-to-rear crashes involving passenger vehicles as striking vehicles and 20% of all passenger vehicle crashes reported to police (Jermakian 2011).

Evaluations of the real-world experiences of vehicles with AEB have demonstrated that the system is very effective in preventing front-to-rear crashes. AEB has been shown to reduce rates of front-impact crashes by 27%, rear-end crashes by 27–50%, and rear-end injury crashes by 35–56% (Cicchino 2017; Fildes et al. 2015; Isaksson-Hellman and Lindman 2015a, 2015b, 2016; Rizzi et al. 2014; Spicer et al. in press). Additionally, AEB has been associated with reductions of 8–20% in rates of insurance claims covering damage to other vehicles inflicted by an at-fault driver, and reductions of 23–45% in those covering third-party injuries (Doyle et al. 2015; Highway Loss Data Institute 2018; Sari et al. 2017).

Although the size of crash reductions attributed to AEB are impressive, the technology has thus far not fully lived up to its estimated potential. Multiple factors could diminish the effectiveness of crash avoidance technologies. Use of systems by drivers is essential, as technologies cannot work if drivers turn them off. Based on current front crash prevention designs examined in the literature, most owners of vehicles with forward collision warning and AEB have reported in surveys that they always keep the systems activated (Braitman et al. 2010; Cicchino and McCartt 2015; Eichelberger and McCartt 2014, 2016; McDonald et al. 2018), and observational studies of vehicles with front crash prevention brought to dealerships for service have found that nearly all vehicles observed had their systems turned on (Reagan et al. 2018; Reagan and McCartt 2016). AEB does not rely on a response from drivers to activate, but emergency braking may mitigate the severity of a crash rather than prevent a crash altogether. As such, appropriate response by drivers to forward collision warnings that activate prior to AEB play a role in how well both systems can reduce crashes. Warning timing, the context in which warnings are issued, and driver trust, perceived warning criticality, and prior experiences are among the factors that can affect how drivers respond to forward collision warnings (Abe and Richardson 2004; Lees and Lee 2007; Ruscio et al. 2015).

The scenarios in which AEB activates can also impact its effectiveness. AEB is designed to activate in crash-imminent situations while minimizing false alerts, and balancing these factors can potentially result in true crash-imminent situations where the system does not activate or activates too late to completely avoid a collision (though it may mitigate such a collision). Limitations in current sensing technologies could also constrain how well AEB responds in various scenarios. If AEB is more effective in some situations than others, it would be expected that the distribution of characteristics of rear-end crashes would be different among those involving striking vehicles with and without the system.

This goal of this study is to explore additional opportunities for increasing AEB effectiveness by identifying the rear-end crash circumstances in which striking vehicles with AEB are overrepresented. We assumed that the circumstances that made up a smaller proportion of rear-end crashes among striking vehicles with AEB compared with vehicles without the system were situations that AEB was more effective at preventing, while the circumstances that were overrepresented were those that AEB was less effective at preventing.

METHODS

Vehicles

Study vehicles in the primary analysis included passenger vehicle series where AEB was an optional feature and where the presence or absence of AEB was known for individual vehicles at the Vehicle Identification Number (VIN) level. Audi, General Motors, Mazda, Mercedes-Benz, and Volvo provided VINs of passenger vehicles with and without AEB. On Acura, Honda, and Subaru study vehicles AEB was tied to trim, which was discernable directly from the VIN. Study vehicles with AEB included only those where AEB operated across the speed range (i.e., excluding low-speed AEB) and that also had forward collision warning.

The control group in the primary analysis included passenger vehicles of the same make, series, and model year of the vehicles with AEB that did not have a front crash prevention system (i.e., no AEB or forward collision warning). A second, much larger, control group of passenger vehicles was also examined to ensure that the results from the primary analysis represented crash patterns in the larger vehicle population. Vehicles in the secondary control group did not offer any kind of front crash prevention system as an option and were matched to the AEB vehicles by class (2-door car, 4-door car, station wagon, luxury car, SUV, luxury SUV) and model year. Because there were no station wagon models without optional AEB to match to station wagons with AEB, station wagons were matched with 4-door cars. Study vehicles with AEB and in the same-model and same-class control groups are listed in Tables A1 and A2 in the Appendix.

Crashes

Rear-end crashes where study vehicles were the striking vehicle were extracted from data from 23 states that had the VINs of crash-involved vehicles available in the crash file. These states included Delaware, Louisiana, Missouri, South Dakota, and Tennessee during 2009–2016; Nevada and Rhode Island during 2009–2013; Florida, Georgia, Idaho, Kansas, Michigan, Minnesota, Nebraska, New Jersey, Oklahoma, Pennsylvania, Texas, Utah, and Wyoming during 2010–2016; Indiana during 2010–2013; Iowa during 2010–2015; and Maryland during 2014–2016.

Data collected on crash characteristics varied among states, and so data were aggregated in a consistent format for analysis. Rear-end crashes were defined as those where the crash type coded by police was a rear end and where the striking vehicle was initially impacted in the front (at 11-, 12-, or 1 o'clock). In two-vehicle crashes the struck vehicle needed to have been initially impacted in the rear (at 5-, 6-, or 7 o'clock). Initial impact points to crash-involved vehicles other than the striking vehicle were not considered in rear-end crashes involving three or more vehicles.

Five characteristics of rear-end crashes involving a study vehicle as the striking vehicle were examined. These included the action of the striking and struck vehicles prior to the crash, type of struck vehicle, surface condition, and speed limit as a proxy for vehicle speed.

Vehicle actions were grouped into six categories: turning, changing lanes, merging or passing, stopping or slowing, moving straight, or other. Most states used categories from the Model Minimum Uniform Crash Criteria (National Highway Traffic Safety Administration 2017) to code vehicle action prior to the crash, which include backing, changing lanes, entering traffic lane, leaving traffic lane, making U-turn, movements essentially straight ahead, negotiating a curve, overtaking/passing, parked, slowing, stopped in traffic, turning left, and turning right. However, some states did not use all these categories, and some allowed assignment to more than one category. Stopping/slowing and merging/passing were grouped together in the current data set because some states did not use both categories, and others used a single category for stopping or slowing. In states that allowed assignment to multiple categories action group was assigned hierarchically, with turning prioritized first, following by changing lanes, merging or passing, stopping or slowing, moving straight, and finally other. About 2% of crashes were assigned in the state data to multiple categories (e.g., were categorized as slowing/stopping and turning).

Type of struck vehicle was determined first by decoding the vehicle's VIN for passenger vehicles, or secondarily from the vehicle type reported by the police if a decodable VIN was not available. Vehicle types included cars, SUVs, pickups, vans, and nonpassenger vehicles or special use vehicles.

Surface condition was classified as dry, wet, snowy or icy, or other. Depending on the state, "other" surface conditions most often included sand, mud, dirt, oil, gravel, or other road debris. Speed limits were categorized as ≤35 mph, 40–45 mph, 50–65 mph, and ≥70 mph. In states where speed limit was coded at the vehicle level rather than at the crash level, the speed limit assigned to the striking vehicle was used. Crash data did not include a reliable indicator of actual vehicle speed.

Texas did not collect information on vehicle action prior to the crash, and so Texas data were excluded from analyses of striking and struck vehicle action. Analyses of struck vehicle action and type were limited to crashes involving two vehicles; other analyses also included rear-end crashes involving three or more vehicles.

Analyses

If the distribution of rear-end crash characteristics differs between striking vehicles with and without AEB, it would follow that the proportion of striking vehicles with AEB would also vary by rear-end crash characteristic (e.g., the proportion of striking vehicles moving straight, slowing, or stopped that had AEB would differ from the proportion of striking vehicles turning, changing lanes, merging, or passing that had AEB). Logistic regression was used to examine the odds that rear-end crashes with various characteristics involved a striking vehicle with AEB. Seven separate models were constructed for each combination of the five rear-end crash characteristics and for the points of impact to the striking and struck vehicles (striking vehicle action, struck vehicle action, struck vehicle type, surface condition, speed limit, striking vehicle point of impact, struck vehicle point of impact). This was done for each of the two control groups (same-model control group, same-class control group), resulting in a total of 14 models. All regression models controlled for driver age group (15–34, 35–54, 55–69, 70+, unknown), driver gender (male, female, unknown), state, and calendar year of the crash.

Regression models using the same-model control group also included a variable that captured the combination of series and model year. Vehicle series with two- and four-wheel drive variants were combined to allow sufficient data for analysis. Vehicle series for which there were no crashes for either a vehicle with AEB or a control vehicle without AEB were dropped from analyses. This primarily eliminated control vehicle series with low AEB take rates. Depending on the analysis, 3–4% of crashes involving striking vehicles with AEB and 15–18% of crashes involving striking vehicles without AEB were removed for not having a matched pair.

Regression models using the larger same-class control group included the same AEB vehicles as the analyses using the same-model control group. In addition to the demographic variables described earlier, these regression models controlled for vehicle class (2-door car, 4-door car, luxury car, SUV, luxury SUV) and model year.

RESULTS

Study vehicles with AEB were the striking vehicle in 1,242 rear-end crashes, same-model control vehicles were so in 12,570 rear-end crashes, and same-class control vehicles were the striking vehicle in 265,872 crashes. The surface was dry, the striking vehicle was moving straight, or the struck vehicle was slowing or stopped in more than two thirds of crashes (Table 1). About a third of crashes occurred at speed limits of 40–45 mph, and about half of vehicles struck were cars.

Relative to either control group, a larger proportion of vehicles with AEB were turning (7.0% vs. 3.7%–4.0%) or slowing/stopped (18.7% vs. 14.6%–15.6%); struck a vehicle that was turning (9.0% vs. 6.2–6.4%) or changing lanes (2.0% vs. 1.0%); struck a nonpassenger vehicle or special use vehicle (3.0% vs. 1.9%); crashed on a snowy or icy road (2.5% vs. 1.5%–1.9%); or crashed on a road were the speed limit was 70 mph or greater (6.0% vs. 4.1%–4.2%) (Table 1). Overall, vehicles with AEB were turning, struck a vehicle that was turning, changing lanes, or that was not a passenger vehicle, or crashed on a road that was snowy/icy or with a speed limit of 70 mph or greater in 25.3% of two-vehicle crashes. In comparison, 15.9% of strikes by same-model and 16.1% of strikes by same-class vehicles without AEB occurred under these conditions.

Table 2 summarizes the results of logistic regression models examining the likelihood that a vehicle had AEB by crash characteristics, controlling for driver age and gender, state, year, and vehicle characteristics. In models using the same-model control group, striking vehicles were significantly more likely to have AEB in crashes where the striking vehicle was turning (OR=2.35, 95% CI 1.76, 3.13) or slowing/stopped (OR=1.43, 95% CI 1.18, 1.72) relative to when it was moving straight; when the struck vehicle was turning (OR=1.66, 95% CI 1.25, 2.21) or changing lanes (OR=2.05, 95% CI 1.13, 3.72) relative to when it was slowing or stopped; when the struck vehicle was not a passenger vehicle or was a special use vehicle relative to a car (OR=1.61, 95% CI 1.01, 2.55); on snowy or icy roads relative to dry roads (OR=1.83, 95% CI 1.16, 2.86); or on roads with speed limits of 70+ mph relative to those with 40–45 mph speed limits (OR=1.49, 95% CI 1.10, 2.03). Results were similar when same-class vehicles without AEB were used as the control group.

It is likely that striking vehicles with AEB were more often slowing/stopped than other vehicles because automatic braking may mitigate the severity of a crash without preventing it entirely. To account for the possibility that striking vehicles with AEB that were slowing due to automatic braking distorted the proportions of other precrash actions, striking vehicle analyses were repeated with slowing/stopped striking vehicles removed (Table A3, see Appendix). Turning vehicles were still significantly more likely to have AEB than striking vehicles that were moving straight (OR=2.30, 95% CI 1.72, 3.08).

Turning is presumably an issue for striking vehicles with AEB because of system designs that disengage when the driver is providing steering input. Thus, it might be the case that vehicles with AEB more often struck turning vehicles not because of challenges associated with detecting and responding to turning vehicles, but because striking and struck tend to turn together. Analyses of struck vehicle actions were performed including only striking vehicles that were moving straight or slowing/stopped (Table A4). Striking vehicles were significantly more likely to have AEB when the struck vehicle was changing lanes relative to when it was slowing or stopping (OR=2.22, 95% CI=1.16, 4.27). While striking vehicles were also more likely to have AEB when the struck vehicle was turning, this comparison did not reach statistical significance (OR=1.39, 95% CI=0.93, 2.09), which suggests that driver steering input in situations where struck vehicles are turning contributed to the overrepresentation of turning struck vehicles with AEB.

If striking or struck vehicles are more likely to approach each other at an angle in rear-end crashes when the striking vehicle has AEB, it should follow that the points of impact on both vehicles would more often be offset from center in these crashes. Struck vehicles were more likely to be impacted at 5 o'clock (9.8% vs. 8.7%–9.1%) or 7 o'clock (11.2% vs. 7.5%) than at 6 o'clock (79.0% vs. 83.4%–83.8%) when the striking vehicle had AEB relative to the control groups. Similarly, striking vehicles with AEB were more often initially impacted at 11 o'clock (6.8% vs. 6.0%) or 1 o'clock (10.3% vs. 8.1%–8.3%) than at 12 o'clock (82.9% vs. 85.7%–85.9%). Comparisons were significant for 1 o'clock and 7 o'clock in primary and secondary analyses when controlling for covariates, and for 5 o'clock in the primary analysis only (Table 2).

Across the two primary study vehicle groups (AEB vehicles and same-model control group), 208 vehicles struck a nonpassenger vehicle or special use vehicle. The majority of these struck vehicles (59.1%) were medium or heavy trucks. A total of 6 (2.9%) were truck tractors without trailers; 3 (1.4%) were auto transporters, concrete mixers, or cargo tanks; 39 (18.8%) were other tractor-trailers; 10 (4.8%) were single-unit trucks pulling trailers; 10 (4.8%) were dump trucks, garbage trucks, or fire trucks; 36 (17.3%) were other single-unit trucks; 19 (9.1%) were unspecified medium or heavy trucks; 45 (21.6%) were motorcycles; 32 (15.4%) were buses; 5 (2.4%) were construction or farm equipment; 1 (0.5%) was a police vehicle; 1 (0.5%) was an ATV; and 1 (0.5%) was an unspecified public vehicle.

DISCUSSION

AEB has proven to be an effective countermeasure for preventing rear-end crashes, but it has not yet lived up to its estimated full crash reduction potential. The current study demonstrates that the distribution of rear-end crash types involving passenger vehicles with AEB differs from that of passenger vehicles without the system. Results suggest that AEB may be less effective at preventing less-common rear-end crash types than it is at preventing the typical rear-end crash. Development of current AEB systems has focused on preventing the most common crash modes, and this analysis identifies additional crash modes that can potentially be addressed in the development of future AEB systems. While rear-end crashes involving atypical circumstances comprise a minority of these crashes, they still make up a consequential number. Nearly 300,000 of the almost 2 million two-vehicle rear-end crashes reported to police in the United States in 2016 where a passenger vehicle was the striking vehicle, or about 4% of the more than 7,000,000 crashes reported to the police in 2016, involved a striking vehicle that was turning; a struck vehicle that was turning, changing lanes, or not a passenger vehicle; or roads that were snowy or icy or that had speed limits of 70 mph or greater (IIHS 2018).

AEB systems that more reliably detect nonpassenger vehicles could also make a meaningful impact on crash statistics for those vehicle types. Using 2011–2015 U.S. crash data, Teoh (2018) estimated that front crash prevention systems on passenger vehicles that worked perfectly could potentially prevent up to 13% of motorcycle crashes. Twelve percent of U.S. passenger vehicle occupant deaths in 2017 were in crashes with large trucks, and one in five of these fatalities occurred when a passenger vehicle struck the rear of a large truck (IIHS 2018). Some of these fatalities could be prevented by stronger rear underride guards (Blower et al. 2011; Zuby and Brumbelow 2011), but AEB that reliably detects large trucks could prevent crashes resulting in rear underride from occurring or lessen the burden on the underride guard.

Consumer information AEB testing programs such as those by IIHS and Euro NCAP are designed to evaluate the performance of AEB in the most common rear-end crash scenarios (e.g., Hulshof et al. 2013). If testing programs promoted good performance in rear-end crash situations where AEB is overrepresented, it could guide development by automakers to improve systems to perform well in those scenarios. For example, a testing scenario with an angled target vehicle that simulates an struck vehicle changing lanes could be accomplished with the Global Vehicle Target currently used in Euro NCAP AEB testing protocols.

AEB may not be designed to consistently activate in some nonstandard situations because of concerns that addressing these scenarios with current sensing technology would result in unnecessary activations, which could lead drivers to disuse the system because they are annoyed by it or have lost trust in it (Kidd and Reagan 2019; Lee and See 2004; Parasuraman and Riley 1997). Consumer use of AEB currently is high, but lane departure warning has suffered from considerable disuse due in part to user annoyance that limits the technology's effectiveness (Braitman et al. 2010; Eichelberger and McCartt 2014, 2016; Flannagan et al. 2016; Reagan et al. 2018; Reagan and McCartt 2016). Work to improve the performance of AEB in atypical scenarios will need to ensure that such designs do not adversely affect AEB use resulting from potential unwanted activations, that performance is not compromised in more typical situations, and that AEB activation while the driver is actively maneuvering the vehicle (i.e., turning) does not create unanticipated safety consequences. It could also be the case, however, that greater reliability of AEB across a wider array of circumstances could increase trust among drivers who have experienced emergency braking events. For example, in a driving simulator study, participants reported higher levels of trust in AEB that adapted to road friction than conventional AEB that initiated braking at a lower time-to-collision when experiencing emergency braking on snowy roads (Koglbauer et al. 2018).

A few limitations of this study should be noted. Because AEB was an optional feature on study vehicles, differences in exposure between drivers who did and did not choose to purchase the systems could have affected rear-end crash patterns. Controlling for driver demographics accounted for these differences to some degree. Vehicles may have had additional crash avoidance systems, and vehicles with AEB were more likely to have other crash avoidance systems than vehicles without front crash prevention, but other crash avoidance systems were not expected to affect the rear-end crash characteristics examined here. Differences by manufacturer were not examined, and performance in these scenarios likely vary by system implementation. It was unknown if AEB was turned on at the time of the crash. Finally, the current study focused on rear-end crashes with vehicles and did not account for other applications of AEB, such as preventing frontal crashes with nonmotorists. Crashes with pedestrians and cyclists that could potentially be prevented by AEB have different common characteristics than those where motor vehicles are struck (Edwards et al. 2014; Hamdane et al. 2015; Jermakian and Zuby 2011; Lenard et al. 2011; MacAlister and Zuby 2015).

AEB had been predicted to be the crash avoidance technology with the ability to prevent the greatest number of crashes (Jermakian 2011; Kusano and Gabler 2014). The technology has demonstrated to be highly effective in the real world, but vehicles with AEB are still involved in some rear-end crashes. Designing systems that can handle atypical scenarios where AEB is currently underperforming, with the encouragement of consumer information testing programs that evaluate AEB performance in these scenarios, could further push AEB towards its full crash reduction potential.

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Table 1. Characteristics of crashes involving striking vehicles with automatic emergency braking (AEB) and control vehicles without front crash prevention (percent)

Crash characteristics	Vehicles with AEB	Same-model control vehicles	Same-class control vehicles
Striking vehicle action	n=1,078	n=11,048	n=224,884
Moving straight	67.0	73.1	74.8
Slowing or stopped	18.7	15.6	14.6
Turning	7.0	3.7	4.0
Changing lanes	1.4	1.9	1.9
Merging or passing	1.1	0.9	0.8
Other	4.9	4.8	3.9
Struck vehicle action	n=843	n=8,666	n=181,308
Straight	17.7	19.1	19.8
Slowing or stopped	66.7	69.7	69.3
Turning	9.0	6.2	6.4
Changing lanes	2.0	1.0	1.0
Merging or passing	1.4	1.0	0.9
Other	3.2	3.0	2.7
Struck vehicle type	n=943	n=9,746	n=210,588
Car	47.9	49.7	49.2
SUV	29.0	30.3	29.9
Pickup	12.8	11.7	12.7
Van	7.1	6.2	5.9
Not a passenger vehicle or special use	3.0	1.9	1.9
Unknown	0.2	0.3	0.3
Surface condition	n=1,242	n=12,570	n=265,872
Dry	84.9	86.3	86.2
Wet	12.4	11.5	12.0
Snowy or icy	2.5	1.9	1.5
Other or unknown	0.2	0.4	0.3
Speed limit (mph)	n=1,242	n=12,570	n=265,872
≤35	27.7	28.8	27.8
40–45	32.1	33.9	35.3
50–65	27.5	26.5	25.6
70+	6.0	4.1	4.2
Unknown	6.8	6.7	7.2
	n=843	n=8,666	n=181,308
Striking vehicle turning; struck vehicle turning, changing lanes, not a passenger vehicle or special use; snowy or icy; or speed limit 70+ mph	25.3	15.9	16.1

Table 2. Results of logistic regressions modeling odds that a striking vehicle in a rear-end crash had automatic emergency braking (AEB)

Crash characteristics	Odds ratio using same-model control (95% CI)	Odds ratio using same-class control (95% CI)
Striking vehicle action		
Moving straight (reference)	1.00	1.00
Slowing or stopped	**1.43 (1.18, 1.72)**	**1.38 (1.17, 1.64)**
Turning	**2.35 (1.76, 3.13)**	**1.86 (1.45, 2.39)**
Changing lanes	0.80 (0.44, 1.44)	0.80 (0.48, 1.35)
Merging or passing	1.74 (0.89, 3.37)	1.48 (0.83, 2.65)
Other	1.08 (0.77, 1.51)	1.23 (0.92, 1.64)
Struck vehicle action		
Moving straight	0.94 (0.76, 1.16)	0.93 (0.78, 1.13)
Slowing or stopped (reference)	1.00	1.00
Turning	**1.66 (1.25, 2.21)**	**1.52 (1.19, 1.94)**
Changing lanes	**2.05 (1.13, 3.72)**	**2.08 (1.27, 3.43)**
Merging or passing	1.67 (0.84, 3.29)	1.53 (0.84, 2.76)
Other	1.25 (0.81, 1.94)	1.20 (0.81, 1.79)
Struck vehicle type		
Car (reference)	1.00	1.00
SUV	1.06 (0.89, 1.26)	0.98 (0.84, 1.14)
Pickup	1.13 (0.89, 1.43)	1.17 (0.95, 1.44)
Van	1.15 (0.84, 1.56)	1.16 (0.89, 1.50)
Not a passenger vehicle or special use	**1.61 (1.01, 2.55)**	**1.53 (1.04, 2.27)**
Unknown	0.79 (0.17, 3.65)	0.87 (0.21, 3.52)
Surface condition		
Dry (reference)	1.00	1.00
Wet	1.14 (0.93, 1.38)	1.10 (0.92, 1.30)
Snowy or icy	**1.83 (1.16, 2.86)**	**1.50 (1.03, 2.20)**
Other or unknown	0.70 (0.21, 2.34)	0.63 (0.20, 1.99)
Speed limit (mph)		
≤35	1.04 (0.88, 1.23)	1.04 (0.89, 1.20)
40-45 (reference)	1.00	1.00
50-65	1.10 (0.93, 1.31)	1.07 (0.92, 1.25)
70+	**1.49 (1.10, 2.03)**	**1.40 (1.08, 1.82)**
Unknown	1.13 (0.86, 1.49)	1.08 (0.84, 1.38)
Striking vehicle point of impact		
11 o'clock	1.28 (0.99, 1.66)	1.22 (0.97, 1.53)
12 o'clock (reference)	1.00	1.00
1 o'clock	**1.33 (1.07, 1.66)**	**1.34 (1.10, 1.62)**
Struck vehicle point of impact		
5 o'clock	**1.36 (1.06, 1.76)**	1.22 (0.97, 1.54)
6 o'clock (reference)	1.00	1.00
7 o'clock	**1.60 (1.25, 2.05)**	**1.63 (1.32, 2.02)**

Note: CI=confidence interval. Statistically significant values are bolded.

APPENDIX

Table A1. Study vehicles with optional automatic emergency braking (AEB)

Class	Make	Model	Model years
2-door car	Honda	Accord 2D	2016
4-door car	Buick	LaCrosse	2014–2015
	Buick	Regal	2014
	Chevrolet	Impala 4D	2014–2015
	Honda	Accord 4D	2016–2017
	Honda	Civic	2016
	Mazda	6	2016
	Subaru	Impreza 4D	2014–2016
	Subaru	Legacy	2013–2016
Luxury car	Acura	RL	2006–2008, 2010–2011
	Acura	TLX	2015
	Audi	A5	2013–2014
	Audi	A6 4D	2016
	Audi	A6 Quattro	2012–2016
	Audi	A7	2012–2016
	Audi	A8	2011–2016
	Audi	RS5	2013
	Audi	RS7	2014
	Audi	S3	2016
	Audi	S5	2013
	Audi	S6	2013, 2015
	Audi	S7	2013–2015
	Cadillac	ATS	2013–2015
	Cadillac	CTS	2014–2015
	Cadillac	XTS	2013–2015
	Mercedes-Benz	CL Class	2007–2010
	Mercedes-Benz	E Class	2010
	Mercedes-Benz	S Class	2007–2010
	Volvo	S80	2008–2010
	Volvo	V70	2008
	Volvo	XC70	2009–2010
SUV	Chevrolet	Suburban	2015
	Chevrolet	Tahoe	2015
	GMC	Yukon	2015
	Honda	Pilot	2016
	Mazda	CX-3	2016
	Mazda	CX-5	2016
	Mazda	CX-9	2016
	Subaru	Forester	2014–2017
Station wagon	Subaru	Impreza SW	2015–2016
	Subaru	Outback	2013–2017
	Subaru	XV Crosstrek	2015–2016
Luxury SUV	Acura	MDX	2010–2012
	Acura	ZDX	2010, 2012
	Audi	Q5 4D	2013
	Audi	SQ5	2014
	Cadillac	Escalade	2015
	Cadillac	SRX	2013–2015
	Volvo	XC60	2010

Table A2. Same-class control vehicles without front crash prevention systems

Class	Make	Model	Model years
2-door car	Dodge	Challenger	2016
	Fiat	500	2016
	Honda	CR-Z hybrid	2016
	Hyundai	Genesis coupe	2016
	Hyundai	Veloster	2016
	Kia	Forte Koup	2016
	Scion	FR-S	2016
	Scion	TC	2016
	Subaru	BRZ	2016
	Toyota	Yaris 3D	2016
	Volkswagen	Beetle	2016
	Volkswagen	Eos	2016
4-door car	Acura	ILX	2013–2015
	Acura	TSX	2013–2014
	Buick	LaCrosse	2013
	Buick	Regal	2013
	Buick	Verano	2013
	Chevrolet	Cruze	2013–2016
	Chevrolet	Impala 4D	2013
	Chevrolet	Impala Limited	2014–2016
	Chevrolet	Sonic	2013
	Chevrolet	Spark	2013–2015
	Chrysler	200 4D	2013–2014
	Dodge	Avenger	2013–2014
	Dodge	Charger	2015–2016
	Dodge	Dart	2013–2016
	Ford	Fiesta	2013–2016
	Ford	Focus	2013–2016
	Honda	Civic	2013–2015
	Honda	Insight hybrid	2013–2014
	Hyundai	Accent	2013–2017
	Hyundai	Azera	2013–2014
	Hyundai	Elantra	2013–2017
	Hyundai	Sonata	2013–2015
	Kia	Cadenza	2014–2016
	Kia	Forte 4D	2013–2016
	Kia	Optima	2013–2016
	Kia	Rio	2013–2017
	Mazda	2	2013–2014
	Mazda	3	2013
	Mazda	6	2013
	Mitsubishi	Lancer	2013–2016
	Mitsubishi	Mirage	2014–2015, 2017
	Nissan	Altima	2013–2015
	Nissan	Juke	2013–2017
	Nissan	Leaf	2013–2016
	Nissan	Maxima	2013–2014
	Nissan	Sentra	2013–2015
	Nissan	Versa	2013–2017
	Subaru	Impreza	2013
	Subaru	Impreza WRX	2013–2014
	Subaru	WRX	2015–2017

	Suzuki	Kizashi	2013
	Suzuki	SX4	2013
	Toyota	Camry	2013–2014
	Toyota	Corolla	2013–2016
	Toyota	Prius C	2013–2015
	Toyota	Yaris 5D	2013–2016
	Volkswagen	CC	2013–2015
	Volkswagen	E-Golf	2015
	Volkswagen	Golf	2013–2015
	Volkswagen	GTI	2013–2014
	Volkswagen	Jetta	2013–2014
	Volkswagen	Passat	2013–2015
Luxury car	Acura	TL	2006, 2012–2014
	Audi	A4	2006–2011
	Audi	A4 Allroad	2016
	Audi	A5	2008, 2016
	Audi	A6 4D	2006–2007, 2009–2015
	Audi	A6 Avant Quattro	2006–2007, 2009–2010
	Audi	A6 Quattro	2006–2007, 2009–2011
	Audi	A8	2006–2010
	Audi	RS4	2007–2008
	Audi	S4	2006–2008
	Audi	S5	2008
	Audi	S6	2007, 2009–2010
	Audi	S8	2007–2009
	Bentley	Azure	2008
	Bentley	Continental	2006–2016
	Bentley	Mulsanne	2013
	BMW	1 Series	2008–2013
	BMW	3 series	2006–2016
	BMW	5 series	2006–2010
	BMW	6 series	2006–2010
	BMW	7 series	2006–2008, 2011
	BMW	M3	2006, 2008–2013
	BMW	M5	2006–2010
	BMW	M6	2006–2010, 2012
	Cadillac	CTS	2006–2014
	Cadillac	CTS-V	2006–2007, 2009–2015
	Cadillac	DTS	2006–2010
	Cadillac	STS	2006–2010
	Cadillac	STS-V	2006–2009
	Ferrari	612 Scaglietti 2D	2008
	Fisker	Karma	2012
	Hyundai	Genesis 4D	2009–2014
	Infiniti	G25	2011–2012
	Infiniti	G35	2006–2008
	Infiniti	G37	2008–2013
	Infiniti	M35	2006–2010
	Infiniti	M45	2006–2010
	Infiniti	Q40	2015
	Infiniti	Q45	2006
	Infiniti	Q60	2014–2015
	Jaguar	F-TYPE	2014–2016
	Jaguar	XJ	2006–2009
	Jaguar	XJ8	2006–2009
	Jaguar	X-TYPE	2006–2008

	Lexus	ES 330	2006
	Lexus	ES 350	2007–2012
	Lexus	IS 250	2006–2013
	Lexus	IS 350	2006–2013
	Lincoln	LS	2006
	Lincoln	MKS	2009
	Lincoln	MKZ	2006–2012
	Lincoln	Town Car	2006–2011
	Maserati	Ghibli	2014–2016
	Maserati	Quattroporte	2006–2016
	Mercedes-Benz	C Class	2005–2007, 2011–2012
	Mercedes-Benz	CLK Class	2006–2007
	Mercedes-Benz	E Class	2003, 2006–2007
	Mercedes-Benz	SLS Class	2012
	Rolls Royce	Phantom	2006–2009
	Saab	9-3	2006–2011
	Saab	9-5	2006–2011
	Tesla	Model S	2012–2014
	Volkswagen	Phaeton	2006
	Volvo	C70	2006–2013
	Volvo	S60	2006–2009
	Volvo	S80	2006
	Volvo	V70	2006–2007
	Volvo	XC70	2006–2007
SUV	Chevrolet	Captiva	2014–2015
	Chevrolet	Suburban	2014
	Chevrolet	Tahoe	2014
	Chevrolet	Trax	2015–2016
	Dodge	Journey	2014–2017
	Ford	Escape	2014–2016
	Ford	Expedition	2014–2017
	GMC	Yukon	2014
	Honda	CR-V	2014
	Honda	HR-V	2016–2017
	Honda	Pilot	2014–2015
	Hyundai	Santa Fe	2014–2016
	Hyundai	Tucson	2014–2015
	Jeep	Compass	2014–2017
	Jeep	Patriot	2014–2017
	Jeep	Wrangler	2014–2017
	Kia	Sorento	2014–2015
	Kia	Sportage	2014–2016
	Mazda	CX-9	2014–2015
	Mitsubishi	Outlander	2014–2016
	Nissan	Armada	2014–2015
	Nissan	Murano	2014
	Nissan	Pathfinder	2014–2016
	Nissan	Rogue	2014–2015
	Nissan	Xterra	2014–2015
	Subaru	B9 Tribeca	2014
	Toyota	4Runner	2014–2016
	Toyota	FJ Cruiser	2014
	Toyota	RAV4	2014–2015
	Toyota	Sequoia	2014–2016
	Toyota	Venza	2014–2015
	Volkswagen	Tiguan	2014–2017

	Volkswagen	Touareg	2014
Luxury SUV	Acura	RDX	2011–2015
	Audi	Q3	2015
	Audi	Q5 4D	2010
	Audi	Q5 Hybrid	2013–2015
	BMW	X1	2013–2015
	BMW	X3	2013–2015
	BMW	X5	2010–2013
	BMW	X6	2010–2014
	Cadillac	Escalade	2010–2014
	Cadillac	SRX	2010–2012
	Infiniti	QX56	2010
	Land Rover	LR2	2010–2015
	Land Rover	LR4	2010–2013
	Land Rover	Range Rover	2012–2013
	Lexus	RX 350	2010–2013
	Lexus	RX 450H	2010–2013
	Lincoln	MKT	2012–2015
	Lincoln	MKX	2010
	Lincoln	Navigator	2010–2015
	Mercedes-Benz	G Class	2011–2012
	Mercedes-Benz	GL Class	2011–2012
	Mercedes-Benz	GLK Class	2011–2012
	Mercedes-Benz	M Class hybrid	2011
	Mercedes-Benz	R Class	2011–2012
	Porsche	Cayenne	2010
	Saab	9-4X	2011
	Toyota	Land Cruiser	2010–2011
	Volvo	XC90	2010–2014

Table A3. Striking vehicle actions among vehicles with and without automatic emergency braking (AEB) that were not slowing or stopped

Striking vehicle action	Proportions			Logistic regression model results	
	Vehicles with AEB n=877	Same-model control vehicles n=9,202	Same-class control vehicles n=191,966	Odds ratio using same-model control (95% CI)	Odds ratio using same-class control (95% CI)
Moving straight	82.3	86.6	87.6	1.00	1.00
Turning	8.6	4.4	4.7	**2.30 (1.72, 3.08)**	**1.83 (1.43, 2.35)**
Changing lanes	1.7	2.2	2.2	0.81 (0.45, 1.45)	0.79 (0.47, 1.32)
Merging or passing	1.4	1.0	0.9	1.67 (0.86, 3.29)	1.49 (0.83, 2.67)
Other	6.0	5.7	4.6	1.07 (0.77, 1.51)	1.22 (0.91, 1.63)

Note: CI=confidence interval. Statistically significant values are bolded.

Table A4. Struck vehicle actions among striking vehicles with and without automatic emergency braking (AEB) that were moving straight, slowing, or stopped

Struck vehicle action	Proportions			Logistic regression model results	
	Vehicles with AEB n=698	Same-model control vehicles n=7,495	Same-class control vehicles n=159,524	Odds ratio using same-model control (95% CI)	Odds ratio using same-class control (95% CI)
Slowing or stopped	71.9	72.6	72.1	1.00	1.00
Moving straight	18.8	20.5	21.0	0.90 (0.72, 1.13)	0.91 (0.74, 1.11)
Turning	5.0	3.6	3.8	1.39 (0.93, 2.09)	1.38 (0.97, 1.96)
Changing lanes	2.0	0.9	0.9	**2.22 (1.16, 4.27)**	**2.16 (1.25, 3.75)**
Merging or passing	0.4	0.3	0.3	0.75 (0.17, 3.35)	1.13 (0.34, 3.76)
Other	1.9	2.0	1.8	0.97 (0.52, 1.79)	1.07 (0.61, 1.87)

Note: CI=confidence interval. Statistically significant values are bolded.