Accident Analysis and Prevention 99 (2017) 142–152

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates

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ARTICLE INFO

Article history:
Received 27 January 2016
Received in revised form 4 August 2016
Accepted 8 November 2016
Available online 26 November 2016

Keywords:
Crash avoidance technologies
Active safety
Autonomous emergency braking
Forward collision warning
Crash risk
Rear-end crashes

ABSTRACT

The objective of this study was to evaluate the effectiveness of forward collision warning (FCW) alone, a low-speed autonomous emergency braking (AEB) system operational at speeds up to 19 mph that does not warn the driver prior to braking, and FCW with AEB that operates at higher speeds in reducing front-to-rear crashes and injuries. Poisson regression was used to compare rates of police-reported crash involvements per insured vehicle year in 22 U.S. states during 2010–2014 between passenger vehicle models with FCW alone or with AEB and the same models where the optional systems were not purchased, controlling for other factors affecting crash risk. Similar analyses compared rates between Volvo 2011–2012 model S60 and 2010–2012 model XC60 vehicles with a standard low-speed AEB system to those of other luxury midsize cars and SUVs, respectively, without the system.

FCW alone, low-speed AEB, and FCW with AEB reduced rear-end striking crash involvement rates by 27%, 43%, and 50%, respectively. Rates of rear-end striking crash involvements with injuries were reduced by 20%, 45%, and 56%, respectively, by FCW alone, low-speed AEB, and FCW with AEB, and rates of rear-end striking crash involvements with third-party injuries were reduced by 18%, 44%, and 59%, respectively. Reductions in rear-end striking crashes with third-party injuries were marginally significant for FCW alone, and all other reductions were statistically significant. FCW alone and low-speed AEB reduced rates of being rear struck in rear-end crashes by 13% and 12%, respectively, but FCW with AEB increased rates of rear-end struck crash involvements by 20%. Almost 1 million U.S. police-reported rear-end crashes in 2014 and more than 400,000 injuries in such crashes could have been prevented if all vehicles were equipped with FCW and AEB that perform similarly as systems did for study vehicles.

1. Introduction

There were nearly 2 million police-reported rear-end crashes in 2014, representing 32% of all police-reported crashes (Insurance Institute for Highway Safety, 2016). Front crash prevention systems, which warn drivers, brake autonomously, or perform both functions when a frontal collision is imminent have been estimated to potentially prevent or mitigate up to 70% of rear-end collisions and 20% of all police-reported crashes if installed on all passenger vehicles (Jermakian, 2011). Autonomous braking can reduce the severity of a crash by lowering the speed of the striking vehicle if it does not prevent the crash entirely.

A few types of front crash prevention systems are available to consumers. Forward collision warning (FCW) was first introduced in the United States by Mercedes-Benz in model year 2000. Systems with both FCW and autonomous emergency braking (AEB) followed, and were first offered in the United States by Acura in model year 2006. Volvo offered the first U.S. AEB system that operates only at low speeds and that does not warn the driver prior to braking autonomously as standard equipment on the XC60 model in model year 2010. Most systems were initially offered as optional equipment in luxury vehicles but have become more widely available in recent years. In model year 2016, 54% of U.S. vehicle series offered a front crash prevention system as optional equipment and 7% included one as standard. Twenty automakers representing 99% of the U.S. auto market have committed to making FCW and AEB standard features on virtually all new passenger vehicles by 2022.

The first research on the effectiveness of FCW alone and FCW with AEB came from the Highway Loss Data Institute ([HLDI], 2012a,b, 2013a, 2015a, 2016a,b), which performed a series of studies comparing U.S. insurance claim rates per insured vehicle year between vehicles with these systems and the same vehicle models where the optional systems were not purchased. Vehicles analyzed included Honda Accords and Fiat Chrysler, Mercedes-Benz, and Volvo models with FCW only, and Acura, Mercedes-Benz, Subaru,

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http://dx.doi.org/10.1016/j.aap.2016.11.009
0001-4575/

and Volvo models with FCW and AEB. On Fiat Chrysler models, FCW came packaged with blind spot monitoring and rear cross-traffic alert, which warn drivers when another vehicle appears in their blind spot while moving forward or backing. On Honda Accord, Subaru, and Volvo models with AEB, front crash prevention came packaged with lane departure warning, which warns drivers when they drift from the lane; on Volvos with AEB, it also came packaged with a driver drowsiness alert.

In HLDI's (2012a,b, 2013a, 2015a, 2016a,b) research, FCW alone was associated with 7%–22% reductions in rates of property damage liability claims, which cover damage caused by the at-fault vehicle to other vehicles and property, and 4%–25% reductions in rates of bodily injury liability claims, which cover medical costs for injuries inflicted by the at-fault vehicle to occupants of other vehicles or others on the road. Systems with FCW and AEB were associated with 10%-16% reductions in property damage liability claim rates and 14%–32% reductions in bodily injury liability claim rates. Reductions were not significant for all automakers. Among vehicles from Mercedes-Benz and Volvo, which offered both FCW only and FCW with AEB, FCW with AEB was associated with larger benefits than FCW alone. In an analogous study in the United Kingdom, Doyle et al., (2015) compared auto insurance claim rates for Volkswagen Golf 7 vehicles equipped with FCW and AEB with rates for control vehicle models, finding reductions of 20% in third-party damage claim rates and 45% in third-party injury claim rates associated with FCW and AEB.

HLDI (2015b) and Doyle et al. (2015) reported comparable reductions in insurance claim rates for Volvo vehicles with standard low-speed AEB when comparing claim rates between Volvos with the standard system and similar vehicles from the same class. In HLDI's (2015b) study, Volvo S60 and XC60 models with low-speed AEB had 15% fewer property damage liability claims and 29% fewer bodily injury liability claims per insured vehicle year than comparison midsize luxury cars and midsize luxury SUVs. Doyle et al. (2015) likewise found that Volvo XC60 models with low-speed AEB in the United Kingdom had 8% fewer third-party damage claims and 21% fewer third-party injury claims per insured vehicle year than comparison SUVs.

Others have focused on the effectiveness of front crash prevention systems in preventing rear-end crashes. Using Swedish insurance data, Issakson-Hellman and Lindman (2015a,b) compared rates of rear-end striking crashes between Volvo models with and without standard low-speed AEB, and between Volvo models with FCW and AEB and the same Volvo models without the optional systems. Vehicles with low-speed AEB and FCW with AEB were involved in 25%–29% and 38%–45%, respectively, fewer rear-end striking crashes per insured vehicle year than comparison vehicles. In Japan, Subaru models with FCW and AEB, coupled with lane departure warning, were likewise involved in fewer rear-end and multiple-vehicle intersection crashes than the same models without the optional systems (Kumagai, 2015).

Two groups of researchers (Fildes et al., 2015; Rizzi et al., 2014) used an induced exposure approach that compared the ratio of striking to being struck in two-vehicle police-reported rear-end injury crashes for vehicles with low-speed AEB and similar vehicles without it. In Sweden, Rizzi et al. (2014) compared Volvo models with standard low-speed AEB with other Volvo models without low-speed AEB and with similar vehicle models from other automakers without AEB. Low-speed AEB was associated with 35%–41% reductions in rear-end striking injury crash involvements. Benefits were greater at lower speed limits. Rear-end striking injury crashes were reduced by 54%–57% among vehicles with low-speed AEB at speed limits less than or equal to 50 km/h, 35%–42% at speed limits of 60–70 km/h, and 12%–25% at speed limits of 80 km/h or higher. Reductions were significant only at speed limits less than or equal to 50 km/h.

Fildes et al. (2015) similarly found that vehicles with low-speed AEB were involved in 38% fewer police-reported rear-end striking injury crashes than similar vehicles without AEB in a meta-analysis of benefits in six mainly European countries. Study vehicles with low-speed AEB included Volvo as well as Volkswagen and Mazda models. Unlike Rizzi et al. (2014), however, Fildes et al. (2015) found no difference in effectiveness between low-speed AEB systems at speed limits above 60 km/h and speed limits of 60 km/h and below.

The primary purpose of the current study was to examine the effectiveness of FCW systems alone, Volvo's AEB system that only operates at lower speeds, and FCW systems with AEB in preventing police-reported rear-end striking crashes in the United States. Crash involvement rates per insured vehicle year were compared between vehicles with FCW systems alone or with FCW and AEB and the same vehicle models where the optional systems were not purchased. To study low-speed AEB, which was a standard feature on certain Volvo models, crash involvement rates for Volvo S60 and XC60 models with the standard low-speed AEB system were compared with those for comparable midsize luxury cars and SUVs, respectively, that did not have standard front crash prevention systems.

Effects were estimated for low-speed AEB at different speed limit levels because these systems might not thought to be effective at higher speed limit levels. Additionally, because primary analyses of low-speed AEB compared Volvo vehicles with vehicles from other automakers, secondary analyses compared the performance of Volvos with low-speed AEB to other Volvo models without the system to assess if primary results reflect characteristics of Volvo drivers rather than effects of the system. Finally, because it has been suggested that front crash prevention systems may affect the risk of being struck in the rear for vehicles with the systems if they affect the frequency of hard braking events, additional analyses examined the effects of systems on rear-end struck crash involvement rates.

2. Methods

2.1. Vehicles in analyses of FCW alone and with AEB

Vehicle series and model years included in the analyses of FCW alone and with AEB are listed in Table A1 in the Appendix. Study vehicles with these systems were limited to series where the system was offered as an optional feature and information was available on presence or absence of the system on individual vehicles. The study focused on vehicles with optional systems because these systems were rarely offered as standard equipment prior to and during the study period.

Vehicle identification numbers (VINs) of Acura, Fiat Chrysler (Dodge and Jeep), Mercedes-Benz, and Volvo vehicles equipped with various collision avoidance technologies, including FCW and AEB, were obtained from manufacturers. Collision avoidance systems on Honda Accord and Subaru vehicles were tied to trim levels, which for these automakers are discernable from the VIN.

Vehicles were excluded from analyses of FCW alone and with AEB if some kind of front crash prevention was standard equipment for that series/model year combination. For example, Acura series where FCW was a standard feature and AEB was offered as an optional feature were excluded from these analyses, as were Volvo vehicles with standard low-speed AEB. Vehicles also were excluded if FCW alone or with AEB was offered, but no vehicles with a system from that series/model year combination were insured in study states during the calendar years analyzed.

The minimum speed at which FCW with and without AEB was operational varied among systems from 0 to 20 mph, and the systems continued to work at high speeds. Warnings on all systems were both auditory and visual. Some systems were capable of detecting imminent collisions with pedestrians in addition to vehicles. All vehicles with FCW alone or with AEB also had adaptive cruise control (ACC), with the exception of Acura and Honda Accord vehicles with FCW alone. Like regular cruise control, ACC allows drivers to set a travel speed, but ACC also decelerates to keep a set safe distance behind the vehicle ahead when traffic slows. When traffic speeds resume, the vehicle accelerates up to the set speed.

On the Honda Accord Touring trim, FCW is radar-based and includes ACC; on other Honda Accord trims, FCW is camera-based and there is no ACC. Front crash prevention was packaged with lane departure warning on Honda Accord models, Subaru models, and Volvo models with AEB, and with blind spot monitoring and rear cross-traffic alert on Fiat Chrysler models with FCW. FCW with AEB on Volvo models was also packaged with a driver drowsiness alert.

2.2. Vehicles in analyses of low-speed AEB

A different approach was used to examine low-speed AEB because it was a standard feature on the study vehicles. Volvo 2011–2012 model S60 and 2010–2012 model XC60 vehicles with standard low-speed AEB were compared with vehicle series listed in Table A2 in the Appendix. The 2010 model XC60 debuted in February 2009, when most automakers were still marketing model year 2009 vehicles; thus, comparison vehicles for the 2010–2012 model XC60 included other 2009–2012 model midsize luxury SUVs without standard AEB. Volvo 2011–2012 model S60 vehicles were compared with other midsize luxury 2011–2012 model four-door cars without standard AEB.

As a secondary test to ensure that effects in comparisons to vehicles from other automakers are not due to characteristics of Volvo drivers rather than low-speed AEB, 2010–2012 model XC60 vehicles were also compared with Volvo 2009–2012 models without low-speed AEB, and 2011–2012 model S60 vehicles were compared with Volvo 2011–12 models without low-speed AEB. Comparison Volvos in this analysis were not limited to vehicles of the same class as the S60 or XC60 because during these years, Volvo only had one other midsize luxury SUV in its lineup (the XC90) and no other midsize luxury four-door cars.

Unlike the FCW with AEB systems examined in this study, Volvo's low-speed AEB system does not warn the driver before engaging in autonomous braking and is only operational at lower speeds. Study Volvos with low-speed AEB had the first generation of the City Safety system that operated at travel speeds up to 19 mph (equivalent to 30 km/h). The first-generation system can prevent crashes altogether if the speed of a vehicle relative to the speed of the vehicle ahead is 9 mph or less, or it can lessen the severity of the crash by reducing the striking vehicle's speed if the speed relative to the vehicle ahead is 10–19 mph.

Vehicles with low-speed AEB and vehicles in the comparison groups may have offered other collision avoidance systems, including FCW alone or FCW with AEB that operated at higher speeds, as optional equipment. Vehicles with these optional systems were not excluded from the study because we could not discern the presence or absence of these features on individual vehicles for most models on which they were offered. However, the percentage of vehicles where these optional features were purchased is believed to be low.

2.3. Crash data

Police-reported data for crashes involving study vehicles were extracted from 22 states that provided VINs with their crash data so that study vehicles could be identified. Data were available during 2010–2013 from Indiana, Nevada, and Rhode Island, and during 2010–2014 from Delaware, Florida, Georgia, Idaho, Iowa, Kansas, Louisiana, Michigan, Minnesota, Missouri, Nebraska, New Jersey, Oklahoma, Pennsylvania, South Dakota, Tennessee, Texas, Utah, and Wyoming. VINs were missing or invalid for 13% of vehicles involved in crashes in these states during these years.

Striking and struck vehicles in rear-end crashes were identified in crash data using the manner of collision, point of impact, and vehicle movement variables. In two-vehicle crashes, a vehicle was the striking vehicle in a rear-end crash if the manner of collision was front-to-rear, no vehicles in the crash were backing, the point of impact on the subject vehicle was the front (11, 12, or 1 o'clock positions), and the point of impact on the struck vehicle was the rear (5, 6, or 7 o'clock positions). In crashes identified as front-to-rear, involving three or more vehicles, and where no vehicles were backing, the subject vehicle was the striking vehicle if it was impacted in the front without consideration of the point of impact on other vehicles. Parked vehicles were not included in counts of the number of vehicles in crashes. The term rear-end striking crash is used in this paper to refer to crash involvements where the subject vehicle was the striking vehicle in a rear-end crash.

Similarly, a vehicle was the struck vehicle in a two-vehicle rear-end crash if the manner of collision was front-to-rear, no vehicles in the crash were backing, the point of impact on the subject vehicle was the rear, and the point of impact on the striking vehicle was the front. In front-to-rear crashes involving three or more vehicles where no vehicles in the crash were backing, the subject vehicle was the struck vehicle if it was impacted in the rear regardless of the points of impact to the other crash vehicles.

Injury crash involvements were those where any person involved in the crash, including occupants of any vehicle or non-occupants, received a K-, A-, B-, or C-level injury on the KABCO scale. Third-party injury crash involvements were those where occupants of vehicles other than the subject vehicle were injured in a multi-vehicle crash, such as occupants of the struck vehicle in a rear-end crash.

Most states coded point of impact as clock positions, but a few coded more or fewer possible impact points. In these states, 11 and 1 o'clock were considered to be the two side impact points closest to the front corners of the vehicle, and 5 and 7 o'clock were considered to be the side impact points closest to the rear corners. If variables were available both for the initial and the most damaged points of impact, the initial point of impact was used.

Among crashes involving study vehicles, information on the point of impact was missing in 4% of crash involvements and information on the manner of collision was missing in 5% of crash involvements. Information on either variable or the other vehicle's point of impact in two-vehicle crashes was missing in 10% of crash involvements. Vehicles with missing data on these variables were treated as if they were not involved in rear-end striking or struck crashes.

All states but Nebraska included the speed limit in their crash data. Speed limit was assigned to the vehicle in about two-thirds of states and to the crash in the remainder. Speed limits were considered invalid if they were less than 5 mph or higher than the state's maximum speed limit in that year. The variable was missing or invalid for 10% of crash involvements involving the study vehicles included in analyses of the effect of low-speed AEB by speed limit in states where it was available.

2.4. Exposure data

Data on vehicle exposure and characteristics of the vehicle's garaging location (density of registered vehicles in the zip code where vehicle is garaged), insurance policy (deductible range of collision coverage), and rated driver (age, gender, marital status, and insurance risk level) were obtained from HLDI. The HLDI database includes approximately 85% of insured U.S. passenger vehicles.

Vehicle exposure was expressed in insured vehicle days, so that a vehicle insured for 6 months would have 183 days of exposure.

For simplicity, exposure is presented in tables as insured vehicle years. Vehicle feature data, crash data, and insurance exposure data were merged by matching VINs within states; because VINs were matched within states, crashes that occurred in a different state than where a vehicle was insured were not captured.

In the study states during the study years, among the vehicle types examined, 22% of vehicles in crashes where the VIN was known did not appear in the HLDI database and an additional 6% were insured in a different state than where they crashed. These vehicles were excluded from both the numerator and denominator of crash rates.

2.5. Regression models

Poisson regression was used to model crash involvement rates per insured vehicle year for vehicles with FCW alone, with FCW and AEB, and with low-speed AEB compared with vehicles without these systems, controlling for a number of other factors that affect crash risk. In the main analyses of FCW alone or with AEB, separate regressions were constructed for each of the six automakers for each of the three primary crash types examined, resulting in 18 separate models. The three crash types included: 1) rear-end striking crashes of all severities, 2) rear-end striking crashes with injuries, and 3) rear-end striking crashes with third-party injuries. Third-party injuries were of interest because rear-end crashes often result in neck injuries to occupants of the struck vehicle (Zuby and Lund, 2010). Additional analyses examined effects of systems on rear-end struck crashes of all severities, with any injuries, and with injuries to occupants of the subject (struck) vehicle, resulting in 18 additional separate models.

To examine low-speed AEB, separate regression models were likewise constructed for each of the three primary crash types for Volvo S60 models vs. other midsize luxury four-door cars, Volvo XC60 models vs. other midsize luxury SUVs, Volvo S60 models vs. other Volvo models without low-speed AEB, and Volvo XC60 models vs. other Volvo models without low-speed AEB. This resulted in 12 separate models. Separate regression models also were constructed for Volvo S60 models vs. other midsize luxury four-door cars and Volvo XC60 models vs. other midsize luxury SUVs for each of the three primary crash types at three speed limit levels (≤35 mph, 40–45 mph, 50+ mph) resulting in 18 additional separate models. Finally, the effects of low-speed AEB on rear-end struck crashes of all severities, with any injuries, and with injuries in the subject vehicle were examined for Volvo S60 models vs. other midsize luxury four-door cars and Volvo XC60 models vs. other midsize luxury SUVs in six separate models.

All regressions controlled for rated driver age (15–24, 25–29, 30–39, 40–49, 50–59, 60–64, 65–69, 70+, unknown), gender, marital status, and insurance risk level (standard risk, nonstandard risk, unknown); state; calendar year; registered vehicle density per square mile (0–99, 100–499, 500+) in the zip code where the vehicle is garaged; and insurance policy deductible range for collision coverage ($0–$250, $251–$500, $501–$1000, $1000+). These covariates were chosen for consistency with previous HLDI (2012a,b, 2013a, 2015a,b, 2016a,b) analyses examining the effects of these same systems on insurance claim rates. The covariates did not significantly predict crash involvement rates in all models, but all covariates were retained because each was a significant predictor in some models.

In each of the manufacturer models examining the effects of FCW alone or FCW with AEB, a single variable capturing the vehicle series and model year was included to control for differences among vehicle series unrelated to collision avoidance systems. Binary variables indicating the presence or absence of collision avoidance features were additionally included.

Collision avoidance features other than front crash prevention that were included in each manufacturer's model as covariates were as follows:

- Acura: adaptive headlights, side-view assist, lane departure warning, lane departure prevention, rear cross-traffic alert.
- Fiat Chrysler: no other systems included as covariates.
- Honda: passenger side-view camera.
- Mercedes-Benz: active cornering lights, adaptive high beams, adaptive headlights, high-intensity discharge headlights, side-view assist, lane departure warning/prevention, night vision, PreSafe (tightens belts, closes windows, and makes other adjustments ahead of a potential collision but does not include FCW or AEB), parking sensors, rear camera, parking guidance (detects size of parking space and guides drivers while parking). Driver drowsiness alert was standard on some Mercedes-Benz series and could not be controlled for separately because it was never optional equipment.
- Subaru: rear camera, side-view assist/rear cross-traffic alert.
- Volvo: adaptive headlights, side-view assist. Some Volvo models offered parking sensors and rear cameras, but data on these features were not available.

Models examining the effects of low-speed AEB included model year and vehicle model as separate variables in each regression. Two-wheel drive and four-wheel drive variants of vehicle models were combined to have sufficient data for analysis. Analyses of low-speed AEB did not control for the presence or absence of other collision avoidance systems on the vehicle because this was unknown.

A logarithmic link function was used in the Poisson regression models. In models for automakers that examined the effects of both FCW alone and with AEB (Acura, Mercedes-Benz, and Volvo), suppose C_i represents the number of crash involvements, E_i represents exposure (i.e., insured vehicle days), F_i represents the presence or absence of FCW alone, and A_i represents the presence or absence of FCW with AEB for vehicle i. Assuming C_i is a Poisson random variable with mean $E_i\lambda_i$, the statistical models were specified as $\log \lambda_i = \beta_0 + \beta_1(f_i) + \beta_2(a_i) + \beta_3(\text{covariates})$. In these models, $\exp(\beta_1)$ represented the rate ratio comparing crash involvement rates for vehicles with FCW alone to vehicles without, and $\exp(\beta_2)$ represented the rate ratio comparing crash involvement rates for vehicles with FCW and AEB to vehicles without.

Subaru only offered FCW with AEB and not FCW alone, and thus Subaru's models did not include a term to estimate the effects of FCW alone; similarly, Fiat Chrysler only offered FCW alone. Likewise, Honda's models included two terms to estimate the effects of their radar-based and camera-based FCW systems and no term to estimate FCW with AEB.

In models examining the effects of low-speed AEB, suppose C_i represents the number of crash involvements, E_i represents exposure, and $v_{i1} - v_{in}$ represent the vehicle model for vehicle i and comparison vehicle model types 1 through n. Assuming C_i is a Poisson random variable with mean $E_i\lambda_i$, models were specified as $\log \lambda_i = \beta_0 + \beta_1\ (v_{i1}) + \ldots + \beta_n(v_{in}) + \beta_{n+1}(\text{covariates})$. $\text{Exp}(\beta_1)$ represented the rate ratio comparing crash involvement rates for the Volvo S60 or XC60 with low-speed AEB to comparison vehicle model 1, and $\exp(\beta_n)$ represented the rate ratio comparing crash involvement rates for the Volvo S60 or XC60 to comparison vehicle model n.

2.6. Pooled estimates

Effects for FCW systems alone and for FCW systems with AEB were pooled across automakers. Effects for low-speed AEB were pooled across comparison models to produce a combined estimate for the Volvo S60 and for the XC60. Additionally, a combined effect for low-speed AEB was calculated by pooling effects from both the S60 and XC60 analyses that used midsize luxury cars or SUVs, respectively, as the comparison vehicles. A combined low-speed AEB effect from the models using other Volvo models as the comparison group was not calculated because the comparison vehicles in the S60 and the XC60 analyses were largely the same.

Effects were pooled using meta-analysis methods outlined below, which are similar to those summarized by Elvik (2001). Heterogeneity was evaluated with the Q statistic (Shadish and Haddock, 1994). Random effects models were used in all analyses of low-speed AEB because heterogeneity was found in some sets of estimates for that system, and fixed effects models were used in analyses of FCW alone and with AEB because no heterogeneity was present there. To pool estimates, rate ratios were log-transformed. For analyses of FCW alone or with AEB, a weight was assigned to each estimate as follows:

$$w_i = \frac{1}{v_i}$$

where v_i represents the estimate's variance. A weight was assigned to each estimate in low-speed AEB analyses as follows:

$$w_{i=\frac{1}{v_i+\sigma_\theta^2}}$$

where v_i represents the estimate's variance and σ_θ^2 is a function of the Q statistic that represents the systematic variation among the estimated effects. The pooled effect for FCW alone, FCW with AEB, or low-speed AEB was calculated as follows:

$$\bar{y} = exp\left(\frac{\sum_{i=1}^{g} w_i y_i}{\sum_{i=1}^{g} w_i}\right)$$

where exp is the exponential function, y_i is the logarithm of each effect estimate, w_i is each estimate's weight, and g is the total number of estimates for that system type. Ninety-five percent confidence intervals were computed using the following equation:

$$95\%CI = exp\left[\left(\frac{\sum_{i=1}^{g} w_i y_i}{\sum_{i=1}^{g} w_i}\right) \pm 1.96 \times 1/\sqrt{\sum_{i=1}^{g} w_i}\right]$$

where g is the total number of estimates that were pooled and w_i is each estimate's weight.

Effect estimates indicated that vehicles with FCW alone, FCW and AEB, or low-speed AEB had significantly lower crash involvement rates than comparison vehicles when estimates and their 95% confidence intervals were less than 1. Percentage reductions were expressed as the rate ratio minus 1, multiplied by 100.

Acura offered FCW alone beginning in model year 2014, and this system was included as a covariate in models for this automaker. However, model results for Acura's FCW system are not reported or included in pooled estimates for FCW alone because there were too few crashes among vehicles of the series/model year combinations that offered the system to produce estimates for rear-end striking crash types. Model year 2014–2015 Acura vehicles with FCW were involved in 36, 10, and 10 rear-end, rear-end with injury, and rear-end with third-party injury crashes, respectively, and model year 2014–2015 Acuras without front crash prevention were involved in 33, 3, and 2 of these crash types, respectively. Standard errors for estimating the effect of FCW in Acuras were very high (>118 for all rear-end striking crash types).

3. Results

3.1. Rear-end striking crashes

Study vehicles were involved in a total of 197,606 crashes, and were the striking vehicle in 23,649 rear-end crashes, 7055 rear-end injury crashes, and 6112 rear-end third-party injury crashes. Rear-end striking crashes made up 12% of the crash involvements among study vehicles in these states, with a larger percentage among comparison vehicles (12%) than among vehicles with FCW alone (9%) and low-speed AEB or FCW with AEB (8% each).

Among the 46,161 injury crash involvements involving study vehicles, the percentage of injury crash involvements that were rear-end striking crashes was larger among comparison vehicles (16%) followed by vehicles with FCW alone (13%), low-speed AEB (10%), and FCW and AEB (8%). Only 5% of rear-end injury crashes involved fatalities or serious (A-level) injuries. For each manufacturer that offered optional FCW alone or with AEB, vehicles with front crash prevention systems were involved in fewer rear-end striking crashes of all types per insured vehicle year than vehicles without front crash prevention; similarly, involvement rates in all types of rear-end striking crashes were lower for the Volvo S60

Table 1
Rear-end striking crash involvement rates of study vehicles with FCW alone, with low-speed AEB, with FCW with AEB, and of comparison vehicles.

Vehicle type	System	Insured vehicle years	Rear-end		Rear-end injury		Rear-end third-party injury	
			Crashes	Rate (×1000)	Crashes	Rate (×1000)	Crashes	Rate (×1000)
Acura	FCW	15,605	36	2.3	10	0.64	10	0.64
	FCW + AEB	27,920	69	2.5	16	0.57	14	0.50
	No system	191,714	799	4.2	236	1.23	212	1.11
Fiat Chrysler	FCW	50,964	197	3.9	54	1.06	50	0.98
	No system	350,696	2225	6.4	675	1.92	602	1.72
Honda	FCW (no ACC)	119,613	527	4.4	165	1.38	134	1.12
	FCW (with ACC)	5,110	17	3.3	6	1.17	6	1.17
	No system	162,771	1092	6.7	328	2.02	261	1.60
Mercedes-Benz	FCW	17,409	49	2.8	21	1.21	18	1.03
	FCW + AEB	24,999	63	2.5	20	0.80	16	0.64
	No system	1,093,924	5136	4.7	1568	1.43	1382	1.26
Subaru	FCW + AEB	14,861	21	1.4	2	0.13	2	0.13
	No system	151,171	465	3.1	124	0.82	103	0.68
Volvo	FCW	3,190	7	2.2	2	0.63	2	0.63
	FCW + AEB	2,475	5	2.0	2	0.81	2	0.81
	No system	101,913	395	3.9	113	1.11	98	0.96
Volvo S60	Low-speed AEB	40,020	139	3.5	34	0.85	27	0.67
Comparison cars	No standard system	703,999	4285	6.1	1271	1.81	1032	1.46
Volvo XC60	Low-speed AEB	61,702	147	2.4	45	0.73	41	0.66
Comparison SUVs	No standard system	1,831,015	7975	4.4	2363	1.29	2100	1.15
	Total	4,971,071	23,649	4.8	7055	1.42	6112	1.23

Table 2
Adjusted rate ratios from Poisson regression models examining the effects of FCW alone, low-speed AEB, and FCW with AEB on rear-end striking crash involvement rates.

Analysis	Rate ratio (95% confidence interval)		
	Rear-end striking	Rear-end striking with injury	Rear-end striking with third-party injury
FCW alone			
Fiat Chrysler	0.70 (0.60, 0.82)	0.62 (0.46, 0.83)	0.65 (0.48, 0.89)
Honda (no ACC)	0.78 (0.64, 0.95)	0.99 (0.68, 1.44)	0.98 (0.65, 1.48)
Honda (with ACC)	0.72 (0.43, 1.19)	1.00 (0.42, 2.38)	1.22 (0.50, 2.95)
Mercedes-Benz	0.73 (0.54, 0.97)	1.05 (0.67, 1.65)	1.05 (0.65, 1.70)
Volvo	0.62 (0.28, 1.42)	0.62 (0.14, 2.76)	0.63 (0.14, 2.87)
Combined FCW effect	0.73 (0.66, 0.81)	0.80 (0.66, 0.98)	0.82 (0.67, 1.01)
Low-speed AEB			
Volvo S60 vs. midsize luxury cars	0.66 (0.61, 0.71)	0.57 (0.50, 0.65)	0.54 (0.47, 0.62)
Volvo XC60 vs. midsize luxury SUVs	0.52 (0.48, 0.56)	0.54 (0.50, 0.60)	0.56 (0.51, 0.62)
Combined low-speed AEB effect	0.57 (0.53, 0.61)	0.55 (0.52, 0.60)	0.56 (0.51, 0.60)
FCW + AEB			
Acura	0.51 (0.27, 0.96)	0.53 (0.19, 1.46)	0.31 (0.08, 1.28)
Mercedes-Benz	0.56 (0.36, 0.89)	0.44 (0.19, 1.02)	0.44 (0.19, 1.02)
Subaru	0.43 (0.27, 0.67)	0.15 (0.04, 0.60)	0.17 (0.04, 0.72)
Volvo	0.61 (0.25, 1.52)	1.00 (0.24, 4.26)	1.10 (0.26, 4.71)
Combined FCW + AEB effect	0.50 (0.38, 0.66)	0.44 (0.26, 0.76)	0.41 (0.23, 0.74)

Note: Results for Acura's FCW system are not reported because there were too few crashes among vehicles that offered the system to produce estimates.

and XC60 with low-speed AEB than for comparison cars and SUVs, respectively (Table 1).

Results of Poisson regressions examining the effects of FCW alone, low-speed AEB, and FCW with AEB on rear-end striking crash involvement rates appear in Table 2. The results control for state, calendar year, registered vehicle density of the vehicle garaging location, collision coverage deductible range, and the age, gender, marital status, and insurance risk of the rated driver. Results for FCW alone and FCW with AEB additionally control for the vehicle series/model year combination and other collision avoidance technologies on the vehicle, the those for low-speed AEB also control for the model year.

FCW alone was associated with a 27% reduction in rear-end striking crash rates, low-speed AEB was associated with a 43% reduction, and FCW with AEB was associated with a 50% reduction (Table 2). Reductions in rear-end striking crash rates with injuries and those with third-party injuries were largest among vehicles with FCW and AEB (56% and 59%, respectively), followed by low-speed AEB (45% and 44%, respectively) and FCW alone (20% and 18%, respectively). All effects were significant with the exception of the effect of FCW alone on rates of rear end striking crashes with third-party injuries, which was marginally significant ($p < 0.06$). Effects were significantly larger for low-speed AEB than for FCW alone, and effects for FCW with AEB did not differ significantly from other system types.

3.2. Effects of low-speed AEB by speed limit

Volvo S60 and XC60 models and their comparison midsize luxury cars and SUVs were involved in 11,333 rear-end striking crashes where the speed limit was known. Rear-end striking crashes were somewhat evenly split among speed limits, with 33% occurring at speed limits of 35 mph or less, 38% occurring at speed limits of 40–45 mph, and 29% occurring at speed limits of 50 mph or above.

Table 3 summarizes the effect of low-speed AEB on rear-end striking crash types at these three speed limits when Volvo S60 and XC60 models were compared with midsize luxury cars and SUVs. Poisson regressions controlled for the same covariates as prior analyses. Combined reductions in rear-end striking crash rates, rear-end striking injury crash rates, and rear-end striking third-party injury crash rates were largest at speed limits of 40–45 mph (53%, 59%, and 58%, respectively), followed by speed limits of 35 mph or less (40%, 40%, and 43%, respectively) and then limits of 50 mph or greater (31%, 30%, and 28%, respectively). All reductions were significant.

3.3. Volvo S60 and XC60 compared with other Volvo models

To ensure that the benefits of low-speed AEB based on comparisons of Volvo S60 and XC60 models with other cars and SUVs were not due to characteristics of Volvo drivers independent of low-speed AEB, secondary analyses compared crash involvement rates between Volvo S60 and XC60 models with low-speed AEB and other Volvo models without low-speed AEB.

Poisson regression model results comparing the Volvos with low-speed AEB with other Volvo models without low-speed AEB are shown in Table 4. Results for rear-end striking crashes when Volvos with low-speed AEB were compared with Volvos without the system were largely consistent with comparisons with non-Volvo SUVs and cars. Because the comparison vehicles in the S60 and XC60 analyses were mostly the same, effects are reported separately for the S60 and XC60 and a combined low-speed AEB effect was not calculated. Rear-end striking crash rates, rear-end striking injury crash rates, and rear-end striking third-party injury crash rates were 43%, 36%, and 35% lower, respectively, among Volvo XC60 vehicles with low-speed AEB than among other Volvos. All reductions were significant. Volvo S60 vehicles with low-speed AEB experienced a significant 23% reduction in rear-end striking crash rates, and non-significant reductions of 3% and 21%, respectively, in rear-end striking crashes with injuries and with third-party injuries.

3.4. Rear-end struck crashes

Additional analyses examined the effects of FCW alone, low-speed AEB, and FCW with AEB on rear-end struck crash involvement rates. Study vehicles with these systems and their comparison vehicles were struck in 38,545 rear-end crashes, 10,253 rear-end crashes with injuries, and 8904 rear-end crashes with injuries to occupants of the subject vehicle.

The effects of systems on rear-end struck crash rates appear in Table 5. Rates of rear-end struck crash involvements, those with injuries, and those with injuries to occupants of the struck vehicle were 13%, 8%, and 15% lower, respectively, for vehicles with FCW alone, and were 12%, 15%, and 14% lower, respectively, for vehicles with low-speed AEB than among comparison vehicles.

Table 3
Adjusted rate ratios from Poisson regression models examining the effects of low-speed AEB on rear-end striking crash involvement rates by speed limit.

Speed limit	Analysis	Rate ratio (95% confidence interval)		
		Rear-end striking	Rear-end striking with injury	Rear-end striking with third-party injury
≤35 mph	Volvo S60 vs. midsize luxury cars	0.65 (0.57, 0.75)	0.78 (0.62, 0.98)	0.64 (0.49, 0.84)
	Volvo XC60 vs. midsize luxury SUVs	0.57 (0.52, 0.63)	0.52 (0.44, 0.62)	0.54 (0.45, 0.65)
	Combined low-speed AEB effect	0.60 (0.55, 0.65)	0.60 (0.52, 0.69)	0.57 (0.49, 0.66)
40–45 mph	Volvo S60 vs. midsize luxury cars	0.51 (0.45, 0.58)	0.37 (0.29, 0.47)	0.33 (0.25, 0.44)
	Volvo XC60 vs. midsize luxury SUVs	0.45 (0.41, 0.49)	0.43 (0.37, 0.51)	0.46 (0.39, 0.54)
	Combined low-speed AEB effect	0.47 (0.43, 0.50)	0.41 (0.36, 0.47)	0.42 (0.37, 0.49)
50+ mph	Volvo S60 vs. midsize luxury cars	0.86 (0.77, 0.97)	0.63 (0.51, 0.77)	0.70 (0.56, 0.87)
	Volvo XC60 vs. midsize luxury SUVs	0.59 (0.54, 0.65)	0.73 (0.63, 0.85)	0.73 (0.62, 0.85)
	Combined low-speed AEB effect	0.69 (0.62, 0.76)	0.70 (0.62, 0.78)	0.72 (0.63, 0.82)

Table 4
Adjusted rate ratios from Poisson regression models examining the effects of low-speed AEB on crash involvement rates, comparing Volvo S60 and XC60 models with low-speed AEB to other Volvo models without low-speed AEB.

Analysis	Rate ratio (95% confidence interval)		
	Rear-end striking	Rear-end striking with injury	Rear-end striking with third-party injury
Volvo S60 vs. other Volvo models	0.77 (0.65, 0.91)	0.97 (0.68, 1.36)	0.79 (0.54, 1.14)
Volvo XC60 vs. other Volvo models	0.57 (0.52, 0.63)	0.64 (0.54, 0.77)	0.65 (0.54, 0.79)

Table 5
Adjusted rate ratios from Poisson regression models examining the effects of FCW alone, low-speed AEB, and FCW with AEB on rear-end struck crash involvement rates.

Analysis	Rate ratio (95% confidence interval)		
	Rear-end struck	Rear-end struck with injury	Rear-end struck with injury in struck vehicle
FCW alone			
Fiat Chrysler	0.93 (0.83, 1.05)	0.98 (0.80, 1.19)	0.88 (0.68, 1.13)
Honda (no ACC)	0.82 (0.72, 0.93)	0.93 (0.74, 1.17)	0.89 (0.69, 1.16)
Honda (with ACC)	0.73 (0.63, 1.00)	0.81 (0.46, 1.41)	0.82 (0.43, 1.55)
Mercedes-Benz	1.02 (0.81, 1.28)	0.79 (0.51, 1.21)	0.71 (0.42, 1.20)
Volvo	0.53 (0.29, 0.98)	0.78 (0.32, 1.91)	0.55 (0.16, 1.86)
Combined FCW effect	0.87 (0.81, 0.94)	0.92 (0.81, 1.06)	0.85 (0.72, 1.01)
Low-speed AEB			
Volvo S60 vs. midsize luxury cars	0.86 (0.81, 0.93)	0.77 (0.68, 0.87)	0.83 (0.74, 0.94)
Volvo XC60 vs. midsize luxury SUVs	0.88 (0.83, 0.94)	0.89 (0.82, 0.97)	0.87 (0.81, 0.94)
Combined low-speed AEB effect	0.88 (0.84, 0.92)	0.85 (0.79, 0.91)	0.86 (0.80, 0.91)
FCW + AEB			
Acura	1.12 (0.71, 1.76)	0.56 (0.23, 1.38)	0.49 (0.15, 1.59)
Mercedes-Benz	1.25 (0.95, 1.65)	1.42 (0.90, 2.22)	1.35 (0.78, 2.33)
Subaru	1.15 (0.94, 1.40)	0.94 (0.65, 1.36)	1.01 (0.65, 1.59)
Volvo	1.52 (0.94, 2.40)	1.05 (0.42, 2.66)	1.23 (0.43, 3.50)
Combined FCW + AEB effect	1.20 (1.04, 1.39)	1.04 (0.80, 1.36)	1.08 (0.79, 1.48)

Note: Results for Acura's FCW system are not reported because there were too few crashes among vehicles that offered the system to produce estimates.

Effects were significant for FCW alone when examining rear-end struck crashes of all severities and marginally significant for rear-end struck crashes with injuries in the subject vehicle ($p < 0.06$), and were significant for low-speed AEB for all three crash types.

FCW with AEB had a different effect on these crashes. Rear-end struck rates were 20% higher for vehicles with FCW and AEB than for the same vehicle models without. Rates of rear-end struck crashes with injuries were 4% higher and with injuries to occupants of the struck vehicle were 8% higher. The increase in the rear-end struck crash rate was significant.

4. Discussion

Consistent with earlier insurance claim analyses, front crash prevention systems appear to be highly effective in reducing police-reported rear-end crashes in the United States. FCW with AEB and low-speed AEB were associated with larger reductions in rates of all rear-end striking crashes, those with injuries, and those with third-party injuries than FCW alone, although the differences in estimated effectiveness between the systems were only significant for low-speed AEB. The estimated reductions of 43–50%, 45–56%, and 44–59% in rear-end striking crash rates of all severities, with injuries, and with third-party injuries, respectively, for vehicles with low-speed AEB or FCW and AEB in the current study are very similar to the 38%–45% reduction in rear-end striking crash rates found in Swedish insurance data for Volvos with FCW and AEB (Issakson-Hellman and Lindman, 2015b) and the 35%–41% reduction in police-reported rear-end striking injury crash rates found in Europe and elsewhere for low-speed AEB (Fildes et al., 2015; Rizzi et al., 2014).

Because the version of Volvo's low-speed AEB system that was evaluated in this study was operational at speeds up to 19 mph, it would be expected to have the greatest effect on urban roads with low speed limits. Low-speed AEB had the weakest effect at speed limits of 50 mph or greater, which was expected, and the strongest effect at speed limits of 40–45 mph, which was surprising. Prior studies have found mixed evidence on the effectiveness of low-speed AEB at varying speed limits, with Rizzi et al. (2014) finding increasing effectiveness at decreasing speed limits when examining roughly the same speed limits as in this study, and Fildes et al.

(2015) finding no difference in effectiveness at speed limits above and below 60 km/h.

One reason for the current finding that low-speed AEB was highly effective at speed limits of 40–45 mph may be the high frequency of intersections on these roads, where drivers may often be involved in rear-end crashes while decelerating. Of the U.S. police-reported rear-end crashes in 2014 occurring at speed limits of 35 mph or less or 40–45 mph, more than half occurred at or near intersections (62% and 60%, respectively). In contrast, only 27% of rear-end crashes at speed limits greater than or equal to 50 mph were intersection-related (Insurance Institute for Highway Safety, 2016). Congestion on roads with higher speed limits results in traffic moving at much slower speeds, and this may also have contributed to the effectiveness of low-speed AEB on roads with higher speed limits.

Although low-speed AEB was least effective at speed limits of 50 mph or greater, it still reduced rear-end striking crashes significantly at these speed limits. This is consistent with evidence indicating that most rear-end crashes in the United States occur at speeds where low-speed AEB would be useful, sometimes even on roads with higher speed limits. For instance, in analyses of rear-end crashes drawn from a sample of tow-away passenger vehicles crashes occurring during 1996–2000, 92% of the striking vehicles at speed limits below 50 mph and 80% of the striking vehicles at speed limits of 50 mph and greater experienced a change in velocity of less than 25 mph (Farmer, 2003). This is close to the relative speed at which Volvo's low-speed AEB system can operate. In a sample of crashes occurring in Germany during 1996–2004, Eis et al. (2005) found that 70% of striking vehicles in rear-end collisions were traveling at speeds lower than 30 km/h (equivalent to 19 mph).

Secondary analyses compared crash involvement rates of Volvo S60 and XC60 models with standard low-speed AEB with the rates of other Volvo models without low-speed AEB. The intent was to examine whether the results from the primary analyses could have been due to the characteristics of Volvo drivers, who may be more safety conscious than drivers of other vehicles. Both the S60 and XC60 had significantly lower rear-end striking crash rates than other Volvo models without low-speed AEB, which suggests that the main findings of the primary analysis are not due to a "Volvo buyer's effect."

The pattern of results for rear-end striking crashes were similar in the primary and secondary analyses, but this was not true for the Volvo S60 in the analysis of rear-end striking crashes with injuries. In this regard, it is important to note that the rates of crashes, injuries, and deaths vary systematically by vehicle class (e.g., Farmer, 2011; HLDI, 2015c,d), and the comparison group of other Volvos for the S60 included vehicles of a range of vehicle classes rather than just cars. The purpose of the secondary analysis was to confirm the general patterns found in the primary study, particularly for the main results on rear-end crashes of all severities, rather than to replicate them precisely.

It has been proposed that front crash prevention systems could possibly increase the risk of being struck in the rear in rear-end crashes for vehicles with the systems if they led to an increase in sudden hard braking, either autonomously or by drivers in response to warnings. Conversely, others have suggested that vehicles with systems could experience reductions in the risk of being rear struck if systems lead to earlier, less severe braking than drivers would have performed without them (Doecke et al., 2012; Schittenhelm, 2009). Effects of front crash prevention systems on rear-end struck crashes in the current study were mixed; vehicles with FCW alone and with low-speed AEB had lower rear-end struck rates than comparison vehicles, while rates for vehicles with FCW and AEB were higher. The reduction in rear-end struck rates for low-speed AEB is not consistent with prior research from HLDI (2013b), which found that the proportion of vehicles repaired for rear damage did not differ between Volvo S60 and XC60 models with low-speed AEB and the same comparison cars and SUVs examined in this study.

It is difficult to pinpoint why effects on rear-end struck crashes varied by system type. One possibility for the disbenefit among vehicles with FCW and AEB could be that vehicles with these systems experienced more hard braking events at high speeds since these were the only systems studied that performed autonomous braking at higher speeds. The placement and type of rear lighting can also affect the risk of being struck in the rear (e.g., Farmer, 1996). On the Honda Accord sedans included in analyses, the trim levels with FCW also had LED stop lamps, while the trims without FCW had incandescent stop lamps. A previous study examining the effectiveness of LED stop lamps found that Honda Accord vehicles of earlier model years than the current study had a much lower risk of being struck in the rear with LED stop lamps compared with incandescent stop lamps (Greenwell, 2013). Thus, it is likely that the presence of LED stop lamps on Honda vehicles with FCW contributed to the reduction in rear-end struck crash rates seen for these vehicles.

Despite the increased risk of being struck in the rear for vehicles with FCW and AEB, the benefits of the system outweigh this risk. Vehicles with the systems experienced larger reductions in rear-end striking rates (50%) than increases in rear-end struck rates (20%). If all vehicles were equipped with FCW with AEB, the risk of being rear-end struck would likely dissipate as following vehicles could brake autonomously in response to the possible hard braking of lead vehicles.

Data were insufficient to compare the effectiveness of different versions of front crash prevention systems. An important difference in systems was whether or not the vehicle also had an ACC system. ACC was paired with front crash prevention on all study vehicles except for some Honda Accords and Volvos with low-speed AEB. ACC could affect rear-end crashes, and it is unclear how much of the effect of FCW and AEB in this study is because of ACC.

Other study limitations should be noted. Forward collision warning systems with and without AEB were offered as optional equipment on study vehicles, and vehicles with systems could be substantially more expensive than the same vehicles without. Analyses controlled for some characteristics that correlate with crash risk, but nevertheless drivers who chose to purchase optional packages or trim levels with systems may differ from drivers who did not purchase the systems, even after controlling for these factors. The effect sizes reported here may be greater or less than the actual effects due to possible unknown differences between drivers.

While comparison vehicles of the same class of the Volvo S60 and XC60 were chosen because of their similarities, the comparison vehicles differed from the Volvo S60 and XC60 in ways other than their lack of low-speed AEB. Differences in vehicle design and the characteristics and travel patterns of drivers of vehicles with and without low-speed AEB could have affected crash rates. Some vehicles with or without low-speed AEB had other collision avoidance technologies, including FCW and AEB that operated at higher speeds. These technologies were optional when offered and were believed to have been purchased by a small percentage of vehicle owners, but they likely would have affected crash rates for vehicles when they were present. Likewise, front crash prevention was packaged with lane departure warning in Honda Accord models with FCW, Subaru models with FCW and AEB, and Volvo models with FCW and AEB; FCW with AEB was also packaged with driver drowsiness alert on Volvos. On Fiat Chrysler models, FCW was packaged with blind spot monitoring and rear cross-traffic alert.

The current study did not examine differences in effects of systems by month or year. It is possible that system performance or driver behavior with the system would change as vehicles age, and that effectiveness would differ by weather condition.

Previous research suggests that the effectiveness of Volvo's low-speed AEB City Safety system may not change with weather condition or vehicle age. Issakson-Hellman and Lindman (2015a) reported similar effectiveness estimates for City Safety in winters with colder and warmer temperatures, and HLDI (2015e) reported no clear change in the effectiveness of City Safety by vehicle age among new to 3-year-old vehicles.

Analyses of FCW alone and with AEB were limited to vehicle series for which the presence or absence of the systems were known on individual vehicles at the VIN level, either because they were supplied by automakers for a subset of their vehicle series/model year combinations (Acura, Fiat Chrysler, Mercedes-Benz, and Volvo), or because the systems were tied to trims and trim levels were discernable from the VIN (Honda and Subaru). Analyses of low-speed AEB were limited to City Safety because it was standard on Volvo S60 and XC60 vehicles and was thus known to be present on those vehicles. Effects may be different for front crash prevention systems that were not included in this study because information on their presence or absence was unavailable.

Data collected from owners of vehicles with front crash prevention systems, including owners of some of the vehicles examined in this study, indicate that most say they always keep their systems turned on (Braitman et al., 2010; Cicchino and McCartt, 2015; Eichelberger and McCartt, 2014, 2016) and nearly all were observed to have their systems turned on when their vehicles were serviced (Reagan and McCartt, 2016). Nevertheless, the status of front crash prevention systems in study vehicles at the time of the crash was not known.

5. Conclusions

In summary, front crash prevention systems seem to be effective in preventing rear-end strikes, which are a common crash type. FCW with AEB and low-speed AEB appear to be somewhat more effective than FCW alone in reducing these crashes.

Based on the 50% reduction in rear-end striking crashes and 56% reduction in rear-end striking crashes with injuries experienced by study vehicles with both FCW and AEB, almost 1 million of the nearly 2 million U.S. police-reported rear-end crashes in 2014 and more than 400,000 injuries in those crashes could have been prevented if all vehicles were equipped with systems that perform similarly to the FCW with AEB systems studied. This represents 16% of all police-reported crashes and 18% of all police-reported injuries. These estimates do not account for the changes in rates of being struck in the rear among vehicles with these systems seen in the current study, because it is unclear how or if the systems would affect rear-struck crash involvements if they were on all vehicles. FCW with AEB was not operational on some vehicles in the current study below speeds of 10–20 mph, and systems that perform at a full range of speeds would likely prevent more crashes and injuries than estimated in the current study.

Acknowledgements

The author would like to thank Adrian Lund, Chuck Farmer, David Zuby, and Anne McCartt of the Insurance Institute for Highway Safety, and Matt Moore of the Highway Loss Data Institute, for their input that improved the design and statistical methods used in this study. She is also grateful to Laurie Hellinga, Lisa Henke, and Bingling Wang of the Highway Loss Data Institute, who provided exposure and vehicle feature data, and Jason Rubinoff and JoAnn Wells of the Insurance Institute for Highway Safety for their assistance in obtaining and formatting state crash data. Pennsylvania data used herein was supplied by the Pennsylvania Department of Transportation. The Pennsylvania Department of Transportation specifically disclaims responsibility for any analyses, interpretations, or conclusions drawn in this publication. This work was supported by the Insurance Institute for Highway Safety.

APPENDIX A.

Table A1
Study vehicle series and model years included in analyses of FCW alone and with AEB.

Make	Series	Model years
Series with optional FCW alone		
Acura	MDX 4D 2WD	2014–2015
Acura	MDX 4D 4WD	2014–2015
Acura	TLX 4D 2WD	2015
Dodge	Charger 4D 2WD	2011
Dodge	Charger HEMI 4D 2WD	2011
Dodge	Charger HEMI 4D 4WD	2011
Dodge	Durango 4D 4 × 2	2011
Dodge	Durango 4D 4 × 4	2011
Honda	Accord 2D	2013–2014
Honda	Accord 4D	2013–2014
Honda	Accord Crosstour 4D 2WD	2013–2014
Jeep	Grand Cherokee 4D 4 × 2	2011
Jeep	Grand Cherokee 4D 4 × 4	2011
Mercedes-Benz	CL class 2D 2WD	2001–2006
Mercedes-Benz	CLK class 2D	2003–2004
Mercedes-Benz	CLK class Convertible	2004
Mercedes-Benz	CLS class 4D 2WD	2007–2010
Mercedes-Benz	E class 4D 2WD	2003–2009
Mercedes-Benz	E class 4D 4WD	2004
Mercedes-Benz	E class SW 2WD	2004–2009
Mercedes-Benz	E class SW 4WD	2004, 2006
Mercedes-Benz	GL class 4D 4WD	2007–2008, 2010
Mercedes-Benz	M class 4D 4 × 2	2010
Mercedes-Benz	M class 4D 4 × 4	2007–2008, 2010
Mercedes-Benz	R class 4D 2WD	2008
Mercedes-Benz	R class 4D 4WD	2007–2008, 2010
Mercedes-Benz	S class LWB 4D 2WD	2001–2006
Mercedes-Benz	S class LWB 4D 4WD	2003–2006
Mercedes-Benz	SL class convertible	2003–2009
Volvo	S80 4D 2WD	2007–2008
Volvo	S80 4D 4WD	2007–2008
Volvo	XC70 SW 4WD	2008
Series with optional FCW and AEB		
Acura	MDX 4D 2WD	2014–2015
Acura	MDX 4D 4WD	2010–2015
Acura	RL 4D 4WD	2006–2012
Acura	TLX 4D 2WD	2015
Acura	ZDX 4D 4WD	2010–2012
Mercedes-Benz	CL class 2D 2WD	2007–2010
Mercedes-Benz	CL class 2D 4WD	2009–2010
Mercedes-Benz	E class 2D 2WD	2010–2010
Mercedes-Benz	E class 4D 2WD	2010–2010
Mercedes-Benz	E class 4D 4WD	2010–2010
Mercedes-Benz	S class hybrid 4D 2WD	2010–2010
Mercedes-Benz	S class LWB 4D 2WD	2007–2010
Mercedes-Benz	S class LWB 4D 4WD	2007–2010
Subaru	Forester 4D 4WD	2014–2015
Subaru	Impreza 4D 4WD	2015
Subaru	Impreza SW 4WD	2015
Subaru	Legacy 4D 4WD	2013–2015
Subaru	Outback SW 4WD	2013–2015
Subaru	XV Crosstrek	2015
Volvo	S80 4D 2WD	2008–2011
Volvo	S80 4D 4WD	2008–2011
Volvo	V70 SW 2WD	2008–2010
Volvo	XC70 SW 2WD	2011
Volvo	XC70 SW 4WD	2008–2011

2D = two-door, 4D = four-door, 2WD = two-wheel drive, 4WD = four-wheel drive, SW = station wagon, LWB = long wheelbase.

Table A2
Comparison vehicle series and model years included in analyses of low-speed AEB.

Comparison	Compared with 2010–2012 model Volvo XC60		Compared with 2011–2012 model Volvo S60	
	Model year	Model	Model year	Model
Similar midsize luxury vehicle models	2009–2012	Acura MDX	2011–2012	Acura TL
	2009–2012	Acura RDX	2011–2012	Audi A4
	2010–2012	Acura ZDX	2011–2012	Audi S4
	2009–2012	Audi Q5	2011–2012	BMW 3 series
	2009–2012	BMW ×3	2011	BMW M3
	2009–2012	BMW ×5	2011–2012	Infiniti G25
	2009–2012	BMW ×6	2011–2012	Infiniti G37
	2009–2012	Cadillac SRX	2011–2012	Lexus ES 350
	2009–2012	Infiniti EX35	2011–2012	Lexus IS 250
	2009–2012	Infiniti FX35	2011–2012	Lexus IS 350
	2009–2012	Infiniti FX50	2011–2012	Lexus IS-F
	2009–2012	Land Rover LR2	2011–2012	Lincoln MKZ
	2009–2012	Lexus RX350	2011–2012	Mercedes C Class
	2010–2012	Lincoln MKT	2011	Saab 9-3
	2009–2012	Lincoln MKX		
	2010–2012	Mercedes GLK Class		
	2009–2012	Mercedes M Class		
	2011	Saab 9-4x		
	2009	Saab 9-7x		
	2009–2012	Volvo XC90		
Other Volvo models without low-speed AEB	2009–2012	Volvo C30	2011–2012	Volvo C30
	2009–2012	Volvo C70	2011–2012	Volvo C70
	2009–2011	Volvo S40	2011	Volvo S40
	2009	Volvo S60	2011	Volvo S80
	2009–2011	Volvo S80	2011	Volvo V50
	2009–2011	Volvo V50	2011	Volvo XC70
	2009–2010	Volvo V70	2011–2012	Volvo XC90
	2009–2011	Volvo XC70		
	2009–2012	Volvo XC90		

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