Effectiveness of Forward Collision Warning Systems with and without Autonomous Emergency Braking in Reducing Police-Reported Crash Rates

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ABSTRACT

Objective: To evaluate the effectiveness of forward collision warning (FCW) and autonomous emergency braking (AEB) in reducing front-to-rear crashes and injuries.

Methods: Poisson regression was used to compare rates of police-reported crash involvements per insured vehicle year in 27 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 collision avoidance systems on the vehicle and other factors affecting crash risk.

Results: FCW alone and FCW with AEB reduced rear-end striking crash involvement rates by 23 percent and 39 percent, respectively. FCW with AEB reduced rates of rear-end striking crash involvements with injuries by 42 percent and rates of rear-end striking crash involvements with third-party injuries by 44 percent, but reductions with FCW alone were not statistically significant (6% and 4%, respectively). Additionally, FCW alone and with AEB reduced involvement rates in all crashes by 12 percent and 6 percent, respectively; multi-vehicle crashes by 11 percent and 5 percent, respectively; injury crashes by 15 percent and 2 percent, respectively; and third-party injury crashes by 6 percent and 9 percent, respectively. Of these, only reductions in all, multi-vehicle, and injury crashes for FCW alone were significant.

Conclusions: FCW alone and FCW with AEB are effective in reducing rear-end crashes and FCW with AEB is effective in reducing rear-end injury crashes, based on the crash experiences of drivers who have purchased the optional technologies. It was surprising that reductions in rear-end injury crash rates for FCW alone were small and non-significant given that the system reduced injury crash rates significantly across all crash types.

Practical applications: Approximately 700,000 U.S. police-reported rear-end crashes in 2013 and 300,000 injuries in such crashes could have been prevented if all vehicles were equipped with FCW with AEB that performs similarly as it did for study vehicles.

Keywords: Crash avoidance technologies, Autonomous emergency braking, Forward collision warning

1. Introduction

Fatalities on U.S. roads have decreased steeply over the last 50 years. Advances in vehicle crashworthiness have been a major factor in this decline (Farmer & Lund, 2015). Recent vehicle technologies help drivers avoid crashes altogether. Electronic stability control, an early collision avoidance technology, reduces single-vehicle fatal crash risk by an estimated 49 percent (Farmer, 2010).

Front crash prevention systems are designed to prevent frontal crashes or lessen their severity. Most systems warn the driver when a frontal collision becomes likely and precharge the brakes to maximize their effectiveness when the driver responds. Some systems brake autonomously if the driver does not respond to the warning, and others brake autonomously at low speeds without a prior warning. 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.

Forward collision warning (FCW) was first introduced in the United States by Mercedes-Benz in 2000. Systems with autonomous emergency braking (AEB) followed, and were first offered in the United States by Acura in 2006. Systems were initially offered as optional equipment in luxury vehicles but have become more widely available in recent years. In model year 2016, 40 percent of U.S. vehicle series offered FCW systems with AEB, most as optional equipment, and an additional 21 percent offered FCW systems without AEB. Ten U.S. automakers pledged in September 2015 to make AEB standard equipment in all of their vehicles.

Front crash prevention systems have the potential to prevent the most crashes of any currently-available collision avoidance system. Using 2004-2008 U.S. data on passenger vehicle crashes, Jermakian (2011) estimated that front crash prevention could prevent or mitigate up to 20 percent of all crashes, 9 percent of crashes with non-fatal moderate or severe injuries, and 3 percent of fatal crashes. For rear-end crashes, the systems were estimated to potentially affect 70 percent of all crashes, 57 percent of non-fatal moderate or severe injury crashes, and 48 percent of fatal crashes.

The first research on the actual effectiveness of FCW alone and FCW with AEB came from the Highway Loss Data Institute ([HLDI], 2012a, 2012b, 2013, 2015a, 2015b), 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 Mercedes and Volvo models with FCW only, and Acura, Mercedes-Benz, Subaru, and Volvo models with FCW and AEB. On Honda Accords, Subaru models, 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 research (2012a, 2012b, 2013, 2015a, 2015b), FCW alone was associated with 7-13 percent reductions in rates of property damage liability claims, which cover damage caused by the at-fault vehicle to other vehicles and property, and 4-24 percent 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 10-15 percent reductions in property damage liability claim rates and 14-35 percent reductions in bodily damage liability claim rates. Reductions were not significant for all automakers. Among Mercedes-Benz and Volvo, which offered vehicles with FCW only and vehicles with FCW and AEB, FCW with AEB was associated with larger benefits than FCW alone.

Doyle, Edwards, and Avery (2015) compared auto insurance claim rates in the United Kingdom for Volkswagen Golf 7 vehicles equipped with FCW and AEB with rates for control vehicle models, finding reductions of 20 percent in third-party damage claim rates and of 45 percent in third-party injury claim rates associated with FCW and AEB. HLDI (2015c) and Doyle et al. (2015) reported comparable reductions in insurance claim rates for AEB systems that operate at low speeds without a prior warning to the driver.

Researchers in Sweden and Japan have examined the effect of FCW systems with AEB on rear-end crash rates. Based on analyses of auto insurance data in Sweden, Volvos equipped with FCW and AEB were involved in 38-45 percent fewer rear-end striking crashes per insured vehicle year than the same Volvo models without the optional systems (Issakson-Hellman & Lindman, 2015a). 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).

Other researchers found that low-speed AEB systems without FCW were associated with reductions of 25-41 percent in rates of rear-end striking crash involvements (Cicchino, 2016; Issakson-Hellman & Lindman, 2015b), 35-47 percent in rates of rear-end striking crash involvements resulting in injuries (Cicchino, 2016; Fildes et al., 2015; Rizzi, Kullgren, & Tingvall, 2014), and 48 percent in rates of rear-end striking crash involvements resulting in injuries to occupants of other vehicles (Cicchino, 2015).

The purpose of the current study was to examine the effectiveness of FCW systems alone and FCW systems with AEB in preventing police-reported crashes and injuries in the United States. The study investigated the effects of systems on U.S. police-reported crash involvements of all types and rear-end striking crash involvements, of all severities and with injuries to anyone in the crash. The systems' effects on involvements in multi-vehicle crashes and crashes resulting in injuries to occupants of other vehicles were also investigated to compare with effects on property damage liability claims and bodily injury liability claims, respectively, found in prior research using insurance data. Crash involvement rates per insured vehicle year for insured vehicles with FCW alone and for vehicles with FCW and AEB systems were compared with rates for the same insured vehicle models/series where the optional systems were not purchased.

Effectiveness estimates were computed for individual automakers, controlling for other collision avoidance technologies offered by each automaker and characteristics of the rated driver, vehicle garaging location, and insurance policy. Effectiveness estimates also were pooled across automakers.

2. Methods

2.1 Data

Vehicle series and model years included in the study are listed in Table 1. Vehicle identification numbers (VINs) of Acura, 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.

Eligible vehicle series were those that offered front crash prevention as an optional feature. Vehicles were excluded if some kind of front crash prevention was standard equipment for that series/model year

Table 1. Study vehicle series and model years

Series with forward collision warning alone		
Make	Series	Model years
Acura	MDX 4D 2WD	2014-2015
Acura	MDX 4D 4WD	2014-2015
Acura	TLX 4D 2WD	2015
Honda	Accord 2D	2013-2014
Honda	Accord 4D	2013-2014
Honda	Accord Crosstour 4D 2WD	2013-2014
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	2007-2011
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, 2010-2011
Mercedes-Benz	M Class 4D 4X2	2010
Mercedes-Benz	M Class 4D 4X4	2007-2008, 2010-2011
Mercedes-Benz	R Class 4D 2WD	2008
Mercedes-Benz	R Class 4D 4WD	2007-2008, 2010-2011
Mercedes-Benz	S Class Long Wheel Base 4D 2WD	2001-2006
Mercedes-Benz	S Class Long Wheel Base 4D 4WD	2003-2006
Mercedes-Benz	SL Class Convertible	2003-2009, 2011
Volvo	S80 4D 2WD	2007-2008
Volvo	S80 4D 4WD	2007-2008
Volvo	XC70 SW 4WD	2008

Series with forward collision warning and autonomous emergency braking		
Make	Series	Model years
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	2007-2011
Mercedes-Benz	CL Class 2D 4WD	2009-2011
Mercedes-Benz	E Class 2D 2WD	2010-2011
Mercedes-Benz	E Class 4D 2WD	2010-2011
Mercedes-Benz	E Class 4D 4WD	2010-2011
Mercedes-Benz	E Class SW 4WD	2011
Mercedes-Benz	S Class Hybrid 4D 2WD	2010-2011
Mercedes-Benz	S Class Long Wheel Base 4D 2WD	2007-2011
Mercedes-Benz	S Class Long Wheel Base 4D 4WD	2007-2011
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 combination; for example, Acura series where FCW was a standard feature and AEB was offered as an optional feature were excluded. Vehicles also were excluded if front crash prevention 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 front crash prevention was operational varied among systems from 0-20 mph. 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 front crash prevention 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 back up, 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. AEB on Volvo models was also packaged with a driver drowsiness alert.

Police-reported data for crashes involving study vehicles were extracted from 27 states that provided VINs with their crash data so that study vehicles could be identified. Data were available during 2010-2013 from Florida, Indiana, Louisiana, Nevada, New Jersey, New Mexico, Oklahoma, Rhode Island, and Utah; 2011-2013 from Mississippi; and 2010-2014 from Delaware, Georgia, Idaho, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, Pennsylvania, South Dakota, Tennessee, Texas, Vermont, Washington, Wisconsin, and Wyoming. VINs were missing or invalid for 14 percent of vehicles involved in crashes in these states during these years.

Striking 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 o’clock, 12 o’clock, or 1 o’clock positions), and the point of impact on the struck vehicle was the rear (5 o’clock, 6 o’clock, or 7 o’clock positions). In crashes identified as front-to-rear, involving 3 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.

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.

All 27 states identified front-to-rear crashes, but only 22 included information on point of impact (Delaware, Florida, Georgia, Idaho, Indiana, Iowa, Kansas, Louisiana, Michigan, Minnesota, Missouri, Nebraska, Nevada, Nevada, Oklahoma, Pennsylvania, Rhode Island, South Dakota, Tennessee, Texas, Utah, and Wyoming). Data from all 27 states were included in analyses of all crash configurations, and only data from the 22 states with point of impact were included in analyses of rear-end crash types.

Most states coded point of impact as clock positions, but a few coded more or fewer possible impact points. In these states, 11 o'clock and 1 o'clock were considered to be the two side impact points closest to the front corners of the vehicle, and 5 o'clock 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 study vehicles in the 22 states with information on the point of impact, the point of impact or the manner of collision each was missing in 5 percent of crash involvements. Either of these variables or the other vehicle's point of impact in two-vehicle crashes was missing information in 10 percent of crash involvements. Vehicles with missing data on these variables were treated as if they were not involved in rear-end striking crashes.

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

Vehicle exposure was expressed in insured vehicle days, so that a vehicle that was 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 percent of vehicles in crashes where the VIN was known did not appear in HLDI's database and an additional 6 percent were insured in a different state than where they crashed. These vehicles were excluded from both the numerator and denominator of crash rates.

2.2 Analyses

Poisson regression was used to model crash involvement rates per insured vehicle year for vehicles with FCW alone or with FCW and AEB compared with vehicles without these systems, controlling for a number of other factors that affect crash risk. Models used a logarithmic link function. Separate regressions were constructed for each of the five automakers for each of the seven crash types examined, resulting in 35 separate models.

The seven crash types examined included: 1) all crashes of all configurations and severities, 2) multi-vehicle crashes, 3) injury crashes of all configurations, 4) third-party injury crashes of all configurations, 5) rear-end striking crashes of all severities, 6) rear-end striking crashes with injuries, and 7) rear-end striking crashes with third-party injuries.

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, 2012b, 2013, 2015a, 2015b) 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, 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. Most manufacturers offered more than one type of front crash prevention system in study vehicles. For Honda Accord vehicles, separate estimates were produced for vehicles with FCW and ACC and for those with FCW but not ACC. Acura offered FCW alone beginning in model year 2014, and this system was included as a covariate in models. 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 crash types.

The collision avoidance features included in each manufacturer's model were as follows:

- Acura: FCW with AEB, FCW alone, adaptive headlights, side-view assist, lane departure warning, lane departure prevention, rear cross-traffic alert.
- Honda: FCW alone with ACC (includes lane departure warning), FCW alone without ACC (includes lane departure warning), passenger side-view camera.
- Mercedes-Benz: FCW with AEB, FCW alone, 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: FCW with AEB (includes lane departure warning), rear camera, side-view assist/rear cross-traffic alert.
- Volvo: FCW with AEB (includes lane departure warning and driver drowsiness alert), FCW alone, adaptive headlights, side-view assist. Some Volvo models offered parking sensors and rear cameras, but data on these features were not available.

Regressions resulted in rate ratios for FCW alone and FCW with AEB that indicated how crash involvement rates for vehicles with the system compared with vehicles without. Effect estimates for FCW systems alone and for FCW systems with AEB were pooled across automakers for each crash type examined using meta-analysis methods (e.g., as in Elvik, 2001). Heterogeneity was evaluated with the Q statistic (Shadish and Haddock, 1994), which indicated that a random effects model was necessary to combine estimates of the effect of FCW alone on all crashes. Thus, random effects models were used for all pooled estimates. To pool estimates, rate ratios were log-transformed. A weight was assigned to each estimate 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 effects for FCW alone or with AEB was calculated as follows:

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

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:

$$95\%\ CI = \overline{y} \times exp\left(\pm 1.96 \times {}^{1}\Big/\sqrt{\sum_{i=1}^{g} w_i}\right)$$

where $\overline{y}$ is the pooled effect estimate, 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 and vehicles with FCW and AEB had significantly lower crash involvement rates than vehicles without the systems when estimates and their 95 percent confidence intervals were less than 1. Percentage reductions were expressed as the rate ratio minus 1, multiplied by 100.

3. Results

3.1 All crash configurations and multi-vehicle crashes

Study vehicles were involved in 68,299 crashes, 58,320 multi-vehicle crashes, 17,212 injury crashes, and 9,955 third-party injury crashes. All vehicles with FCW alone or with FCW and AEB were involved in fewer total and multi-vehicle crashes per insured vehicle year than study vehicles from the same manufacturer without front crash prevention systems. Vehicles with front crash prevention systems from 4 of the 5 manufacturers were involved in fewer injury or third-party injury crashes per insured vehicle year than vehicles from the same manufacturer without front crash prevention (Table 2).

Results of Poisson regressions examining the effects of FCW alone and FCW with AEB on crash involvement rates appear in Table 3. The results control for the vehicle series/model year combination, state, calendar year, other collision avoidance technologies on the vehicle, 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. When the estimates of effectiveness were pooled across manufacturers, FCW alone was associated with reductions of 12 percent in all crash involvements (RR=0.88, 95% CI=0.79-0.98), 11 percent in multi-vehicle crash involvements (RR=0.88, 95% CI=0.81-0.97), 15 percent in injury crash involvements (RR=0.85, 95% CI=0.76-0.96), and 6 percent in third-party injury crash involvements (RR=0.94, 95% CI=0.79-1.12) per insured vehicle year.

When the estimates of effectiveness for FCW with AEB were pooled across automakers, the system was associated with reductions of 6 percent in all crash involvements (RR=0.94, 95% CI=0.88-1.01), 5 percent in multi-vehicle crash involvements (RR=0.95, 95% CI=0.88-1.03), 2 percent in injury crash involvements (RR=0.98, 95% CI=0.86-1.12), and 9 percent in third-party injury crash involvements (RR=0.91, 95% CI=0.75-1.09) per insured vehicle year when controlling for the same covariates. The reductions in all, multi-vehicle, and injury crash involvement rates were significant for FCW alone. Other reductions were not significant.

Table 2. Crash involvement rates of study vehicles with FCW alone, with FCW with AEB, and without front crash prevention systems

Make	System	Insured vehicle years	All		Multi-vehicle		Injury		Third-party injury	
			Crashes	Rate (x1000)	Crashes	Rate (x1000)	Crashes	Rate (x1000)	Crashes	Rate (x1000)
Acura	FCW	11,438	305	26.7	268	23.4	66	5.8	44	3.8
	FCW + AEB	28,281	777	27.5	670	23.7	170	6.0	109	3.9
	No system	185,199	5,967	32.2	5,024	27.1	1,399	7.6	907	4.9
Honda	FCW (no ACC)	95,925	4,079	42.5	3,476	36.2	924	9.6	522	5.4
	FCW (with ACC)	4,352	142	32.6	123	28.3	41	9.4	22	5.1
	No system	120,846	6,745	55.8	5,669	46.9	1,599	13.2	815	6.7
Mercedes-Benz	FCW	18,475	491	26.6	399	21.6	108	5.8	62	3.4
	FCW + AEB	25,834	735	28.5	604	23.4	196	7.6	102	3.9
	No system	1,206,932	41,887	34.7	35,270	29.2	10,695	8.9	6,256	5.2
Subaru	FCW + AEB	15,645	407	26.0	351	22.4	104	6.6	53	3.4
	No system	164,974	4,431	26.9	3,638	22.1	1,085	6.6	586	3.6
Volvo	FCW	3,787	93	24.6	77	20.3	27	7.1	17	4.5
	FCW + AEB	2,832	65	23.0	54	19.1	16	5.7	12	4.2
	No system	106,488	3,175	29.8	2,697	25.3	782	7.3	448	4.2

Table 3. Adjusted rate ratios from Poisson regression models examining the effects of FCW alone and FCW with AEB on crash involvement rates

System	Rate ratio (95% confidence interval)			
	All	Multi-vehicle	Injury	Third-party injury
FCW alone				
Honda (no ACC)	0.87 (0.81, 0.94)	0.89 (0.82, 0.96)	0.83 (0.72, 0.97)	0.97 (0.78, 1.20)
Honda (with ACC)	0.73 (0.62, 0.88)	0.75 (0.62, 0.91)	0.85 (0.61, 1.18)	0.95 (0.60, 1.51)
Mercedes-Benz	0.98 (0.89, 1.07)	0.96 (0.87, 1.07)	0.81 (0.67, 0.98)	0.80 (0.61, 1.03)
Volvo	0.92 (0.73, 1.15)	0.90 (0.70, 1.16)	1.25 (0.82, 1.91)	1.39 (0.81, 2.39)
FCW alone pooled	0.88 (0.79, 0.98)	0.89 (0.81, 0.97)	0.85 (0.76, 0.96)	0.94 (0.79, 1.12)
FCW + AEB				
Acura	0.95 (0.79, 1.14)	0.94 (0.77, 1.16)	0.95 (0.68, 1.33)	0.90 (0.57, 1.41)
Mercedes-Benz	0.89 (0.79, 1.01)	0.89 (0.77, 1.01)	0.99 (0.79, 1.25)	0.83 (0.60, 1.14)
Subaru	1.00 (0.90, 1.11)	1.02 (0.91, 1.15)	1.00 (0.81, 1.24)	0.92 (0.69, 1.24)
Volvo	0.85 (0.66, 1.10)	0.87 (0.66, 1.15)	0.87 (0.52, 1.46)	1.22 (0.67, 2.23)
FCW + AEB pooled	0.94 (0.88, 1.01)	0.95 (0.88, 1.03)	0.98 (0.86, 1.12)	0.91 (0.75, 1.09)

3.2 Rear-end crashes

Study vehicles were the striking vehicle in 7,490 rear-end crashes, 2,267 rear-end injury crashes, and 1,964 rear-end third-party injury crashes. In the 22 states where striking vehicles could be identified, there were 64,210 crashes involving study vehicles. Rear-end striking crashes made up 12 percent of all crash involvements in these states, with a larger percentage among vehicles without front crash prevention (12%) than among vehicles with FCW alone (9%) or FCW with AEB (8%).

Among the 15,802 injury crash involvements in these states, the percentage of injury crash involvements that were rear-end striking crashes was larger among vehicles without front crash prevention (15%) than among vehicles with FCW alone (12%) or FCW with AEB (9%). Only 4 percent of rear-end injury crashes involved fatalities or serious (A-level) injuries. For each manufacturer, 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 (Table 4).

Table 4. Rear-end striking crash involvement rates of study vehicles with FCW alone, with FCW with AEB, and without front crash prevention systems

Make	System	Insured vehicle years	All		Injury		Third-party injury	
			Crashes	Rate (x1000)	Crashes	Rate (x1000)	Crashes	Rate (x1000)
Acura	FCW	10,004	15	1.5	5	0.50	5	0.50
	FCW + AEB	24,456	56	2.3	12	0.49	10	0.41
	No system	167,726	641	3.8	199	1.19	178	1.06
Honda	FCW (no ACC)	86,989	341	3.9	99	1.14	77	0.89
	FCW (with ACC)	3,873	10	2.6	4	1.03	4	1.03
	No system	110,104	616	5.6	174	1.58	129	1.17
Mercedes-Benz	FCW	16,216	46	2.8	18	1.11	16	0.99
	FCW + AEB	23,977	60	2.5	19	0.79	15	0.63
	No system	1,122,116	4,992	4.4	1,543	1.38	1,369	1.22
Subaru	FCW + AEB	11,435	19	1.7	2	0.17	2	0.17
	No system	121,437	332	2.7	88	0.72	70	0.58
Volvo	FCW	3,020	7	2.3	2	0.66	2	0.66
	FCW + AEB	2,285	5	2.2	2	0.88	2	0.88
	No system	94,409	350	3.7	100	1.06	85	0.90

After controlling for the same covariates as in the previous models and with estimates pooled across automakers, Poisson regression revealed that FCW alone was associated with a 23 percent reduction in rear-end striking crash rates (RR=0.77, 95% CI=0.64-0.91) and FCW with AEB was associated with a 39 percent reduction (RR=0.61, 95% CI=0.46-0.79) (Table 5). Both reductions were significant.

However, FCW alone and FCW with AEB differed in the extent of their effectiveness in reducing rates of rear-end striking injury or third-party injury crashes (Table 5). FCW with AEB reduced rates of rear-end striking crashes with injuries 42 percent (RR=0.58, 95% CI=0.35-0.97) and with third-party injuries by 44 percent (RR=0.56, 95% CI=0.32-0.98). In contrast, FCW alone was associated with non-significant declines of 6 percent (RR=0.94, 95% CI=0.68-1.29) and 4 percent (RR=0.96, 95% CI=0.68-1.35), respectively, in rear-end striking injury and third-party injury crash rates.

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

System	RR (95% CI)		
	Rear-end	Rear-end injury	Rear-end third-party injury
FCW alone			
Honda (no ACC)	0.81 (0.63, 1.03)	0.91 (0.56, 1.47)	0.88 (0.51, 1.50)
Honda (with ACC)	0.64 (0.33, 1.23)	0.99 (0.34, 2.89)	1.23 (0.41, 3.66)
Mercedes-Benz	0.75 (0.55, 1.01)	1.00 (0.62, 1.61)	1.03 (0.62, 1.73)
Volvo	0.66 (0.29, 1.49)	0.65 (0.14, 2.89)	0.65 (0.14, 3.01)
FCW alone pooled	0.77 (0.64, 0.91)	0.94 (0.68, 1.29)	0.96 (0.68, 1.35)
FCW + AEB			
Acura	0.53 (0.27, 1.04)	0.58 (0.21, 1.61)	0.34 (0.08, 1.41)
Mercedes-Benz	0.67 (0.44, 1.01)	0.63 (0.31, 1.29)	0.63 (0.31, 1.28)
Subaru	0.54 (0.34, 0.88)	0.21 (0.05, 0.86)	0.26 (0.06, 1.08)
Volvo	0.71 (0.28, 1.76)	1.20 (0.28, 5.16)	1.37 (0.32, 5.92)
FCW + AEB pooled	0.61 (0.46, 0.79)	0.58 (0.35, 0.97)	0.56 (0.32, 0.98)

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 was associated with slightly larger reductions in rear-end striking crash rates than FCW alone, although the difference in estimated effectiveness between the systems was not significant. FCW with AEB significantly reduced rates of rear-end striking crashes with injuries and third-party injuries, but FCW alone did not. This benefit for AEB is consistent with the system's potential to mitigate the severity of rear-end crashes that do occur by reducing the striking vehicle's speed.

The estimated reductions of 39 percent, 42 percent, and 44 percent in rear-end striking crash rates of all severities, with injuries, and with third-party injuries, respectively, for vehicles with FCW and AEB in the current study are nearly identical to the estimated reductions associated with low-speed AEB of 41 percent, 47 percent, and 48 percent, respectively, in U.S. police-reported crashes (Cicchino, 2016). They are also very similar to the 38-45 percent reduction in rear-end striking crash rates found in Swedish insurance data for Volvos with FCW and AEB (Issakson-Hellman & Lindman, 2015a), the 35-41 percent 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).

FCW with AEB and FCW alone reduced total crash involvement rates by 6 percent and 12 percent, respectively, although only the reduction for FCW alone reached significance. The difference in effect sizes between the system types was not significant. It is possible that these systems will have a larger effect on all police-reported crashes when they are installed in all vehicles, because strikes in rear-end crashes made up a smaller percentage of all crash involvements among study vehicles without front crash prevention systems (12%) than they do among national crash involvements (18% in 2013) (Insurance Institute for Highway Safety, 2015). This may be partly because all study vehicles were either luxury vehicles or new vehicles, whose drivers may be less likely to strike other vehicles. It is well-documented that newer vehicles are involved in proportionally fewer frontal impacts and more rear impacts than older vehicles (e.g., Farmer, 1996; Kahane & Hertz, 1998).

The multi-vehicle and third-party injury crashes examined in the current study are similar to the types of crashes covered by property damage liability claims and bodily injury liability claims, respectively, in insurance data. Reductions in police-reported multi-vehicle crash rates associated with FCW alone in the current study are consistent with the reductions in property damage liability claim rates found by HLDI (2012a, 2012b, 2013, 2015a, 2015b) when examining vehicles from the same automakers (Table 6). Reductions in police-reported multi-vehicle crashes for vehicles with FCW plus AEB were slightly smaller than reductions in property damage liability claim rates (Table 6), and it is unclear why that is the case.

HLDI generally found larger benefits on rates of bodily injury liability claims than the present study found on third-party injury crash rates (Table 6). Doyle et al. (2015) similarly reported a large reduction in third-party injury claim rates for the Volkswagen Golf 7’s AEB system. One possible explanation for this discrepancy is that injuries recorded by the police do not reliably reflect injuries treated by medical personnel (Farmer, 2003). In particular, whiplash is a common injury among struck vehicle occupants in rear-end crashes (Zuby et al., 1999), and whiplash may not yet be symptomatic when police respond to the crash scene.

Table 6. Percentage reductions in insurance claim rates associated with FCW alone and with AEB (HLDI 2012a, 2012b, 2013, 2015a, 2015b) compared with reductions in police-reported crash involvement rates in the current study

		Crashes of all severities		Crashes with third-party injuries	
System	Study	Measure	Percentage reduction	Measure	Percentage reduction
FCW alone	HLDI	Property damage liability claims	7-13%	Bodily injury liability claims	4-24%
	Current study	Police-reported multi-vehicle crashes	11%	Police-reported third-party injury crashes	6%
FCW + AEB	HLDI	Property damage liability claims	10-15%	Bodily injury liability claims	14-35%
	Current study	Police-reported multi-vehicle crashes	5%	Police-reported third-party injury crashes	9%

It was also unexpected that reductions in rear-end injury crash involvement rates were small and not significant for FCW systems. This finding is inconsistent with how these systems reduced injury crash involvement rates significantly across all crash types in the current study, and reduced bodily injury liability claim rates by large amounts for some manufacturers studied by HLDI (2012b, 2015a). Analyses of rear-end crashes with injuries were based on small numbers of crashes, and so these estimates may change as more data accumulate.

Data were insufficient to compare the effectiveness of different versions of FCW and AEB 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. 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. Honda Accord vehicles without ACC had the lowest rear-end effectiveness estimate of all study systems, but differences are not large and not conclusive.

Other study limitations should be noted. Front crash prevention systems 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.

Front crash prevention was packaged with lane departure warning in Honda Accord models, Subaru models, and Volvo models with AEB; AEB was also packaged with driver drowsiness alert on Volvos. It is unlikely that lane departure warning affected rear-end striking crash rates, but either system may have affected rates of all crash involvements and crash involvements with injuries.

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, McCartt, Zuby, & Singer, 2010; Cicchino & McCartt, 2015; Eichelberger & McCartt, 2014a; Eichelberger & McCartt, 2014b) and nearly all were observed to have their systems turned on when their vehicles were serviced (Reagan & McCartt, 2016). Nevertheless, the status of front crash prevention systems in study vehicles at the time of the crash was not known.

4.1 Practical applications

In summary, front crash prevention systems seem to be effective in preventing rear-end crashes, which are a common crash type. FCW with AEB appears to be somewhat more effective than FCW alone in reducing rear-end striking crashes, and also is effective in reducing rear-end striking crashes with injuries.

Approximately 700,000 of the 1.8 million U.S. police-reported rear-end crashes in 2013 and 300,000 injuries in those crashes could have been prevented if all vehicles were equipped with FCW with AEB that performs similarly as it did for study vehicles, representing 13 percent each of all police-reported crashes and injuries. This figure is similar to the approximately 750,000 police-reported crashes and 350,000 injuries in those crashes Cicchino (2016) estimated could have been prevented in 2013 if all vehicles were equipped with low-speed AEB. FCW with AEB was not operational on some vehicles in the current study below speeds of 10-20 mph, while the low-speed AEB system studied in Cicchino (2016) was not operational at speeds of 20 mph and above. AEB systems that perform at a full range of speeds would likely prevent more crashes and injuries than estimated in the current study and by Cicchino (2016).

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