Effectiveness of Volvo's City Safety Low-Speed Autonomous Emergency Braking System in Reducing Police-Reported Crash Rates

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Abstract

Objective: To estimate the effect on police-reported crash and injury rates of Volvo's City Safety system, which brakes autonomously at speeds up to 19 mph when a front-to-rear collision is imminent.

Methods: Poisson regression was used to compare police-reported crash involvement rates per insured vehicle year in 27 U.S. states during 2010-2014 between Volvo 2011-2012 model S60 and 2010-2012 model XC60 vehicles with standard City Safety and other luxury midsize SUVs and cars without the system, respectively, controlling for other factors affecting crash risk.

Results: City Safety reduced rates of rear-end striking crash involvements by 41%, rear-end striking crash involvements with injuries by 47%, and rear-end striking crash involvements with third-party injuries by 48%. Additionally, City Safety was associated with reductions of 14% in crash involvement rates, 13% in multi-vehicle crash involvement rates, 12% in injury crash involvement rates, and 8% in third-party injury crash involvement rates. Reductions in rates of all rear-end striking crash involvements, those with injures, and those with third-party injuries were largest at speed limits of 40-45 mph (54%, 65%, and 66%, respectively), followed by speed limits of 35 mph or less (39%, 43%, and 49%, respectively) and of 50 mph or greater (25%, 30%, and 27%, respectively).

Conclusions: City Safety appears to be highly effective at reducing rear-end crashes and associated injuries reported to police, even on roadways with speed limits higher than the system's operating range.

Practical applications: Nearly one-third of all police-reported crashes are rear-end crashes. If all vehicles on the road in 2013 had been equipped with low-speed AEB that performed similarly to City Safety, approximately 750,000 police-reported rear-end crashes and 350,000 injuries in such crashes could have been prevented that year.

Keywords: Crash avoidance technologies, Autonomous emergency braking, Low-speed autonomous emergency braking

1. Introduction

There were 1.8 million police-reported rear-end crashes in 2013, representing 32% of all police-reported crashes (National Highway Traffic Safety Administration, 2015). Front crash prevention systems, which warn drivers or brake autonomously 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).

Some front crash prevention systems brake autonomously at low speeds without first warning the driver. Volvo introduced a low-speed autonomous emergency braking (AEB) system called City Safety in the United States as standard equipment on the 2010 model XC60 and the 2011 model S60. Early versions of City Safety 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. Beginning in model year 2013, City Safety systems sold in the United States operated at travel speeds up to 30 mph (equivalent to 50 km/h).

Several studies have investigated the effectiveness of City Safety and other low-speed AEB systems in reducing crashes by comparing crash rates among vehicles with a standard system with other similar vehicle models without low-speed AEB. In the United States, the Highway Loss Data Institute ([HLDI], 2015a) compared rates of insurance claims per insured vehicle year for Volvo model S60 and XC60 vehicles with standard City Safety and for similar midsize luxury cars and midsize luxury SUVs, respectively, without standard AEB. Volvos with City Safety had 18% fewer collision claims, which cover damage to the at-fault driver's vehicle; 15% fewer property damage liability claims, which cover damage caused by the at-fault driver to other vehicles and property; and 29% fewer 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, per insured vehicle year.

In an analogous study in the United Kingdom, Volvo XC60 models with standard City Safety experienced 6% fewer own-damage claims, 8% fewer third-party damage claims, and 21% fewer third-party injury claims per insured vehicle year than comparison SUVs (Doyle, Edwards, & Avery, 2015).

Others have focused on the effectiveness of low-speed AEB in preventing rear-end crashes. Using Swedish insurance data, Issakson-Hellman and Lindman (2015) compared rates of rear-end striking crashes between Volvo models with and without standard City Safety. Volvos with City Safety were involved in 25%-29% fewer rear-end striking crashes per insured vehicle year than Volvo models without. City Safety operated at speeds up to 30 km/h on 2010-2012 models and up to 50 km/h on 2013-2014 models. No difference was found in the effectiveness of systems that operated at higher and lower speeds.

Two groups of researchers (Fildes et al., 2015; Rizzi, Kullgren, & Tingvall, 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 City Safety with other Volvo models without City Safety and with similar vehicle models from other automakers without AEB. City Safety 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 City Safety 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 models with City Safety 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 goal of the current study is to establish effectiveness estimates for City Safety in police-reported crashes in the United States. This included deriving effectiveness estimates specifically for rear-end crashes, which have not previously been done in the United States. The study examined police-reported crash involvement rates per insured vehicle year among insured Volvo 2011-2012 model year S60 and 2010-2012 model year XC60 vehicles with the first generation of City Safety that operated at speeds up to 19 mph. The rates for these vehicles were compared with the rates for similar midsize luxury four-door cars, midsize luxury SUVs, and other Volvo models without standard AEB systems. Rates were examined in all police-reported crash involvements, multi-vehicle crash involvements, injury crash involvements, crash involvements resulting in injuries to occupants of other vehicles, rear-end striking crashes, rear-end striking injury crashes, and rear-end striking crashes resulting in injuries to occupants of other vehicles. Crash involvement rates were also examined at different speed limits.

2. Methods

2.1 Vehicles

Comparison vehicles for the Volvo 2011-2012 model S60 and 2010-2012 model XC60 appear in Table 1. 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 City Safety, 2010-2012 model XC60 vehicles were also compared with Volvo 2009-2012 models without City Safety, and 2011-2012 model S60 vehicles were compared with Volvo 2011-12 models without City Safety.

Vehicles with City Safety and vehicles in the comparison groups may have offered other collision avoidance systems, including forward collision warning (FCW) alone or FCW with AEB that operated at higher speeds, as optional equipment. Because these features were optional, it was not possible to discern their presence on most vehicles on which they were offered. However, the percentage of vehicles where these optional features were purchased is believed to be low.

2.2 Crash data

Police-reported crashes involving the study vehicles were examined in 27 states. Data on crashes during 2011-2014 were included in the S60 analyses, and data on crashes during 2010-2014 were included in XC60 analyses. Data were extracted 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.

Table 1. Comparison vehicle models

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 X3	2011	BMW M3
	2009-2012	BMW X5	2011-2012	Infiniti G25
	2009-2012	BMW X6	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 City Safety	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		

All 27 states were included in the analyses of all crash configurations and of multi-vehicle crashes. A total of 22 states with information on point of impact were included in the analyses of rear-end crashes; data from Mississippi, New Mexico, Vermont, Washington, and Wisconsin were excluded from these analyses. Rear-end crashes were identified using the manner of collision variable. Front-to-rear collisions where any vehicle was backing prior to the crash were excluded. Striking vehicles in two-vehicle rear-end crashes were identified when the point of impact on the subject vehicle was at the 11, 12, or 1 o'clock position, and the point of impact on the struck vehicle was at the 5, 6, or 7 o'clock position. In rear-end crashes involving three or more vehicles, the point of impact was considered only for the striking vehicle. 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 a crash involvement in which the subject vehicle was the striking vehicle in a rear-end crash.

Among the study vehicles in the 22 states included in the analyses of rear-end crashes, 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 crashes.

Some states coded more or fewer than 12 clock positions as possible impact points. In these states, 11 and 1 o'clock were considered to be the side impact points closest to the vehicle's front, and 5 and 7 o'clock were considered to be the side impact points closest to the vehicle's rear. The initial point of impact was used when available, and the most damaged point of impact was used otherwise.

Injury crashes were defined as 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 crashes were defined as multi-vehicle crashes where occupants of vehicles other than the subject vehicle (e.g., occupants of the struck vehicle in a rear-end crash) were injured.

All states but Nebraska and New Mexico included the speed limit in their crash data during all study years; New Mexico included the speed limit in 2012-2013. 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 16% of crash involvements involving study vehicles in states where it was available.

2.3 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 as insured vehicle years, so that a vehicle insured for 6 months would have half a year of exposure. The 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. VINs were missing or invalid for 14% of vehicles involved in crashes in the study states during the years analyzed.

In the study states during the study years, 23% of study Volvos and midsize car and SUV comparison vehicles that appeared in the police-reported crash data 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.

2.4 Analyses

Poisson regression was used to model crash involvement rates per insured vehicle year for vehicles with City Safety compared with vehicles without City Safety, controlling for a number of other factors that affect crash risk. Models used a logarithmic link function. Separate regression models were constructed for each of the seven crash types examined 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 City Safety, and Volvo XC60 models vs. other Volvo models without City Safety. This resulted in 28 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 six crash types at three speed limit levels (≤ 35 mph, 40-45 mph, 50+ mph) resulting in 42 additional separate models.

All of the regression models controlled for rated driver age (15-24, 25-29, 30-39, 40-49, 50-59, 60-64, 65-69, 70+, unknown), gender, driver marital status, and driver insurance risk level (standard risk, nonstandard risk, unknown); state; calendar year; model year of study vehicle; registered vehicle density per square mile (0-99, 100-499, 500+) of insured vehicle garaging location; and insurance policy deductible range for collision coverage ($0-$250, $251-$500, $501-$1000, $1000+). These covariates were chosen for consistency with the previous HLDI (2015a) study examining the effects of City Safety 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.

Vehicle model was also included in each regression. Two-wheel drive and four-wheel drive variants of vehicle models were combined to have sufficient data for analysis. Each regression resulted in a series of rate ratios that indicated how crash involvement rates for the Volvo S60 or XC60 compared with the rate for each comparison vehicle model. For example, analyses comparing the S60 with midsize luxury cars resulted in 14 rate ratios, with one for each of the 14 comparison models. Effects were pooled across comparison models to produce a combined estimate for the Volvo S60 and for the XC60. Additionally, a combined effect for City Safety 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 City Safety 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 (e.g., as in Elvik, 2001). Heterogeneity was tested with the Q statistic (Shadish and Haddock, 1994). Random effects models were used in all analyses because heterogeneity was found in some sets of estimates. Rate ratios for each vehicle model 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 effect was calculated as follows:

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

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

$$95\% \ CI = \overline{y} \times exp \ \pm 1.96 \times \frac{1}{\sum_{i=1}^{g} w_i}$$

where $\overline{y}$ is the pooled estimate, g is the total number of estimates pooled, and w_i is each estimate's weight.

The effect estimates summarized below indicate that vehicles with City Safety had significantly lower crash involvement rates than comparison vehicles when effect estimates and their 95% confidence intervals are less than 1. Percentage reductions are expressed as the rate ratio minus 1, multiplied by 100.

3. Results

3.1 Volvo S60 and XC60 compared with midsize luxury cars and SUVs

Volvo S60 and XC60 vehicles with City Safety and comparison midsize luxury cars and SUVs were involved in 93,852 crashes, 80,156 multi-vehicle crashes, 22,258 injury crashes, and 13,336 third-party injury crashes. Total and multi-vehicle crash involvement rates for the Volvo S60 were lower than those for 11 of the 14 comparison car models, and injury and third-party injury crash involvement rates for the S60 were lower than those for 12 of the 14 comparison car models (Table 2).

For the Volvo XC60, total and multi-vehicle crash involvement rates were lower than for all comparison SUV models (Table 3). Injury crash involvement rates were lower for the XC60 than for 17 of the 20 comparison SUV models, and third-party injury crash rates were lower than for 12 of the 20 comparison SUV models.

Table 2. Crash involvement rates of Volvo S60 models with City Safety and comparison midsize luxury cars without City Safety.

Type	Insured vehicle years	All		Multi-vehicle		Injury		Third-party injury	
		Crashes	Rate (x1000)	Crashes	Rate (x1000)	Crashes	Rate (x1000)	Crashes	Rate (x1000)
Acura TL	68,317	2,701	39.5	2,272	33.3	629	9.2	337	4.9
Audi A4	51,844	2,370	45.7	2,012	38.8	524	10.1	312	6.0
Audi S4	7,786	244	31.3	197	25.3	51	6.6	33	4.2
BMW 3 series	133,305	6,238	46.8	5,179	38.9	1,453	10.9	838	6.3
BMW M3	1,943	58	29.9	44	22.6	17	8.7	12	6.2
Infiniti G25	21,248	1,090	51.3	912	42.9	254	12.0	132	6.2
Infiniti G37	67,566	2,883	42.7	2,375	35.2	700	10.4	373	5.5
Lexus ES 350	80,526	3,178	39.5	2,719	33.8	746	9.3	425	5.3
Lexus IS 250	43,290	2,415	55.8	2,063	47.7	559	12.9	328	7.6
Lexus IS 350	5,334	240	45.0	206	38.6	73	13.7	41	7.7
Lexus IS-F	1,112	31	27.9	24	21.6	7	6.3	2	1.8
Lincoln MKZ	57,755	2,466	42.7	2,066	35.8	560	9.7	300	5.2
Mercedes C class	107,579	5,424	50.4	4,510	41.9	1,284	11.9	707	6.6
Saab 9-3	2,253	95	42.2	79	35.1	30	13.3	17	7.5
Total comparison midsize luxury cars*	649,858	29,433	45.3	24,658	37.9	6,887	10.6	3,857	5.9
Volvo S60	37,275	1,336	35.4	1,122	29.7	304	8.1	173	4.6

*Insured vehicle years per model do not sum to total insured vehicle years due to rounding.

Table 3. Crash involvement rates of Volvo XC60 models with City Safety and comparison midsize luxury SUVs without City Safety.

	Insured	All		Multi-vehicle		Injury		Third-party injury	
	vehicle		Rate		Rate		Rate		Rate
Type	years	Crashes	(x1000)	Crashes	(x1000)	Crashes	(x1000)	Crashes	(x1000)
Acura MDX	199,175	6,082	30.5	5,182	26.0	1,367	6.9	892	4.5
Acura RDX	61,134	2,132	34.9	1,846	30.2	524	8.6	309	5.1
Acura ZDX	5,941	237	39.9	199	33.5	53	8.9	35	5.9
Audi Q5	87,945	3,092	35.2	2,704	30.7	669	7.6	417	4.7
BMW X3	50,952	1,777	34.9	1,512	29.7	458	9.0	255	5.0
BMW X5	127,666	4,400	34.5	3,797	29.7	921	7.2	581	4.6
BMW X6	15,917	682	42.8	554	34.8	145	9.1	104	6.5
Cadillac SRX	243,334	8,520	35.0	7,247	29.8	2,052	8.4	1202	4.9
Infiniti EX35	27,603	924	33.5	792	28.7	231	8.4	133	4.8
Infiniti FX35	52,289	1,989	38.0	1,717	32.8	470	9.0	299	5.7
Infiniti FX50	3,113	95	30.5	83	26.7	24	7.7	14	4.5
Land Rover LR2	14,997	646	43.1	573	38.2	134	8.9	96	6.4
Lexus RX350	482,015	15,657	32.5	13,533	28.1	3,902	8.1	2408	5.0
Lincoln MKT	23,300	771	33.1	664	28.5	212	9.1	124	5.3
Lincoln MKX	112,196	3,772	33.6	3,296	29.4	921	8.2	553	4.9
Mercedes GLK Class	98,763	3,924	39.7	3,402	34.4	993	10.1	586	5.9
Mercedes M Class	132,382	4,704	35.5	4,060	30.7	1,077	8.1	714	5.4
Saab 9-4x	539	17	31.5	12	22.3	3	5.6	2	3.7
Saab 9-7x	4,902	210	42.8	165	33.7	44	9.0	29	5.9
Volvo XC90	48,842	1,642	33.6	1,452	29.7	405	8.3	254	5.2
Total comparison midsize luxury SUVs*	1,793,005	61,273	34.2	52,790	29.4	14,605	8.1	9,007	5.0
Volvo XC60	61,483	1,810	29.4	1,586	25.8	462	7.5	299	4.9

*Insured vehicle years per model do not sum to total insured vehicle years due to rounding

The results of Poisson regression models examining the effect of City Safety on crash involvement rates are summarized in Table 4. After controlling for model year, state, calendar year, registered vehicle density, collision coverage deductible range, and the age, gender, marital status, and insurance risk of the rated driver, City Safety was associated overall with significant reductions of 14% in crash involvement rates, 13% in multi-vehicle crash involvement rates, 12% in injury crash involvement rates, and 8% in third-party injury crash involvement rates when results for the S60 and the XC60 were pooled. Patterns were similar for the S60 and XC60, with bigger reductions in injury crashes for the S60.

Table 4. Adjusted rate ratios from Poisson regression models examining the effects of City Safety on crash involvement rates, comparing Volvo S60 and XC60 models with City Safety to midsize luxury cars and SUVs without City Safety.

	Rate ratio (95% confidence interval)			
Comparison	All	Multi-vehicle	Injury	Third-party injury
Volvo S60 vs. midsize luxury cars	0.88 (0.84, 0.93)	0.89 (0.84, 0.94)	0.82 (0.77, 0.88)	0.84 (0.79, 0.90)
Volvo XC60 vs. midsize luxury SUVs	0.85 (0.82, 0.88)	0.86 (0.83, 0.90)	0.92 (0.87, 0.97)	0.96 (0.92, 1.01)
Combined effect	0.86 (0.84, 0.89)	0.87 (0.84, 0.90)	0.88 (0.84. 0.92)	0.92 (0.88, 0.96)

Volvo S60 and XC60 models and comparison cars and SUVs were striking vehicles in 10,513 rear-end crashes, 3,148 rear-end injury crashes, and 2,699 rear-end third-party injury crashes. Rear-end striking crash rates were lower for the Volvo S60 than for all comparison car models, and rear-end striking injury and third-party injury crash rates for the S60 were lower than for 13 of the 14 comparison car models (Table 5). The Volvo XC60 had lower rear-end striking crash rates of all types than for 19 of the 20 comparison SUV models (Table 5). The Saab 9-4x, the only SUV with lower rates than the XC60, was only involved in one rear-end striking crash and no rear-end striking injury crashes during the study period.

There were 88,518 crashes involving study vehicles in the 22 states where rear-end crashes were analyzed, and rear-end striking crashes made up 12% of these crash involvements. Rear-end striking crashes comprised a larger percentage of crash involvements among comparison SUVs and cars (12% each) than among Volvo XC60 (8%) or S60 (9%) vehicles with City Safety. Similarly, rear-end striking injury crashes made up larger proportions of injury crash involvements among comparison SUVs (15%) and cars (16%) than among Volvo XC60 (8%) and S60 (10%) models. Only 4% of rear-end striking injury crashes resulted in serious (A-level) or fatal injuries.

Table 5. Rear-end striking crash involvement rates of Volvo S60 and XC60 models with City Safety and comparison midsize luxury cars and SUVs without City Safety.

Type	Insured vehicle years	Rear-end		Rear-end injury		Rear-end third-party injury	
		Crashes	Rate (x1000)	Crashes	Rate (x1000)	Crashes	Rate (x1000)
Midsize luxury cars							
Acura TL	64,003	320	5.0	90	1.41	66	1.03
Audi A4	46,380	275	5.9	74	1.60	63	1.36
Audi S4	6,633	28	4.2	9	1.36	8	1.21
BMW 3 series	123,779	753	6.1	269	2.17	213	1.72
BMW M3	1,738	6	3.5	1	0.58	1	0.58
Infiniti G25	19,959	112	5.6	32	1.60	27	1.35
Infiniti G37	63,155	288	4.6	88	1.39	73	1.16
Lexus ES 350	75,906	316	4.2	94	1.24	77	1.01
Lexus IS 250	40,314	312	7.7	93	2.31	79	1.96
Lexus IS 350	4,698	31	6.6	7	1.49	6	1.28
Lexus IS-F	977	6	6.1	2	2.05	1	1.02
Lincoln MKZ	54,703	295	5.4	82	1.50	62	1.13
Mercedes C Class	100,856	664	6.6	186	1.84	154	1.53
Saab 9-3	1,951	13	6.7	3	1.54	3	1.54
Total comparison midsize luxury cars*	605,053	3,419	5.7	1,030	1.70	833	1.38
Volvo S60	34,645	117	3.4	28	0.81	22	0.64
Midsize luxury SUVs							
Acura MDX	179,770	587	3.3	171	0.95	160	0.89
Acura RDX	55,366	259	4.7	77	1.39	67	1.21
Acura ZDX	5,308	16	3.0	6	1.13	5	0.94
Audi Q5	76,772	305	4.0	80	1.04	74	0.96
BMW X3	46,570	188	4.0	62	1.33	51	1.10
BMW X5	117,632	557	4.7	155	1.32	146	1.24
BMW X6	15,117	86	5.7	24	1.59	23	1.52
Cadillac SRX	229,426	923	4.0	280	1.22	234	1.02
Infiniti EX35	25,315	96	3.8	29	1.15	20	0.79
Infiniti FX35	48,697	245	5.0	62	1.27	55	1.13
Infiniti FX50	2,786	12	4.3	4	1.44	4	1.44
Land Rover LR2	13,779	114	8.3	32	2.32	30	2.18
Lexus RX350	440,742	1731	3.9	523	1.19	466	1.06
Lincoln MKT	21,905	82	3.7	29	1.32	28	1.28
Lincoln MKX	104,915	400	3.8	122	1.16	105	1.00
Mercedes GLK Class	91,637	485	5.3	162	1.77	138	1.51
Mercedes M Class	123,276	536	4.3	173	1.40	157	1.27
Saab 9-4x	441	1	2.3	0	0	0	0
Saab 9-7x	4,630	32	6.9	10	2.16	9	1.94
Volvo XC90	44,885	194	4.3	53	1.18	40	0.89
Total comparison midsize luxury SUVs*	1,648,967	6,849	4.2	2,054	1.25	1,812	1.10
Volvo XC60	55,567	128	2.3	36	0.65	32	0.58

*Insured vehicle years per model do not sum to total insured vehicle years due to rounding.

Table 6 displays the results of Poisson regression models comparing rates of all rear-end striking crashes, those with injuries, and those with third-party injuries between Volvo models with City Safety and comparison cars and SUVs, controlling for the same covariates as previous models. City Safety was associated with reductions of 41% in rear-end striking crash rates, 47% in rear-end striking injury crash rates, and 48% in rear-end striking third-party injury crash rates when effects for the S60 and XC60 were pooled. All effects were significant. Results again were similar for the S60 and the XC60.

Table 6. Adjusted rate ratios from Poisson regression models examining the effects of City Safety on rear-end striking crash involvement rates, comparing Volvo S60 and XC60 models with City Safety to midsize luxury cars and SUVs without City Safety.

	Rate ratio (95% confidence interval)		
Comparison	Rear-end	Rear-end injury	Rear-end third-party injury
Volvo S60 vs. midsize luxury cars	0.69 (0.64, 0.75)	0.57 (0.49, 0.65)	0.54 (0.46, 0.63)
Volvo XC60 vs. midsize luxury SUVs	0.53 (0.49, 0.57)	0.51 (0.46, 0.56)	0.51 (0.46, 0.57)
Combined effect	0.59 (0.55, 0.63)	0.53 (0.49, 0.57)	0.52 (0.48, 0.57)

3.2 Effects by speed limit

Volvo S60 and XC60 models and their comparison midsize luxury cars and SUVs were involved in 78,277 crashes and 9,447 rear-end striking crashes where the speed limit was known. Among all crash involvements, 46% occurred at speed limits less than or equal to 35 mph, 30% occurred at speed limits of 40-45 mph, and 23% occurred at speed limits of 50 mph or greater. Rear-end striking crashes were more evenly split among speed limits, with 33% occurring at speed limits of 35 mph or less, 37% occurring at speed limits of 40-45 mph, and 29% occurring at speed limits of 50 mph or above.

Table 7 summarizes the effect of City Safety on all crash involvements, multi-vehicle crash involvements, injury crash involvements, and third-party injury crash involvements 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. When effects were combined across cars and SUVs, City Safety was associated with a significant 14% reduction in crash involvement rates at each speed limit. In multi-vehicle crashes, effects were similar among the speed limits examined and ranged from 12% to 14%. Effects on injury and third-party injury crash involvement rates were largest at speed limits of 40-45 mph (16% and 20%, respectively), followed by speed limits of 35 mph or less (13% and 9%, respectively). At speed limits of 50 mph and greater, City Safety was associated with a non-significant decline of 1% in injury crash involvement rates and a significant 14% increase in third-party injury crash involvement rates.

Results were consistent between S60 and XC60 models in injury crashes and third-party injury crashes. In total and in multi-vehicle crash involvements, the S60 experienced the largest reductions at speed limits of 40-45 mph, followed by speed limits of 50 mph or greater, with small and non-significant reductions at speed limits of 35 mph and lower. The XC60 experienced the largest reductions in total crash involvement rates at speed limits of 35 mph and lower, followed by speed limits of 50 mph and greater and then limits of 40-45 mph.

The effects of City Safety on rear-end striking crash types by speed limit are summarized in Table 8. 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 (54%, 65%, and 66%, respectively), followed by speed limits of 35 mph or less (39%, 43%, and 49%, respectively) and then limits of 50 mph or greater (25%, 30%, and 27%, respectively). All reductions were significant. Results were consistent between S60 and XC60 models for rear-end striking crashes and those crashes with third-party injuries. In rear-end striking crashes with any injuries, the S60 experienced the smallest reductions at speed limits of 35 mph and less; the XC60 followed the pattern for the S60 and XC60 combined results.

Table 7. Adjusted rate ratios from Poisson regression models examining the effects of City Safety on crash involvement rates by speed limit, comparing Volvo S60 and XC60 models with City Safety to midsize luxury cars and SUVs without City Safety.

		Rate ratio (95% confidence interval)			
Speed limit	Comparison	All	Multi-vehicle	Injury	Third-party injury
≤ 35 mph	Volvo S60 vs. midsize luxury cars	0.96 (0.89, 1.03)	0.95 (0.88, 1.03)	0.81 (0.74, 0.88)	0.87 (0.78, 0.96)
	Volvo XC60 vs. midsize luxury SUVs	0.80 (0.77, 0.84)	0.80 (0.77, 0.84)	0.90 (0.85, 0.96)	0.93 (0.86, 1.00)
	Combined effect	0.86 (0.82, 0.90)	0.86 (0.82, 0.90)	0.87 (0.82, 0.91)	0.91 (0.86, 0.96)
40-45 mph	Volvo S60 vs. midsize luxury cars	0.82 (0.76, 0.89)	0.83 (0.76, 0.90)	0.80 (0.74, 0.88)	0.71 (0.64, 0.80)
	Volvo XC60 vs. midsize luxury SUVs	0.89 (0.85, 0.93)	0.90 (0.85, 0.94)	0.85 (0.79, 0.92)	0.84 (0.78, 0.90)
	Combined effect	0.86 (0.82, 0.90)	0.87 (0.83, 0.91)	0.84 (0.79, 0.89)	0.80 (0.76, 0.85)
50+ mph	Volvo S60 vs. midsize luxury cars	0.87 (0.82, 0.92)	0.87 (0.83, 0.91)	0.94 (0.86, 1.02)	1.03 (0.93, 1.15)
	Volvo XC60 vs. midsize luxury SUVs	0.86 (0.82. 0.90)	0.88 (0.84, 0.92)	1.00 (0.94, 1.08)	1.19 (1.11, 1.28)
	Combined effect	0.86 (0.83, 0.89)	0.88 (0.85, 0.91)	0.99 (0.94, 1.04)	1.14 (1.08, 1.21)

Table 8. Adjusted rate ratios from Poisson regression models examining the effects of City Safety on rear-end striking crash involvement rates by speed limit, comparing Volvo S60 and XC60 models with City Safety to midsize luxury cars and SUVs without City Safety.

Speed limit	Comparison	Rate ratio (95% confidence interval) Rear-end	Rear-end injury	Rear-end third-party injury
≤ 35 mph	Volvo S60 vs. midsize luxury cars	0.61 (0.53, 0.70)	0.70 (0.53, 0.92)	0.51 (0.37, 0.70)
	Volvo XC60 vs. midsize luxury SUVs	0.60 (0.54, 0.67)	0.51 (0.43, 0.62)	0.52 (0.42, 0.63)
	Combined effect	0.61 (0.56, 0.66)	0.57 (0.49, 0.66)	0.51 (0.43, 0.61)
40-45 mph	Volvo S60 vs. midsize luxury cars	0.55 (0.49, 0.63)	0.44 (0.35, 0.57)	0.40 (0.30, 0.53)
	Volvo XC60 vs. midsize luxury SUVs	0.41 (0.37, 0.45)	0.31 (0.26, 0.38)	0.31 (0.25, 0.39)
	Combined effect	0.46 (0.42, 0.50)	0.35 (0.30, 0.41)	0.34 (0.29, 0.40)
50+ mph	Volvo S60 vs. midsize luxury cars	0.92 (0.81, 1.05)	0.58 (0.46, 0.73)	0.70 (0.56, 0.89)
	Volvo XC60 vs. midsize luxury SUVs	0.65 (0.59, 0.72)	0.76 (0.65, 0.89)	0.74 (0.63, 0.88)
	Combined effect	0.75 (0.68, 0.82)	0.70 (0.61, 0.80)	0.73 (0.64, 0.84)

3.3 Volvo S60 and XC60 compared with other Volvo models

To ensure that the benefits of City Safety based on comparisons of Volvo S60 and XC60 models with other cars and SUVs were not due to characteristics of Volvo drivers independent of City Safety, secondary analyses compared crash involvement rates between Volvo S60 and XC60 models with City Safety and other Volvo models without City Safety. Volvo S60 models with City Safety were involved in more total crashes and fewer crashes of other types per insured vehicle year than comparison Volvo models (Table 9). Crash involvement rates for the Volvo XC60 were about the same as rates for comparison Volvo models in third-party injury crashes, and were lower in all other crash types examined.

Rear-end striking crashes made up a larger percentage of crash involvements among other Volvo models (12%) than among Volvo XC60 (8%) and S60 (9%) models with City Safety in the 22 states where rear-end striking crashes could be identified. Rear-end striking injury crashes comprised 14% of injury crash involvements among other Volvo 2009-2012 models, 13% among other Volvo 2011-2012 models, 8% among Volvo XC60 models with City Safety, and 10% among Volvo S60 models with City Safety.

Table 9. Crash involvement rates of Volvo S60 and XC60 models with City Safety and comparison Volvo models without City Safety.

Vehicles	Insured vehicle years (27 states)	All	Multi-vehicle	Injury	Third-party injury	Insured vehicle years (22 states)	Rear-end	Rear-end injury	Rear-end third-party injury
Model year 2011-2012									
Volvo C30	9,860	356	305	94	58	8,511	46	12	11
Volvo C70	13,643	492	414	110	62	12,933	60	19	16
Volvo S40	4,340	215	179	49	24	4,074	19	3	2
Volvo S80	4,756	163	136	37	17	4,420	18	4	3
Volvo V50	740	29	25	7	4	613	3	1	1
Volvo XC70	4,721	110	97	25	10	3,965	11	1	1
Volvo XC90	18,557	623	562	149	98	17,040	64	15	13
Total model year 2011-2012 comparison Volvos*	56,617	1,988	1,718	471	273	51,557	221	55	47
Rate (x1000) for model year 2011-2012 comparison Volvos		35.1	30.3	8.3	4.8		4.3	1.07	0.91
Volvo S60	37,725	1,336	1,122	304	173	34,645	117	28	22
Rate (x1000) for S60		35.4	29.7	8.1	4.6		3.4	0.81	0.64
Model year 2009-2012									
Volvo C30	18,974	665	562	176	104	16,408	81	20	19
Volvo C70	24,925	836	698	186	109	23,624	97	32	28
Volvo S40	28,168	1,227	1043	304	172	26,407	150	39	33
Volvo S60	10,409	400	334	93	51	9,464	53	15	14
Volvo S80	30,738	1,013	858	246	144	28,996	115	32	27
Volvo V50	5,511	190	166	36	27	4,565	17	4	4
Volvo V70	3,416	81	68	20	11	3,100	9	1	1
Volvo XC70	17,853	409	339	103	54	14,932	38	9	7
Volvo XC90	48,842	1,642	1452	405	254	44,885	194	53	40
Total model year 2009-2012 comparison Volvos*	188,837	6,463	5,520	1,569	926	172,379	754	205	173
Rate (x1000) for model year 2009-2012 comparison Volvos		34.2	29.2	8.3	4.9		4.4	1.19	1.00
Volvo XC60	61,483	1,810	1,586	462	299	55,567	128	36	32
Rate (x1000) for XC60		29.4	25.8	7.5	4.9		2.3	0.65	0.58

*Insured vehicle years per model do not sum to total insured vehicle years due to rounding.

Poisson regression model results comparing the Volvos with City Safety with other Volvo models without City Safety are shown in Table 10. Compared with other Volvo models, the S60 with City Safety was involved in 7% fewer crashes, 9% fewer multi-vehicle crashes, 3% fewer injury crashes, and 8% more third-party injury crashes per insured vehicle year. Only the reduction in multi-vehicle crashes reached significance. The XC60 was involved in 13% fewer crashes, 12% fewer multi-vehicle crashes, 6% fewer injury crashes, and 4% more third-party injury crashes per insured vehicle year; only the reductions in all and multi-vehicle crash involvements reached significance.

Results for rear-end striking crashes when Volvos with City Safety were compared with Volvos without City Safety were largely consistent with comparisons with non-Volvo SUVs and cars (Table 10). Rear-end striking crash rates, rear-end striking injury crash rates, and rear-end striking third-party injury crash rates were 41%, 37%, and 35% lower, respectively, among Volvo XC60 vehicles with City Safety than among other Volvos. All reductions were significant. Volvo S60 vehicles with City Safety experienced a significant 19% reduction in rear-end striking crash rates, a non-significant 4% increase in rear-end striking injury crash rates, and a non-significant 15% reduction in rear-end striking third-party injury crash rates.

Table 10. Adjusted rate ratios from Poisson regression models examining the effects of City Safety on crash involvement rates, comparing Volvo S60 and XC60 models with City Safety to other Volvo models without City Safety.

	Rate ratio (95% confidence interval)			
Comparison	All	Multi-vehicle	Injury	Third-party injury
Volvo S60 vs. other Volvo models	0.93 (0.83, 1.04)	0.91 (0.92, 1.00)	0.97 (0.86, 1.10)	1.08 (0.92, 1.27)
Volvo XC60 vs. other Volvo models	0.87 (0.79, 0.95)	0.88 (0.81, 0.96)	0.94 (0.86, 1.03)	1.04 (0.96, 1.13)
	Rear-end		Rear-end injury	Rear-end third-party injury
Volvo S60 vs. other Volvo models	0.81 (0.68, 0.98)		1.04 (0.71, 1.52)	0.85 (0.56, 1.29)
Volvo XC60 vs. other Volvo models	0.59 (0.53, 0.65)		0.63 (0.52, 0.77)	0.65 (0.52, 0.80)

4. Discussion

The current study adds to the body of evidence demonstrating that low-speed AEB is reducing front to rear crashes and injuries in those crashes. Compared with other midsize luxury SUVs and cars, Volvo S60 and XC60 models with standard City Safety were involved in 41% fewer rear-end striking crashes, 47% fewer rear-end striking injury crashes, and 48% fewer rear-end striking third-party injury crashes per insured vehicle year in the United States. These reductions are similar to the declines in police-reported rear-end striking injury crash rates of 38% found in Europe and elsewhere for vehicles with low-speed AEB (Fildes et al., 2015) and of 35%-41% found in Sweden for Volvos with City Safety (Rizzi et al., 2014).

The estimated benefits of City Safety in the current study also are comparable to the benefits found for U.S. vehicles with optional FCW systems with AEB that operate at higher speeds in a complementary study also using police-reported crash data: reductions of 39% in rear-end striking crash rates, 42% in rear-end striking injury crash rates, and 44% in third-party injury crash rates (Cicchino, 2016).

Because the version of City Safety 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. City Safety 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 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 City Safety 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 2013 occurring at speed limits of 35 mph or less or 40-45 mph, more than half occurred at or near intersections (66% and 59%, respectively). In contrast, only 25% of rear-end crashes at speed limits greater than or equal to 50 mph were intersection-related (Insurance Institute for Highway Safety, 2015). 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 City Safety on roads with higher speed limits.

Although City Safety 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 City Safety 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).

The multi-vehicle and third-party injury crash involvements examined in the currently study capture similar crash types to the property damage liability claims and bodily injury liability claims, respectively, examined in HLDI's (2015a) study of City Safety. City Safety was associated with nearly identical reductions in multi-vehicle crash involvement rates (13%) and in property damage liability claim rates (15%). However, HLDI (2015a) found a much larger reduction in bodily injury liability claim rates (29%) compared with reductions third-party injury crash rates in the current study (8%). This same discrepancy was found in a complementary study of FCW systems with autonomous emergency braking that operate at higher speeds than City Safety (Cicchino, 2016). One possible reason for this inconsistency is that a large proportion of injuries in rear-end crashes are neck sprains and strains (Zuby & Lund, 2010), injuries that may not be evident when police arrive at crash scenes but are reported subsequently to insurers.

Secondary analyses compared crash involvement rates of Volvo S60 and XC60 models with standard City Safety with the rates of other Volvo models without City Safety. 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 City Safety, which suggests that the main findings of the primary analysis are not due to a "Volvo buyer's effect."

Although the pattern of results for rear-end striking crashes were similar in the primary and secondary analyses, this was not true for all crash types examined. 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 2015b; HLDI 2015c), and the comparison group of other Volvos included vehicles of a range of vehicle classes rather than just SUVs or 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, rather than to replicate them precisely.

This study was not without limitations. 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 City Safety could have affected crash rates. Some vehicles with or without City Safety 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. Additionally, City Safety could be turned off and the status of the system at the time of a crash was unknown.

4.1 Practical applications

City Safety appears to work as intended in preventing rear-end crashes and rear-end crashes resulting in injuries, and the extent of its effectiveness appears to be similar to that of AEB systems that operate at higher speeds and warn drivers before braking autonomously. If all vehicles were equipped with low-speed AEB that performed similarly to City Safety, approximately 750,000 of the 1.8 million U.S. police-reported rear-end crashes in 2013 and 350,000 injuries in those crashes could have been prevented. This represents 13% of the nearly 5.7 million police-reported crashes and 15% of the 2.3 million police-reported injuries that year. Cicchino (2016) estimated that FCW systems with AEB that operate at higher speeds could have prevented approximately 700,000 police-reported crashes and 300,000 injuries in those crashes during 2013 if installed on all vehicles. The City Safety system in the current study operated at speeds up to 19 mph, while some systems studied by Cicchino (2016) did not operate below speeds of 10-20 mph. AEB systems that perform at a full range of speeds could potentially prevent a larger proportion of crashes and injuries than estimated in the current study and by Cicchino (2016).

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