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Effectiveness of front crash prevention systems in reducing large truck real-world crash rates

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ABSTRACT

Objective: Forward collision warning (FCW) and automatic emergency braking (AEB) have the potential to prevent or mitigate many large truck crashes. While these systems are known to be effective in passenger vehicles, less is known about their effectiveness in large trucks. The objective of this study was to estimate the effectiveness of these systems in reducing real-world crash rates of large trucks.

Methods: Data on Class 8 trucks operating on limited-access highways during 2017–2019 were obtained from SmartDrive Systems. Detailed data on exposure measures and crash circumstances were extracted from video footage by both automated means and manual coding. Crash rates were compared by front crash prevention technology (FCW, AEB, neither), both for all police-reportable crashes overall and for relevant crash types.

Results: FCW was associated with a statistically significant 22% reduction in the rate of police-reportable crashes per vehicle miles traveled, and a significant 44% reduction in the rear-end crash rate of large trucks. AEB also was associated with significant reductions—12% overall and 41% for rear-end crashes. Warnings were issued in 31% of rear-end crashes for FCW-equipped trucks. AEB intervened in 43% of rear-end crashes; about two thirds of these interventions involved autobrake activations. On average, speed was reduced by over half between the time of the intervention and impact for both systems. Observed reductions in same-direction sideswipe and roadway departure crashes per mile traveled were smaller in magnitude than those of rear-end crashes; these were consistent with other crash avoidance technologies suspected to be bundled with FCW/AEB in some cases, and very few front crash prevention interventions occurred in these types of crashes.

Conclusions: FCW and AEB are effective countermeasures for crashes in which large trucks rear-end other vehicles. Large truck safety is expected to improve as new trucks are increasingly equipped with these systems. FCW has the advantage that some of these systems can be retrofitted to existing trucks, so benefits can be realized sooner and with less investment.

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Introduction

Front crash prevention systems, namely forward collision warning (FCW) and automatic emergency braking (AEB), monitor the road environment ahead using radar or video camera sensors or both. FCW systems typically sound an audible alert if a front collision is likely, allowing the driver to begin an avoidance maneuver. AEB systems, which generally include FCW functionality, apply the vehicle's foundation brakes to prevent or mitigate a forward impact if the driver does not intervene. While the designs of these systems (e.g., functional speed range, sensitivity, maximum braking force, warning strategy, warning type) vary across manufacturer and over time, have varied within manufacturer as technology improved, generally they are designed to address front-to-rear crashes with moving vehicles. Some front crash prevention systems can detect stationary vehicles or vulnerable road users—pedestrians, bicyclists, and motorcyclists. If these systems on passenger vehicles reliably detect pedestrians and motorcyclists, many crashes potentially could be prevented or mitigated (Jermakian and Zuby 2011; Teoh 2018).

AEB systems are more common in the passenger vehicle fleet. Although no federal mandate exists for AEB, 20 automakers representing 99% of the United States automobile market have agreed to make AEB standard on virtually all new passenger vehicles by September 1, 2022 (Insurance Institute for Highway Safety 2016). AEB has existed in large trucks, and its availability in the fleet has been increasing as well, with greater market penetration for larger fleets (Belzowski and Herter 2015). Suites of crash avoidance technologies that include AEB (e.g., Bendix Wingman, Wabco OnGuard) have become default equipment on at least one truck model from Volvo, Peterbilt, Freightliner, and Mack, and on all models by International (Truck Safety Coalition 2017).

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Table 1. Crash involvements and exposure, without study group restrictions.

Technology	Crashes	VMT	Hours driven	Crash rate per 100 million VMT	Crash rate per 1 million hours
Neither	703	695,512,131	11,667,979	101.1	60.3
FCW	222	287,811,774	4,910,670	77.1	45.2
AEB	1,133	1,285,367,450	21,885,043	88.1	51.8

While FCW and AEB systems have been shown to reduce front-to-rear crash rates for passenger vehicles (Cicchino 2017), less is known about their effectiveness in large trucks. Jermakian (2012) showed that FCW (and thus, also AEB) has the potential to prevent or mitigate over 30,000 police-reported crashes involving large trucks annually. Using slightly different assumptions, Camden et al. (2017) estimated this number as about 19,000 crashes annually. Kuehn et al. (2011) examined real-world crashes with in-depth investigations and estimated that 52% of rear-end crashes could have been avoided or mitigated had the striking truck had AEB. Woodrooffe et al. (2013) forecasted the benefit of front crash prevention on trucks at 22–24% of police-reportable crashes, using assumptions based on one real-world system's design. In a survey of trucking carriers, companies that implemented front crash prevention technologies reported a 14% reduction in crashes and a 15% reduction in the average cost of these crashes (Belzowski and Herter 2015), but a study involving data obtained from multiple carriers did not find a statistically significant effect of FCW on rear-end crashes (Hickman et al. 2013). This discrepancy could be due to carriers attributing observed crash reductions related to other safety technologies to FCW/AEB or to uncontrolled variation in carriers' data/business practices in the multicarrier effectiveness study. Regardless, it remains unclear to what degree FCW/AEB affect rear-end crash rates for large trucks; increasing our understanding of this relationship is the purpose of the current study.

Methods

Data for the current study were obtained from SmartDrive Systems, whose core business offers a video safety program for commercial fleets. SmartDrive was able to determine the presence/activations of FCW and AEB as well as code various circumstances of crashes and estimate exposure amongst their customer fleets' vehicles, mostly using algorithms and automated methods, but also through manual video review (especially for crash circumstances). FCW was identified by the presence of at least one activation (audible warning), and AEB was identified by at least one activation (audible warning plus system-initiated braking) from vehicle telematics data. It is possible that some FCW/AEB vehicles were misclassified as a result of not having any activations, but very few vehicles had only one activation, suggesting that this would not be a major issue. Data were anonymized and completely free of identifying information, with carriers grouped by a generic index variable.

All data were restricted to crashes and exposure during 2017–2019 of Class 8 trucks (mostly tractor-semitrailers with a gross vehicle weight rating of 33,000+ pounds) operating on limited-access highways. There were about 25,000 trucks operated by these carriers during the three-year study period, although not all trucks were operated throughout the entire study period. The restriction to limited access highways minimized variation by rural/urban, traffic patterns, and road conditions involved in front-to-rear crashes, and improved the ability to code various crash factors. All 62 carriers in the study operated trucks both with and without front crash prevention technologies, and many operated trucks with only one of the front crash prevention systems. So some analyses were further restricted to two study groups (carriers with both AEB and none, and carriers with both FCW and none) to minimize the situation of carrier-to-carrier differences being attributed to the type of front crash prevention technology. Crashes that were rated as at least police-reportable in severity, which was done by manually reviewing videos, were included in the study, and exposure measures (at the individual truck level) included vehicle miles traveled (VMT) and hours driven. These were the two exposure measures collected by SmartDrive. They are highly correlated and may differ in situations of heavily congested traffic. Based on the make and model of trucks in the study, many of the ones equipped with AEB also will have lane departure warning (LDW) and electronic stability control (ESC), as these were often part of a package (e.g., the Bendix Wingman Fusion system). Blind spot warning (BSW) also was an option on some of these trucks, and whether it was equipped might have been associated with a truck having the FCW or AEB options. Further, it is possible that carriers investing in FCW also invested in other technologies that were not bundled, but the presence of these technologies was unknown in these data.

Crashes were disaggregated by type for crash types relevant to front crash prevention technology (rear-ending another vehicle), as well as BSW, LDW, and ESC (same-direction sideswipe and roadside departure), using a crash type variable and using more detailed information such as point of impact for each involved vehicle as a check on the crash type variable. If front crash prevention systems result in more braking, it is possible that they also will be associated with more frequent crashes in which the equipped vehicle is rear-ended, so this crash type was considered as well. Other crash outcomes included whether there was an FCW/AEB trigger (i.e., whether a warning was issued or autobrake was initiated, the highest level trigger occurred), the speed reduction between the FCW/AEB trigger and impact, and the drivers' attempted avoidance maneuvers. FCW/AEB triggers were recorded only for crashes. External factors including weather condition, time of day, and traffic condition during crashes were examined, but their distributions did not differ by front crash prevention technology so they were not further examined.

Rate ratios and 95% confidence intervals were calculated assuming asymptotic normality (with standard error

Table 2. Crash involvements and exposure, with study group restrictions.

Technology	Crashes	VMT	Hours driven	Rate per 100 million VMT	Rate per 1 million hours
Neither	559	563,925,006	9,539,032	99.1	58.6
FCW	222	287,811,774	4,910,670	77.1	45.2
Neither	697	692,343,022	11,608,358	100.7	60.0
AEB	1,133	1,285,367,450	21,885,043	88.1	51.8

Technology	Ratio of rates per VMT	95% CI	Ratio of rates per hours	95% CI
FCW vs. neither	0.778	(0.666, 0.909)	0.771	(0.660, 0.901)
AEB vs. neither	0.876	(0.797, 0.962)	0.862	(0.785, 0.948)

Note: CI = confidence interval.

estimated as the square root of $1/n + 1/m$, where n and m are the crash counts for the two rates being compared) for comparisons across front crash prevention technology, with "neither technology" used as the reference category. Statistical significance was considered at the 0.05 type-1 error level.

Results

Overall counts of crashes and exposure during the 2017–2019 study period are provided in Table 1. Crash rates per VMT were lowest for FCW-equipped trucks, and those with AEB had lower crash rates per VMT than trucks without front crash prevention technology. These comparisons, however, could be subject to some carrier-to-carrier variation. Comparisons based on rates per hours driven were similar to those based on rates per VMT throughout the analyses. Trucks equipped with AEB comprised the largest portion of the study sample, and those with FCW the smallest.

Table 2 presents comparisons restricted to carriers with exposure in both categories. In other words, the FCW vs. neither comparison is performed for carriers that had exposure both with FCW-equipped trucks and trucks without front crash prevention—and analogously for the AEB vs. neither comparison. FCW was associated with a statistically significant 22% reduction in the crash rate per VMT (calculated with the rate ratio in Table 2 as $100 \times [0.778 - 1]$). AEB was associated with a statistically significant 12% reduction in the crash rate per VMT (calculated as $100 \times [0.876 - 1]$).

These comparisons, however, may include the possible effects of other crash avoidance technologies. For instance, many of the trucks in the study with AEB (particularly the International Prostar/Prostar Premium models) had the Bendix Wingman Fusion system option, which includes LDW and ESC. In other cases, technologies such as these and BSW were available and may have been selected with FCW/AEB. The rest of the analysis focuses on understanding the effect of front crash prevention in terms of performance in relevant types of crashes, to the extent possible given the uncertainty in which other crash avoidance technologies were on trucks.

Crash rate ratios were disaggregated by crash types relevant to FCW, AEB, and to other technologies frequently coupled with these, as shown in Table 3. FCW and AEB had the largest effects (44% and 41%, respectively, both statistically significant) on crashes in which the truck rear-ended another vehicle—the type of crash they are designed to address. Slightly elevated rates of being struck in the rear were observed for trucks with FCW and AEB, although the differences were not statistically significant. Smaller, non-significant reductions were observed for sideswipe (same direction) crashes. FCW was associated with a significant reduction in the rate of roadside departure crashes. These results are consistent with LDW, ESC, and BSW often being fitted to trucks when they had AEB and FCW, but the largest effects still were for crashes in which the truck rear-ended another vehicle.

Table 4 shows the prevalence of FCW/AEB triggers (i.e., a forward collision warning was issued or autobrake was initiated) by crash type. Since no comparison is made with trucks without front crash prevention in this table, data in this table were not restricted to the FCW/neither and AEB/neither study groups. Forward collision warnings were issued in about a third of crashes (31%) where a FCW-equipped truck rear-ended another vehicle. For AEB-equipped trucks (which typically also have FCW functionality), 17% of rear-end crashes involved drivers receiving a warning only, and 26% involved an autobrake event (AEB intervened in 43% of rear-end crashes). For both FCW- and AEB-equipped trucks, these percentages were much lower for other crash types.

Speed reductions between a FCW/AEB trigger and the time of collision are examined in Table 5. This analysis, necessarily, was restricted to crashes with FCW/AEB triggers, so the sample sizes are small and match the numerators of Table 4 except for one unknown speed-at-trigger value. For crashes in which the truck rear-ended another vehicle, on average, speed was reduced in this interval by over two thirds for FCW-equipped trucks and about one half to two thirds for AEB-equipped trucks.

Lastly, Table 6 shows attempted avoidance maneuvers for these crash types, except for trucks that were rear-ended by another vehicle. The avoidance maneuver "brake only" was more common among trucks equipped with front crash prevention in crashes in which they rear-ended another vehicle than for trucks without either technology. The "brake and steer" maneuver was less common among trucks equipped with front crash prevention. Avoidance maneuvers generally differed less across front crash prevention technology for other crash types.

Table 3. Crash counts, rate ratios, and 95% confidence intervals by crash type.

	Per VMT			
	FCW vs. neither		AEB vs. neither	
Crash type	Rate ratio (95% CI)	Crash counts	Rate ratio (95% CI)	Crash counts
Rear-ended other vehicle	0.560 (0.321, 0.976)	16/56	0.593 (0.428, 0.822)	76/69
Rear-ended by other vehicle	1.139 (0.696, 1.865)	25/43	1.164 (0.823, 1.629)	108/50
Sideswipe (same direction)	0.891 (0.684, 1.160)	80/176	0.964 (0.820, 1.133)	408/228
Roadside departure	0.632 (0.419, 0.954)	30/93	0.865 (0.677, 1.105)	167/104
	Per hour driven			
	FCW vs. neither		AEB vs. neither	
Crash type	Rate ratio (95% CI)	Crash counts	Rate ratio (95% CI)	Crash counts
Rear-ended other vehicle	0.555 (0.318, 0.967)	16/56	0.584 (0.422, 0.809)	76/69
Rear-ended by other vehicle	1.129 (0.690, 1.849)	25/43	1.146 (0.819, 1.602)	108/50
Sideswipe (same direction)	0.883 (0.678, 1.150)	80/176	0.949 (0.807, 1.116)	408/228
Roadside departure	0.627 (0.415, 0.946)	30/93	0.852 (0.667, 1.088)	167/104

Note: CI = confidence interval.

Table 4. Percent and number of crashes with FCW/AEB triggers by crash type and technology.

	FCW trucks		AEB trucks			
	Warning		Warning only		Autobrake	
Crash type	Percent of crashes	Number of crashes	Percent of crashes	Number of crashes	Percent of crashes	Number of crashes
Rear-ended other vehicle	31%	5/16	17%	13/76	26%	20/76
Rear-ended by other vehicle	4%	1/25	5%	5/108	2%	2/108
Sideswipe (same direction)	0%	0/80	2%	7/408	<1%	2/408
Roadside departure	0%	0/30	2%	3/167	2%	3/167

Table 5. Percentage and average change in speed between the FCW/AEB trigger and impact by crash type and technology.

	FCW trucks		AEB trucks			
	Warning		Warning only		Autobrake	
Crash type	Average percent change	Average speed change	Average percent change	Average speed change	Average percent change	Average speed change
Rear-ended other vehicle	−70%	−30 mph (n = 5)	−52%	−19 mph (n = 13)	−61%	−24 mph (n = 20)
Rear-ended by other vehicle	−89%	−48 mph (n = 1)	−43%	−7 mph (n = 5)	−59%	−13 mph (n = 1)
Sideswipe (same direction)	–	– (n = 0)	−24%	−10 mph (n = 7)	−61%	−34 mph (n = 2)
Roadside departure	–	– (n = 0)	−23%	−14 mph (n = 3)	−21%	−12 mph (n = 3)

Table 6. Attempted avoidance maneuvers (percent of crashes) by crash type and technology.

			Technology	
Crash type	Avoidance maneuver	Neither	FCW	AEB
Rear-ended other vehicle	Brake only	41 (n = 29)	50 (n = 8)	57 (n = 43)
	Steer only	1 (n = 1)	0 (n = 0)	0 (n = 0)
	Brake and steer	31 (n = 22)	19 (n = 3)	12 (n = 9)
	None	27 (n = 19)	25 (n = 4)	30 (n = 23)
	Other/unknown	0 (n = 0)	6 (n = 1)	1 (n = 1)
Sideswipe (same direction)	Brake only	10 (n = 23)	12 (n = 10)	10 (n = 39)
	Steer only	1 (n = 2)	0 (n = 0)	3 (n = 13)
	Brake and steer	15 (n = 35)	12 (n = 10)	16 (n = 65)
	None	69 (n = 160)	71 (n = 57)	67 (n = 275)
	Other/unknown	5 (n = 12)	4 (n = 3)	4 (n = 16)
Roadside departure	Brake only	8 (n = 8)	7 (n = 2)	7 (n = 12)
	Steer only	7 (n = 7)	3 (n = 1)	2 (n = 3)
	Brake and steer	8 (n = 8)	7 (n = 2)	6 (n = 10)
	None	61 (n = 63)	67 (n = 20)	71 (n = 119)
	Other/unknown	17 (n = 18)	17 (n = 5)	14 (n = 23)

Note: Percentages may not sum to 100 due to rounding.

Discussion

Front crash prevention driver assistance technologies have great potential to improve large truck safety, as outlined by Jermakian (2012) and Kuehn et al. (2011). While both FCW and AEB show strong safety benefits in the current study, one advantage of FCW systems is that some can be retrofitted to existing vehicles, allowing benefits to be realized sooner or with less investment. The National Transportation Safety Board (NTSB) (2015) suggests that ESC is necessary to realize the full benefit of AEB on commercial vehicles, especially on combination unit trucks, to ensure stability and prevent jackknifing during hard-braking events. ESC has been mandated on all new typical three-axle truck tractors manufactured on or after August 1, 2017, and on remaining truck tractors and buses manufactured on or after August 1, 2019 (Office of the Federal Register 2015), so this is promising in terms of both experiencing the benefits of ESC on large trucks (Wang 2011) and in terms of realizing the full benefit of AEB as new trucks are increasingly equipped with this system. While the cost-effectiveness of fleet-wide implementation of AEB on large trucks is not entirely established (Camden et al. 2017), truck crashes can be costly and individual carriers' analyses of technology and crash costs may vary.

A major benefit of the current study was the level of detail in the data collected and analyzed. Having trucks both with and without front crash prevention technologies sampled from the same carriers and having SmartDrive code the information directly, rather than by carrier self-report, minimized carrier-to-carrier differences that could have affected the study results. Knowing detailed circumstances of crashes allowed for not only looking at relevant crash types, but also for looking at the rate of FCW/AEB triggers and associated speed reductions during those crashes, as well as looking at crash types related to other safety technologies suspected to have been on many study trucks. If front crash prevention technology results in increased braking, and since false activations are known to happen (Grove et al. 2016), there is a concern that these technologies could increase the risk of being rear-ended by other vehicles. Such increases, albeit not statistically significant, were observed in the current study. However, if FCW or AEB causes crashes in which the truck is rear-ended, there should be an elevated prevalence of FCW/AEB triggers observed when looking at those crashes. This was not observed in the current study, suggesting that increases in rear-end-struck crash rates were not due to system activations. Conversely, if FCW or AEB prevents crashes in which the truck rear-ends another vehicle, there would not be an elevated prevalence of triggers in those crashes, since many would have been prevented and thus unobserved; in these crashes, FCW/AEB triggers likely would indicate reductions in crash severity, which is a secondary benefit of these systems. Interventions in rear-end crashes occurred at a higher rate for AEB than for FCW, suggesting larger reductions in the severity of such crashes that did happen. Also, autobrake interventions suggest that, at least initially, drivers did not brake as hard as the system in these crashes. In the current study, there were very few FCW/AEB triggers among crashes in which the truck was rear-ended by another vehicle. Also, results for other crash types were consistent with LDW, ESC, and BSW being effective for the crashes they are designed to prevent.

The current study has several limitations. While one likely benefit of AEB, and possibly of FCW, is due to reducing impact speeds and thus crash severity (NTSB 2015), the study sample did not contain a large number of severe crashes or a way to determine resulting injury severity (or fatality): therefore, this could not be directly estimated. The current study did demonstrate large reductions in speed between a FCW/AEB trigger and impact in front-to-rear crashes, but it is not clear how this would compare with crashes in which truck drivers braked in similar situations without front crash prevention technologies. By definition, the entire study sample consists of video-monitored drivers who may exhibit safer driving behavior than truck drivers in general, whether due to the monitoring or to the safety culture of their carriers that chose to use such monitoring technology. However, it is unclear how this would bias the estimated effect of AEB in either direction. The finding that AEB had a smaller benefit than FCW was unexpected and likely reflects that these systems often were installed on different carriers. However, both systems are shown to be strongly effective in reducing the risk of front-to-rear crashes.

Another limitation is that it is unclear how carriers decided which drivers operated trucks with front crash prevention and which ones did not—and there is likely variation by carrier in these practices. If newer trucks that are more likely to have advanced technologies are offered to senior and safer drivers as an incentive, this could lead to inflated benefit estimates; on the other hand, if crash-involved trucks are replaced without such incentive, then drivers with higher crash rates, a known risk factor for future crashes (Teoh et al. 2017) could be more likely to have front crash prevention, thus resulting in underestimated benefits. However, having multiple carriers likely reduces any such biases through variation in such practices. How drivers behave in response to having these systems is an interesting avenue of future research, especially in terms of exploring unintended consequences.

The current study adds to the state of knowledge by estimating a 41% reduction in real-world police-reportable front-to-rear crashes per mile traveled for trucks with AEB compared with those without—and a 44% reduction for FCW. Equipping new trucks with FCW and AEB driver assistance systems will gradually improve truck safety, and improved understanding of the benefits of these systems should help encourage these investments.

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