USING NATURALISTIC DATA TO EVALUATE HEAVY VEHICLE CRASH AVOIDANCE SYSTEMS PERFORMANCE

Alrik L. Svenson
National Highway Traffic Safety Administration
United States

Kevin Grove, Jon Atwood, Myra Blanco
Virginia Tech Transportation Institute
United States

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ABSTRACT

This study evaluated the real-world performance of crash avoidance systems (CASs) on commercial heavy vehicles using naturalistic data collection. The crash avoidance systems evaluated included: FCW, AEB (first generation systems)[1], and LDW. First, the study analyzed whether CAS activations were false (no potential threat), advisory (possible threat identified), or imminent (an activation in response to a real and immediate roadway conflict). Second, the study also examined behavior in drivers' longitudinal driving performance such as changes in activation rates, driving speeds, or driving headways. Third, the study characterized some of the environmental conditions (traffic, weather, driving maneuvers, etc.) that were associated with CAS activations. Finally, the study demonstrated how driving speeds, brake response times, and decelerations could be used to help model real world conflicts in which CAS may provide safety benefits. The output of the study may be used by CAS suppliers and truck OEMs in tailoring the performance or design of their CAS products, and by regulatory agencies in evaluating the effectiveness and overall performance of such crash avoidance systems. A total of 150 CAS-equipped tractor-trailers and their drivers from across the U.S. were recruited from seven commercial fleets to participate for up to 15 months in the field study. Data collection occurred between November 2013 and August 2015. A total of 2.9 million miles and 90,000 hours of driving data were recorded in the study. The study recorded video of the driver's face and torso, video of the forward roadway, vehicle network data, and parametric data whenever the trucks were in motion. Approximately 6,000 CAS activations were sampled for further evaluation, including all emergency braking activations. Results include several observations on CAS and driver performance. First, false activations were observed in the data, including many stationary object alerts within the sample. Overpasses, overhead signage, roadside infrastructure (signs, etc.), and curves in the road were common causes of false stationary object alerts. Second, there were several observations about when the truck drivers' actions triggered CAS activations versus when other vehicles triggered activations. Finally, there were observations of drivers potentially misusing controls for the lane departure warnings. The real-world situations and driver behaviors that generate activations, as well as driver behaviors in response to activations can be used by system manufacturers to improve the performance of CAS devices. False positive activations caused concern among fleet managers because drivers' trust and use of the system is paramount to its effectiveness. This study is limited to heavy vehicle CAS systems as their performance and implementation differs from light vehicles, so results may be different on other vehicle platforms. Naturalistic methods are a valuable tool for understanding real-world performance. As CAS technologies and other automation features become more and more capable, naturalistic research will allow all interested parties to better understand the benefits and unintended consequences of real-world usage.

[1] Defined here to mean systems that can automatically brake on moving, but not stopped/fixed objects.

INTRODUCTION

In 2015, 4,067 people were killed and an estimated 116,000 people were injured in crashes involving large trucks [1]. Fifty-nine percent of fatal crashes and 52% of injury crashes involving large trucks were front impacts [1]. These front impacts are more likely to result in injuries or fatalities, and in recent years, crash avoidance systems (CASs) have become commercially available to help prevent or mitigate these collisions. CASs use a bumper-mounted radar and an in-vehicle interface to provide audible and visual alerts to potential threats in front of the truck. Some of these systems are also equipped with automatic emergency braking (AEB) which under certain conditions automatically apply the brakes if the driver does not respond. In 2013, a new generation of CASs became commercially available in which AEB was always active. This generation[2] of CAS technology has the potential to reduce or mitigate front impacts on large trucks and may be an important tool for reducing roadway collisions.

CAS technologies are currently required for heavy vehicles by the European Commission in the European Union [2, 3]. CASs are currently available as optional equipment in the US; therefore, fleets must make cost/benefit decisions on whether to purchase them and the types of systems to purchase. This study aims to investigate the causes of and reactions to CAS activations in the real world so that their potential benefits may be better understood.

METHODS

Naturalistic Approach

This study recruited the drivers of 150 truck-tractors from seven different companies across the US. The vehicles were equipped with either Meritor WABCO OnGuard or Bendix Wingman Advanced CAS technologies. These products were the latest generation of CAS technologies commercially available in 2013. Data collection took place between November 2013 and May 2015.

Each truck was equipped with a small, window-mounted data acquisition system (DAS) designed by the Virginia Tech Transportation Institute (VTTI) called the MiniDAS. VTTI technicians and researchers traveled to participating fleet terminals to recruit drivers and install vehicles on-site. The MiniDAS recorded continuous video of the driver and forward roadway, vehicle network data, kinematic data, Global Positioning System (GPS) data, and CAS activations whenever the trucks were in motion. Participating drivers drove their normal revenue-producing routes for up to one year with the MiniDAS installed. By collecting naturalistic data, results could be analyzed for any behavioral changes that might have taken place.

CAS Activations

Naturalistic methods of data collection were used to understand how truck drivers experience CAS activations and what benefits CASs may provide. Both the OnGuard and Wingman Advanced systems provide multiple types of audio-visual feedback to drivers. Using a radar mounted on the front bumper of the truck, the systems detect potential threats and provide feedback based on the urgency of the situation. The first level of alert is a following distance alert (FDA), in which the driver receives an audible alert and visual feedback about a slower moving vehicle within the headway threshold. The second level of alert is an impact alert (IA), in which the driver receives a heightened audible and visual alert at a time to collision (TTC) typically around 2.0-2.5s. The heightened alert is usually a faster audible tone, a change in color of the visual display, and a change in picture that shows the truck closer to the lead vehicle. The CASs in the study also provided drivers with a stationary object alert (SOA). SOAs are similar in urgency to IAs, but are only presented if the object detected is not moving, and the driver may see a different visual image. At the most urgent level, the CAS can activate AEB. AEB activation is generally accompanied by a change in audible and visual alerts to help get the driver's attention. Both the OnGuard and Wingman Advanced have AEB that is "always active"; that is, the CAS can automatically brake the vehicle if it is traveling above 15 mph, regardless of whether or not cruise control is set.

The CASs in the study have an optional lane departure warning (LDW) feature, which uses a separate camera mounted on the top-center of the windshield. Seventy-five of the 150 vehicles in the study were equipped with LDWs, and their data were also recorded on the MiniDAS. One unique feature of the LDWs was that the drivers had access to a button that would deactivate the alert for 15 minutes. Using naturalistic methods to observe drivers and their use of the button provided some unique insight into their behavior and potential preferences for feedback on lane keeping.

Evaluating CAS Activations

[2] When the study was initiated, commercially available AEB systems did not react (auto-brake) on stopped/fixed objects. At the time of this paper's publication heavy vehicle AEB systems that can brake on stopped/fixed objects were becoming available in the marketplace in North America. NHTSA has initiated a new field study to examine the performance of the latest generation of heavy vehicle AEB systems.

The different types of CAS activations are intended to convey multiple types of feedback to the driver. The alerts cover a range of urgency, from the relatively low urgency FDA to the high urgency AEB. A series of classifications was created to evaluate whether the urgency of activations matched up with the urgency of external conditions at a basic level. The classifications were based on whether a safety-critical event (SCE) took place immediately prior to the activation. SCEs have been defined and used in previous naturalistic studies [4, 5, 6]. The key attribute of an SCE is that an immediate driver response (steering, braking, or a combination of the two) is required to prevent a crash or similar adverse event. Two categories were created: Activations in Response to SCE, and Advisory Activations. Activations in Response to SCE require a driver response *at the point of activation*, while Advisory Activations are more informational in nature and do not require a response *at the point of activation.* It is important to note that "advisory" does not mean an activation is inappropriate. For example, FDAs are designed to give low-urgency feedback to drivers and may be the most appropriate type of feedback in advisory situations. Similarly, "Activations in Response to SCE" does not necessarily mean an activation was appropriate. Again, using FDA as an example, if an FDA is observed prior to an SCE, a higher-urgency activation may have been appropriate. This study will use the above categories to describe the conditions in which different types of CAS activations were observed, but the "appropriateness" of any particular activation is subjective and unique to the situation at hand. The categories are used to broadly describe the urgency of situations in which CAS activations take place, in order to evaluate how they generally align with the urgency of the feedback CAS activations provide.

In addition to the Activations Prior to SCE and Advisory Activations, a third category called False Activations was created to describe activations that appeared to be triggered by invalid objects. The evaluation for False Activations was based on video of the forward roadway, in conjunction with the data recorded from the vehicle network describing the speed and distance of the object being tracked. An invalid object could be a vehicle in another lane of travel, static objects outside the lane of travel (street signs, guard rails, etc.), or overhead objects (overpasses, overhanging signage, etc.). These activations could be considered "inappropriate" and may have adverse effects on driver acceptance and trust of the technology. Most importantly, by using naturalistic methods to observe False Activations that occur during real-world use, the data can be used to make improvements to the next generation of the technology.

RESULTS

Naturalistic Data Collection

Recruiting the required number of drivers for this study was at times challenging. Truck drivers often change jobs, vehicles, and routes on short notice, and the study team was limited to meeting participants in select terminals belonging to participating fleets. Participants who could no longer reach these terminals were removed from the study to prevent loss of equipment or secure data. A total of 167 drivers was recruited, including team operations and replacement participants for some drivers who left the study. While each driver could participate for up to 15 months, on average drivers participated for about 4 months. Some participants left the study early due to reasons described above, while others participated less than the full duration due to missing scheduled meetings with researchers to harvest data. To keep the data truly naturalistic, the study team did not want to impact the operations of the companies involved or the schedules of participating drivers. If a driver was not able to meet with researchers, the driver was not penalized and researchers attempted to reschedule at the driver's convenience.

In total, over 2.4 million miles and 85,000 hours of naturalistic driving data were collected during the study. The data covered all 48 states in the contiguous US, with higher density in the mid-Atlantic, southeast, and southwest regions, which is where participating company terminals were concentrated. The data contained 885,241 CAS activations across all types (Table 1).

Type of CAS Activation	Number Observed
Automatic Emergency Braking (AEB)	264
Impact Alert (IA)	1,965
Stationary Object Alert (SOA)	8,604
Lane Departure Warning (LDW)	410,590
Following Distance Alert (FDA)	463,818
Total	885,241

Table 1.
Quantities of Observed CAS Activations

The quantities represent the relative urgency of each type of activation, with higher urgency activations such as AEB, IA, and SOA being relatively rare, and lower urgency activations such as FDA and LDW being relatively common. The difference between low-urgency and high-urgency activations is pronounced, with FDA and LDW counts being an order of magnitude greater. It should also be noted that only half the trucks in the study were equipped with LDW capabilities. However, not all types of activations were always recorded properly. Issues with vehicle networks and the data collection equipment meant that the variables representing some activations were not recorded properly on all vehicles in the study. To account for this and normalize the data into a more practical form, the rate of CAS activations per hour of driving were calculated (Table 2). Table 2 also includes the number of vehicles on which data for the activation were recorded (*N*) and the standard error for the rate (S.E.). The two brands of CAS included in the study have been de-identified as Company A and Company B in the table, and will remain de-identified in other results.

Table 2.
Rates of Observed CAS Activations

Activation Type	Company	Mean Hourly Rate of Activations	S.E.	N
AEB	A	0.006	0.001	69
	B	0.003	0.005	49
IA	A	0.03	0.005	69
	B	0.02	0.003	49
SOA	A	0.23	0.1	69
	B	0.07	0.005	49
FDA	A	7.20	0.57	69
	B	4.29	0.41	81
LDW	A	2.44	0.4	19
	B	14.48	1.68	64

The lower urgency activations of FDA and LDW are an order of magnitude more common than the higher urgency activations of AEB, IA, and SOA. Using the 70-hour duty limit as a benchmark, truck drivers in the study on average experienced less than 1 AEB per 70-hour period, 1 to 2 IAs per 70-hour period, and about a dozen SOAs per 70-hour period. In contrast, drivers experienced hundreds of FDAs and LDWs (when equipped) on average per 70-hour period. Any differences between the two types of CASs in the study could stem from several factors, including differences between the participants operating the vehicles, differences in driving conditions, differences in roadway conditions, or possibly differences between the design of the systems (such as providing multiple levels of a particular type of activation). The possible implications of these frequencies, particularly the high frequencies of FDA and LDW, will be discussed further below.

Reliability of CAS Activations

To explore the reliability of CAS activations, a sample of 6,000 was selected for inspection. The sample includes all AEB and IA activations from both brands of CAS, as well as approximately equal numbers of SOAs, FDAs, and LDWs from each company that were randomly selected. A breakdown of the sample is shown in Table 3. Note that each brand of CAS did not have an equal number of vehicles participating in the study, nor equal hours per vehicle that did participate.

Table 3.
CAS Activations Sampled for Inspection

Brand of CAS	LDW	FDA	SOA	IA	AEB	Total
Company A	760	903	227	1,424	234	3,548
Company B	752	905	227	538	30	2,452
Total	1,512	1,808	454	1,962	264	6,000

Each sampled activation was evaluated to determine if it was an Activation Prior to SCE, an Advisory Activation, or a False Activation. Those classified as Activations Prior to SCE went through a process of recording the causes and severity of the SCE, recording environmental and traffic variables at the time of activation, and describing the general context that generated the activation (i.e., a lead vehicle braking, truck passing a lead vehicle, etc.). Those classified as Advisory or False only went through a process of recording environmental variables, traffic variables, and general driving context. Figure 1 shows aggregate results for AEB, IA, SOA, and FDA activations (which are radar-based). Figure 2 shows the results for LDW (which are camera-based). Note that the LDW sensor is designed the to detect only one type of SCE, an unintentional lane departure. The two figures have been labeled accordingly.

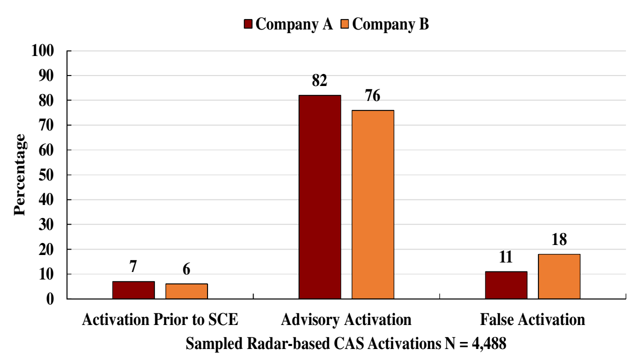

Figure 1. Performance of radar-based CAS activations, separated by brand of CAS.

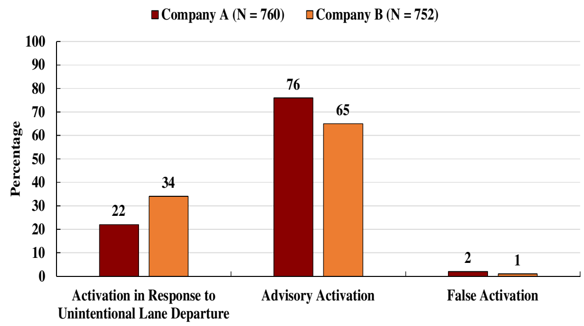

Figure 2. Performance of camera-based LDW activations, separated by brand of CAS.

The radar-based CAS activations were mostly advisory in nature, with false activations being observed across both brands in the study. LDWs were also mostly advisory (i.e., intentional lane crossings), with a relatively small number of false activations. Importantly, however, about 1 in 5 or 1 in 3 (depending on brand) of LDWs were safety-critical activations alerting drivers that their truck had unintentionally crossed a lane marking and required a correction.

As described earlier, the radar-based CAS activations are designed to convey degrees of urgency, and this can be seen when the results are broken down by type of activation. Figure 3 shows how activations of each type were categorized for Company A, while Figure 4 shows how activations of each type were categorized for Company B.

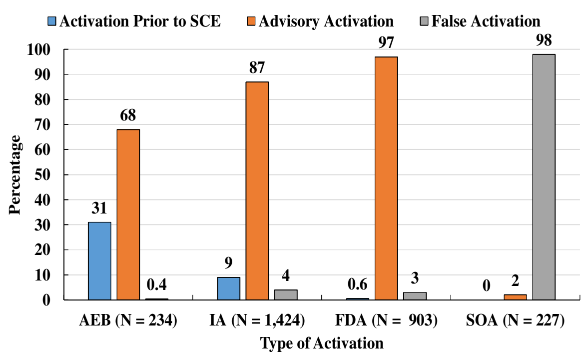

Figure 3. Performance of radar-based CAS activations for Company A.

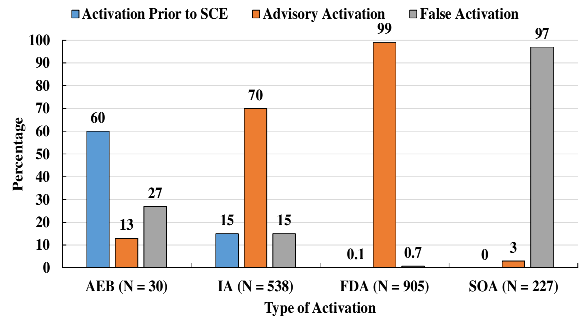

Figure 4. Performance of radar-based CAS activations for Company B.

By breaking the results down by type of activation, the progression of urgency can be seen. AEB, the most urgent activation, had the highest proportion of alerts triggered in safety-critical situations for each company. IA, the second-most urgent activation, had the second highest proportion of alerts triggered in safety-critical situations for each company. FDA, the lowest urgency activation, was almost entirely advisory for both brands. This progression appears to match the general intent of the activations, with more-urgent activations more likely to require an immediate reaction from the driver.

The breakdowns by activation type also shed light on some results that do not appear to match the design intent. First, SOA activations were almost entirely false for both brands. These activations are similar in urgency to IAs but are triggered by objects that are not moving. Review of video data of the forward roadway showed that overpasses, overhanging signage, and guardrails while navigating curves were common triggers for false activations. The causes of these triggers could not be determined, but could be due to alignment issues with the radar, changes in the grade of the roadway, detection issues with the CAS, or other causes.

The breakdowns also show that false activations of AEB and IA were observed across both brands. More false activations occurred for Company B. As mentioned above, AEB and IA activations were relatively infrequent, and a false AEB or IA was an even rarer occurrence. However, a false activation of AEB means that the vehicle is automatically braking in an inappropriate situation. This could create a safety-critical situation where one would not have otherwise occurred, and will be discussed in further detail. On a related note, a relatively high proportion of advisory AEBs were observed with Company A. An advisory AEB activation means that the activation took place before the situation became safety critical and before a reaction would have been required by the driver. In these situations, there is a question of timing, and whether a less-urgent type of activation would have been more useful to the driver.

False CAS Activations

False activations merit concern because they could distract from valid activations or reduce trust in the CAS technology. Figure 5 summarizes the percentage of false activations observed for each type of CAS activation, separated by brand of CAS.

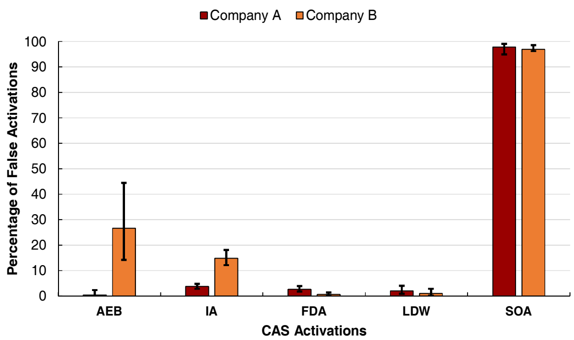

Figure 5. Summary of the percentage of false activations for each activation type, with 95% confidence intervals shown.

This figure emphasizes the two major observations seen with false activations. First, nearly all SOAs were false activations. While these activations do not apply brakes automatically, they could be particularly problematic for driver trust and acceptance. Drivers may not realize that one particular type of activation is more prone to false activations than others when making judgements about activations. The SOA activation is also similar to IA in urgency, and if drivers are not aware of which type of alert they are receiving in the moment, they may believe that they are receiving a false IA.

The second major observation is the relatively high rates of false AEBs and IAs. FDAs appeared to have lower rates of false activation, despite being lower in urgency. False AEBs are particularly concerning due to the potential for automatic braking to cause a critical incident. In total, 9 out of 264 observed AEBs were classified as false, but 8 out of 30 observed AEBs for Company B were false. Valid and false AEBs were further inspected to determine the duration of AEB activations (and, by extension, the automatic braking), the maximum decelerations during AEB activations, and the changes in speed during AEB activations.

AEB Activations

To learn more about how AEB activations may slow the vehicle in the real world, as well as any impacts that false AEBs may have on driving, AEBs in Response to SCEs, advisory AEBs, and false AEBs were inspected further. First, the average durations of each classification of AEB were calculated. The duration of each AEB, which was recorded on the vehicle network, corresponds to the duration in which brakes were automatically applied by the CAS. Figure 6 summarizes the average durations in seconds, separated by brand of CAS and classification of the activation. Note that these durations do not include manual braking, which could be engaged prior to or during an AEB in addition to the automatic braking.

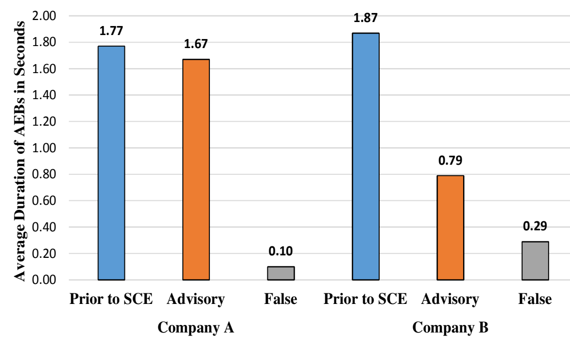

Figure 6. Average duration of AEB activations in seconds, separated by classification and brand of CAS.

For Company A’s CAS, AEBs in Response to SCEs averaged 1.77 s in duration and advisory AEBs averaged 1.67 s. The one false AEB was 0.10 s in duration. For Company B’s CAS, AEBs in Response to SCEs averaged 1.87 s in duration and advisory AEBs averaged 0.79 s. The eight false AEBs averaged 0.29 s. First, this shows that false AEBs were typically much shorter in duration than valid AEB activations, though the sample of false AEBs is small. Second, it may show a slight difference in how AEBs are triggered between the two brands. Recall that Company A had only 1 false activation, but had a relatively high percentage of advisory AEBs (Figure 3). Figure 6 shows that Company A’s AEBs in Response to SCEs and advisory AEBs were on average similar in duration. In contrast, recall that Company B had a higher rate of false AEB activations but a relatively lower percentage of advisory activations (Figure 4). Figure 7 shows that Company B’s advisory AEBs were about half the duration of AEBs in Response to SCEs on average. This may indicate a difference in how the two brands approach AEBs or determine whether AEBs have been “resolved.” Neither approach is necessarily better or worse, but it is worth noting that the two systems may handle short-headway advisory situations differently.

Figure 7 summarizes the average maximum decelerations associated with AEB activations in g-force, separated by brand of CAS and classification. Note that these values may include a combination of manual and automatic braking, as the accelerometer on VTTI's data collection unit and the output on the vehicle network cannot separate the two. The values in Figure 8 represent the average maximums *within the period of automatic braking being active*. Any manual braking force after AEB has deactivated is not included.

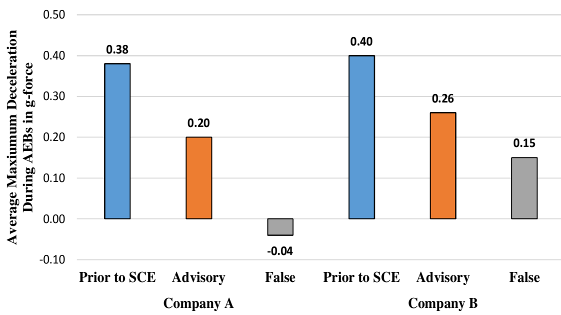

Figure 7. Average maximum decelerations of AEB activations, separated by classification and brand of CAS.

The results show that despite AEBs in Response to SCEs and advisory AEBs being similar in duration for Company A, on average less maximum brake force was applied during advisory AEBs (0.20 g) than AEBs in Response to SCEs (0.38 g). A similar result was observed for Company B, with advisory AEBs applying lower maximum braking force on average (0.26 g) than AEBs in Response to SCEs (0.40 g). These differences in average maximum brake force could be due to differences in driver braking on top of automatic braking, which is included in the values. Regardless of whether the differences in peak braking force are due to the driver's contribution to braking or the automatic braking, the technology appears to be following this design principal with net braking that results in lower peak values on average when the situation is less urgent. However, there is still a question of whether automatic braking is appropriate unless it is absolutely needed. Drivers could prefer audio/visual alerts in these borderline cases, and must be aware that CAS technologies may assess the urgency of situations differently than the drivers themselves would.

One final observation is that the false AEB activations had the lowest maximum braking forces on average. For Company A, the truck actually accelerated during the one false AEB, due to the driver applying throttle throughout the relatively short AEB activation. For Company B, the eight false AEBs resulted in an average maximum braking force of 0.15 g. While this is lower than the average maximum braking forces observe in AEBs in Response to SCEs or advisory AEBs, it is still enough to slow the vehicle.

To further explore the issue, the changes in speed during AEB activations were calculated. Figure 8 shows the average changes in speed that occurred *within the period of automatic braking being active.* Again, manual braking force may have contributed to this, and any changes in speed before or after AEB was active are not included.

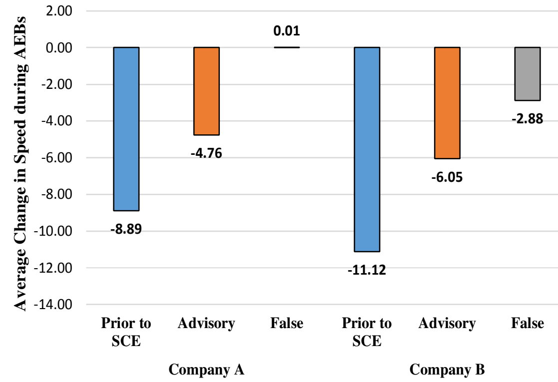

Figure 8. Average changes in speed during AEB activations, separated by classification and brand of CAS.

These results generally align with the average maximum braking forces that were observed. The trucks on average slowed more during AEBs in Response to SCEs than during advisory AEBs for both brands of CAS. For Company A, the truck actually accelerated during the false AEB activation because the driver applied the throttle throughout its duration. For Company B, the eight false AEB activations on average slowed the vehicle by 2.88 mph. Like the maximum decelerations shown in Figure 7, this is less change in speed on average than AEBs in Response to SCEs or advisory AEBs for either brand. In total, false AEBs were shorter in duration, resulted in lower maximum decelerations, and resulted in less change in speed on average compared to valid AEBs. However, there is still the potential for automatic braking on false activations to impact safety, driver trust, and driver acceptance.

Changes in Driving Behavior

One of the major features of the naturalistic data collection was the ability to observe drivers using CAS technology in their own trucks while driving their normally scheduled delivery routes. Additionally, the length of data collection, up to 15 months, allowed for the longitudinal analysis of some factors.

The first factor to be tested was whether the rates of CAS activations changed over time for participants. The hourly rate at which each driver received CAS activations per week in the study was calculated, and a mixed negative binomial regression model was used to test for any changes over time. The total count of activations within each week was the response variable, and the log of total hours driven in a particular week was the offset term, with linear and quadratic terms used to model the change in the hourly rate of activations as a function of week in study [7].

Among participants using Company A's CAS, 234 AEB activations were observed across 38,605 hours of driving. One driver appeared to be an outlier with 64 AEB activations across 1,300 hours of driving, whereas no other individual driver received more than 9 AEB activations. The initial analysis showed a significant increase in AEB activations over time, $t = 3.26$, $p = .0012$, but after the individual with 64 activations was removed, the result was no longer significant, $t = 1.61$, $p > .05$. Because inspection of forward video ruled out false activations for all of this participant's AEBs, this participant was likely an outlier due to a combination of personal driving habits and external driving conditions. Participants using Company B's CAS experienced 30 AEB activations in 11,758 hours. Analysis did not show a significant change over time, $t = .70$, $p > .05$.

Similar analysis for changes in IAs, SOAs, and LDWs did not result in significant changes over time for participants using either brand of CAS. Analysis of FDAs, however, did yield significant results. Participants using Company A's CAS were found to have a significant negative curvature, $t = -4.03$, $p < .0001$. This negative curvature indicates a slight, temporary increase over the first few weeks of participation in the rate at which FDAs were received given by the following model:

$$e^{1.59 + .02 * week - .0005 * week^2} \quad (1)$$

However, this result may be significant due to the large quantity of FDAs that were experienced and may not be appropriate as a model for the population as a whole. Figure 9 plots the average changes in FDAs experienced by drivers against each individual driver's rates.

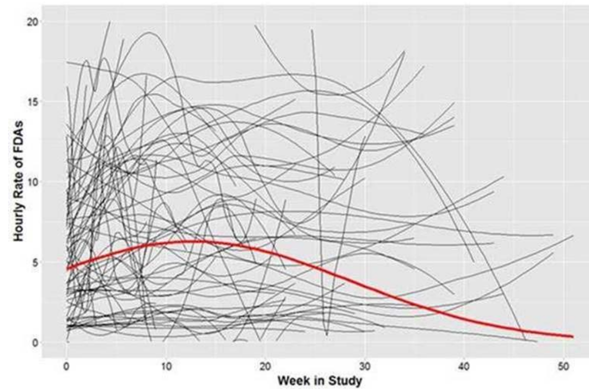

Figure 9. Plots of the average rate of FDAs per week in study for all drivers (red line) and the average rates of FDAs per week in study for each individual driver (black lines). *Note the wide range of results for individual drivers and the smaller number of drivers who participated into the end of the study.*

Plotting both the average and individual drivers highlights two major caveats with this result being statistically significant. First, individual drivers were observed to have a wide range of FDA rates that changed in different ways over time. Second, drivers participated for varying durations of time, and most drivers did not participate for the full duration. The average driver only participated for about 16 weeks, and the graph shows how fewer drivers were factored into the tail of the curve. time. Additionally, driver experience and the roadway conditions over time are not accounted for in this model and could have major impacts on the rates at which participants received FDAs.

Participants using Company B's CAS were also found to have a significant change over time, $t = 3.08$, $p = .0028$. The change was meaningful over the first 8 weeks of participation, with drivers receiving approximately 2.5 more activations per hour in their eighth week of participation compared to their first. However, this change appeared to level off after the eighth week, and subsequent analysis did not find a significant change over time after the eighth week, $t = -1.01$, $p > .05$. Like the previous results, this could be affected by driver experience, driving conditions, or several other factors that change over time. However, the change is a meaningful amount and may have implications for how drivers interact with the technology.

In addition to CAS activations, the MiniDAS recorded headway from the vehicle network. Because the CAS provide feedback based on headway, the data were analyzed to see if participants changed their average headway over time. Each participant's average headway was calculated for each week of participation in the study. The analysis found that drivers using Company A's CAS exhibited a small statistically significant quadratic change in their average headway over time. The predicted headway in seconds as a function of the week of participation is estimated as:

$$headway = 2.83 - .01 * week + .0002 * week^2 \qquad (2)$$

This equation predicts a small decrease in headway of about a quarter of a second over the first few weeks of participation, which then levels off over the remainder of the study (Figure 10).

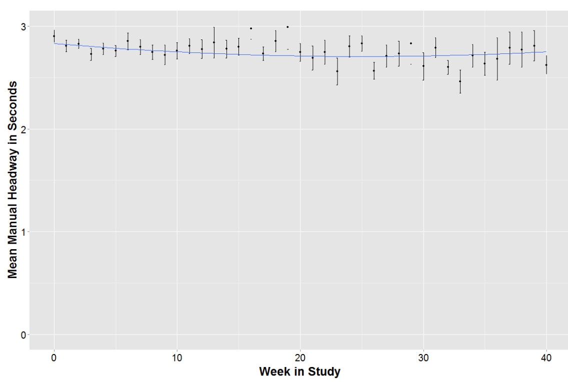

Figure 10. Average overall driving headway in seconds by week in study. Note that this includes manual driving and cruise control usage.

However, this result includes the use of cruise control. The CAS technologies included in this study feature adaptive cruise control, in which the vehicle uses the radar to control *both speed and headway* when a slower lead vehicle is present in the radar's threshold. Cruise control usage was recorded on the vehicle network, and a second analysis was performed in which cruise control usage was excluded from the data. This analysis found lower average headways and a small statistically significant quadratic change over time. The predicted manual driving headway in seconds as a function of the week of participation is estimated as:

$$headway = 2.39 - .016 * week + .0003 * week^2 \qquad (3)$$

This equation also predicts a small decrease in headway of about a quarter of a second over the first few weeks of participation, which then levels off over the remainder of the study (Figure 11).

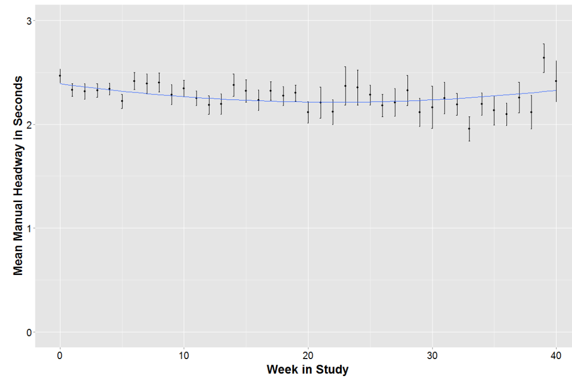

Figure 11. Average manual driving headway in seconds by week in study.

Essentially, removing cruise control usage slides the predicted curve to a lower starting value without changing its shape or magnitude. Drivers using Company B's brand of CAS did not exhibit a statistically significant change in headway over time, both with or without cruise control usage factored in.

Although these results are statistically significant, their real-world implications are not as clear. The results imply that drivers on average kept a shorter headway than what adaptive cruise control attempted to maintain, since removing cruise control usage reduced the predicted headway of the model throughout. This matches previous research on the same data set, which found that drivers in general maintained shorter headways than adaptive cruise control, even in adverse weather conditions [8]. Second, as noted earlier, there are several factors which could be contributing to the change over time, including driver age and experience, seasonal weather changes, traffic or route changes, or other factors. However, despite these caveats, both the change in the rate of FDAs and the change in average headways in the early weeks of participation warrants further investigation. There could be an acclimation period when drivers begin using the technology, followed by a return to their pre-CAS-installation driving behavior over time. Conversely, drivers could be using the system normally at first and then adapting over time, leading to small changes in behavior. Additional research that includes the age and experience of drivers, as well as feedback from drivers on how they use the technology, would help determine how meaningful these results are and whether there are any subpopulations that exhibit stronger changes over time.

Context of CAS Activations

Another major feature of naturalistic data collection is the ability to observe the contexts and driving conditions in which CAS activations took place. Using definitions of traffic density and maneuverability that were adapted by VTTI [7,9], the data were analyzed to investigate the driving conditions in which activations in response to SCEs and advisory activations took place. The categories of density and maneuverability are referred to as Levels of Service (LoS), and range from A1 (least restrictive conditions) to F (most restrictive conditions). Figure 12 summarizes the LoS for AEB and IAs in Response to an SCE. Figure 13 summarizes the LoS for each advisory AEB and IA.

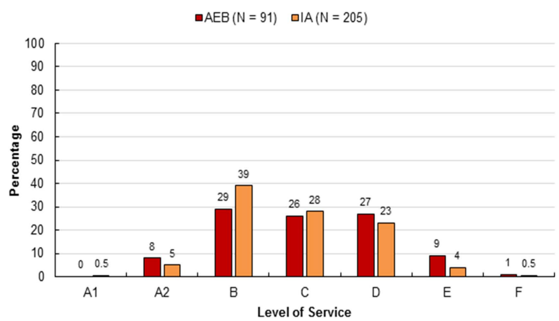

Figure 12. Percentages of AEBs and IAs in Response to SCEs that were observed within each LoS.

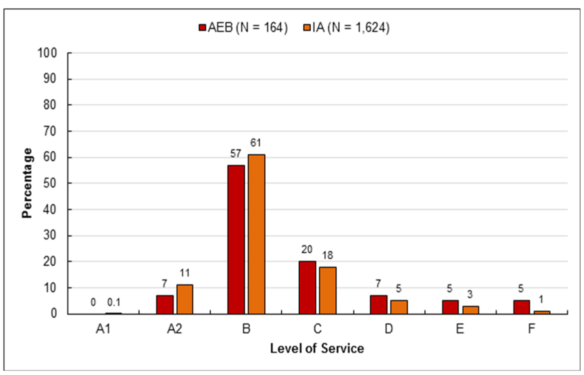

Figure 13. Percentages of advisory AEBs and IAs that were observed within each LoS.

AEBs and IAs in Response to SCEs were most likely to occur in LoS B, C, or D. These represent traffic conditions in which traffic flow may be stable but there are restrictions on maneuverability and traffic speed. Advisory AEBs and IAs were more heavily weighted to LoS B, which represents relatively low levels of restriction. Based on these results, AEBs and IAs in Response to SCEs may be more likely to occur in LoS C and D, which are more restrictive, while advisory AEBs and IAs may be more likely to occur in LoS B, which is less restrictive.

Sampled LDWs in Response to SCEs (unintentional lane departures) and advisory LDWs (intentional lane departures) were also categorized based on LoS. Figure 14 summarizes the LoS in which *unintentional* lane departures were observed, separated by whether they occurred on the left (LLDW) or right (RLDW) side. Figure 15 summarizes the LoS in which *intentional* lane departures were observed, separated by whether they occurred on the left (LLDW) or right side (RLDW).

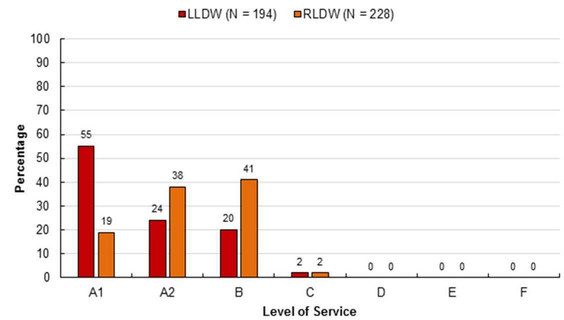

Figure 14. Percentages of LDWs in Response to SCEs (unintentional lane departures) that were observed within each LoS.

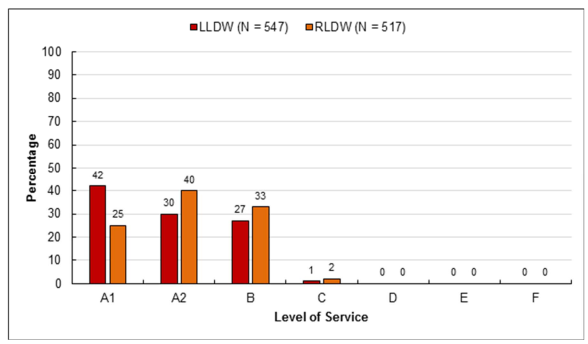

Figure 15. Percentages of advisory LDWs (intentional lane departures) that were observed within each LoS.

Both unintentional and intentional lane departures were most likely to occur in LoS A1, A2, and B. These represent free-flow conditions with little to no restrictions. This may indicate that drivers are devoting more resources to lane-keeping when traffic is denser and maneuverability is lower. Additionally, a higher percentage of LDWs were observed on the left side in LoS A1, whereas more LDWs on the right side were observed in LoS A2 and B. LoS A1 represents the free flow of traffic without lead vehicles, while LoS A2 and B represent the free flow of traffic with a lead vehicle. This may indicate that participants favored a particular side of the road depending on whether a lead vehicle was present, but may also be a function of road types or driving times in which a lead vehicle is more likely to be present.

In addition to traffic conditions, the types of maneuvers that led to CAS activations were analyzed. Video of each AEB and IA was reviewed to determine the context of the interaction between the participant in the subject vehicle (SV) and the lead vehicle (LV) that generated the CAS activation. Note that in this context the LV is whatever vehicle the radar was tracking that caused the activation. This could be a vehicle that merged or changed lanes in front of the participant's truck and that became the LV once the radar tracked it as the closest object. These contexts were grouped into four broad categories. LV Action encompasses all contexts in which a maneuver performed by the LV precipitated the CAS activation. This would include an LV merging, changing lanes, braking, turning, etc. SV Approaching LV encompasses contexts in which the participant was driving faster than the LV and reached a headway necessary to generate the activation, but was not attempting to pass or change lanes. SV Passing LV encompasses contexts in which the participant reached a headway necessary to generate an activation in the process of passing or changing lanes. The Other category includes contexts that do not fit into the categories above. Figure 16 summarizes the broad contexts of AEBs and IAs in Response to SCEs, while Figure 16 summarizes the broad contexts of advisory AEBs and IAs.

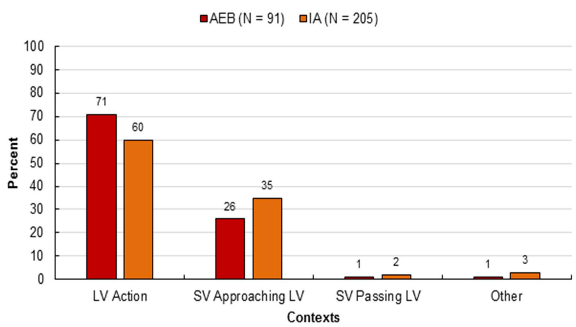

Figure 16. Percentages of AEBs and IAs in Response to SCEs that were observed in each driving context.

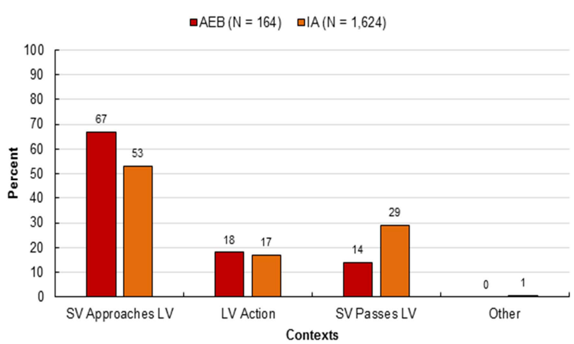

Figure 17. Percentages of advisory AEBs and IAs that were observed in each driving context.

AEBs and IAs in Response to SCEs were most likely to be preceded by an LV action (71% and 60%, respectively). Advisory AEBs and IAs were most likely to involve the SV approaching or passing the LV (81% and 82%, respectively). This result may help the next generation of CASs to provide activations that are more appropriate to the situation. For example, in the context of SV Approaching LV, the lead vehicle is likely to be at relatively stable speed with a headway decreasing at a relatively constant rate. In the context of SV Passes LV, the participant is likely to be accelerating and may have their turn signal activated. These were deemed advisory because the participant seemed aware of the lead vehicle and approached in a more controlled manner based on video. In these situations, it may be possible to factor these conditions into determining the most beneficial CAS activation. Conversely, the context of LV action is more likely to have a change in speed or a disjointed headway due to vehicles moving in front of the truck. If these are more likely to be safety critical, these factors may be useful in determining when higher urgency activation types are most beneficial.

Participant Controls of CAS Technology

The radar-based CAS activations were not under the control of drivers, and drivers could not control radar-based CAS activations other than through their driving habits. However, the camera-based LDWs did provide a means of control to drivers. Each of the 75 vehicles equipped with LDWs was also equipped with a button in the center console that could disable LDWs for up to 15 minutes. Use of this button could be tracked from data in the vehicle network, and the data were analyzed to see if and how participants chose to use it. One of the vehicles did not record LDWs properly, and this vehicle and its participating driver were excluded from analysis.

For each of the 74 participants with data that were recorded properly, the rate of button presses per hour was calculated. Remember that each button press disables LDWs for up to 15 minutes, so a rate of 4 button presses per hour means that the participant was essentially disabling the system, unless the button press was to re-enable LDWs. The hourly rates of button presses were then grouped into categories ranging from 0 through 4. The percentage of participants who fell into each group is summarized in Figure 18.

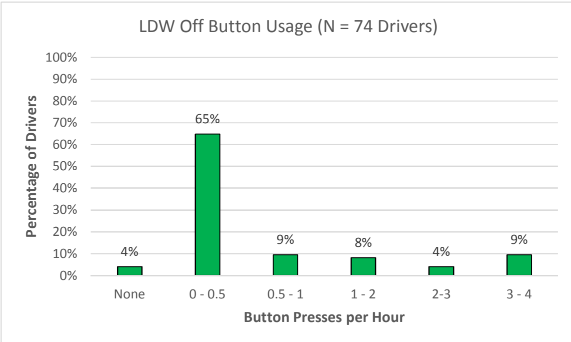

Figure 18. Percentages of drivers that were observed to use the LDW off button at different rates.

Most drivers, 65%, used the button sparingly at a rate of less than once every other hour, with an additional 4% never using the button. Another 17% fell into middle groupings, using the button between 0.5 and 2 times per hour. Finally, 13% of drivers used the button frequently, at a rate over 2 presses per hour. The intent of the button is to prevent false activations when the lane markings are unclear or difficult for the camera to read. Based on these results, some participants were using the button in ways that were not intended. Upon further inspection of the video, this unintended usage fell into two categories. The first type was perpetual, in which participants kept LDWs disabled for extended periods with button presses every 15 minutes. These participants typically averaged 3 to 4 presses per hour over all of their driving. Drivers observed pressing the button this frequently did not appear to be reacting to lane markings or traffic conditions. In the video, they could be seen using the visual cue of the button changing color to know when to press it again, or an LDW would make them realize the system was enabled and lead to them disabling it. The second type was situational, which typically fell into the 1 to 3 presses per hour range. In videos of these participants, they were observed to use the button frequently in certain situations, some of which were not intended. One particular situation was team operations when one driver was in the cab sleeping. The sound of LDWs is meant to mimic a rumble strip and can be very loud in order to grab the driver's attention, but it would also wake up a person sleeping in the cab.

The use of the LDW off button reveals several interesting things about driver behavior. First, the results show that if drivers receive control over some aspects of the CAS, there is potential to abuse it. This could be simply because they do not understand the purpose of the system, and this could in turn go back to trust or acceptance issues due to false activations. Second, the results show that drivers also desire some control over the system and will use it appropriately in most cases. Third, the results show that there are some unintended uses that relate to driver control, such as team operations with one driver sleeping. These cases are particularly tricky, because providing more refined control could prevent misuse or open the door for additional methods of abuse.

CONCLUSIONS

The research found that AEBs, IAs, FDAs, and LDWs were generally reliable, but that SOAs were mostly false. Most AEBs were valid, but false AEBs were observed in the data. These false AEBs were on average shorter in duration, had lower peak decelerations, and resulted in less speed reduction than valid AEBs, mitigating some of the safety concerns. Since this study was conducted, a new generation of CAS technologies is coming to market [10, 11], and the improved sensors and algorithms on these systems may reduce reliability concerns.

The research found little evidence of drivers adapting their behavior to CAS technology. The evidence that was found showed drivers receiving more alerts and reducing their headways early in the study, which would not seem to indicate safer driving behaviors. However, these results did not factor in driver age, experience, weather, traffic, road type, and other important factors that could affect behavior. The results show that the systems worked well in preventing or mitigating collisions when conflicts unfold, and that these conflicts were more often due to actions of drivers around the truck rather than the actions of the truck driver. Other studies have also found that light vehicles around trucks tend to be the cause of conflicts [12], and this observation may be key in making the systems desirable and useful to drivers.

Finally, the results showed that drivers likely want some degree of control over how CAS activations are triggered or how activations are presented. However, the results also show that any control provided to the drivers must consider the potential for misuse or abuse. Naturalistic methods can help designers learn what kind of controls will balance driver needs with system availability.

A large amount of naturalistic data was collected as part of the research effort, and these data provide valuable insight into heavy vehicles equipped with CAS technology. Profiles of traffic conditions, vehicle actions, driver speed, driver headway, brake reaction time, and decelerations are now available to further CAS benefit modeling efforts.

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