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Field Study of Light-Vehicle Crash Avoidance Systems: Automatic Emergency Braking and Dynamic Brake Support

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6. AUTHORS Carol A. Flannagan,* David J. LeBlanc,* Raymond J. Kiefer,** Scott Bogard,* Andrew Leslie,* Chad T. Zagorski,** Clark W. Zimmerman,** William S. Materna,** Christopher S. Beck** *University of Michigan Transportation Research Institute (UMTRI) **General Motors			
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13. ABSTRACT

From a methodological perspective, the telematics-based, large-scale data collection technique has strengths for evaluating safety systems, including cost, sample size, drivers using their own vehicles, ability to look at long-term effects, data efficiency, and the ability to get "rapid-turnaround" large-scale results. These strengths are particularly notable for examining rare events such as last-second automatic braking (or steering), near crash, or crash events. This type of telematics-based data collection is also helps understand impacts of safety systems that are rapidly emerging globally. The ability to collect data rapidly at this scale (in this case, ~1 million miles of driving data per month), especially when events are rare, is critical to understanding the real-world performance of these and future vehicle systems.

This field study report uses high-priority data addressing driver assistance actions and corresponding driving behavior associated with production crash avoidance-equipped passenger vehicles. A prior year-long study addressed forward collision warning (FCA) and lane departure warning (LDW) technologies by capturing data from almost 2,000 vehicles. This report focuses on automatic emergency braking (AEB) and dynamic brake support (DBS) systems offered by GM as "Front Automatic Braking" (FAB) and "Intelligent Brake Assist" (IBA), respectively. These systems are jointly referred to as the Collision Preparation System (CPS).

The goal of this field study, focused on examining a production FAB and IBA system, is to study system behavior, driver behavior, safety-relevant findings, and observations on system performance and maturity. As in the prior work, this study made use of the unique telematic capability of GM's OnStar-equipped vehicles to gather data in participating vehicles. Data was captured on 1,021 production vehicles (all MY 2015 Cadillacs) equipped with FAB and IBA from consenting vehicle owners over a 1-year period; the vehicles involved operated in 46 of 50 States.

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1 Executive Summary

This is the final report for of the project, “Field Study of Light Vehicle Crash Avoidance Systems” (Task Order 0007 under NHTSA Contract DTNH22-11-D-00236). The project described in this report is a field study program that uses a carefully selected set of high-priority data addressing driver assistance system actions, and corresponding driving behavior, associated with a large sample of drivers of production crash avoidance-equipped passenger vehicles. A prior study addressed forward collision warning (FCA) and lane departure warning (LDW) technologies by capturing data from almost 2,000 vehicles for a year, and the report has been published (Flannagan et al., 2016). The subject of this final report focuses on automatic emergency braking (AEB) and dynamic brake support (DBS) systems, offered by General Motors (GM) as “Front Automatic Braking” (FAB) and “Intelligent Brake Assist” (IBA), respectively. These systems are jointly referred to as the “Collision Preparation System” (CPS).

The goal of this field study, focused on examining a production FAB and IBA system, is to study system behavior, driver behavior, safety-relevant findings, and observations on system performance and maturity. As in the prior work, this study made use of the unique telematic capability of GM’s OnStar-equipped vehicles to gather data in participating vehicles. Data was captured on 1,021 production vehicles (all Model Year 2015 Cadillacs) equipped with FAB and IBA from consenting vehicle owners over a 1-year period; the vehicles involved operated in 46 of 50 States.

The nearly 12 million miles of data collected included high-level trip summary data as well as detailed event-based data surrounding FAB, IBA, and combined “FAB+IBA” activations, referred to subsequently as “events” or “CPS events.” All events were accompanied by a multimodality FCA system imminent alert whose characteristics were configurable by the driver, (i.e., a red flashing windshield alert and either “Safety Alert” seat vibrations or a beeping alert). Although FCA alerts occur much more frequently than FAB/IBA events, data on FCA activations were only captured when they occurred in conjunction with CPS events. In addition, we estimate that ~50 percent of FCA alerts that would have otherwise occurred prior to a CPS-event onset may have been missed because the FCA signal persists for half of the time between CPS-event data recording samples (FCA: 0.04 s versus sample interval: 0.08 s).

Overall, for 96 percent of the driving time, the system was (set by the driver) at the vehicle menu setting that provides for full FAB/IBA capability (as well as FCA system alerts), indicating an extremely high rate of system usage by drivers (compared to 91% for FCA from the prior study). These results suggest that the benefits of the systems evaluated in this effort can be expected to apply to similarly-equipped vehicles. Results indicated an overall CPS event rate of 1.04 events per 10,000 miles, and 44 percent of the vehicles never triggered a single event during the study. These results suggest long-term adaptation is unlikely to occur, since adaptation would seemingly require enough events to justify reliance on the system. Furthermore, the results illustrate that FAB/IBA events are designed to occur later in an emerging forward conflict (e.g., in comparison to a forward collision imminent alert), and thus rarely occur.

At event onset, initial host vehicle speeds, as well as the vehicle-to-vehicle kinematic conditions, varied widely. FAB, IBA, and (rare) FAB+IBA activations accounted for 78 percent, 21 percent, and 1 percent of the observed events. Fifty-four percent of events lasted no longer than 0.08 s and occurred at speeds of 10 mph or less. These may not have been perceived by the driver other than the presence of a visual indication when the system engages.

One way to identify potential unwanted system activations was to look for repeat events. In particular, if events occurred at the same location, especially with different vehicles, the activations might occur because of characteristics of the location. Fifty-five locations of repeat events were identified, but 89 percent of these cases occurred at low speeds, generally in driveways or parking lots. Moreover, none involved different vehicles at the same location. In general, repeat events indicating unwanted activations due to location characteristics do not appear to be a significant issue.

Events occurring above 10 mph and lasting 0.16 s or longer, subsequently referred to as "key events," make up 30 percent of all events. Key events had an associated overall event rate of 0.31 per 10,000 miles, and 65 percent of the vehicles in the study never triggered a key event.

Nearly 87 percent of key events involved either FAB alone with "light" automatic braking levels or IBA alone. Events that involved both FAB and IBA systems (0.7% of all events) or "full" levels of FAB automatic braking (0.5% of all events) were relatively rare, but tended to last longer and involve relatively large speed reductions. Average key-event durations were highest for (combined) FAB+IBA events (1.27s), followed by IBA events (0.44s) and FAB events (0.34s). The corresponding trend across event types was also observed for total speed reductions, with the greatest average reduction for FAB+IBA events (16.2 mph), following by IBA events (2.7 mph), and finally, FAB events (0.5 mph). While the driver may be aware of short-lived events (due to accompanying FCA imminent alerts), these events ultimately have little effect on vehicle speed. Speed reductions were also similar for FAB and IBA events if very short events, common among FABs, are removed. An examination of the proportion of host speed reductions observed in key events indicated 28.2 percent was attributable to FAB, 52.4 percent to IBA, and 19.4 percent for only 10 combined FAB+IBA events. In terms of relative-speed reduction, the corresponding proportions are 48.4 percent, 40.5 percent, and 11.1 percent, respectively. It should be noted that most events include some driver braking (including about half of all FAB events), and that IBA requires "panic" braking to be triggered. Together, these results highlight how FAB and IBA systems contribute to the safety benefits of the system as a whole, and support offering (or packaging) these two systems together.

Direct assessment of safety benefits using the OnStar data collected was challenging due to extremely high system usage and consequent absence of a control group that didn't use the system. To address the question of safety benefits, we turned to crash data obtained from OnStar's Automatic Collision Notification (ACN) database. These crashes are among more severe crashes, as ACN requires either an air bag deployment or a relatively high delta-V.

For the vehicles in the study, we obtained all ACN events that occurred during the study period. Of the 8 total events, there were 2 frontal crashes. A rough comparison to SHRP2 data, in which no vehicles were equipped with AEB systems, suggests we would have expected to observe 11 frontal striking ACN events in the current dataset if FAB/IBA were not present or ineffective.

To further explore safety benefits, a more general ACN analysis was conducted, encompassing a larger set of production vehicles of the same make/models as the current dataset. In addition, these vehicles included those with and without the FAB system to allow comparison. This additional ACN analysis indicated that FAB/IBA equipped vehicles had 17 percent fewer ACN events overall and 11 percent fewer frontal ACN events compared to unequipped vehicles (without FAB, IBA, or FCA systems).

From a methodological perspective, the telematics-based, large-scale OnStar data collection technique employed in the current effort has several distinct strengths for evaluating safety systems, including cost, sample size, drivers using their own vehicles where they can turn systems off, ability to look at long-term effects, data efficiency, and the ability to get “rapid-turnaround” large-scale results. These strengths are particularly notable for examining rare events, such as last-second automatic braking (or steering), near crash, or crash events (including ACN events). Since this technique currently focuses on key high-priority numeric data, it complements and benefits from the extensive set of multi-channel video and continuously measured kinematic information gathered in traditional FOTs. This type of telematics-based data collection appears is also ideally suited for understanding the safety impacts of safety systems that are rapidly emerging globally. The ability to collect data rapidly at this scale (in this case, ~1 million miles of driving data per month), especially when events are rare, is critical to understanding the real-world performance of these and future vehicle systems.

2 Introduction

2.1 Program Overview

This is the final report for of the project, "Field Study of Light Vehicle Crash Avoidance Systems" (Task Order 0007 under Contract DTNH22-11-D-00236). The project described is a field study program that makes use of a carefully selected set of high-priority data addressing driver assistance system actions, and corresponding driving behavior, associated with a large sample of drivers of production crash avoidance-equipped passenger vehicles. A prior study of this task order addressed forward collision warning (FCW) and lane departure warning (LDW) technologies by capturing data from almost 2,000 vehicles for a year, and the final report has been published (Flannagan et al., 2016), the subject of the current final report, focuses on automatic emergency braking (AEB) and dynamic brake support (DBS) systems.

Note the functions that NHTSA calls FCW, AEB, and DBS are marketed by GM as "Forward Collision Alert" (FCA), "Front Automatic Braking" (FAB) and "Intelligent Brake Assist" (IBA). This GM terminology is used in the remainder of the paper. In addition, "Collision Preparation System" (CPS) is a GM engineering term that is used sometimes to collectively refer to the integrated FAB/IBA system. In the makes and models used in data collection, all vehicles were equipped with FAB and IBA systems (as well as FCA and LDW, and potentially other "Active Safety" systems). These systems use multiple radar sensors in addition to a forward-looking camera. Data from just over 1,000 vehicles was collected for a year in order to address:

- Real-world drivers' use of the FAB/IBA system;
- FAB/IBA system performance measures in natural use; and
- Driver interactions with the FAB/IBA system, including system settings, responses in event situations, and driver adaptation over time.

The field study approach in both efforts harnesses the unique and powerful data collection capabilities of the OnStar system to collect data from a large set of customer-owned GM production vehicles that are equipped with the necessary modules to enable capturing critical, high-priority information about the safety systems under study. These large-scale data can provide timely understanding of the safety impact and driver acceptance of the safety systems. This is well suited to support decision-making regarding NHTSA's Crash Avoidance New Car Assessment Program (NCAP) and global NCAP activities, including associated system performance requirements.

This program is conducted through an IDIQ contract between NHTSA and the Virginia Tech Transportation Institute (VTTI). The technical team consists of IDIQ subcontractor University of Michigan Transportation Research Institute (UMTRI) in collaboration with its own research partner General Motors (GM). GM is a subcontractor to UMTRI for this effort, and the resources and capabilities of its OnStar unit played a fundamental role in enabling data collection. This teaming arrangement is the same as for the prior field study analysis of FCA and LDW systems. UMTRI and GM conduct the technical work and creates the associated reports and presentations. VTTI provides project oversight and administration as the IDIQ prime contractor, but is not directly involved in any of the technical activities of this task order.

2.2 Main Study Areas

The goal of this field study is to understand how FAB/IBA systems operate in the field and how drivers respond to them. The four areas of research questions include system behavior, driver behavior, safety-relevant findings and observations on system performance and maturity.

Table 1 lists the research questions under each theme as envisioned in the data analysis plan. The question indices are provided for reference to that plan. The Results section is organized by analysis, and the Discussion section is organized by the research themes in Table 1. These themes are also summarized below.

Table 1 Research Themes and Questions

Theme	Index	Research Questions
	P-1	How often do FAB and IBA events occur?
	P-2	What is the distribution of FAB and IBA rates across vehicles and driver demographics?
System performance ("P")	P-3	What circumstances tend to surround FAB and IBA events? (e.g., driver speed, time of day, road type)
	P-4	How often is the FAB/IBA system available, i.e., ready to assist the driver, and in which situations is the system not available?
	B-1	What are the conditions and scenarios that lead to such events, including the driver's control actions before onset of FAB/IBA?
Driver behavior ("B")	B-2	What is the nature and timing of driver responses (brake, throttle, steering, over rides) to FAB and IBA events?
	B-3	Do drivers turn FAB/IBA "off," and if so, what factors may lead to this choice?
	B-4	Does the pattern of FAB/IBA activations change with increased vehicle exposure (adaptation)?
Safety impacts	S-1	What are the potential safety benefits of FAB/IBA?
	S-2	How does the potential safety benefit of FCA compare to potential benefits of FAB/IBA?
System field assessment	M-1	What are important beneficial system properties, and how are they manifested in deployment?
	M-2	What may be opportunities for feature improvement?

Questions of *system performance* cover rates at which FAB and IBA events occur, conditions under which they occur, and characteristics of events. The two systems in this study, FAB and IBA, both address forward collision situations but in different ways. We are interested in rates and scenarios for the systems together, as well as ways in which they differ when considered separately. As in prior work, we are also interested in the conditions that give rise to FAB and IBA events. This includes the road types on which events occur and whether events occur in the same location multiple times, in particular to examine the possibility of unwanted FAB activations.

Unlike warning systems that provide briefly presented alerts, FAB and IBA engage automatic braking, and these events have the potential to play out over a longer time-frame. The way in which they play out can be characterized in terms of how long events last, deceleration levels, and speed reductions. These qualities of the event experience are also of interest in this study.

Although FAB and IBA engage vehicle systems, *driver behavior* is still a key element of how the systems perform in general. Drivers may override an event by steering, braking or accelerating. Driver braking behavior may shift an event from FAB to IBA or vice-versa. At a more basic level, drivers may turn the FAB/IBA system completely off if they are dissatisfied with its performance.

Ultimately, the purpose of these systems is to help the driver avoid rear-end crashes with a vehicle they are following or approaching ahead, or reduce the harm associated with these crashes. We are interested in *safety impacts* including speed reductions associated with the systems. Using crash data, we can also investigate whether the equipped vehicles in our study experience fewer crashes than expected for non-equipped vehicles.

Finally, we provide *general assessments* and observations of how these systems operated in the field.

3 Methods

3.1 General Approach

This study makes use of the unique telematic capability of GM's OnStar-equipped vehicles to capture data on production vehicles from consenting owners and send it wirelessly from remote locations across virtually the entire United States. Although the amount of data that can be captured from any one trip is limited relative to the extensive set of video and numeric data gathered in a traditional field operational test (FOT), the ease of high-priority data capture allows massive samples to be collected relatively affordably in a rapid-turnaround manner. The data collected in the current effort include event and trip information from 1,021 vehicles over the course of approximately 1 year of their normal driving. The data were analyzed with some reference to other FOT datasets available at UMTRI, including the advanced crash avoidance systems (ACAS) FOT study and the safety pilot (SP) study, to augment and further develop the data analysis and interpretation. The followings sections provide details on the study methods.

3.2 Participants

Study participants were recruited by email from a list of OnStar subscribers to the Onboard Vehicle Diagnostics (OVD) service who were owners of 2015 Cadillacs equipped with FAB and IBA systems (note these systems are always offered together on the vehicle examined). Specific models included in the study were: Escalade, SRX, XTS, CTS, and ATS, all pictured in Figure 1.

Figure 1 MY 2015 Cadillac Vehicles in Study

Consenting participants gave permission for OnStar to capture key data from advanced vehicle technologies and provide de-identified data to UMTRI for analysis. Participants received 12 months free OnStar services in exchange for their participation. As described below, the data collection occurred automatically "over the air," without any further action on the part of the participants (e.g., taking their vehicle to have data downloaded or acquisition systems installed).

At the time the vehicle owners agreed to participate in the study, they were asked to provide information on the primary driver age, primary driver gender, and the percentage of time that they felt the primary driver drove the vehicle. This was the only personal information included in the dataset, which was associated with a random vehicle identification number as part of the de-identified dataset provided to UMTRI for analysis. There was no information in the dataset about who was driving at any time.

Participants were recruited in waves until the goal of 1,000 vehicles was reached. The final sample size was 1,021 vehicles.

3.3 Technology Systems and Interfaces

The *Front Automatic Braking (FAB) and Intelligent Brake Assist (IBA)* systems in the production vehicles included in this study are intended to help the driver avoid or reduce the harm caused by rear-end crashes. If the FAB system detects that a front-end collision situation is imminent while following a detected vehicle traveling in the same direction (which may have come to a stop), and the driver has not already applied the brakes, the FAB system can automatically apply brakes to help reduce the collision's severity. Depending on the situation, the vehicle may automatically brake moderately or heavily. The FAB system may even help avoid the collision altogether at very low speeds. The FAB system evaluated is also always offered with IBA, which may activate when the brake pedal is applied quickly by providing a boost to braking based on the speed of approach and distance to the vehicle ahead. The IBA system automatically disengages when the brake pedal is released. Note that driver braking can occur such that the IBA does not engage (because brake-pedal application is not fast enough) while FAB does engage.

The FAB and IBA production systems evaluated (sometimes collectively referred to here as the Collision Preparation System, or CPS), share the forward-looking sensors used for the FCA system, which include a long/mid-range radar, two short-range radars, and a forward-looking camera mounted on the windshield ahead of the rearview mirror. When driving in a forward direction above 2 mph (4 km/h), the FCA/FAB/IBA system detects vehicles directly ahead that are in the projected path of the vehicle. When the system detects a vehicle ahead, a green FCA "vehicle ahead" system icon is lit to indicate the system is capable of providing FCA system alerts and FAB/IBA activations. When the driver's vehicle is detected to be following a vehicle ahead much too closely, the "vehicle ahead" icon turns amber to indicate a "Headway Alert" condition. When the driver's vehicle is detected to be approaching a vehicle ahead too quickly, the FCA system provides a red flashing imminent collision alert on the windshield (either via a HUD icon or set of horizontally aligned LEDs reflected into the windshield). Additionally, five vibration pulses occur on both sides of the driver's seat bottom (referred to as the "Safety Alert Seat"), or eight rapid high-pitched beeps are presented from the front speakers. (The factory default setting for the "Alert Type" used for various "Active Safety" systems was "Safety Alert Seat" for the vehicles evaluated, and this setting could be changed to "Beeps" using a vehicle settings menu.)

Immediately before an FAB event, or at the time of a FAB or IBA event onset, the FCA system provides the FCA multi-modality alert as described above. The FAB system can bring the vehicle to a complete stop to try to avoid a potential crash, and engage the electric parking brake (EPB), at which point the driver can release brakes with the EPB button or a firm press of accelerator. With the exception of the MY15 Cadillac SRX, the brake pedal did not move when automatic FAB occurred in the vehicles studied. The driver can override an FAB or IBA event at any point in time.

The FAB/IBA system vehicle settings menu (labelled "Automatic Collision Preparation") allow the driver to select "Off" (each of the FCA, FAB, and IBA systems were turned off), "Alert" (the FCA system was turned on coupled with very limited FAB functionality and no IBA functionality), and "Alert and Brake" (the FCA, FAB, and IBA systems were all turned on). The factory default Automatic Collision Preparation setting on the vehicles examined was "Alert and Brake."

In addition, it should be noted the vehicles studied had an FCA control located on the steering wheel, which allows the driver to set the FCA timing to a “Far,” “Medium,” or “Near” alert timing. The factory default setting for FCA timing was “Far.” The FCA timing setting affected the timing of both the Headway Alert and Imminent Collision alerts. In addition, changing the FCA timing setting automatically changes the (full-speed range) adaptive cruise control (ACC) following gap setting (Far, Medium, or Near). Similarly, changing the gap setting while ACC is active also changes the FCA timing setting. The FCA/ACC gap setting, as well as the Automatic Collision Preparation and Alert Type settings (described above), remained at the factory default setting, or the driver’s chosen setting, until it was changed by the driver.

3.4 Data Collection

This section presents an overview of the data collection, which was performed by a combination of production crash avoidance modules on the GM production vehicles, together with OnStar’s onboard module and back-end system capabilities. In general, there were three types of data captured as part of this study.

1. Detailed kinematic FAB/IBA related data captured around each FAB/IBA event by the CPS module
2. GPS location buffer data captured around each FAB/IBA event by the OnStar module
3. Trip summary data consisting of high-level information about each trip captured by the CPS module

The way in which the onboard data was packaged and transmitted to the OnStar servers and then to UMTRI is shown in Figure 2. Data were captured on the vehicle and moved over the air using the OnStar system to their back-office servers. The data was then anonymized and subsequently transferred to UMTRI researchers using secure techniques. UMTRI then parsed the data and loaded the results into a secure database for processing and analysis. The subsections below provide details on the set of signals captured and used to address research questions.

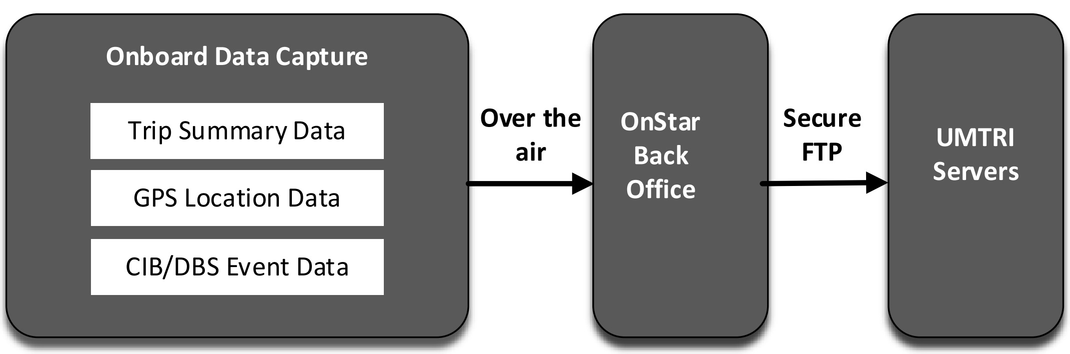

Figure 2 Data transmittal from vehicles to OnStar to UMTRI

3.4.1 Event data

The onboard data collection defines an “event” as an episode in which either an FAB or IBA event is triggered. Onboard the crash avoidance module, four seconds of data were collected, with each of the signals shown in Table 2 being recorded every 0.08 s (12.5 Hz). This means there were 50 data records per FAB/IBA event, with each record containing values for the variables described in Table 2. The window of data collection was designed such that the four-second window ended when the CPS system was no longer active. This could occur either because the situation was resolved, the driver overrode the system, or the vehicle was in a crash.

Table 2 Event data elements

Event Data Signals
Vehicle speed
Lateral acceleration and yaw rate
Driver brake and accelerator pedal switch positions
ACC engagement state
FCA alert level
Forward target position - range and lateral offset
Forward target motion - speed and relative acceleration
Automatic braking state and braking levels
Type of braking intervention (FAB, IBA)
FCA status flags
Driver overrides
ESC active or not

3.4.2 GPS Location Data

Geographically locating events was done using the location services of the OnStar system. The active safety external object calculating module (EOCM) records FAB/IBA events independently of OnStar. To determine if an FAB/IBA event has occurred, the OnStar module checked for an increment in the FAB/IBA event incident counter. This counter check occurred every 30s. If the current value of the counter was not equal to the last value, the OnStar module would then save to memory the rolling buffer of GPS location data along with the FAB/IBA event data for upload to the OnStar backend servers. The GPS location data from the OnStar system was captured at 1Hz.

An illustration of this activity is shown in Figure 3. The figure shows both the EOCM and OnStar time scales. The OnStar FAB/IBA counter checks are shown at 30 s intervals along the bottom of the figure. Time 0 (zero) indicates the point when there has been an event and the OnStar module finds an increase in the counter. The module then continues to collect GPS data for 12 more seconds before saving the FAB/IBA event to memory.

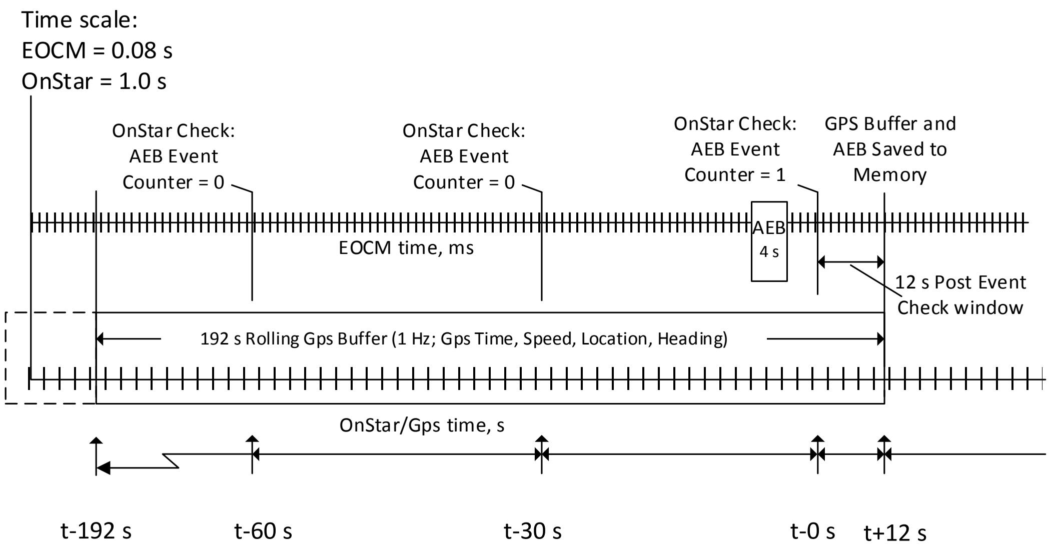

Figure 3 GPS Buffer Data Collected by the OnStar Module

To determine the exact location of the FAB/IBA event a correlation algorithm was used that compared vehicle speed collected by both the GPS module and the EOCM module. The algorithm linearly interpolated between the 1 Hz GPS speed points from the OnStar buffer to create a 12 Hz (0.08 s) speed trace. Next, a fit measure (sum of speed differences) was calculated by comparing the 50-point EOCM speed measure to each set of 50 points in the 192 s higher frequency GPS-speed trace (i.e., a moving window). The measure of error was saved for each comparison and then searched for a minimum error value. If the minimum error value was below a threshold, the offset into the buffer was saved and the event flagged. An illustration of the fit is shown below in Figure 4. The figure shows both the 1 Hz and 12.5 Hz GPS speed traces over the 192s window. The speed from the EOCM is also shown located along the traces corresponding to the best fit criteria. For the event depicted here the alignment is obvious since there is a pronounced change in vehicle speed between 175 and 179 seconds.

[Speed Sync]

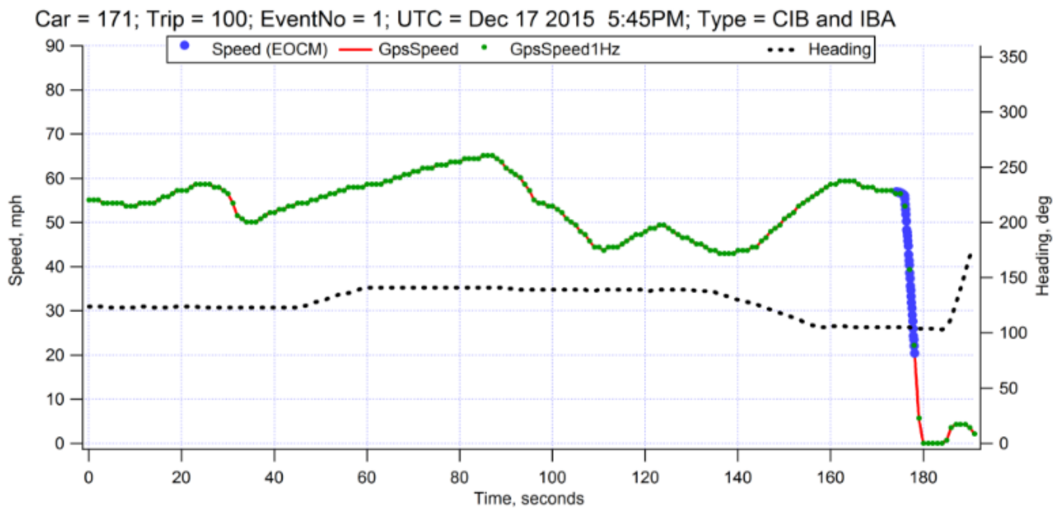

Figure 4 Example FAB/IBA Event and GPS Speed Alignment

3.4.3 Trip summary data

In addition to event and GPS location data, trip summary data was also saved after every ignition cycle. Trip level data consisted of State values, or aggregated statistics intended to describe the nature of the trip. The set of trip summary variables used to support the analyses presented in later sections ate shown in Table 3 below.

Table 3 Trip Summary Data

Trip Summary Data
Vehicle ID (anonymized)
Time at start and end of trip
GPS location at start and end of trip
GPS validity flags
Odometer at start and end of trip
Speed histogram for trip
Number of FAB/IBA braking events during the trip
Time with ACC engaged
Driver "Collision Preparation" setting:[1] FAB/IBA enabled (includes FCA); Limited FAB but no IBA (includes FCA); or no FCA, FAB, or IBA.
Driver "Alert Type" setting: audible "Beeps" or "Safety Alert Seat" vibration non-visual alerts for various Active Safety systems, including FCA
ACC/FCA gap setting choices by driver
Sum of time during the trip with a forward target

Note[1]: These vehicle menu settings are conveyed to the driver as "Alert and Brake," "Alert," and "Off," respectively.

3.5 Data Validation

Prior to the start of data collection, UMTRI and GM conducted a series of activities designed to verify the protocols for data retrieval work as well as to verify that the data collected accurately captures the FAB/IBA events with measures that reflect the performance of the host vehicle and the relative kinematics between the host and lead vehicles. These tests were conducted at both the GM Proving Grounds (GMPG) in Milford, Michigan, and at “Mcity,” a University of Michigan test facility (see, for example, https://mcity.umich.edu/our-work/mcity-test-facility/). Additionally, a set of on-road tests were conducted to validate trip level summary data including exposure measures, histograms of system state, and counts of events like wiper activation, lane departure warnings, brake activity, adaptive cruise control, etc. A brief description of each of these efforts is given below.

3.5.1 Validation Test Equipment

In the test conducted at GMPG and Mcity, the host vehicle was equipped with a data collection system capable of recording signals from multiple vehicle CAN buses. This system also included a real-time kinematics (RTK) GPS receiver with centimeter level accuracy. In parallel with measures from the data logger, OnStar invoked scripts on-board the host vehicle to upload captured FAB/IBA and trip level summary data to a backhaul server for data comparison purposes.

The lead vehicle in these tests was also equipped with a data logger and RTK system. The host vehicle used in both UMTRI and GMPG testing was a 2015 Cadillac Escalade. Additionally, at GMPG, a braking robot was used in the lead vehicle to create highly repeatable lead vehicle deceleration events. At UMTRI and Mcity, a towable surrogate target (for representing the lead vehicle) was used for testing. A picture of the UMTRI surrogate target is shown in Figure 5.

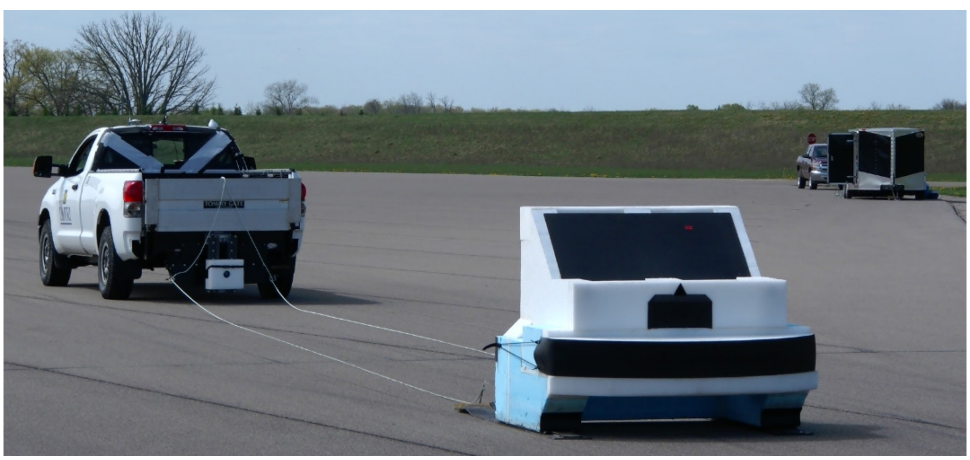

Figure 5 UMTRI Towable Target for FAB and IBA Testing

3.5.2 Validation Testing

A total of 41 validation tests were conducted at both GMPG and Mcity. The test categories were: stopped, slower at constant speed, and slowing lead vehicle. In addition to testing various speed combinations and different levels of lead vehicle deceleration, wiper activation, ACC engagement, and approach angle were also considered.

Data from these tests were collected by two independent systems. The OnStar system recorded 81 different measures described in Section 3.4. The other data collection was done using laptops in both the host and lead vehicles. High precision GPS (RTK) was collected continuously in both vehicles, while a set 35 measures from the CAN bus was recorded for each test on the host vehicle.

To compare the measures from both sources (laptop and OnStar) a data synchronization methodology was developed. Time from three sources was used: (1) CAN time from the host, collected at 1000 Hz; (2) GPS Time from the RTK system, recorded on both the host and lead vehicle at 40 Hz; and (3) internal engine time (called "OnStar time") was recorded on the host vehicle at its native frequency. To perform the synchronization, the GPS and OnStar time were adjusted to CAN time using two approaches:

- A GPS time offset was calculated by comparing the host speed from CAN and GPS as shown Figure 6. The time correction was done by shifting the GPS speed measure and visually confirming alignment.
- For OnStar time a linear regression approach to derive a set of conversion gain and offset values for each time reference as shown in Figure 7.

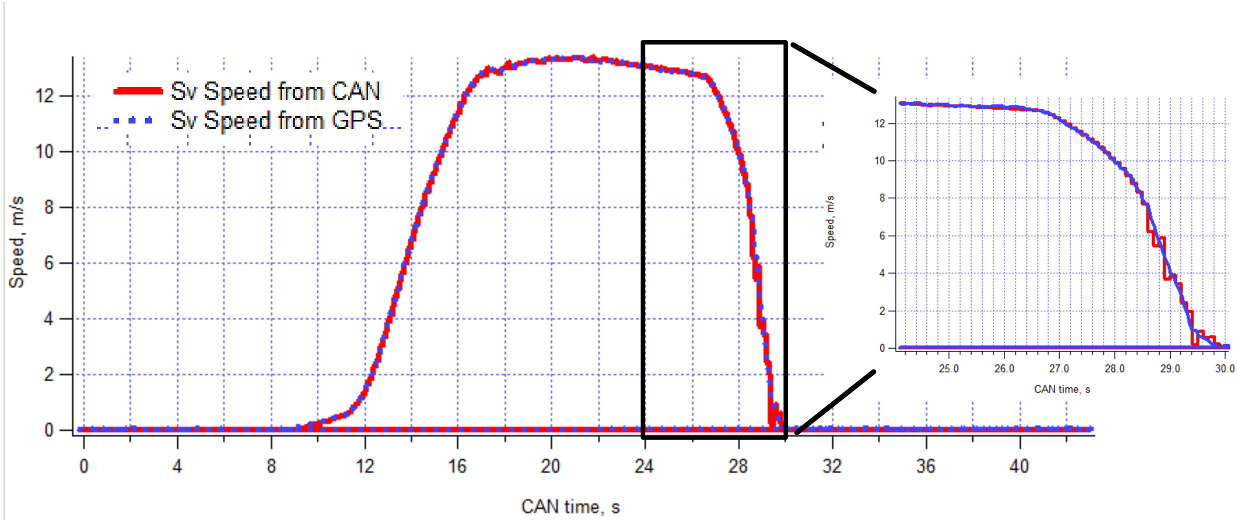

Figure 6 GPS and CAN time synchronization example

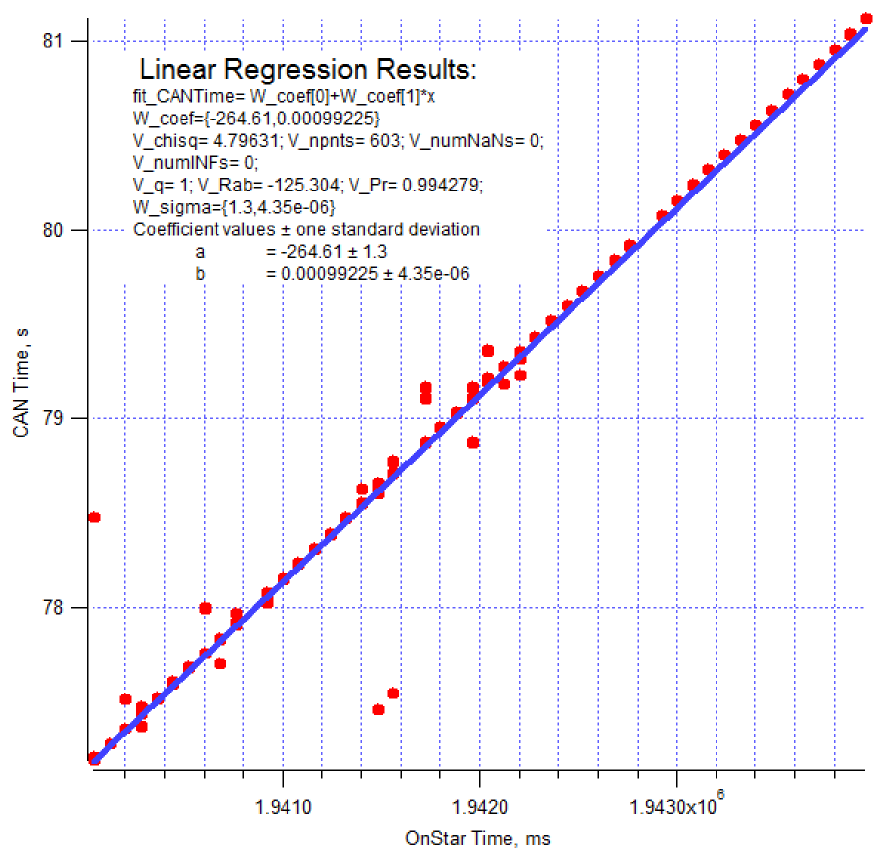

Figure 7 OnStar time and CAN time synchronization example

The results of the tests were used to validate speed, acceleration, range, and range-rate for both the host and lead vehicles. An example from one test comparing speed, range and range-rate between the independent measuring systems is shown in Figure 8, which was taken from a lead vehicle slowing test. The figure shows the 4-second window collected by OnStar and the corresponding measures collected by the laptop on the host and RTK GPS on both the host and lead vehicles. In this test both the host and lead vehicles are travelling at 35 mph when the lead vehicle slows at a deceleration target rate of -1.3 m/s^2. The top graph shows the speed of the host and lead vehicles. The middle graph shows the distance (range) between the two vehicles from OnStar and calculated from GPS, and the bottom graph shows the derivative of range (range-rate or closing speed) from OnStar and GPS. The figure shows agreement between the two independent sources is good with the exception of range-rate at zero range where the OnStar measure stays at a higher closing speed relative to GPS. This test resulted in an impact between the host and surrogate target, so the difference in range-rate near impact results from either a close-range sensing issue with the host or a change in the distance between the lead vehicle and surrogate as a result of the impact by the host. In this report the measured OnStar range-rate at the time of impact (Range = 0) is deemed to be the best estimate of actual impact speed for these data.

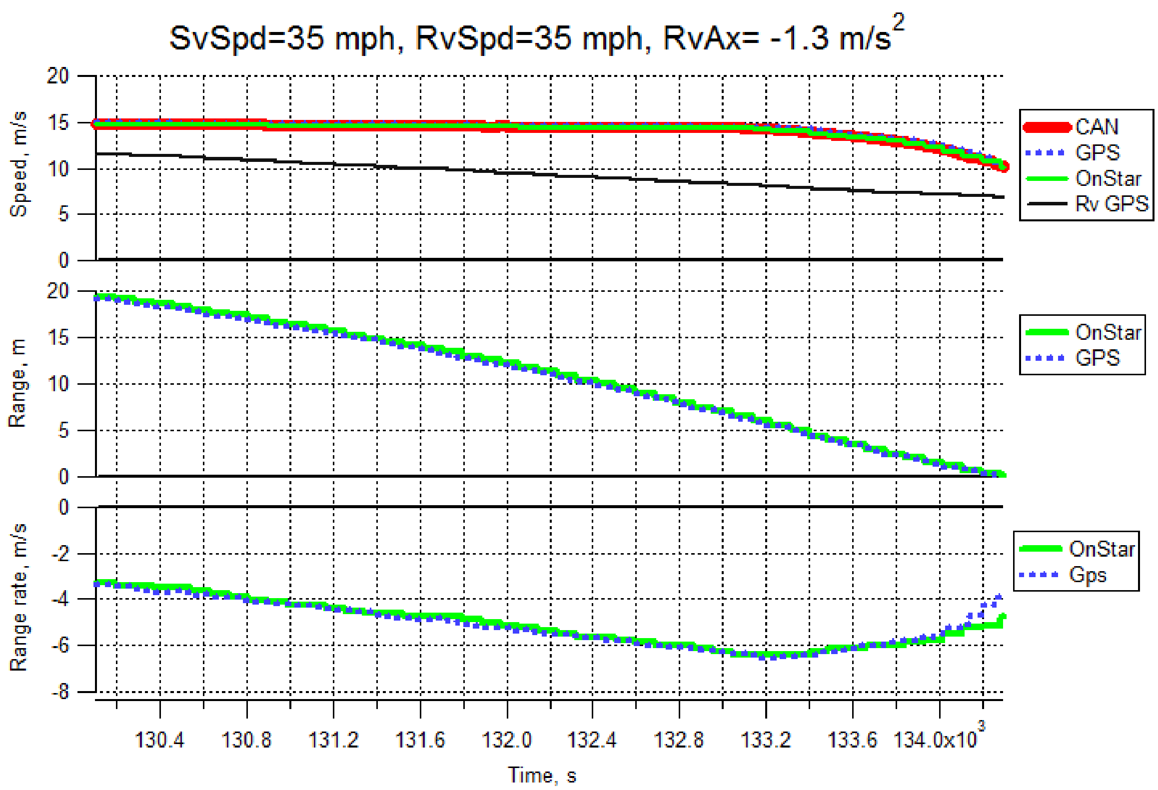

Figure 8 Speed, Range, and Range-rate from CAN, GPS and OnStar

3.5.3 On-road Testing

A combination of on-road and Mcity tests were conducted to validate the trip summary data (described earlier) collected by OnStar. The intent of these tests was to intentionally generate ACC, FCA and LDW events under a variety of conditions to compare the counts collected by OnStar with the actual events experienced during the on-road testing. For forward conflicts (ACC and FCA) a lead vehicle was used. To remove variability in the testing, a fixed circular four-mile route was used in all the tests.

In addition to testing changes in driver settings, the tests verified that the time between ignition cycles influences how data are initialized. In these vehicles, the memory location is not re-initialized until power is reset on the collection module and can vary between the ignition off event and up to 3 minutes after ignition off depending actions by the driver. The implications of this learning was that counts and histograms could be accumulated across ignition cycles and those cases needed to be flagged and properly handled to prevent the over-sampling when aggregating across drivers and trips.

3.6 Analysis Approach

The *Results* section describes the specific statistical and descriptive approaches used to answer each research question. These analyses generally followed the data analysis plan (Flannagan, LeBlanc, & Kiefer, in press) that was delivered as part of the project. Statistical models were developed using either SAS 9.4 or R statistical software packages.

3.7 Models and Algorithms to Aid Analysis

The FAB/IBA events captured in this large-scale study proved to be very diverse, both in terms of the initial state of the vehicles, how the event played out, and the event outcome. Figure 9 below shows a framework that was developed for purpose of categorizing the FAB/IBA event, the circumstances leading to the event, and outcomes associated with the events. Consider this as four stages, described in the subsections below.

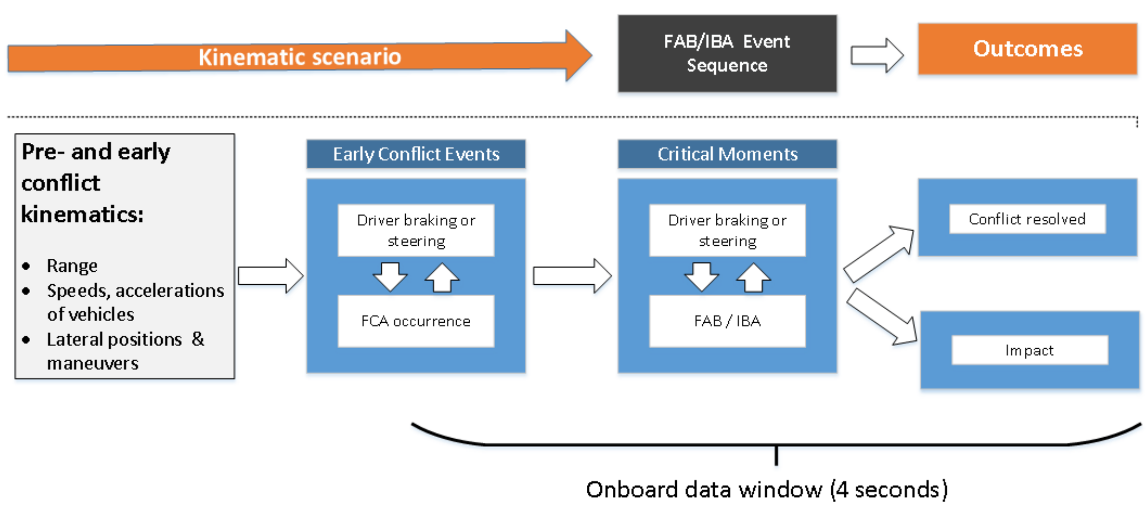

Figure 9 Framework for describing events

3.7.1 Kinematic scenarios

On the left of the figure, we consider the first stage, specifically vehicle-to-vehicle kinematics and the scenarios that lead up to the event. The kinematic scenario may well begin many seconds before the event, and can be described both in terms of the kinematic values and in terms of descriptive scenarios, which are simply common circumstances in forward conflicts.

Table 4 presents a set of the most common forward conflict scenarios based on the prior study of FCA (Flannagan et al., 2016). Because the onboard data events in this study contain only four seconds of data and there are relatively few FAB/IBA events, scenario assignment was somewhat simplified and done based on the data that were available.

Table 4 Kinematic scenarios for FCA events based on lead vehicle motion (rows) and four key characteristics of the host and the target from Flannagan et al. (2016)

	Consistent LV target throughout	LV target moves out of path	Host steering around LV target	Target likely false (e.g., phantom)
LV stopped	Approaching stopped lead vehicle	(Not possible)	Steering around a stopped vehicle	False stationary target
LV decelerating	Approaching decelerating lead vehicle	Decelerating lead vehicle leaves path	Steering around a decelerating lead vehicle	False decelerating target
LV moving, at constant speed	Approaching slower lead vehicle moving at constant speed	Slower lead vehicle moving at constant speed leaves path	Steering around a slower lead vehicle moving at constant speed	False slower target

Figure 9 shows that a given FCA scenario will develop into an "early conflict event." This second stage can be described by the kinematic values during the 4-second data collection window, as well as key variables: if, when, and how much the driver braked, and if and when the FCA imminent crash alert was presented.

3.7.2 FAB/IBA event sequences

The third stage involves characterizing (and categorizing) the time-course of the FAB/IBA event sequence, which can help determine whether the outcome is a resolution of the conflict (no impact) or an impact of the subject (or driver's) vehicle with the lead vehicle ahead (albeit perhaps at reduced crash impact speeds). This characterization facilitated analyses of the characteristics and outcomes of different types of events. A set of common event sequences were developed, using the key items described above, based on how the actual events play out, in much the same way that pre-crash scenarios are developed – through observation and clustering of meaningful similarities and differences.

For instance, one event sequence type might be: "No driver braking, FAB activates at full braking level," or "Ongoing ACC braking is augmented by FAB, and then the driver brakes, leading to IBA." In addition to identifying common event sequences, the level of braking also was seen as an important descriptor.

3.7.3 Actual outcomes

The final stage of the event is the outcome, which the figure shows is either the conflict being resolved without impact, or that an impact occurred. In this study, crashes that were severe enough to meet ACN criteria were identified from ACN data directly.

3.7.4 Virtual outcomes

In order to study the potential safety contributions of FAB/IBA, we measured the speed and range-rate magnitude decreases between the beginning and end of the CPS event. Since it was not possible to clearly distinguish the relative contributions of driver braking and CPS system braking, the driver and system are treated as a combined system.

4 Results

4.1 Vehicle Sample Characteristics

The sample consisted of 1,021 vehicles, with the primary driver gender consisting of 554 males (54%) and 467 females (46%). Average reported primary driver age was 58.4 years old, ranging from 21 to 92 years old. Figure 10, which provided an Age X Gender breakdown, shows that male primary drivers were somewhat older than female counterparts in the sample. Of the primary drivers, 716 (70%) reported driving the vehicle at least 90 percent of the time, 227 (22%) reported driving the vehicle 70-80 percent of the time, and 78 (8%) reported driving the vehicle less than 70 percent of the time. Participant vehicles were spread across the entire United States, and located in 46 of 50 States, as shown in Figure 11, which provided vehicle count categories.

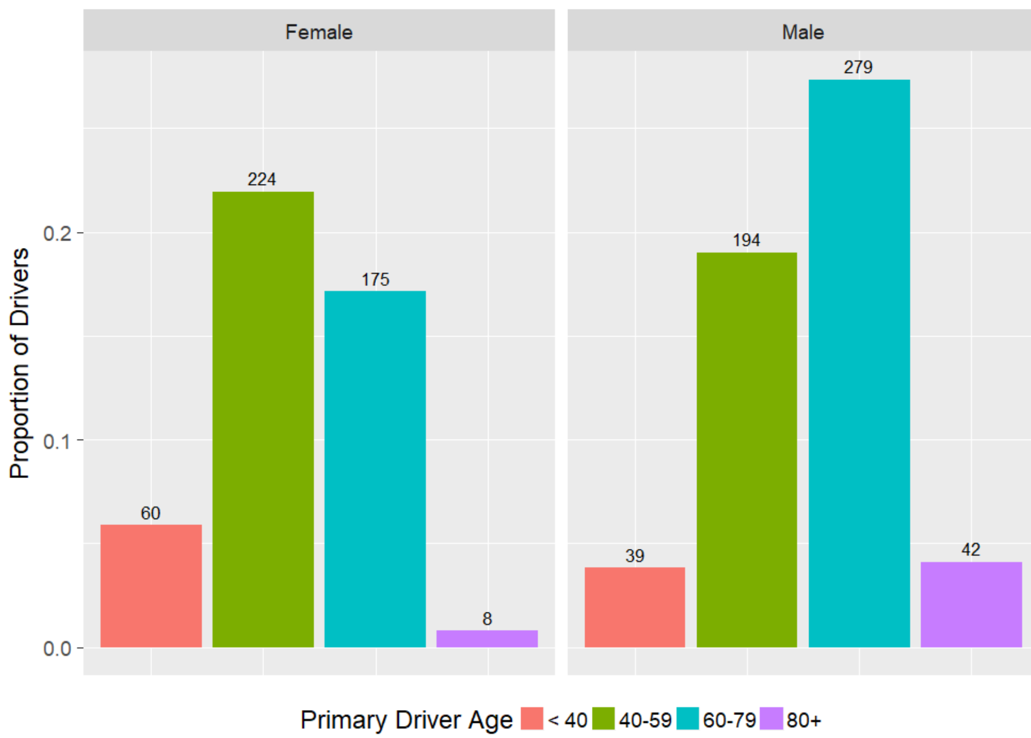

Figure 10 Age by gender breakdown of primary drivers

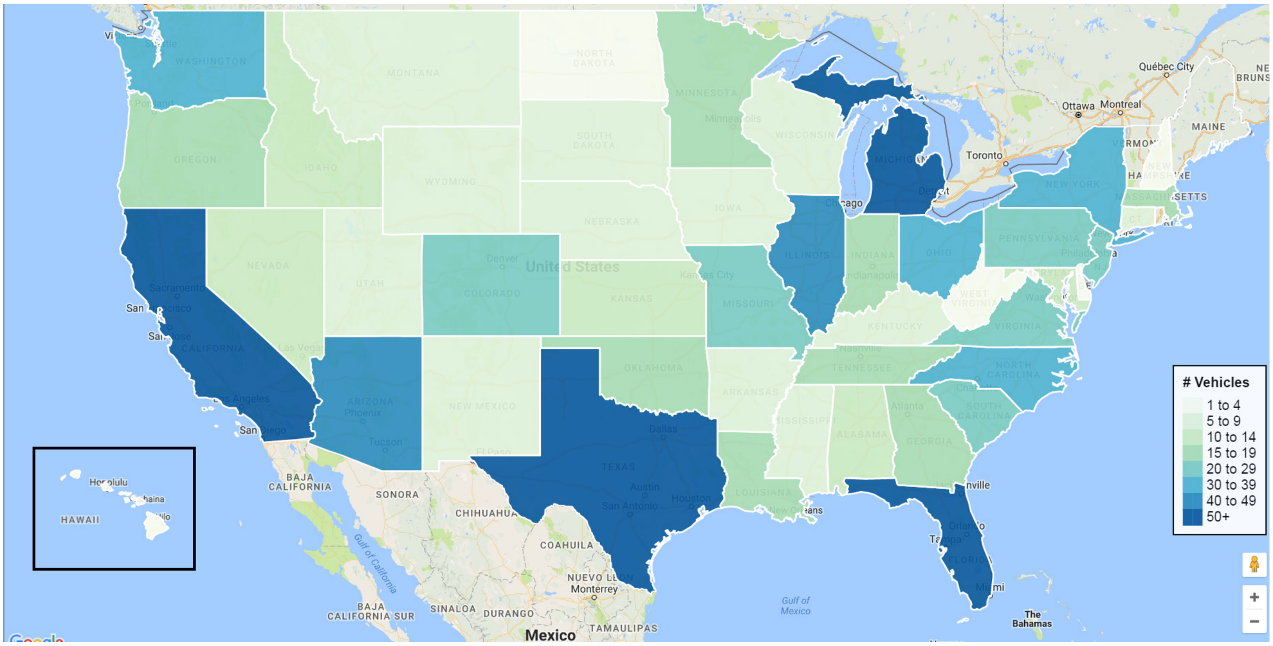

Figure 11 Distribution of vehicle home States across U.S. States. Only Maine, Vermont, Rhode Island, and Alaska had no resident vehicles in the study.

4.2 Descriptive Statistics

4.2.1 Travel

The 1,021 vehicles used in this study accumulated 1,106,210 trips covering 11,891,341 miles of driving with an average trip length of approximately 10.7 miles. Per-vehicle total miles traveled during the study ranged from 337 to 39,493 miles, with a mean of 11,716 miles and median of 10,855 miles. The majority of driving was at relatively lower speeds, as only 36.4 percent of trips exceeded 55 mph at any point.

4.2.2 Setting Choices

Table 5 shows the percentage of driving time under the CPS and FCA/ACC gap settings. The vast majority (94%) of vehicles did not show a change in the CPS system settings during the course of the entire study. Across all of the vehicle miles, the “Alert+Brake” setting (the factory default) was used for 96.4 percent of vehicle driving time. The remaining time was divided almost equally between the “Alert” (1.9%) and “Off” (1.7%) settings. Out of the 1,021 vehicles in the study, only 59 vehicles (6%) changed setting to one that lasted for at least one trip, with other vehicles either never changing the setting during the course of the study or switching for less than half of a trip’s driving time. In addition, only 37 vehicles (4%) took the majority of their trips with the CPS system in a setting other than “Alert+Brake.” Of those 37 vehicles, 20 had a majority trip setting of “Alert,” and 17 had a majority trip setting of “Off.”

Table 5 Settings as a percentage of driving time

Collision Preparation System		Forward Collision Alert (FCA)/ Adaptive Cruise Control (ACC)	
Setting	**Percentage of Driving Time**	**Timing/Gap Setting**	**Percentage of Driving Time**
Off	1.7	Near	27.4
Alert	1.9	Medium	27.5
Alert + Brake	96.4	Far	45.1

For FCA/ACC, the timing/gap setting were more evenly used. This result contrasts with the previous study of FCA/LDW-equipped vehicles (the prior work), in which the Far setting was used for 65.7 percent of the miles for drivers with the Safety Alert Seat (Near: 13.9%; Medium: 17.9%; Off 2.5%) (Flannagan et al., 2016).

4.2.3 Events

During the study, 1,237 CPS (FAB, IBA, or combined FAB and IBA) events were observed. These will simply be referred to as "events" throughout the remainder of the paper. The breakdown of these events by speed (+/- 10 mph), duration (+/- 0.08 s) and event type (FAB, IBA, or a combined FAB and IBA event) is shown in Figure 12. (Note the +0.08 s duration category, given the sampling rate, implies an event recorded as a 160 ms duration or longer). Of the original 1237 events, 569 (46%) occurred at speeds higher than 10 mph, and 370 (30%) of events occurred at speeds higher than 10 mph and lasted more than 0.08 s (the minimum recordable time). Of these 370 key "events of interest," which will be the focus of much of the remaining discussion, 66 percent involved only an FAB activation, 31 percent involved only a IBA activation, and 3 percent involved both FAB and IBA activations.

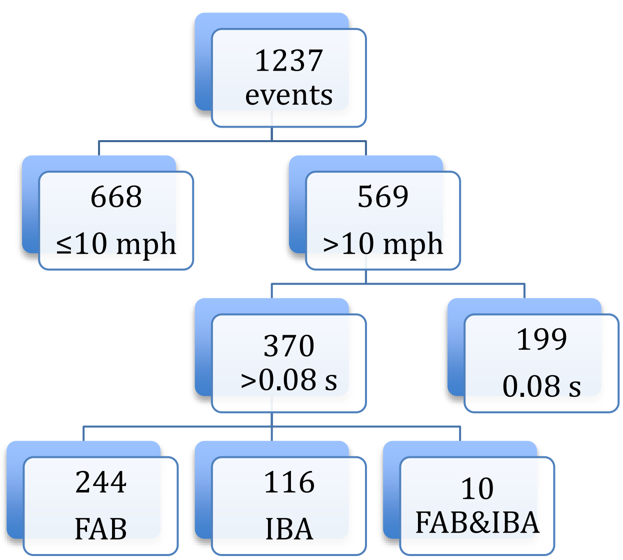

Figure 12 Flowchart for categorizing events

Table 6 shows a summary of the event occurrence rates per 10,000 miles for vehicles by event type and speed threshold. While 56 percent of drivers experienced at least one event, only 34.7 percent experienced an event at speeds above 10 mph. In addition, the FAB event rate is over twice that of the IBA event rate, regardless of speed threshold. The low occurrence rate in the combined FAB & IBA category reflects the fact that only 17 events in the study had both types of intervention (10 of which were over the 10-mph threshold).

Table 6 Event rates per 10,000 miles per vehicle

Event Type	Speed	Mean	Median	5th Percentile	95th Percentile	Vehicles w/ any Events
Any	All	1.27	0.64	0.00	4.99	56.0%
	10+ mph	0.51	0.00	0.00	2.22	34.7%
FAB	All	1.03	0.00	0.00	3.98	48.8%
	10+ mph	0.36	0.00	0.00	1.78	26.6%
IBA	All	0.23	0.00	0.00	1.30	18.0%
	10+ mph	0.14	0.00	0.00	0.94	12.9%
FAB & IBA	All	0.012	0.00	0.00	0.00	2.0%
	10+ mph	0.006	0.00	0.00	0.00	1.0%

As will be discussed in greater detail later in the paper, the majority of the events lasted less than a half second. FAB events are the shortest at 0.28s on average (0.23s for events over 10 mph), followed by IBA events at 0.31s (0.34s for events over 10 mph). The co-occurring FAB and IBA events are substantially longer, lasting 1.07s on average (1.27s for events over 10 mph).

As a reminder, all vehicles in the current effort were also equipped with an FCA system that could provide an imminent crash alert prior to, or at the start of, an event. However, a pre-CPS FCA imminent alert may not have been detected by the data acquisition system since the data sampling rate (every 80 ms) was two times higher than alert state output (every 40 ms). This suggests we may only have captured approximately 50 percent of pre-CPS FCA imminent alerts that would have otherwise occurred. In addition, a pre-CPS FCA imminent alert may not occur due to a variety of reasons, including when there is close time proximity between the onset the FCA imminent alert and CPS event (e.g., when there is a suddenly appearing lead vehicle target) or under lower speeds with lead vehicle targets that never been detected by the sensors to be moving.

In 7.8 percent of the observed events, there was an FCA observed prior to (as opposed to at) event onset within the 4-second window captured around events. This rate increases to 16.3 percent when limiting to events occurring at greater than 10 mph, which is consistent with the higher minimum speed requirement for the FCA system. If we assume that 50 percent of the pre-CPS FCA imminent alerts are missed, an FCA system imminent alert is estimated to have occurred prior to 15.6 percent of all observed events and 32.6 percent of events occurring at greater than 10 mph.

The FCA alert occurrence also appears to be related to the event type, having been captured prior to (as opposed to at) event onset in 13.6 percent of FAB events, 21.1 percent of IBA events and 50.0 percent of the mixed (FAB and IBA) with event onsets occurring at initial host vehicle speeds of greater than 10 mph. However, as shown in Table 7, FCA setting, which is based on driver preference, does not appear to be related to the type of event.

Table 7 Number of events by FCA setting and event type

Setting	FAB	IBA	FAB&IBA
Far	379	96	8
Medium	267	67	5
Near	316	95	4

Though the ACC system was active (i.e., ACC was actively controlling speed) in 8.9 percent of trips, it was only active at, or just before, 41 events (3.3% of all events). Since ACC has braking capability, its own braking response may help avoid the need for FAB or IBA. Once FAB or IBA are triggered, ACC is disabled.

4.3 Summary of Key Descriptive Statistics

Table 8 summarizes the key high-level descriptive statistics for this study.

Table 8 Key Descriptive Statistics for Study

Total Vehicles	1021
Total Trips	1,106,210
Total Miles of Driving	11,891,341
Total Number of "IBA only" Events	258
Total Number of "FAB only" Events	962
Total Number of "IBA and FAB" Events (both occurred)	17
Total Number of Events	1237
Overall Event Rate per 10,000 miles	1.04
Overall Event Rate per 10,000 miles for events at 10+ mph speeds*	0.48
Mean Per-Vehicle Event Rate per 10,000 miles	1.27
Mean Per-Vehicle Event Rate per 10,000 miles for events at 10+ mph speeds*	0.51

**Denominator for these rates is all driving; numerator is events that occur at 10+ mph*

4.4 Event Characteristics

In this section, we focus on the 370 events that were both higher speed (10 mph or greater) and of longer duration (160 ms or longer). Figure 13 shows the distribution of initial speed for each event type. Initial speed is lowest for IBA (i.e., IBA only) and highest for FAB (i.e., FAB only), with combined FAB+IBA events (when both events occur during 4-second data collection window) falling between the two. Note in general, throughout this paper, distributions surrounding these combined events should be interpreted with caution due to the small number (n=10) of these combined events meeting the host vehicle speed and event duration criterion above.

Figure 14 shows the event type corresponding distributions for event duration. Here, IBA and FAB durations are similarly short-lived, whereas IBA shows a considerably wider range of durations. In contrast, the combined FAB and IBA (denoted “FAB+IBA”) events are generally longer-lasting, with some of these events exceeding two seconds. Note that because of the small sample for FAB+IBA events, combined with smoothing, the FAB+IBA density curve in Figure 14 extends below the shortest-duration FAB+IBA event, which lasted 0.48s. Average duration for an FAB event was 0.34s, for an IBA event was 0.44s, and for the combined FAB+IBA events was 1.27s.

The observed host vehicle speed reduction (ΔV) over the course of the event follows a similar pattern to event duration, with FAB, IBA, and FAB+IBA events having an average of 0.5, 2.7, and 16.2 mph speed reductions. Figure 15 and Figure 16 show speed reduction distributions in both absolute speed and percent (relative to initial speed) terms, respectively. The graphs make it clear that across these events, speed reductions when IBA is involved (either alone or when combined with FAB) are generally greater than when FAB occurs alone. When both an FAB and IBA activation occurred, there was a larger speed reduction than with either FAB alone or IBA alone events, sometimes bringing the vehicle to a stop (100% of initial speed achieved during the event). Thus, although rarely observed, combined FAB+IBA events last a considerably longer time and result in substantially higher speed reductions than FAB only or IBA only events.

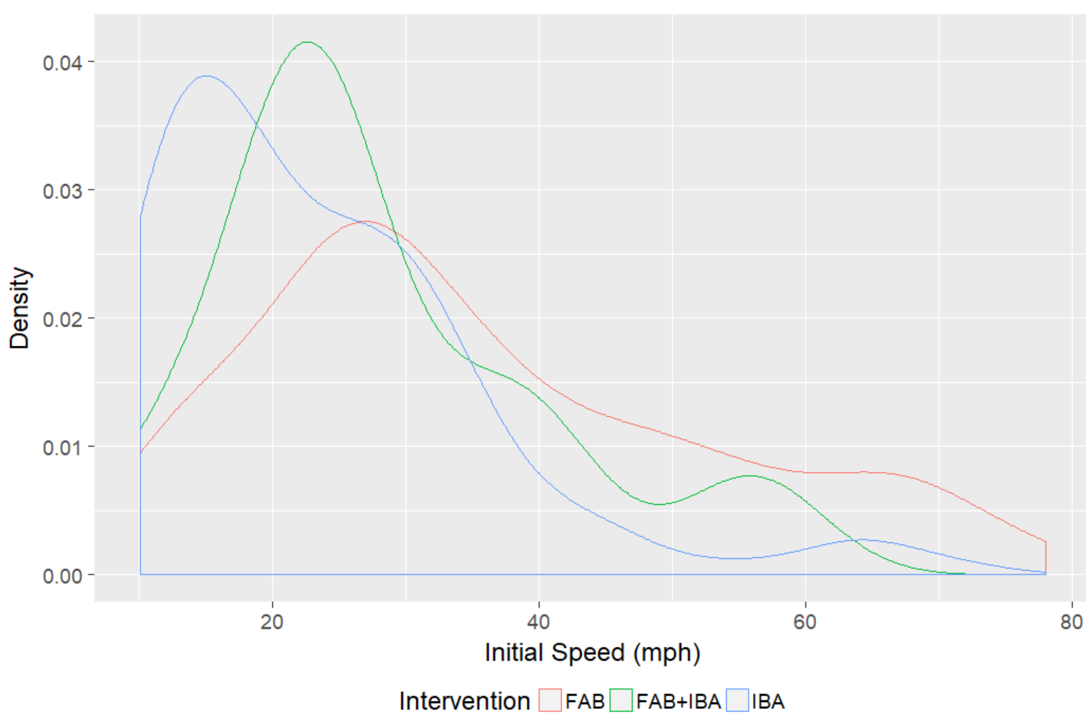

Figure 13 Distribution of initial speed by event type

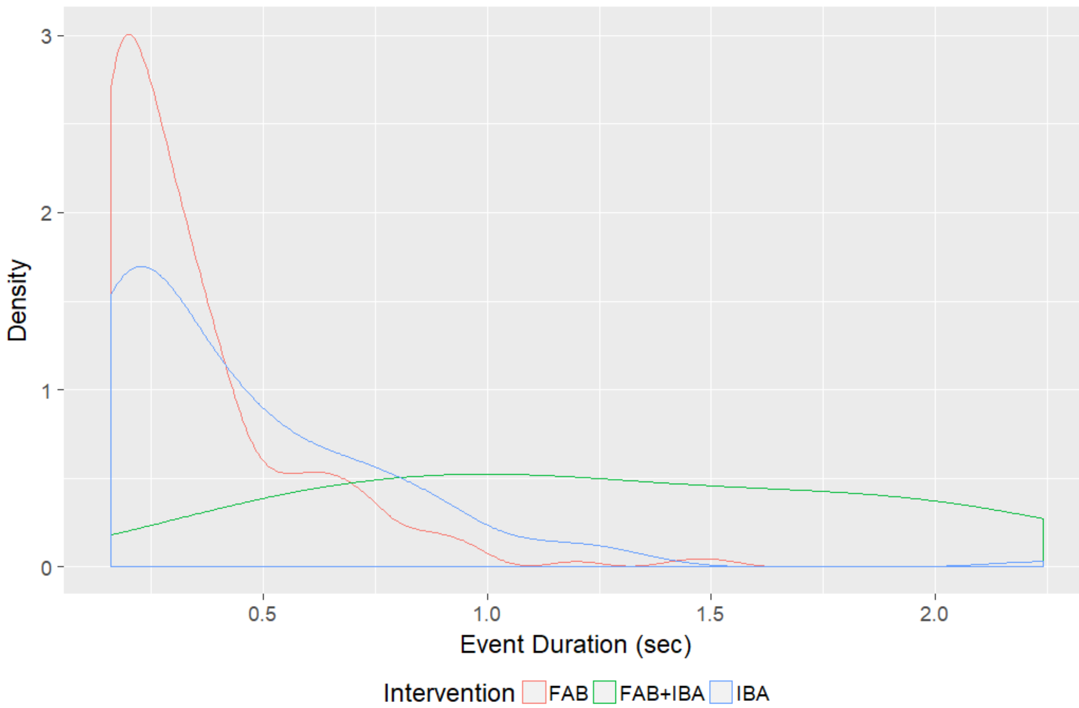

Figure 14 Distribution of event duration by event type

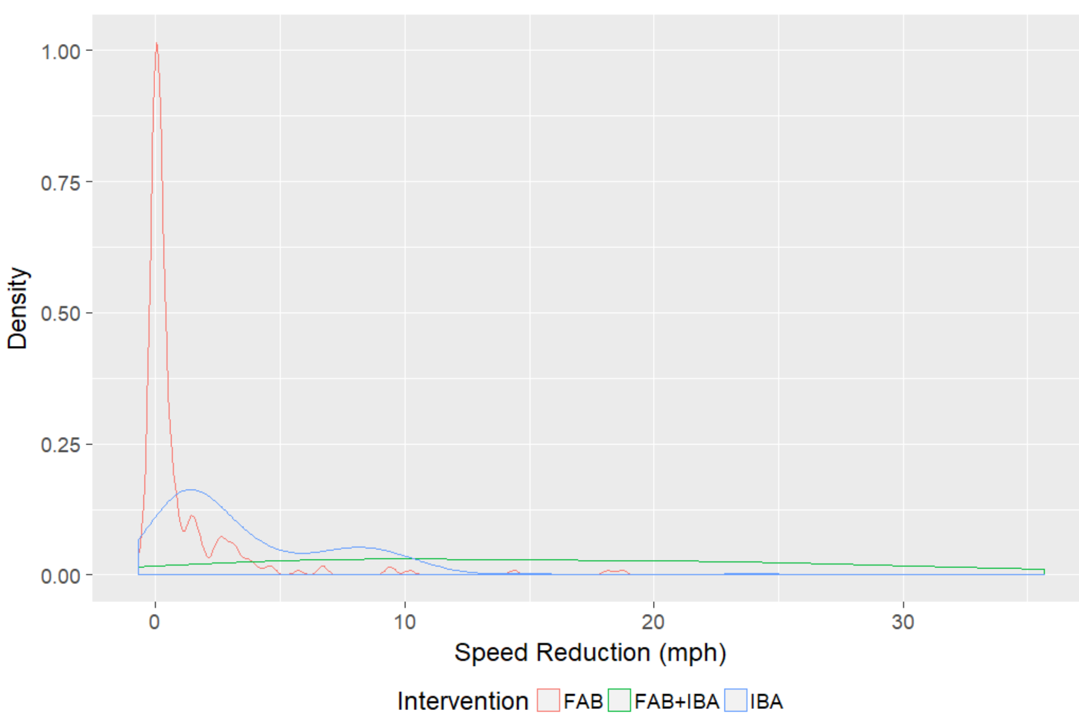

Figure 15 Distribution of absolute speed reduction by event type

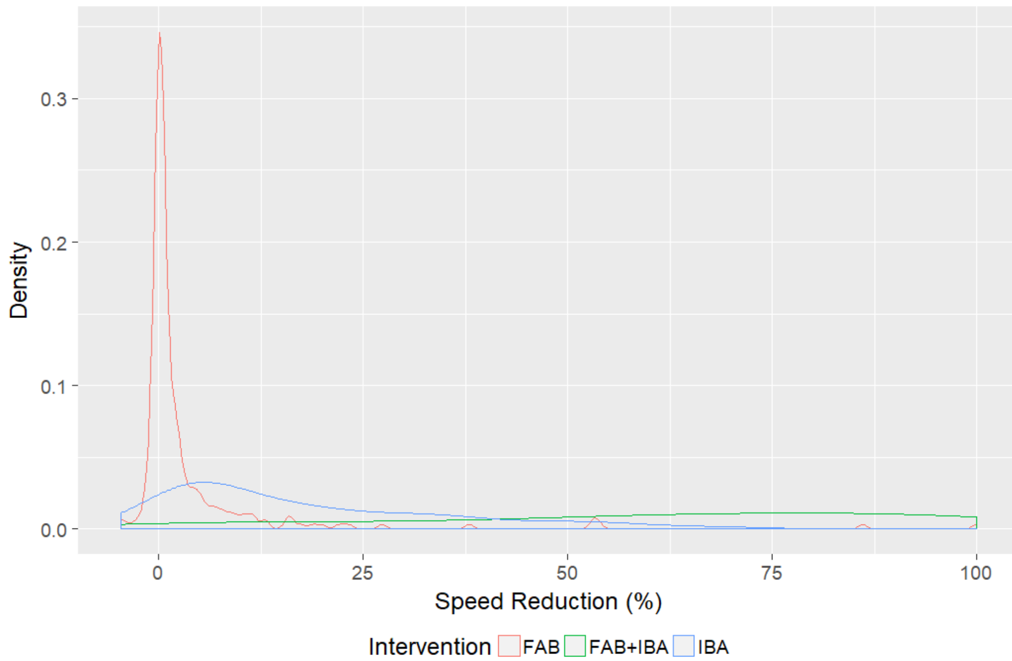

Figure 16 Distribution of percent initial speed by event type

Figure 17 shows the distribution of minimum deceleration (or peak deceleration) for each event type. These results are consistent with the speed reduction results reported above, indicating that FAB events generally involve less deceleration (i.e., lower peak decelerations) than IBA events, and that combined FAB+IBA events involve higher and longer-lasting deceleration levels (on average) than either FAB only or IBA only events.

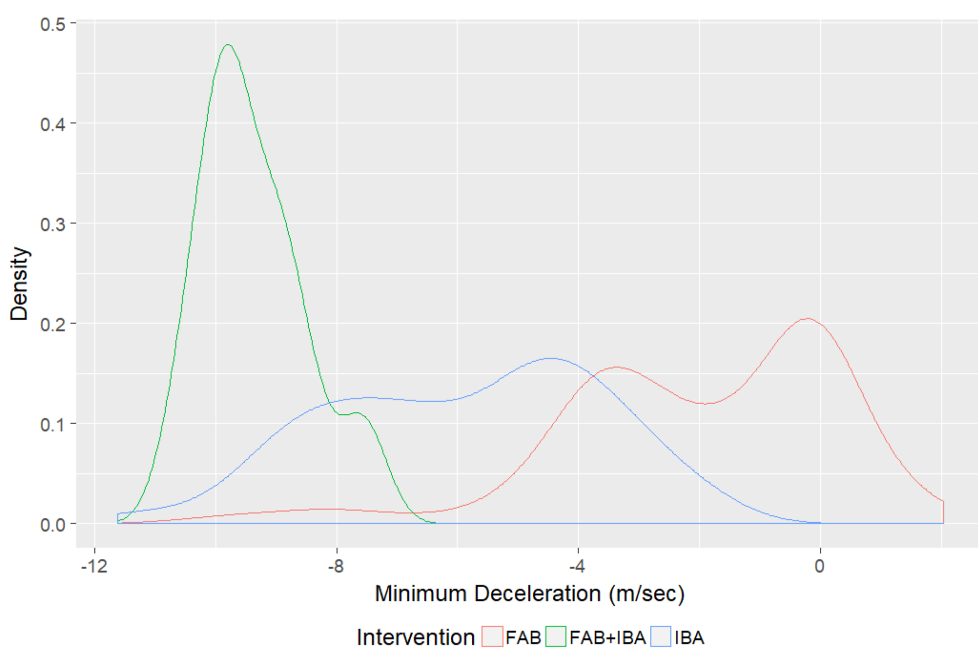

Figure 17 Distribution of minimum deceleration by event type

Finally, in Figure 18 we examine the distribution of the three event types as a function of initial speed, event duration, and host speed change. Across the three data panels, combined FAB+IBA events (green dots) show the longest durations and greatest speed changes. In the middle panel, it can be seen that event duration and speed change appear linearly related, with the slope of the relationship representing deceleration, and that generally IBA events result in somewhat higher deceleration than FAB events (blue dots above red dots), with the combined FAB+IBA events (green dots) showing the same general relationship. Thus, the FAB+IBA events are mostly characterized by long durations rather than unusually high deceleration. This can be seen more clearly in Figure 19, which includes linear fits. The slope for FAB events is very similar to the slope for IBA events, but the intercept for FAB is lower (indicating a greater number of low-speed-reduction events). Although Figure 17 indicates that combined FAB+IBA events involve higher peak deceleration compared to other events, Figure 18 and Figure 19 suggest that because they are uniformly long-duration, their distribution of peak deceleration is concentrated at high (hard deceleration) values. The slope of the FAB+IBA curve in Figure 19 is somewhat steeper than that of the FAB and IBA curves, indicating the additional contribution of slightly higher average deceleration levels compared to the FAB-only and IBA-only event types.

Finally, the third (rightmost) panel of Figure 18 shows that there are many FAB

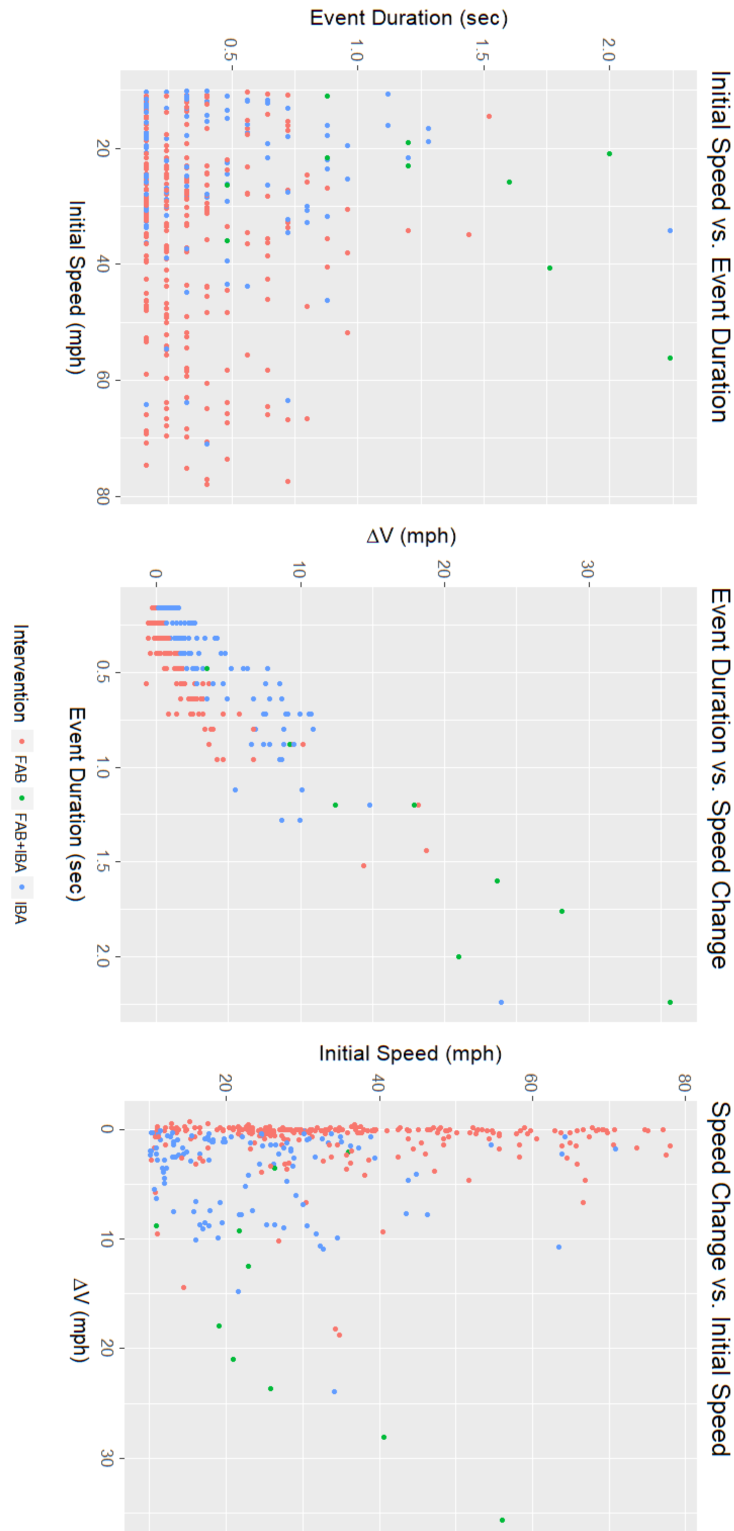

Figure 18 Three-panel plot of initial speed, event duration, and host speed change for key events.

events occurring at all speeds that result in very little speed change, and as can be seen in the leftmost panel of Figure 19, this is consistent with the observation that FAB events are characteristically short-lived. IBA or combined FAB+IBA events, in contrast, more consistently reduce speed. However, when FAB does result in speed reductions, IBA and FAB events look generally similar on these general dimensions. This likely explains the lower intercept for FAB events in Figure 19, which may be driven by a large number of FAB events clustered near 0.16 duration and minimal speed change.

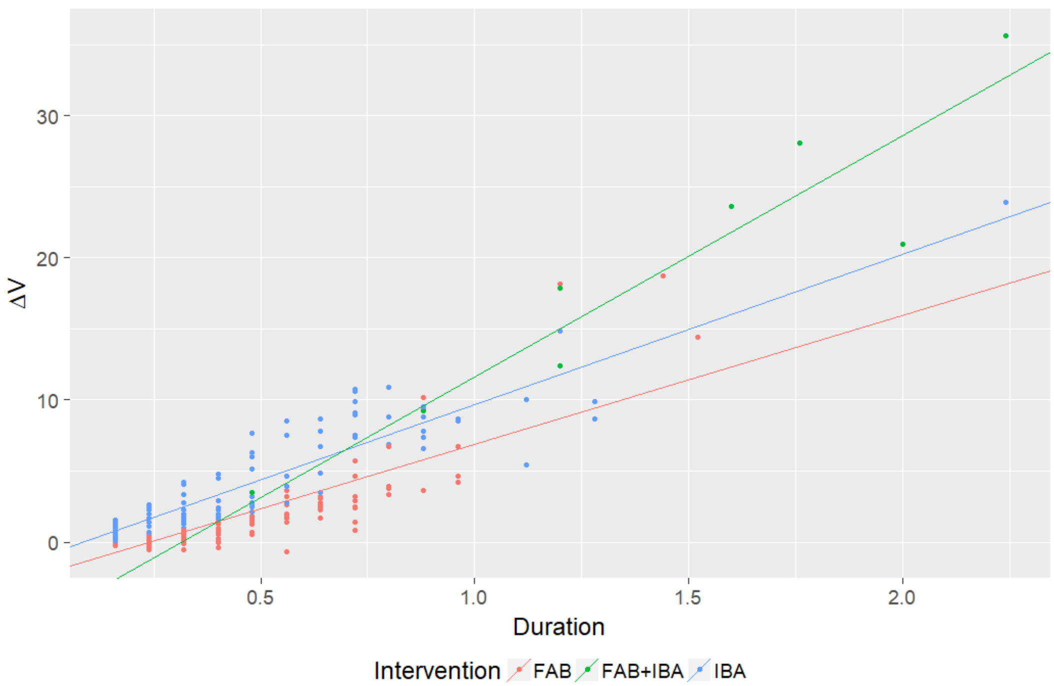

Figure 19 Closeup view of center panel in Figure 18 showing change in speed by event duration

4.5 Repeat FAB Events

The locations of events were compared to each other to identify whether there were instances of multiple events occurring at the same location, which is of particular interest for exploring the presence of undesired FAB activations. Fifty-five such locations were identified. Google aerial and street views were used to identify the road types for these repeat event locations. The average duration of repeat FAB only events was 0.31s (median=0.24s, 95th percentile: 0.88s), which is close to the overall average duration of all events (0.28s).

Of these repeat FAB events, all were repetitions within the same vehicle in the same location (i.e., no two vehicles ever triggered repeat events at the same location). The average initial speed of same-location events was below 10 mph for 49 (89% of) locations, and of these, nearly all (48 of 49) occurred in parking lots or driveways. Of the six higher-speed (10+ mph) event locations (11% of all repeat event locations), one was on a freeway, one was on a major street, and four were on local roads (as was one lower-speed repeat FAB event). Inspection of Google street view for these higher-speed events did not reveal any road characteristics (e.g., overpass) that readily indicated a reason for triggering the repeat FAB events.

4.6 Events by Kinematic Scenario

Kinematic scenarios were developed based on kinematic conditions assessed at the time of event onset for the 370 “key event” sample described earlier (vehicle at 10 mph and above at event onset, event duration lasting 0.16 s or longer). Because of the relative small number of events in this sample, the scenarios were simplified to three types of host vehicle behavior and three types of lead vehicle behavior. Scenario definitions are as follows.

- Host vehicle
  - Constant: Acceleration between -0.7 and 0.3 m/s^2
  - Slowing: Acceleration < -0.7 m/s^2
  - Accelerating: Acceleration ≥ 0.3 m/s^2
- Lead vehicle
  - Stopped: Speed between -2.2 to 0.5 m/s
  - Constant or accelerating: Acceleration ≥ -1.0 m/s^2

(Note that is this category, less than 15 percent of these cases involved a lead vehicle accelerating.)

  - Slowing: Acceleration < -1.0 m/s^2

Table 9 shows the number of key events (as described above) in each of the nine possible scenarios based on these scenario definitions. Each of these nine scenarios are all represented, though when the lead vehicle is slowing, the host vehicle is generally slowing as well. The most common scenarios involve the host at constant speed with the lead vehicle most often stopped or at a constant speed (or accelerating).

Table 9 Number of key events by event scenario

		Lead Vehicle			
		Stopped	**Constant or Accelerating**	**Slowing**	**Total**
Host Vehicle	Constant	66	64	18	148
	Slowing	43	23	55	121
	Accelerating	39	48	14	101
Total		148	135	87	370

Table 10 shows these events further broken down by event type. Not surprisingly, IBA events are almost all associated with a slowing or stopped host vehicle, whereas FAB events are rarely associated with a slowing host vehicle. Combined FAB+IBA events all involve a slowing lead vehicle, requiring greater and more urgent speed reductions than when the lead vehicle is not decelerating.

Table 10 Count of events by event type and kinematic scenario

Host Vehicle	Lead Vehicle	FAB	IBA	FAB&IBA
Constant	Stopped	61	5	0
Slowing	Stopped	1	42	0
Accelerating	Stopped	39	0	0
Constant	Constant Speed or Accel.	64	0	0
Slowing	Constant Speed or Accel.	3	20	0
Accelerating	Constant Speed or Accel.	48	0	0
Constant	Slowing	16	0	2
Slowing	Slowing	3	49	3
Accelerating	Slowing	9	0	5
Total		244	116	10

4.7 Events by Response Scenario

Since FAB can operate independent of the driver, we characterized driver response in terms of the sequence of event states particularly with respect to FAB (i.e., little or no driver action) and IBA (i.e., driver braking triggering additional automatic braking). Thus, the driver may respond to the situation or in response to an FAB event onset, and though we cannot clearly tell based on the available data exactly what the driver is responding to, we can identify if and when he/she is braking during an event.

Table 11 shows the set of event sequences for the defined key events we have been discussing, along with the count of such events, as well as corresponding average durations, speeds, and host speed reductions, as wells the percentage of these events in which an FCA was detected prior to the event (as opposed to at the time of the event) within the 4-second data collection window. Any state lasting less than 0.1 s was eliminated, leaving no event (FAB, IBA, or FAB+IBA) with more than three states. Note that the FAB system has three levels of authority: low speed FAB (up to high braking level at lower speeds), light FAB (lower braking level at higher speeds), and full FAB (up to high braking level at higher speeds).

The vast majority (95%) of the key events either involved light FAB only (n=205, or 55%), IBA only (n=116, or 31%), or low-speed FAB only (n=32, or 9%). These events generally resulted in speed reductions of 1-4 mph. The 13 events that involved either both (FAB+IBA) systems or “Full FAB” resulted in larger speed reductions (822 mph) and lasted 0.9-1.8 s. FCA was also present prior to the event (as opposed to at event onset) in the 4-second data collection window in a much larger proportion of events (about half) for these scenarios relative to other scenarios shown in Table 11.

Table 11 Event sequences and characteristics

Event Type	Sequence			Event Count	Duration(s)	Initial Speed (mph)	Host Speed Red. (mph)	FCA Present Prior to CPS Onset (%)
	State 1	**State 2**	**State 3**					
FAB*	Light FAB			205	0.33	39.1	0.75	14.3
FAB	Light FAB	Full FAB		4	0.90	51.0	8.12	50.0
Both	Light FAB	IBA		5	1.31	33.5	17.78	60.0
Both	Light FAB	IBA	Full FAB	2	1.80	23.4	22.30	50.0
Both	Low Speed FAB	IBA		2	1.04	15.0	13.35	0.0
FAB	Low Speed FAB			32	0.40	14.2	1.49	3.1
FAB	Low Speed FAB	Light FAB		3	0.59	15.3	1.3	0.0
IBA	IBA			116	0.44	23.7	3.77	15.5

*Includes one combined event with the FAB state of less than 0.08 s.

In looking closely at the time-series data for FAB events, we noted that there is brake pedal movement in many events that do not reach the threshold of triggering IBA. To trigger IBA, driver braking must not only occur but have certain “panic” characteristics (e.g., rapid pedal depression). However, driver braking of any kind suggests that the driver may be “engaged” during a potential unfolding forward crash scenario.

To explore driver response to CPS events further, we reclassified driver response into three categories across the key events: (1) IBA events, (2) Brake pedal travel of at least 2 percent (categorized as “Insufficient Braking”), and (3) No brake pedal travel (categorized as “No Braking Response”; acceleration and steering may have occurred). (Note for this analysis, the SRX vehicles were excluded because the FAB system engages the brake pedal and thus we cannot distinguish between CPS and driver braking contributions.) Results indicated that no driver braking response occurred in about 48 percent of the cases examined, and that driver braking did not trigger an IBA event in about 19 percent of additional cases. In contrast, in about one third of the cases the driver’s braking triggered an IBA event.

Table 12 Driver braking behavior categories during key CPS events (SRX excluded)

Driver Response During Event	Count	Percent	Avg. Duration (s)	Avg. Initial Speed (mph)	Avg. Delta V (mph)	Proportion FCA Presence Prior to CPS Onset
Reaches IBA level	94	32.87%	0.48	24.18	4.11	0.18
Insufficient Braking	54	18.88%	0.50	31.23	2.47	0.13
No Braking Response	138	48.25%	0.29	35.75	0.45	0.14
All Events	286	100.00%	0.39	31.09	2.03	0.15

4.8 Assessing Contributions to Safety

One of the ways to assess the relative contribution of the FAB and IBA systems to safety in this group of key events (10+ mph at event onset, 0.16+ s event duration) is to look at the speed reduction achieved across event types. Table 13 shows the average speed reduction for each scenario and event type (for combinations of these factors observed). The two largest average speed reductions are for combined FAB+IBA events, followed by other event types when the host speed is constant or slowing and the lead vehicle is slowing.

One possible way to approach estimating safety attributable to each event type and scenario is to calculate the total speed reduction observed in each cell of Table 13 and look at that amount as a percentage of all of the speed reduction across all of the events. This approach is shown in Table 14. Across all events, IBA, FAB, and combined FAB+IBA events are responsible for 52.4 percent, 28.2 percent, and 19.4 percent of the total speed reductions, respectively. In addition, overall, and within each event type, the majority of total speed reductions are occurring under lead vehicle slowing scenarios. Note that since we cannot separate the driver's contribution to braking from the CPS system's contribution, the IBA and combined FAB+IBA events include driver "panic" braking behavior (that engages IBA rather than FAB). Thus, the contribution of driver braking is necessarily included in the percentages in Table 14, which reflect the combined actions of driver and vehicle in these events.

Table 13 Average speed reduction in mph by kinematic scenario and event type

Host Vehicle	Lead Vehicle	FAB	IBA	FAB&IBA
Constant	Stopped	0.564	0.587	
Slowing	Stopped	0.280	3.542	
Accelerating	Stopped	0.746		
Constant	Const/Accel	0.701		
Slowing	Const/Accel	1.072	1.971	
Accelerating	Const/Accel	0.687		
Constant	Slowing	3.714		5.45
Slowing	Slowing	7.969	5.022	19.01
Accelerating	Slowing	0.808		18.87
All Scenarios		0.965	3.769	16.23

Table 14 Percentage of overall benefit in speed reduction by kinematic condition and event type

Host Vehicle	Lead Vehicle	FAB	IBA	FAB&IBA
Constant	Stopped	4.1%	0.4%	0.0%
Slowing	Stopped	0.0%	17.8%	0.0%
Accelerating	Stopped	3.5%	0.0%	0.0%
Constant	Const/Accel	5.4%	0.0%	0.0%
Slowing	Const/Accel	0.4%	4.7%	0.0%
Accelerating	Const/Accel	4.0%	0.0%	0.0%
Constant	Slowing	7.1%	0.0%	1.3%
Slowing	Slowing	2.9%	29.5%	6.8%
Accelerating	Slowing	0.9%	0.0%	11.3%
All Scenarios		28.2%	52.4%	19.4%

Another possible approach for examining safety contributions is to look at change in range-rate over the course of the event. In the following discussion, for simplicity purposes, it should be made clear that positive (rather than negative) values indicate a magnitude decrease in range-rate over the event, resulting in situations that are generally less safety-critical than at the start of the event. Figure 20 shows change in range-rate versus event duration by system type for the 370 key events. As shown in the upper left corner of Figure 20, a large number of FAB events resulted in implausibly high magnitude range-rate decreases. On further investigation, these events all proved to be stationary targets where the system may have shifted from a moving target to a stationary target rather than measuring the change to a single target. Thus, in Figure 20, the FAB events with targets classified as stationary are plotted in purple and the regression lines for FAB and IBA events exclude classified stationary targets. Note the two regression lines are nearly the same.

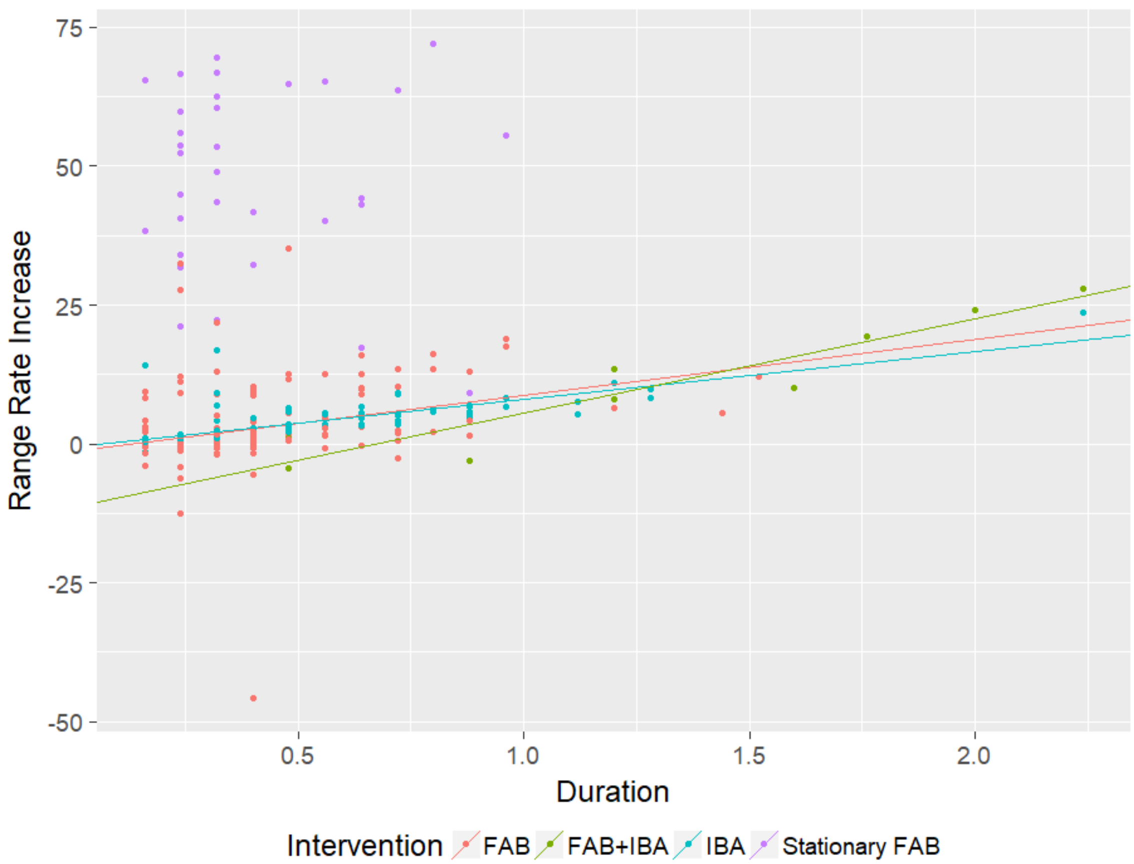

Figure 20 Range-rate change vs. event duration as a function of event type with stationary FAB separate

Removing stationary targets from analysis, Table 15 shows the average change in range-rate by kinematic scenario and system type (for combinations of these factors observed). To express this as a relative safety measure, we multiply the average change in range-rate by the number of events in each category, as seen in Table 16. Table 16 indicates that almost half of the range-rate benefit is attributable to FAB events. In turn, IBA and dual FAB+IBA are responsible for 40.5 percent and 11 percent of the range-rate benefit, respectively. Compared to the speed-reduction results (see Table 14), this represents a greater relative contribution of FAB to estimated benefits. This is because IBA and combined FAB+IBA events tend to occur more often in cases where the lead vehicle is slowing. For these lead-vehicle-slowing cases, unlike with lead vehicle stopped or lead vehicle moving at constant speed cases (and note earlier results indicating lead vehicle acceleration occurred in only 5 percent of lead events), the calculated range-rate reduction is not equivalent to a host speed reduction and, in fact, the range-rate reduction will be less than the speed reduction due to the lead vehicle slowing.

Table 15 Increase in range-rate for by kinematic condition and event type

Host Vehicle	Lead Vehicle	FAB	IBA	FAB+IBA
Constant	Stopped	0.286	2.125	
Slowing	Stopped	0.280	4.068	
Accelerating	Stopped	0.166		
Constant	Const/Accel	2.870		
Slowing	Const/Accel	1.305	2.684	
Accelerating	Const/Accel	3.577		
Constant	Slowing	2.447		0.559
Slowing	Slowing	5.406	2.779	14.167
Accelerating	Slowing	1.398		11.688
		0.286	2.125	

Table 16 Percentage of overall benefit in range-rate increase by kinematic condition and event type

Host Vehicle	Lead Vehicle	FAB	IBA	FAB+IBA
Constant	Stopped	1.3%	1.2%	0.0%
Slowing	Stopped	0.0%	18.6%	0.0%
Accelerating	Stopped	0.5%	0.0%	0.0%
Constant	Const/Accel	20.0%	0.0%	0.0%
Slowing	Const/Accel	0.4%	5.9%	0.0%
Accelerating	Const/Accel	18.7%	0.0%	0.0%
Constant	Slowing	4.3%	0.0%	1.1%
Slowing	Slowing	1.8%	14.8%	4.6%
Accelerating	Slowing	1.4%	0.0%	6.4%
		48.4%	40.5%	11.1%

4.9 Description of "Top 20" Events With Highest Host Vehicle Speed Change

Earlier sections have indicated that of the 370 "key" events (as defined earlier), many are short-lived events that reduce speed by less than a few mph. This section focuses discussion on a set of "Top 20" events (or cases) that were selected based on the amount of speed that is removed from the host vehicle's motion during the activation of the event (FAB, IBA, or FAB+IBA), including the driver braking contribution. These cases, which include two actual crashes, provide insight into specific situations in which the system may help prevent injury and/or serious property damage. The following characteristic of these Top 20 events were examined.

1. FAB and/or IBA involvements
2. The driver's role in braking and/or steering, to resolve the conflict
3. Whether a crash occurred, and if not, "near crash" measures
4. Whether any unwanted event activations may have occurred

The Top 20 events were defined based on the amount of speed reduction achieved by the CPS system and driver together (in cases where the driver braked), from the CPS onset to the end of the event. The amount of speed reduction across these events ranged from 9.5 mph to 35.6 mph, and the types of assistance are evenly distributed, including 7 FAB-only events, 7 IBA-only events, and 6 events including both FAB and IBA activations.

In the Top 20 events, there are two crashes in which the equipped vehicle appears to rear-end other vehicles. The first crash, with corresponding event data indicated below, involves an SRX and ends with an impact with a relative speed of 11 mph. In this crash, which occurred on a paved road at a rural, unsignalized intersection, the lead vehicle was slowing, possibly to turn onto the intersecting minor road. Weather archives suggest overcast conditions at the time of this daytime event, with rain not reported in the area until several hours after event, so that dry pavement can be reasonably assumed. When the 4 seconds of event data begins, the equipped vehicle is at 56 mph and the lead vehicle is traveling at 22 mph, but is slowing toward 11 mph at impact time.

An FCA imminent alert is requested at a time to collision of approximately 3 seconds. The driver lifts off the accelerator pedal 0.64 seconds after this request, and applies the brake at 1.36 sec after the alert request. By the time driver braking begins, the FAB has already triggered for 0.16 seconds. Upon driver braking, the IBA system is immediately engaged. The peak deceleration during the event is 9.9 m/s^2, and the average deceleration is 7.1 m/s^2 throughout the braking period. The lead vehicle, which has slowed to 9.8 mph at the time of impact, is struck by the equipped vehicle that has slowed to 20.4 mph, resulting in a delta-V of 10.6 mph. There is no sustained steering attempt by the following equipped vehicle.

The event data for the second crash, shown in Figure 21 below, begins with the equipped Escalade traveling at 22 mph and following an 18 mph lead vehicle at a distance of 21 meters. This incident occurs at a major freeway interchange in a large city in the late afternoon on a weekday in which no precipitation was reported (based on online archive from Wunderground.com). The lead vehicle begins to slow at 3 m/s^2 and the equipped vehicle data shows no evidence of driver reaction. At a TTC of roughly 1 sec, the FAB begins applying moderate braking (ramping toward 3 m/s^2), and simultaneously the driver's foot moves from the accelerator pedal to the brake pedal, at which time the system state transitions to IBA and a request for up to

12 m/s^2 is made. The actual acceleration peaks at 7.6 m/s^2, with an average deceleration rate over the period of braking of 4.0 m/s^2. The impact occurs at just over 10 mph relative speed.

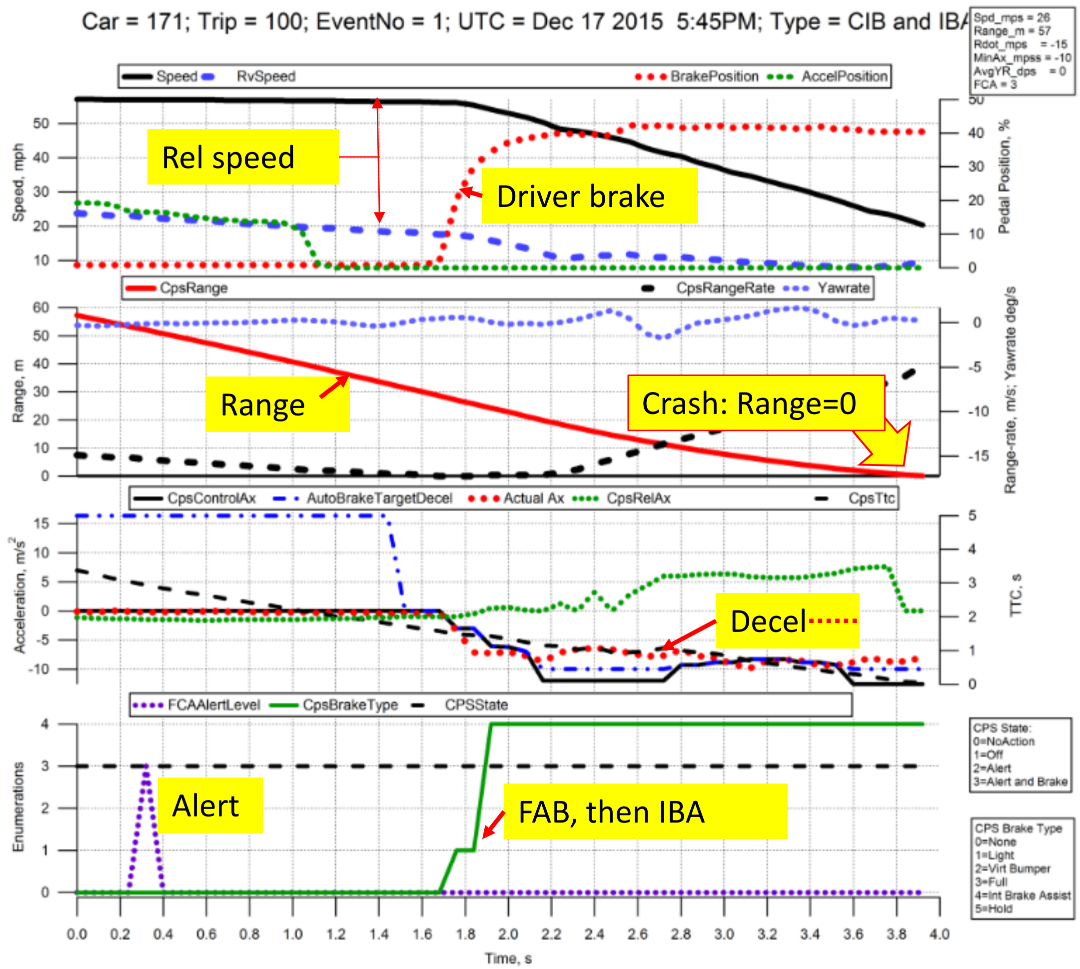

Figure 21 Time-series data for Car 171, Trip 100, Event 1

Of the 20 events, 6 (30%) of events occurred in which the FCA imminent alert was observed prior to the CPS onset (as opposed to at CPS onset) in the 4-second data collection window. Note that the data collection sampling rate may miss up to 50 percent of FCA imminent alerts that would have otherwise occurred prior to the CPS event. In addition, events without the FCA imminent alert included activity that could have either suppressed or delayed an alert, including ACC braking, rapid switching of primary forward target, and firm driver acceleration. These delay/suppressions are visible based on close examination of the data, and account for all but three of the Top 20 cases (85% of the cases) where FCA imminent alerts were not observed prior to CPS onset.

Overall, from these 20 events, nine events (45%) result in a minimum range of 1m or less between the equipped host vehicle and the lead vehicle. Although sensing at these small ranges appears to have some momentary inaccuracies, these results were closely examined and considered reliable. This clearly indicates that, in addition to the crashes described above, there are several very near crash events among the Top 20.

For these Top 20 events, the scenarios in which these events occur include:

- 8 decelerating vehicles that come to a stop before the point of minimum range occurs,
- 9 decelerating vehicles that are still moving when the point of minimum range occurs,
- 1 lead vehicle that is stopped during the entire 4-second window,
- 1 lead vehicle at a constant, slower speed, and
- 1 potential unwanted activation event.

As seen above, 17 of 20 events (85%) involve a slowing lead vehicle. The peak decelerations within each event ranged between 4.6 m/s^2 and 10.5 m/s^2. Nine of the 20 events (45%) had peak decelerations of over 9.0 m/s^2, and 14 of 20 (70%) were over 8.0 m/s^2. Thus, most of these Top 20 events include substantially high host vehicle decelerations. Furthermore, the role of driver braking during these events can be characterized as follows.

- In 13 cases, driver braking triggered IBA (these cases included two crashes with impact speeds of 10 and 11 mph, respectively)
- In 5 cases, driver braking occurs, but does not trigger IBA
- In 2 cases, no driver braking occurs

Note that driver braking during an FAB event can be substantial but still not trigger IBA. In one case, the FAB requested 0.3 g, and the actual deceleration reached 0.7 g, suggesting that driver braking was strong, but insufficient to trigger IBA. The two cases with no driver braking included a case in which ACC automatic braking occurred for several seconds, followed by FAB automatic braking (which in combination resolved the conflict), and a lower-speed case in which the driver was accelerating and had reached 11 mph when the FAB activated and quickly brought the vehicle speed to a stop in about 1 second.

A few possible steering events were seen, but the data available does not support a clear indication of the target's lateral position or relative lateral speed. CPS events that end while the vehicle is still closing, but with longitudinal kinematics predicting that braking will avoid the crash, could also be ones in which the event ends because the target leaves the CPS-equipped vehicles' sensors fields-of-view.

In summary, circumstances of these Top 20 events are quite varied, with different lead vehicle scenarios, initial speeds, peak decelerations, and outcomes. Decelerating lead vehicles account for 85 percent of these events, which is a substantially higher proportion than for the 370 key events (23.5%). FAB, IBA, and combined FAB+IBA events each appear in about one third of the Top 20 events, also substantially over-representing combined events and underrepresenting FAB events compared to the larger set of key events (3% combined; 31% IBA; 66% FAB). Also of note is that almost half of these events involved a minimum range of 1 meter or less, including two crash events. Resolution of these Top 20 events is almost always through a combination of driver and system braking. Steering was judged to possibly have played a part in resolving two of these 20 events; a rate which appears roughly consistent with other studies of forward crash avoidance resolution. In previous studies, steering was involved in 4 percent of driver actions following a forward crash alert in scenarios where both vehicles were in the same lane throughout the event, and steering was involved in 3 percent of scenarios in which one or the other vehicle had a lane movement near the alert event (Ervin et. al, 2005).

4.10 Automatic Collision Notification Data Analysis

ACN events are crashes that meet certain criteria, and their data are automatically transferred to OnStar at the time of the event. ACN is triggered in frontal, side, or rear impact crashes by any air bag deployment or when exceeding a minimum delta-Velocity impact (dependent on whether the direction of impact is frontal, side, or rear). Rollover crashes may also trigger notification.

Among the 1,021 monitored vehicles in this study, there were a total of 8 ACN events. 7 ACN events did not trigger an air bag deployment, and included 1 frontal, 3 rear, 2 left, and 1 right impact cases. None of these 7 events were associated with a CPS event. 1 ACN event involved a frontal impact with an air bag deployment, but any association with a CPS event could not be determined, since the air bag deployment interfered with CPS data collection.

For comparison purposes, the Second Strategic Highway Research Program (SHRP2) Naturalistic Driving Study (TRB, 2013) contained 32 rear-end-striking events in the most severe category,[1] which is comparable to an event triggering an ACN, in 35 million miles of driving. Applying this rate to the 11,891,341 driving miles accumulated in this study, we would expect 11 frontal striking events in the ACN dataset for this vehicle population (compared to the 2 observed here). Note that the SHRP2 study population over-represented younger drivers, particularly with respect to our study population, so it may not be a fully appropriate comparison set.

To address the problem of the small sample of crash data in the current data, GM provided a much larger sample of ACN events that occurred during the time of data collection for a set of matched GM vehicles (December 3, 2015, to December 3, 2016). Namely, the larger ACN sample included MY 2013 to MY 2015 GM vehicles of the same models as our study population: Escalade, SRX, XTS, CTS and ATS. These forward collision system equipment groups were categorized as: (1) FCA-only (camera sensor); (2) FAB/IBA/FCA (radar and camera sensors; as in current study); and (3) No forward collision systems. In addition to ACN events, monthly vehicle odometer readings were available for a subset of the vehicles. These values were used to estimate total miles traveling during the time for each of the three vehicle groups.

Table 17 shows the number of vehicles in each forward collision system equipment group as a function of crash type (frontal ACN, non-frontal ACN, no ACN crash). Table 18 shows, for each of these corresponding equipment groups, the average annualized mileage, the percentage of vehicles with frontal and non-frontal ACN-related crashes, and the frontal ACN and total ACN crash rate (per mile) for each vehicle group.

[1] Level 1 crash severity is defined as "Severe Crash. Any crash that includes an air bag deployment; any injury of driver, pedal cyclist, or pedestrian; a vehicle rollover; a high delta-V; or that requires vehicle towing. Injury if present should be sufficient to require a doctor's visit, including those self-reported and those apparent from video." (Schofield, 2015)

Table 17 ACN-related crashed by forward collision system group type

Forward Collision System Group	Frontal ACN Crash	Non-Frontal ACN Crash	No ACN Crash	Total Vehicles
FAB/IBA/FCA	96	75	51509	51680
FCA only	394	381	211321	212096
None	331	304	172120	172755
Total	821	760	434950	436531

Table 18 Miles traveled and crash rates for large ACN dataset by forward collision system group type

Forward Collision System Group	Average Daily Miles per Vehicle	Annualized Miles per Vehicle	Percent Vehicles With Frontal Crash	Percent Vehicles with Non-Frontal Crash	Frontal as Percent of All Crashes	Frontal Crash Rate per Million Miles	Overall Crash Rate per Million Miles
FAB/IBA/ FCA	36.1	13173	0.186%	0.145%	56.14%	0.141	0.251
FCA only	31.9	11628	0.186%	0.180%	50.84%	0.160	0.314
None	33.3	12145	0.192%	0.176%	52.13%	0.158	0.303
Total	33.0	12015	0.188%	0.174%	51.93%	0.157	0.301

Figure 21 shows the ACN-related crash rates by system for all ACN crash types, as well as for frontal ACN crashes types only. Error bars for all such crashes in FAB/IBA/FCA equipped vehicles do not overlap with those with FCA only and overlap only slightly with vehicles with no system. For frontal crashes, the relative rates are lowest for FAB/IBA/FCA equipped vehicles but confidence intervals are larger because of small samples, and these confidence intervals overlap across the different forward collision system groups. On average, FAB/IBA/FCA equipped vehicles have 17 percent fewer ACN events overall and 11 percent fewer frontal ACN events compared to unequipped vehicles without FAB, IBA, or FCA systems.

In addition, we examined the crash delta-V (dV), which is the change in speed of the ACN vehicle, as a result of the crash (as opposed to the relative speed of impact). For FAB-equipped vehicles, mean dV in frontal ACN crashes was 13.7 mph (CI: 11.7-15.6); for FCA-camera only vehicles, mean dV in frontals was 14.2 mph (CI: 13.3-15.1); and for unequipped vehicles, mean dV in frontals was 14.9 mph (CI: 14.-15.9).

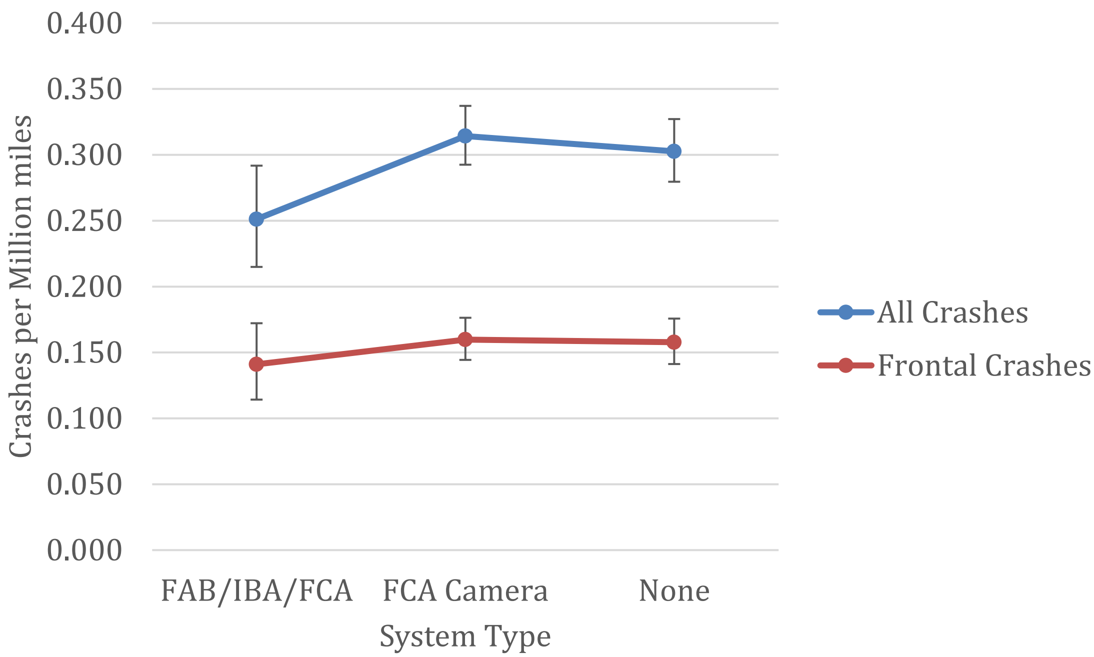

Figure 22 Automatic Collision Notification crash rate per million miles by system type (all crashes and frontals only)

Finally, to better understand the extent to which ACN frontal crashes are relevant to FAB, IBA, or FCA systems, we looked at data from the National Automotive Sample System—Crashworthiness Data System (NASS-CDS) from 2006 to 2015. The challenge in analyzing ACN data is that we do not have context information surrounding the crash to determine whether the systems under examination here would have been relevant to avoiding or mitigating the frontal ACN crash (which, for example, could have been due to an intersection rather than rear-end crash). The CDS dataset, in contrast to the current ACN dataset, includes both reconstructed vehicle kinematics (direction of impact and delta-V) and crash configurations based on police records and accident investigation.

Using CDS, we looked at all frontal crashes that should meet notification criteria, either from an air bag deployment or delta-V≥18 mph. Among these crashes, 24.7 percent resulted from rear-end crashes or stopped objects (including parked cars) in the path of the vehicle, whereas over 50 percent of ACN notification level frontal crashes stem from intersection crashes, angle configurations (e.g., target vehicle turns across the path of the host vehicle) and loss of control. The remaining frontal crash types include run-off-road, lateral maneuvers such as lane-change or turning (which normally result in side impacts), head-on collisions, and collisions after an avoidance maneuver, each of which is relatively uncommon (among frontal crashes). Consequently, these results point out the challenges of using ACN data in isolation to understand Active Safety feature effectiveness, and the importance of understanding ACN crashes in a broader context. With respect to the current effort, the implications of these CDS finding on estimating FAB/IBA/FCA effectiveness is further addressed in the Discussion section.

5 Discussion

5.1 System Performance Questions

The original research questions related to system performance include (from Table 1): How often do events occur? (Note "event" refers collectively to FAB, IBA, and combined "FAB+IBA" events in the discussion below.) What is the distribution of event rates across drivers? What circumstances surround events? How often is the system available?

A key outcome of this study is the general observation that these events are quite rare, and longer-lasting events of greater significance (i.e., lasting longer than 0.5 seconds) are extremely rare. Of the nearly 12 million miles covered in this study, there were only 1,237 events, which translates to an overall event rate of 1.04 events per 10,000 miles). Across the 1,021 vehicles, 44 percent never triggered an event. When we average the rate across vehicles, the per-vehicle average rate is 1.27 per 10,000 miles.

In addition, the majority of events were short-lived (0.08 s) and at low host-vehicle speeds, defined here as 10 mph or less. Many of these low-speed events occurred in driveways or on local roads. Only 30 percent of all events occurred above these low speeds and lasted more than 0.08 s. These will be subsequently referred to as "key events," even though it should be pointed that many of these events do not result in substantial speed reductions. It should be noted that all events were accompanied by a multi-modality FCA imminent alerts (i.e., a red flashing windshield alert and either Safety Alert Seat vibrations or a beeping alert), which may have aided the driver in inferring when an event occurred, even if it was not detectable based on deceleration caused by automatic braking.

The overall key-event rate was 0.31 per 10,000 miles. The average vehicle key-event rate was 0.52 per 10,000 miles with 65 percent of vehicles never reporting a key event (resulting in a median vehicle event rate of 0.00). The 95th percentile vehicle-average key event rate was 2.22 events per 10,000 miles.

Among key events, FAB events occurred about twice as often as IBA. There were only 17 instances of both systems operating (corresponding to 1.4% of all events), but in most cases, the event was long-lasting with relatively large speed changes. Initial speeds for all event types ranged widely. Average key event durations were longest for (combined) FAB+IBA events (1.27s), followed by IBA events (0.44s) and FAB events (0.34s).

Minimum (or peak) deceleration during a key event followed a similar pattern with the lowest minimum (hardest braking) for FAB+IBA events, followed by IBA and FAB events. However, across all key events, as would be expected, those that lasted longer produced the greatest speed reductions, and in general, the average deceleration (indicated by the slope of the lines in Figure 19) was similar for FAB and IBA events. In general, FAB events include a large number of short-lived events with light automatic braking that have negligible speed reductions. In contrast, any event involving IBA (either in combination with FAB or alone) necessarily indicates that the driver is braking the vehicle in an aggressive manner, presumably in response to a forward crash conflict. Thus, for IBA, there are relatively few short-duration (and consequently low-speed reduction events) compared to FAB, and in combination with FAB (i.e., FAB+IBA cases), there are no events lasting less than 0.48 seconds. However, irrespective of whether there is an FAB only or IBA only event (or put in another way, whether or not there is driver braking triggering IBA during an event), the level of deceleration is similar on average and the speed reduction achieved is largely dependent on how long the event lasts.

The kinematic circumstances at the onset of key events were distributed across all nine combinations of host-vehicle movement (slowing, constant speed, accelerating) and target-vehicle movement (stopped, slowing, constant speed or accelerating). However, all such IBA only events tended to occur when the host vehicle was slowing (because the driver must be on the brake to engage IBA) and FAB events occurred more often when the host was traveling at constant speed. All key FAB+IBA events occurred when the target vehicle was slowing.

While system availability was not available in the data collected, based on the prior study of FCA and LDW (Flannagan et al., 2016), we can reasonably infer that the system was available the vast majority of driving time (when a target was present).

5.2 Driver Behavior Questions

The original research questions related to driver behavior include (from Table 1): What are the conditions and driver control actions before the onset of FAB and IBA? What is the nature and timing of driver responses to events? Do drivers turn the system off? Does the pattern of activations change with experience?

Two key results of this study are that drivers rarely turn the system off, and that combined, FAB+IBA, events rarely happen (1.4% of all events). Overall, for 96 percent of the driving time, the system was at the "Alert+Brake" system setting which provides full FAB/IBA capability, as well as FCA system alerts. Thus, the benefits of the systems evaluated can be expected to apply to all equipped vehicles given this extremely high rate of usage. In addition, because of the rarity of the events, long-term adaptation is unlikely to occur, since adaptation would seemingly require enough events to justify reliance on the system.

The question of the nature and timing of driver responses is more challenging in this system context than in the previous study of "warning only" FCA and LDW systems. Since the system itself chooses when and how to automatically engage the brakes, much of what we observe is the behavior of the system rather than the driver. However, driver braking is generally observed with significant events involving relatively longer event durations. Many FAB events are short-lived, resulting in negligible speed reductions. While the driver may be aware of these short-lived events occur (because of the accompanying FCA imminent alerts), these events ultimately have little effect on vehicle speed.

It is important to note that engaging IBA requires braking behavior generally indicative of panic braking. Thus, not all driver braking will engage IBA, and indeed, for 28 percent of FAB-only key events, the driver was braking at some level, albeit below the level called for by the FAB or IBA system.

With respect to the sequence of FAB and IBA events, nearly 87 percent of key events involved either FAB alone with "light" automatic braking levels or IBA alone. Events that involved both FAB and IBA systems (0.7% of all events) or "full" levels of FAB automatic braking (0.5% of all events) were relatively rare, but tended to last longer and involve relatively large speed reductions.

5.3 Safety-Impact Questions

The original research questions related to safety impacts include (from Table 1): What are the potential safety benefits of FAB/IBA, and how does the potential safety benefit of FCA compare to potential benefits of FAB/IBA?

Direct assessment of safety benefits is challenging within the context of the OnStar data collection portion of this study (in part due to extremely high rate at which drivers have the system active, resulting in the lack of a system-inactive comparison group); though available comparisons to SHRP2 data hint at a substantial reduction in the rate of rear-end crash related, frontal ACN-level events. Based on the rate of rear-end striking events in the most severe category observed in the SHRP2 dataset, we would have expected to observe 11 frontal striking ACN events in the current dataset, and yet only 2 such events were observed. However, differences between the SHRP2 versus current dataset, particularly with respect to differences in driver ages (with an older population used in the current study), confound a straightforward, direct comparison.

In an attempt to address the shortcomings of the limited number of crashes in the current dataset, a more general ACN analysis encompassing all the matched production vehicles in the current dataset was conducted. This analysis indicated a trend that reductions in frontal crashes are higher for FAB/IBA/FCA-equipped vehicles (with radar and camera sensors, as in current study) than for non-equipped and FCA-only (camera sensor) equipped vehicles. In general, the frontal crash rates for FCA-only vehicles was similar to unequipped vehicles of the same types. However, based on NASS-CDS-data, it should be stressed that only about 25 percent of ACN-level frontal crashes are addressable by these forward collision systems. Thus, the observed mean reduction in frontal crash rates in FAB/IBA/FCA-equipped vehicles relative to unequipped vehicles (11%) would be equivalent to a 45 percent reduction in relevant (rear-end striking) ACN-level crashes, if we can assume that the full 11 percent reduction in ACN events was related to rear-end striking and was addressed by FAB. It should be noted this promising magnitude of this crash effectiveness estimated corresponds well to that recently reported by Cicchino (2017), which examined police-reported crashes.

An indirect assessment of system benefits is seen in the distribution of host vehicle speed and relative speed reductions across the various vehicle-to-vehicle kinematic scenarios and systems (FAB, IBA, or combined FAB+IBA). In all cases, it should be noted that the estimated benefits include the driver's braking contribution. For the host speed reduction observed in key events, 28.2 percent was attributable to FAB, 52.4 percent to IBA, and 19.4 percent for only 10 combined FAB+IBA events. In terms of relative speed reduction, the corresponding proportions are 48.4 percent, 40.5 percent, and 11.1 percent, respectively, indicating the contributions of FAB and IBA become much closer when using relative rather than host speed reductions.

Comparing across OnStar data collection studies, the contrast in event rates between FCA and FAB/IBA event rates is dramatic. The mean imminent alert rate for FCA was once per ~70 miles (Flannagan et al., 2016), whereas overall, events occurred in the current study about once every ~10,000 miles. This indicates, as anticipated, that FCA events are experienced by drivers fairly regularly whereas FAB/IBA events are relatively rare.

This appropriately suggests that FAB and IBA events are reserved for fairly extreme conditions where either the event arises quickly (leaving little opportunity for an FCA imminent alert to precede the event onset) or where the driver does not respond to the FCA imminent alert. The FAB/IBA system is capable of reducing speeds by more than provided by the driver, and thus can reduce the severity of a crash or avoid it altogether. It is difficult to estimate how much braking the driver was responsible for in the current dataset (particularly when IBA was activated), but the crash and near crashes cases seen in the "Top 20" events indicate that the additional automatic braking called for by the system was needed.

In general, the systems evaluated can be viewed as part of a continuum. Adaptive cruise control (ACC), generally sold as a convenience feature, contributed in reducing speed in two of the top 20 events observed, and when engaged, is a way to help drivers stay out of FCA imminent alert approach conditions. FCA, in turn, anticipates and alerts the driver to many emerging forward conflict events involving slower moving, slowing or stopped lead vehicles. Previous OnStar data collection research indicated reaction time was on average 110 ms faster when FCA was turned on relative to when the system was turned off under FCA alerting conditions (Flannagan et al., 2016). Finally, FAB and IBA event are designed to occur later in an emerging forward conflict, and thus rarely occur. Thus, for cases when ACC is not engaged (the vast majority of driving), considering the timeline of a rear-end crash conflict, the FAB and IBA events can be viewed as the last line of defense for drivers who fail to respond to an FCA imminent alert, or when a rear-end situation develops very rapidly. Note that in the majority of FAB and IBA events (as well as FCA events), the driver actively responds to the situation in some way. Most events include some driver braking (including about half of all FAB events), but it may occur too late (e.g., when FAB system automatic braking comes on first) or be insufficient for resolving the forward conflict.

5.4 System Field Assessment

The original research questions related to system field assessment include (from Table 1): What are important beneficial system properties, and how are they manifested in deployment, and what may be opportunities for feature improvement?

With regard to opportunities for system improvement, fundamentally it should be noted that driver engagement of the system evaluated is extremely high (i.e., system is on for almost all vehicles and miles). This suggests that the trade-offs made by system designers to triggering system activations under "valid" conditions, and suppressing such activations under "invalid," unwanted conditions, resulted in high levels of system use. Furthermore, repeat events do not appear to be a significant issue, which gives some indication that these systems do not respond repeatedly to features of a roadway that might mimic a target. It is also noted there are a number of brief FAB activations that may represent an opportunity for algorithm refinement, providing such refinements do not lead to unacceptable levels of reductions system performance for "valid" events. Also, given that drivers often respond during the events observed, sometimes braking insufficiently, sometimes resulting in the system changing from FAB to IBA, suggests that the system may be improved by perhaps making stronger assumptions that the driver response is a reliable indicator of a hazard.

As described above in the section on safety benefits, the system evaluated provided significant braking in last-minute rear-end crash, forward conflict situations in cases when the driver did not respond sufficiently (or at all). Notably, two of the largest speed-reduction events in this dataset involved no driver braking at all. As discussed earlier, FAB and IBA operate as a last line of defense in preventing or mitigating rear-end crashes. Both FAB and IBA contribute to the safety benefits of the system as a whole, further suggesting that the two systems are jointly useful as part of a package of systems (as opposed to offering the FAB and IBA systems individually).

5.5 Final Comments

From a methodological perspective, the telematics-based, large-scale OnStar data collection technique employed in the current effort has several distinct strengths for evaluating safety systems, including cost, sample size, drivers using their own vehicles where they can turn systems off, ability to look at long-term effects, data efficiency, and the ability to get "rapid-turnaround" large-scale results. These strengths are particularly notable for examining rare events, such as last-second automatic braking (or steering), near crash, or crash events (including ACN events). Since this technique currently focuses on key high-priority numeric data, it complements and benefits from the extensive set of multi-channel video and continuously measured kinematic information gathered in traditional FOTs. This type of telematics-based data collection appears is also ideally suited for understanding the safety impacts of safety systems that are rapidly emerging globally.

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