AAA Foundation for Traffic Safety

RESEARCH BRIEF

Potential Reductions in Crashes, Injuries, and Deaths from Large-Scale Deployment of Advanced Driver Assistance Systems

Technologies designed to improve traffic safety by helping drivers avoid crashes are becoming increasingly common in the U.S. vehicle fleet. Some of these technologies provide warnings and rely on the driver to take corrective action; others are designed to automatically brake or steer, taking an active approach to help avoid a crash. It is anticipated that the increasing market penetration of these systems and improvements in their functionality and performance will contribute to overall improvements in traffic safety. This research brief presents a synthesis of existing research on the potential safety benefits of selected Advanced Driver Assistance Systems and provides new estimates of the numbers of crashes, injuries, and deaths that such systems could potentially help prevent based on the characteristics of the crashes that occurred on U.S. roads in 2016.

Introduction

This research brief reviews recent literature and provides updated statistical estimates regarding the numbers of crashes, injuries, and deaths that could theoretically be addressed by equipping all cars, pickup trucks, vans, minivans, and sport utility vehicles (hereafter, collectively referred to as "passenger vehicles") with selected Advanced Driver Assistance Systems (ADAS). Technologies included in the scope of this brief are designed to prevent or reduce the severity of specific types of crashes, or to help the driver do so. Specific technologies examined are: forward collision warning (FCW), automatic emergency braking (AEB), lane departure warning (LDW), lane keeping assistance (LKA), and blind spot warning (BSW) systems. Driver assistance technologies designed primarily for driver convenience (e.g., adaptive cruise control systems; parking assistance systems) are outside the scope of this review. It should be noted that in estimating the numbers of crashes, injuries, and deaths that these technologies could theoretically help prevent or mitigate, this research brief does not attempt to quantify the likely actual real-world reductions in crashes, injuries, and deaths attributable to these technologies.

Forward Collision Warning (FCW) and Automatic Emergency Braking (AEB) Systems

FCW and AEB systems typically use radar, lidar, or cameras to determine the distance between the equipped vehicle and other vehicles/objects directly ahead, and estimate time-to-collision and thus determine whether a crash is imminent. FCW systems warn the driver when the system determines an imminent threat but rely on the driver to take action; AEB systems automatically apply the vehicle's brakes to attempt to avoid the crash or at least reduce its severity. Most vehicles equipped with AEB also include a warning component prior to engaging automatic braking. Current-generation systems are designed to detect other vehicles, but some are designed to detect pedestrians as well. Most current systems are designed to be effective within a specific range of speeds and may not function under certain environmental conditions (e.g., rain, fog, glare/bright background light) depending on the underlying technology used. The target population for these technologies — crashes of the types that these technologies could potentially help prevent or mitigate — comprises rear-end crashes that occur in the absence of specific circumstances that might prevent the technology from activating or prevent it from helping avoid or mitigate the crash.

Several studies have attempted to estimate the target population of FCW and AEB. Analyzing rear-end crashes between 2002-2006 in which the striking vehicle was a passenger vehicle, Farmer (2008) estimated that FCW systems could have theoretically prevented an estimated 69-81% of all rear-end crashes, 76-81% of angle crashes, and 23-24% of single-vehicle crashes, which totaled approximately 2.3 million crashes and 7,166 fatal crashes per year between 2002 and 2006. A subsequent study by Jermakian (2011) attempted to refine the estimates reported by Farmer by taking into account known system limitations and estimated that if these systems were outfitted on all vehicles and worked perfectly, they could theoretically address approximately 70% of all rear-end crashes in which a passenger vehicle was the striking vehicle and 18% of single-vehicle crashes, totaling an estimated 1,454,000 crashes and 5,633 fatal crashes annually between 2004 and 2008. Those estimates represented 20% of all passenger-vehicle crashes, 9% of those resulting in injuries, and 3% of all fatal crashes of passenger vehicles, respectively. The National Highway Traffic Safety Administration (NHTSA) estimated that crash types addressable by FCW and AEB systems capable of detecting pedestrians comprised 52% of all police-reported crashes involving pedestrians and 90% of fatal vehicle-pedestrian crashes (Yanagisawa et al., 2017).

Studies of police-reported motor vehicle crash data and insurance claim data have attempted to quantify the actual effects of these systems by comparing selected vehicles of the same model with and without the systems of interest. The Highway Loss Data Institute (HLDI, 2015a) estimated that the Honda Accord's FCW system (in conjunction with an LDW system) reduced the frequency of bodily injury liability claims by 24% and property damage liability claims by 10%. Another study by HLDI (2015b) estimated that Subaru's EyeSight system (which includes FCW, AEB, LDW, and adaptive cruise control) reduced the frequency of bodily injury liability and property damage liability claims by 35% and 15%, respectively. Cicchino (2017a) examined crash involvement rates of several vehicles that offered FCW and/or AEB as optional equipment and estimated that FCW alone, low-speed AEB alone, and both together reduced incidence of rear-end-striking crashes by 27%, 43%, and 50%, respectively. HLDI (2018) estimated that Subaru's EyeSight system reduced the frequency of bodily-injury claims for crashes involving pedestrians by 35% (2018).

Lane Departure Warning (LDW) and Lane Keeping Assistance (LKA) Systems

LDW and LKA systems typically use cameras to determine the position of the vehicle in relation to lane markings. LDW alerts the driver if the system detects that the vehicle is beginning to leave its travel lane when the turn signal is not activated; LKA automatically steers the vehicle to prevent it from leaving the lane. LDW and LKA systems are dependent upon the presence and visibility of lane markings and thus may not function when sensors are blocked or dirty or when lane markings are absent, degraded, or obscured by rain, snow, dirt, etc. These systems may not function on sharp curves or in areas with complex roadway geometry. The target population for LDW and LKA systems generally includes crashes in which a vehicle leaves its travel lane unintentionally. These can include single-vehicle road departure crashes, sideswipe crashes, and head-on crashes.

Several studies have attempted to estimate the target population of LDW and LKA systems. Farmer (2008) estimated that LDW systems were potentially relevant to approximately 13-16% of single-vehicle crashes, 66-88% of head-on crashes, 55-67% of sideswipe crashes involving vehicles traveling in the same direction and 57-74% of vehicles traveling in opposite directions, totaling 483,000 crashes and 10,345 fatal crashes annually between 2002 and 2006. Jermakian (2011) estimated that if all vehicles were equipped with LDW technology, the systems could theoretically address 6% of all single-vehicle crashes of passenger vehicles, 27% of head-on crashes of passenger vehicles, 29% of same-direction sideswipe crashes of passenger vehicles, and 25% of opposite-direction sideswipe crashes of passenger vehicles, which together comprised 3% of all passenger vehicle crashes and 24% of fatal passenger vehicle crashes. This amounted to 179,000 crashes and 7,529 fatal crashes annually between 2004 and 2008. Although the actual number of real-world crashes prevented might differ, the target population for LKA would be the same as that for LDW.

Studies of police-reported crashes and insurance claim data have sought to quantify the real-world safety impact of LDW and LKA systems. HLDI (2015c) found no statistically significant effect of Mazda's LDW system on property damage liability or collision insurance claims after accounting for the effects of other ADAS technologies besides LDW that were installed on the same vehicles. HLDI's studies of other Honda and Subaru ADAS systems (HLDI 2015a & 2015b) were unable to isolate the effects of LDW or LKA from those of other ADAS systems installed on the same vehicles. Cicchino (2017b) estimated that LDW systems have reduced equipped vehicles' involvement in all crashes by 11% and injury crashes by 21% compared with that of similar vehicles without the LDW systems. A European study estimated that Volvo's LDW and LKA systems reduced the systems' target crashes by 53%, which equated to 30% of all single-vehicle and head-on crashes that resulted in injuries (Sternlund et al., 2017).

Blind Spot Warning (BSW) Systems

BSW systems typically use cameras, radar, or lidar to detect vehicles traveling in the equipped vehicle's blind spot and provide some form of warning to the driver (e.g., illuminating a warning light on the edge of the side-view mirror or an auditory alert) if a vehicle is detected in the blind spot while the turn signal is activated. The target population for BSW systems is comprised of sideswipe crashes between vehicles traveling in the same direction in adjacent lanes where the vehicle changing lanes is slightly ahead of a vehicle in its blind spot, as well as the subset of front-to-rear crashes in which the lane-changing vehicle is struck in the rear. This is distinct from sideswipe crashes targeted by LDW and LKA systems. Those systems target crashes in which the lane departure is unintentional, whereas BSW systems target crashes in which the driver is changing lanes on purpose but fails to notice the presence of another vehicle.

Farmer (2008) estimated that BSW systems could potentially prevent approximately 26% of lane-change crashes. Jermakian (2011) estimated similarly that BSW systems could prevent approximately 24% of all lane-changing crashes between 2004 and 2008, which amounted to 395,000 total crashes including 393 fatal crashes annually over the study period.

HLDI (2015c) estimated that Mazda's BSW system reduced collision claims by 3%, property damage liability claims by 11%, and bodily injury liability claims by 18% after controlling for the effects of other safety systems present on the same vehicles. A study by Cicchino (2017c) of police-reported crashes of similar vehicles with and without BSW systems estimated that the systems reduced all lane-change crashes of equipped vehicles by 14%. Results for injury crashes, while not statistically significant, suggested roughly a 23% reduction in lane-change crashes that resulted in injuries.

Collectively, these studies have demonstrated that the potential safety benefits of ADAS are substantial. However, there is considerable variability in the magnitudes of the benefits estimated both within and across system types. In addition, there have been significant shifts in the relative contributions of specific types of crashes to the overall traffic safety problem in the United States in the past decade. The purpose of the following analysis is to provide updated estimates of the numbers of crashes, injuries, and deaths that selected ADAS systems have the potential to prevent or mitigate based on the numbers and types of crashes in the United States in 2016.

Data Analysis

The data analysis presented in this review sought to quantify the number of crashes, injuries, and deaths that occurred in the United States in 2016 that theoretically might have been avoided or reduced in severity had the involved vehicles been equipped with the technologies of interest. Data on police-reported crashes and injuries that occurred in crashes were from the NHTSA's Crash Report Sampling System (CRSS), which comprises a representative sample of all police-reported motor vehicle crashes nationwide (NHTSA, 2018). Data on deaths that occurred in crashes were from the NHTSA's Fatality Analysis Reporting System (FARS), which is a census of all fatal motor vehicle crashes nationwide (NHTSA, 2017). Data from the CRSS were weighted to produce nationally representative estimates. Deaths reported in the CRSS were excluded from the analysis to avoid double-counting of crashes also represented in FARS.

Variables pertaining to the vehicle, driver, geometry of the crash, environmental conditions, and the sequence of events of the crash were used to identify crashes that the systems of interest are designed to prevent or mitigate. The general approach to the analysis was a simple two-step process. The first step was to identify crashes of the general type that each respective technology is designed to address (e.g., LDW systems are designed to prevent crashes in which the vehicle leaves its travel lane unintentionally). The second step was to subtract specific subsets of those crashes that the technology likely would not have prevented due to its known limitations (e.g., sensors not functioning reliably in inclement weather) or idiosyncratic factors present in the crash (e.g., the driver was intoxicated and thus might not have responded appropriately to warnings).

Crashes of potential interest in the current analysis were those that involved a passenger vehicle in the first harmful event of the crash. There were an estimated 6,950,000 such crashes in the United States in 2016, resulting in 3,034,000 injuries and 32,702 deaths.

Forward Collision Warning and Automatic Emergency Braking

As noted previously, FCW and AEB systems are designed to prevent or mitigate crashes in which a forward-moving vehicle strikes the vehicle in front of it (i.e., rear-end crashes). Many current-generation FCW and AEB systems are also designed to detect and respond to pedestrians and cyclists. For the purpose of the current analysis, the target population for FCW and AEB systems was taken to be crashes in which a forward-moving passenger vehicle rear-ends the vehicle in front of it or strikes a pedestrian or cyclist in the first harmful event of the crash. There were an estimated 2,484,000 such crashes in 2016, resulting in approximately 1,111,000 injuries and 6,933 deaths.

Some of these crashes occurred in conditions that FCW and AEB systems would not likely be successful in preventing or mitigating, such as:

- Crashes that occurred in rain, snow, or fog, which can prevent a vehicle's sensors from functioning reliably.
- Crashes that occurred on roads covered in snow, ice, slush, sand, mud, or standing water, which might decrease the efficacy of the vehicle's brakes.
- Crashes that occurred off the paved road surface, which might affect the vehicle's braking or handling characteristics and thus diminish braking efficacy.
- Crashes in which the vehicle lost traction or experienced an equipment failure, or the driver executed an avoidance maneuver to avoid a previous critical event.
- Crashes in which the driver was reportedly asleep, ill, or impaired by drugs or alcohol.

After subtracting the above-mentioned crashes, there were an estimated 1,994,000 crashes, 884,000 injuries and 4,738 deaths that could have been potentially prevented or mitigated by FCW or AEB systems in 2016 (Table 1). A large majority of the crashes potentially preventable by FCW or AEB are rear-end crashes (85%); however, most of the fatalities that these systems have the potential to prevent are fatalities of pedestrians and cyclists (74%) (Table 2).

Table 1. Numbers of Crashes, Injuries, and Deaths that Forward Collision Warning and Automatic Emergency Braking Systems Could Potentially Help Prevent.

	Crashes	Injuries	Deaths
Total Rear-End and Pedestrian/Cyclist Crashes	2,484,000	1,111,000	6,933
Unlikely Preventable by FCW / AEB			
Inclement Weather	243,000	98,000	523
Adverse Surface Conditions	129,000	48,000	296
Occurred off Road	2,000	1,000	112
Loss of Control	50,000	33,000	373
Driver Asleep/Ill/Impaired	66,000	47,000	891
Total Unlikely Preventable by FCW / AEB	490,000	227,000	2,195
Potentially Preventable by FCW / AEB	1,994,000	884,000	4,738

Table 2. Major Types of Crashes, Injuries, and Deaths that Forward Collision Warning and Automatic Emergency Braking Systems Could Potentially Help Prevent.

	Crashes	Injuries	Deaths
		Number (Column %)	
Rear-End	1,687,000 (84.6)	739,000 (83.6)	987 (20.8)
Single Vehicle vs. Ped/bike	83,000 (4.2)	81,000 (9.2)	3,501 (73.9)
Turn Into/Across Path	109,000 (5.5)	32,000 (3.6)	45 (0.9)
Others	115,000 (5.8)	33,000 (3.7)	205 (4.3)
Total	1,994,000 (100.0)	884,000 (100.0)	4,738 (100.0)

Lane Departure Warning and Lane Keeping Assistance

LDW systems are designed to help the driver prevent crashes in which the vehicle departs its travel lane when the driver did not intend to do so; LKA systems are designed to prevent the vehicle from leaving its travel lane unintentionally. Thus, for the purpose of this analysis, the target population for LDW and LKA systems was taken to be crashes in which a passenger vehicle left its travel lane prior to the first harmful event in the crash and was not coded as turning, merging, passing, changing lanes, or otherwise leaving the travel lane on purpose. There were 1,395,000 crashes that met these criteria, which resulted in 589,000 injuries and 15,445 deaths.

Many of these crashes, however, occurred in scenarios that LDW and LKA systems would not likely address, including:

- Crashes that occurred in rain, snow, or fog, which might obstruct the vehicle's cameras.
- Crashes that occurred on roads covered in snow, ice, slush, sand, mud, or standing water, which might obscure lane markings.
- Crashes in which the vehicle lost traction or experienced an equipment failure, or the driver executed an avoidance maneuver to avoid a previous critical event.
- Crashes in which the driver was reportedly asleep, ill, or impaired by drugs or alcohol.

After subtracting the above-mentioned crashes, there were an estimated 519,000 crashes, 187,000 injuries, and 4,654 deaths that could potentially have been prevented or mitigated by LDW or LKA systems in 2016 (Table 3). The single crash type that accounted for the greatest proportion of these crashes, injuries, and deaths was road departure crashes, however, a substantial proportion of the fatalities potentially preventable by LDW or LKA systems occurred in head-on crashes as well (Table 4).

Table 3. Numbers of Crashes, Injuries, and Deaths that Lane Departure Warning and Lane Keeping Assistance Systems Could Potentially Help Prevent.

	Crashes	Injuries	Deaths
Total Unintentional Lane Departure Crashes	1,395,000	589,000	15,445
Unlikely Preventable by LDW /LKA			
Inclement Weather	295,000	108,000	1,717
Adverse Surface Conditions	135,000	51,000	1,096
Loss of Traction/Control	242,000	129,000	4,215
Driver Asleep/Ill/Impaired	203,000	114,000	3,763
Total Unlikely Preventable by LDW / LKA	876,000	402,000	10,791
Potentially Preventable by LDW / LKA	519,000	187,000	4,654

Table 4. Major Types of Crashes, Injuries, and Deaths that Lane Departure Warning and Lane Keeping Assistance Systems Could Potentially Help Prevent.

	Crashes	Injuries	Deaths
		Number (Column %)	
Road Departure	240,000 (46.2)	109,000 (58.3)	2,536 (54.5)
Sideswipe/Angle	103,000 (19.8)	25,000 (13.4)	406 (8.7)
Head-On	14,000 (2.7)	20,000 (10.7)	1,320 (28.4)
Others	162,000 (31.2)	33,000 (17.6)	392 (8.4)
Total	519,000 (100.0)	187,000 (100.0)	4,654 (100.0)

Blind Spot Warning

Blind spot warning systems are designed to alert the driver if a vehicle is traveling in his or her blind spot, which becomes relevant if the driver intends to change lanes. The target population for BSW systems was taken to be crashes in which the driver was attempting to change lanes, merge, pass another vehicle, or turn across multiple lanes of traffic and struck or was struck by another vehicle that was traveling in the same direction in an adjacent lane, with the impact occurring on the side or rear of the vehicle that was changing lanes. There were an estimated 349,000 such crashes resulting in 100,000 injuries, and 348 deaths in 2016.

Some of these crashes, however, occurred in scenarios in which BSW systems would not likely help the driver to avoid crashing, such as:

- Crashes that occurred in rain, snow, or fog, which might obstruct the vehicle's sensors.
- Crashes in which the vehicle lost traction or experienced an equipment failure, or the driver executed an avoidance maneuver to avoid a previous critical event.
- Crashes in which the driver was reportedly asleep, ill, or impaired by drugs or alcohol.

After subtracting the above-mentioned crashes, there were an estimated 318,000 crashes, 89,000 injuries, and 274 deaths that could potentially have been prevented by BSW systems in 2016 (Table 5). As expected, most of these were sideswipe crashes, however, a substantial minority of them were rear-end crashes in which a vehicle was rear-ended immediately after an unsafe lane change, and turn-across-path crashes in which a driver turned across the path of another vehicle traveling in the same direction in an adjacent lane in his or her blind spot and was struck on the side (Table 6).

Table 7 shows the crashes potentially preventable with the help of each of these respective systems, as well as the aggregate total number of crashes potentially preventable by all of these systems, as a percentage of all crashes that involved passenger vehicles. The aggregate total is slightly

Table 5. Numbers of Crashes, Injuries, and Deaths that Blind Spot Warning Systems Could Potentially Help Prevent.

	Crashes	Injuries	Deaths
Total Same-Direction Lane-Change Crashes	349,000	100,000	348
Unlikely Preventable by BSW			
Inclement Weather	25,000	8,000	17
Loss of Traction/Control	3,000	2,000	22
Driver Asleep/Ill/Impaired	3,000	1,000	35
Total Unlikely Preventable by BSW	31,000	10,000	74
Potentially Preventable by BSW	318,000	89,000	274

Table 6. Major Types of Crashes, Injuries, and Deaths that Blind Spot Warning Systems Could Potentially Help Prevent.

	Crashes	Injuries	Deaths
		Number (Column %)	
Sideswipe	195,000 (61.3)	40,000 (44.9)	115 (42.0)
Rear-End	69,000 (21.7)	30,000 (33.7)	87 (31.8)
Turn Across Path	54,000 (17.0)	19,000 (21.3)	71 (25.9)
Total	318,000 (100.0)	89,000 (100.0)	274 (100.0)

Table 7. Total Numbers of Crashes, Injuries, and Deaths that Selected Advanced Driver Assistance Systems Could Potentially Help Prevent Individually and in Aggregate.

	Crashes	Injuries	Deaths
Total Passenger-Vehicle Crashes	6,950,000	3,034,000	32,702
Potentially Preventable by FCW/AEB	1,994,000 (29%)	884,000 (29%)	4,738 (14%)
Potentially Preventable by LDW/LKA	519,000 (7%)	187,000 (6%)	4,654 (14%)
Potentially Preventable by BSW	318,000 (5%)	89,000 (3%)	274 (1%)
Total Potentially Preventable by All Systems Above	2,748,000 (40%)	1,128,000 (37%)	9,496 (29%)

smaller than the sum of the individual contributions of each system due to some overlap in the crashes addressed by each. For example, a BSW system might help avoid a crash in which a driver is rear-ended after performing an unsafe lane change by discouraging the driver from performing the lane change maneuver, and an AEB system might help prevent the same crash by automatically applying the brakes of the other vehicle when the lane-changing vehicle suddenly enters its lane.

In total, all of the technologies examined are estimated to have the potential to prevent approximately 40% of all passenger-vehicle crashes, 37% of injuries that occur in crashes involving passenger vehicles, and 29% of all deaths in crashes that involve passenger vehicles. Notably, FCW/AEB and LDW/LKA systems were each estimated to have the potential to help prevent approximately 14% of fatalities; however, FCW/AEB systems were estimated to be relevant to more than four times as many crashes and injuries as LDW/LKA. This is because the types of crashes targeted by LDW/LKA systems, i.e., lane departure crashes and especially single-vehicle road departure crashes, tend to be more severe than most other crash types. FCW and AEB systems have the potential to prevent a substantial number of fatalities, especially involving pedestrians and cyclists; however, most of the overall crashes to which they are relevant are rear-end crashes, which are rarely fatal. The overall contribution of BSW systems to crash reductions was the smallest by all measures, but they are still estimated to have the potential to help prevent as many as 318,000 crashes annually.

Discussion

This research brief estimates that ADAS technologies including forward collision warning, automatic emergency braking, lane departure warning, lane keeping assistance, and blind spot warning systems, if installed on all vehicles, would have had the potential to help to prevent or mitigate roughly 40% of all crashes involving passenger vehicles, and 37% of all injuries and 29% of all fatalities that occurred in those crashes. Most of the crashes that these technologies have the potential to prevent are rear-end crashes potentially addressed by FCW and AEB systems. However, the largest shares of fatalities that these technologies have the potential to prevent are pedestrians and cyclists killed in crashes potentially preventable by FCW and AEB, and vehicle occupants killed in lane-departure crashes potentially preventable by LDW and LKA. It is important to note that this research brief does not attempt to quantify the efficacy of the technologies examined, but rather to quantify the number of crashes that such technologies could theoretically prevent if they were installed on all passenger vehicles and successfully prevented all crashes that they were theoretically capable of preventing. Furthermore, the inclusion criteria for crashes in this analysis did not take into account unique capabilities or limitations of any specific manufacturer's implementation of a particular system on a particular vehicle; it attempted to capture the typical capabilities and limitations of current and near-term future systems. It is anticipated that sensors and algorithms will continue to improve over the coming years.

In consideration of past findings, it is important to address the variation in estimates from previous studies to the present study. For instance, other researchers excluded crashes where speeding was a known factor (Farmer, 2008; Jermakian, 2011), whereas the present study did not exclude such crashes. Particularly, LDW and LKA systems are not designed to activate during low-speed driving (e.g., at speeds below roughly 30-35 mph) and might not reliably activate when driving at high speeds on curvy roads. While actual vehicle travel speed was not available in the data examined, few of the crashes and very few of the fatalities classified as potentially preventable by these technologies occurred on roads with speed limits below 30 mph; thus, excluding crashes on low-speed roads would have had minimal impact on the results. The data did not contain any information about the radius of curvature of the roadway. The data contained only a crude binary indicator of whether the police indicated that the driver was "speeding," but not actual vehicle travel speed; thus, there was insufficient information to identify crashes that these systems would be unable to prevent or mitigate due to the combination of speed and curvature. Thus, it is possible that LDW and LKA systems might not actually be able to prevent all of the crashes classified as potentially preventable. Similarly, BSW systems would not be expected to help the driver avoid a crash in which a vehicle in an adjacent lane was traveling at a much higher speed than the lane-changing vehicle, or crashes in which two vehicles simultaneously attempted to move into the same space from opposite directions. These data analyzed for the current study did not contain sufficient information to reliably identify such crashes.

Another difference between the current study versus the previous studies is that the current study excluded crashes in which the police indicated that the driver was ill, asleep, or impaired by alcohol or drugs. While these issues are likely underreported in the data, the analysis assumed that these technologies — particularly the warning systems — would not have prevented crashes in which the police had determined that the driver was impaired with sufficient confidence to indicate such on the police crash report form. It is possible that AEB and LKA — systems that temporarily take partial control of the vehicle automatically if the driver takes no action — would help prevent some specific crashes involving impaired drivers that were classified as not likely preventable in the current analysis. However, if those specific crashes were prevented, the impaired drivers might have been involved subsequently in other crashes that the technology could not prevent. Therefore, in the interest of producing a more conservative estimate, all crashes in which the police reported that the relevant driver was impaired were still classified as likely not preventable by the technologies.

Providing warnings to drivers might not always result in successful crash avoidance or mitigation. For instance, individual differences in driver reaction times may impact one's ability to respond quickly and correctly to a warning, especially if the driver is not fully alert and attentive. Previous studies have demonstrated, unsurprisingly, that distracted drivers tend to exhibit longer brake reaction times to a decelerating lead vehicle than the nondistracted driver (Lee, Llaneras, Klauer, & Sudweeks, 2007). While collision warnings are likely to be especially beneficial to a distracted driver, the proportion of all theoretically relevant crashes (i.e., the quantity estimated in the current study) that they will actually prevent or mitigate is unclear. In many cases active systems such as AEB and LKA might be more likely to successfully prevent or mitigate crashes than their counterparts that only provide warnings and rely on the driver to take action. Cicchino (2017a) estimated that standalone FCW reduced rear-end crashes by 27% when implemented as a stand-alone system and by 50% when implemented in conjunction with AEB. In providing a common set of estimates for FCW and AEB and for LDW and LKA, this research brief does not intend to imply that both would actually prevent the same number of crashes, only that the population of crashes to which the technologies are theoretically relevant is the same.

Limitations

This study has several limitations that should be noted. The results of the current study represent a theoretical upper bound of the potential safety benefits of these systems, not their expected actual benefits. These results represent the benefits that would be observed if all vehicles were equipped with these systems, the systems functioned properly 100% of the time, and drivers take timely and proper action in response to warnings 100% of the time, and all crashes deemed "likely preventable" in the current study actually did occur under conditions in which the system had the ability and opportunity to act. Real-world safety benefits would not likely be this large. However, the current study provides insights into the numbers and types of crashes that could versus could not plausibly be prevented or mitigated by the types of ADAS technologies available today.

The data examined for the current study included information about the sequence of crash events, but not the timing of those events, precluding determination of whether an event leading to a crash would have allowed enough time for the system to intervene. Another unknown is how the driver's reactions to alerts or interventions will change the outcome of a collision (i.e., whether a collision would be avoided altogether, reduced substantially in severity, reduced only slightly in severity, or possibly even replaced with another different crash caused by a driver's incorrect response to a warning).

The analysis presented here was not able to account for possible unintended consequences of the systems. For example, if drivers become over-reliant on the systems, it is possible that they might become involved in crashes when relying on the systems to provide assistance in conditions in which they cannot (i.e., outside of their operational design domain), or become involved in crashes when driving a different vehicle (e.g., an older family vehicle, a rental car, etc.) not equipped with a system upon which the driver had come to rely. A previous study by the NHTSA in collaboration with the AAA Foundation found that a substantial minority of early-adopters of radar-based backing assistance systems reported having had a crash or close call while driving a different vehicle not equipped with the technology, because they incorrectly expected the unequipped vehicle to provide warnings (Jenness et al., 2007).

Implications

While the results of the current study indicate that the technologies examined hold great promise for reducing the numbers of crashes, injuries, and deaths on U.S. roads, they also highlight the limits of their effectiveness. The results suggest that if all passenger vehicles in the United States were equipped with the technologies examined, and that the technologies prevented all of the crashes that they were theoretically capable of preventing, they could plausibly have prevented slightly less than one-third of all deaths that occurred in crashes involving passenger vehicles. A similar number of fatalities occurred in crashes of the same general types but were deemed likely unpreventable by these specific technologies due to their having occurred under adverse environmental conditions, after the driver lost control of the vehicle or while the driver was impaired, suggesting potential roles for sensors and algorithms that function reliably in the presence of precipitation and on wet roads, increasing market penetration of proven technologies such as electronic stability control, and measures to prevent drowsy or intoxicated drivers from driving.

Beyond these crashes, results also point to categories of crashes not well addressed by these technologies, principally angle crashes that involve vehicles on intersecting paths or vehicles turning across one another's paths, which accounted for more than 3,500 additional fatalities in 2016 that the systems examined here would not likely address. It is possible that enhancements to algorithms used in FCW and AEB systems might help to address some of these crashes; however, in the future, such crashes might be more effectively prevented by vehicle-to-vehicle communications than by vehicle systems acting in isolation.

Finally, as ADAS technologies become more prevalent and more familiar, there may be a risk that some drivers will place too much trust in these and adapt their driving behaviors in inappropriate ways that counteract the potential benefits of the systems to some degree (Sullivan, Flannagan, Pradhan, & Bao, 2016), intentionally or unintentionally. A recent study by the AAA Foundation found substantial lack of awareness of certain safety-critical limitations of ADAS technologies among owners of vehicles equipped with the technologies (McDonald et al., 2018). It is important for drivers to remain vigilant and aware of their systems' own capabilities and limitations.

Current and future vehicle safety systems have the potential to dramatically reduce the number of crashes, injuries and fatalities on our roadways. This research brief estimates that ADAS technologies including forward collision warning, automatic emergency braking, lane departure warning, lane keeping assistance and blind spot warning systems, if installed on all vehicles, would have had the potential to help prevent or mitigate roughly 40% of all crashes involving passenger vehicles, and 37% of all injuries and 29% of all fatalities that occurred in those crashes. Results also illuminate types of crashes not well addressed by such systems — information that could be used to guide further system refinements as well as highlight the potential for vehicle-to-vehicle and vehicle-to-infrastructure communication to provide further benefits beyond those provided by safety systems that operate on the level of the individual vehicle.

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