VALUING THE SAFETY BENEFITS OF CONNECTED AND AUTOMATED VEHICLE TECHNOLOGIES

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ABSTRACT

Connected and automated vehicle (CAV) technologies have a promising future in improving traffic safety, including mitigating crash severity and decreasing the possibility of crashes by offering warnings to drivers and/or assuming vehicle control in dangerous situations. Given the complexities of technology interactions and crash details, the overall safety impacts of multiple CAV technologies have not yet been estimated. This research seeks to fill that gap by using the most current U.S. General Estimates System crash records to estimate the economic and functional-years crash-related savings from each CAV application. Safety benefits of Forward Collision Warning, Cooperative Adaptive Cruise Control, Do Not Pass Warning, Control Lost Warning, Cooperative Intersection Collision Avoidance Systems, Electronic Stability Control, and other safety-related CAV-type technologies are estimated here.

Results suggest that eleven CAV technologies, such as Forward Collision Warning, when combined with Cooperative Adaptive Cruise Control, and Cooperative Intersection Collision Avoidance Systems, can save Americans $76 billion each year (along with almost 740,000 functional-life-years saved per year). These estimates are based on pre-crash scenarios that depict the critical event occurring immediately prior to a crash (e.g., rear-end and intersection-related situations) and under conservative effectiveness scenario assumptions; the savings are due to crash avoidance and/or moderation of crash severities. Among the various combinations of driving situations and technology applications, Forward Collision Warning coupled with Cooperative Adaptive Cruise Control is anticipated to offer the biggest safety benefits, by saving more than $53 billion (in economic costs) and 497,100 functional person-years in 2013.

Keywords: Safety Benefits, Connected and Automated Vehicle Technologies, Pre-Crash Scenarios, General Estimate System, Crash Data

INTRODUCTION

Advanced transport technologies, including connected-vehicle technology (e.g., Vehicle-to-Vehicle [V2V] and Vehicle-to-Infrastructure [V2V]) and automated vehicle (AV) technology, have a promising future in improving traveler safety by warning drivers of dangerous conditions and/or taking the control of automated (including semi-automated) vehicles. For example, Forward Collision Warning (FCW) is a relatively simple application based on (all-weather) radar and sometimes lasers and cameras that detects an impending collision by recognizing the speed, acceleration, and locations of nearby vehicles and providing an FCW-using driver with warnings to avoid a possible crash (Harding et al., 2014). This will reduce some of the most common crash types, including rear-end crashes. If the vehicle also has automated emergency braking enabled, the vehicle can self-slow or self-stop. If automated steering exists, the vehicle self-shift laterally to avoid collisions. In comparison, a Cooperative Intersection Collision Avoidance System (CICAS) is a special Vehicle-to-Infrastructure (V2I) safety application that moderates the count and severity of intersection-related crashes by warning drivers about likely violations of traffic control devices and then helping drivers avoid the collision (Misener, 2010). Adaptive Cruise Control (ACC) requires relatively minimal Automated Vehicle (AV) technology on board, so that it can detect a vehicle immediately ahead (in the same lane) of a vehicle and adjust the latter's speed to maintain adequate distance from the vehicle in front. Cooperative Adaptive Cruise Control (CACC) is an extension to the ACC, aiming to increase traffic throughput by safely permitting shorter following distances between vehicles (Jones, 2013). Such applications are expected to largely improve roadway safety while saving vehicle owners and others much money, pain and suffering. This paper estimates the safety benefits of advanced vehicle technologies in monetary and life-year terms, after summarizing relevant literature on V2V, V2I, and AV technologies.

There has been solid investigation in this topic area over the past 10 or so years. In 2006, the U.S. National Highway Transportation Safety Administration (NHTSA) entered into a cooperative research agreements for Advanced Crash Avoidance Technologies (ACAT) with multiple manufacturers and research teams, including Honda, Volvo, Ford, General Motors, the University of Michigan, and the Virginia Tech Transportation Institute. Those agreements focused on evaluating the safety benefits of several advanced transport technologies by creating an original simulation method, the Safety Impact Methodology (SIM) (Funke et al., 2011). The SIM investigated the safety benefits of Advanced Collision Mitigation Braking Systems (A-CMBS), Lane Departure Warning (LDW) systems, and the Pre-Collision Safety System (PCSS), by integrating historical crash data (from the U.S.) and naturalistic driving data to populate the simulation model. The following paragraphs describe many of those sponsored-research results.

Gordon et al. (2010) focused on crashes occurring after a subject vehicle exits the travel lane and developed the target crash types based mainly on the NASS General Estimates System (GES) and National Automotive Sampling System Crashworthiness Data System (NASS CDS) data sets to investigate the system effectiveness of LDW. Their results suggest that use of LDW systems can reduce 47% of all lane-departure-related crashes, corresponding to 85,000 crashes annually.

Perez et al. (2011) identified backing-up crash scenarios from national and state crash data sources and estimated that the backing-crash countermeasures (like backup collision intervention, via automated braking) could prevent almost 65,000 backup crashes a year (64,823 estimated), among the over 200,000 (201,583) backing-up crashes (typically in parking spaces and at driveways) that occurred in the U.S. in 2004.

Wilson et al. (2007) collected driving data from 78 U.S participants to evaluate the performance and safety benefits of Road Departure Crash Warning (RDCW) technology. With the RDCW activated, a 10- to 60-percent reduction in departure conflict frequency was observed at speeds above 55 mph. With an assumption of 100 percent deployment and 100 percent device availability, an annual reduction of 9,400 to 74,800 U.S. road-departure crashes (all at high speeds) was predicted.

To better estimate the safety benefits of advanced transportation technologies, Najm et al. (2010) investigated V2V and V2I systems and the crash types whose frequencies may be affected by such applications. They estimated that V2V systems, like FCW, Blind Spot Warning (BSW) and Lane Change Warning (LCW), can serve as primary crash countermeasures, reducing U.S. light-duty vehicle-involved crashes by 76 percent. They further estimated that V2I systems, like Curve Speed Warning (CSW), Red Light Violation Warning (RLVW), and Stop Sign Violation Warning (SSVW), if deployed anywhere they could be useful, could address 25 percent of all light-duty-vehicle crashes in the U.S.

Based on Najm et al.'s (2010) 37 pre-crash scenarios, Jermakian (2011) estimated the maximum potential for U.S. crash reductions for four crash avoidance technologies: Side View Assist, FCW, LDW, and Adaptive Headlights. He extracted crash records from the 2004-2008 NASS GES and FARS data sets in order to calculate the frequency of all related crash types. He estimated that FCW holds the greatest potential for preventing crashes of any severity, up to 1.2 million crashes per year in the U.S., or 20 percent of the annual 5.8 million police-reported crashes. LDW appeared relevant for 179,000 crashes per year, but these can be quite severe, to his total estimate from implementation of LDW was a savings of up to 7,500 fatal crashes, or 4 percent of all lane-departure-related crashes per year. He also estimated that Side View Assist and Adaptive Headlights could prevent 395,000 and 142,000 crashes per year, or 24 percent of lane-changing-related crashes and 4 percent of all front-to-rear, single-vehicle, and sideswipe same-direction crashes.

More recently, Rau et al. (2015) developed a method to determine crashes that can be addressed by AV technologies by mapping specific AV-based safety applications to five layers of crash information, including crash location, pre-crash scenario details, driving conditions, travel speeds, and driver conditions. Their study results mapped crashes to several Level 2, 3 and 4 automation technologies (L2, L3 and L4 - using NTHSA's [2013] definitions) and various AV safety applications, including ACC and Automatic Emergency Braking (AEB). But they did not take the next step: to anticipate crash reductions.

In reality, the safety benefits of combining connected vehicle (CV) and AV technologies are important for many more crashes, but detailed work in this area has not yet been undertaken or at least not published. Driver error is considered a major culprit in over 90% of all road crashes (NHTSA, 2008), and Singh (2015) recently estimated that 94 percent of public roadway crashes can be assigned to human errors, based on statistical results he derived from the 2005 to 2007

National Motor Vehicle Crash Causation Survey (NMVCCS). This paper's research estimates the safety benefits from CV and AV technology combinations, rather than considering only V2V or V2I technology, in the absence of driving automation. These combinations will reduce the impact of human error during the driving process and should improve overall traffic safety, unless, of course, travelers (both motorized and non-motorized) abuse the system, by becoming much more reckless in their travel behaviors.

The remainder of this paper is organized as follows: Section 2 describes the method of estimating the safety benefits of these technologies, Section 3 presents the analysis results of eleven combinations of connected and automated vehicle technologies, and Section 4 offers conclusions.

METHODOLODY

In this section, Najm's (2007) latest pre-crash typology is presented first to help map the V2V, V2I and AV safety applications to specific crash types. In this way, safety benefits for each application can be estimated, using economic costs and functional-years lost per typical crash of each variety. The final part of this section introduces three technology-effectiveness scenarios, to reflect uncertainty in how many crashes will benefit from such technologies and hopefully cover the range of the total economic benefits and quality-life-years to be saved by the various CV and AV applications.

Typology of Pre-Crash Situations

Pre-crash scenarios depict vehicle movements and the critical event immediately prior to a crash, which enables researchers to determine which traffic safety issues should be of the first priority and determine whether to investigate and design countermeasures to avoid them, or mitigate their severity if they cannot be avoided. Najm et al. (2007) defined a new typology of 37 pre-crash scenarios for crash avoidance research based on the 44-crash typology generated by General Motors (GM) in 1997 and pre-crash scenarios typology devised by USDOT in his 2003 report (Najm, 2003). His new typology (shown as Table 1) utilizes the U.S. GES crash database, since it is updated annually, is nationally representative, and offers important for identifying pre-crash events; thus, it is the best available source for identification and description. The coding schemes enabled the researchers to identify each pre-crash scenario leading to all single-vehicle and multi-vehicle crashes based on GES variables and codes. The main variables in the 2004 GES crash database include Critical Event (P_CRASH2), Vehicle Maneuver (MANEUV_I), First Harmful Event (EVENT1_I) and Crash Type (ACC_TYPE).

The Critical Event (P_CRASH2) variable depicts the critical event, which is coded for each vehicle, and identifies the circumstances leading to the vehicle's first impact in the crash. The pre-crash scenario Vehicle Failure, for example, has the identification code P_CRASH=1-4.

The Vehicle Maneuver (MANEUV_I) variable represents vehicle maneuver, which describes the last action this vehicle's driver engaged in, either immediately before the impact or just before the driver has recognized the impending danger. The codes related to this variable in the 2004 GES database are as follows: 1 = going straight, 2 = decelerating in traffic lane, 3 = accelerating in traffic lane, 4 = starting in traffic lane, 5 = stopped in traffic lane, 6 = passing or overtaking another vehicle, 7 = disabled or parked in travel lane, 8 = leaving a parked position, 9 = entering a parked position, 10 = turning right, 11 = turning left, 12 = making a U-turn, 13 = backing up, 14 = negotiating a curve, 15 = changing lanes, 16 =merging, 17 = corrective action to a previous critical event, 97 = other.

Other variables used in the 2004 GES pre-crash scenarios are presented. The First Harmful Event (EVENT1_I) variable describes the first injurious or damaging event of the crash, and the Crash Type (ACC_TYPE) variable specifies crash type of the vehicle involved based on the first harmful event and the pre-crash circumstances. Typical crash types include Drive Off Road, Control/Traction Loss and Avoid Collision with Vehicle, Pedestrian, Animal. The Violations Charged (MVIOLATN) variable indicates which violations are charged to the drivers, which will be used to identify the Running Red Light and Running Stop Sign pre-crash scenarios. The Traffic Control Device (TRAF_CON) depicts whether or not traffic control devices were present for a motor vehicle and the type of traffic control device.

However, several variables and their value meanings were of difference between 2004 GES and 2013 GES due to the changes of data coding (NHTSA, 2014). Those variables include Traffic Control Device, Violations Charged, and First Harmful Event. In addition, the variable, describing vehicle role in crashes, has been deleted in the 2013 GES records, which does not critical impacts on our safety benefits analysis. The reason is this variable only influences the exact frequencies of pre-crash scenarios with rear-end crashes, but not the total frequencies of rear-end crashes addressed on corresponding safety applications.

In coding the year-2013 NASS GES data to identify passenger-vehicle crash counts, crash records differed between the GES Accident file and Vehicle file. After eliminating incomplete and incorrect data records , 34,794 valid crash records (involving at least one light-duty vehicle) remained in the 2013 NASS GES files. When sampling weights are applied, these records represent approximately 5,508,000 crashes and 20,503 fatalities nationwide, including 1,608,000 single-vehicle crashes and 3,900,000 multi-vehicle crashes.

In our study, only light-duty vehicle crashes (i.e., those involving passenger cars, sports utility vehicles, vans, minivans, and pickup trucks) are investigated. The GES variables of Body type and Special Use were queried to identify all light-duty vehicles. Body type was set to include types 01-22, 28-41, and 45-49. Special Use was set equal to 0. Furthermore, in order to eliminate double counting of crashes in each scenario, pre-crash scenarios were updated by removing all scenarios in the number order via a process of elimination; in this way, the resulting frequency distribution sums to 100 percent. For example, one crash record can be assigned to pre-crash scenarios 1, 5 and 10, but this crash record will only belong to pre-crash scenario 1 because of its number order.

The 37 scenario identification codes can be used to select records from the GES database, and all pre-crash scenarios can be categorized into crash types, a more general term to segment or distinguish crashes. Table 1 illustrates each pre-crash scenario and the crash types to which they belong.

Table 1. Mapping of Crash Types to New Pre-Crash Scenario Typology (Najm et al., 2007)

No.	Pre-Crash Scenario	Crash Type
1	Vehicle Failure	Run-Off-Road
2	Control Loss With Prior Vehicle Action	

3	Control Loss Without Prior Vehicle Action	
4	Running Red Light	Crossing Paths
5	Running Stop Sign	
6	Road Edge Departure With Prior Vehicle Maneuver	Run-Off-Road
7	Road Edge Departure Without Prior Vehicle Maneuver	
8	Road Edge Departure While Backing Up	
9	Animal Crash With Prior Vehicle Maneuver	Animal
10	Animal Crash Without Prior Vehicle Maneuver	
11	Pedestrian Crash With Prior Vehicle Maneuver	Pedestrian
12	Pedestrian Crash Without Prior Vehicle Maneuver	
13	Pedalcyclist Crash With Prior Vehicle Maneuver	Pedalcyclist
14	Pedalcyclist Crash Without Prior Vehicle Maneuver	
15	Backing Up Into Another Vehicle	Backing
16	Vehicle(s) Turning - Same Direction	Lane Change
17	Vehicle(s) Changing Lanes - Same Direction	
18	Vehicle(s) Drifting - Same Direction	
19	Vehicle(s) Parking - Same Direction	Parking
20	Vehicle(s) Making a Maneuver - Opposite Direction	Opposite Direction
21	Vehicle(s) Not Making a Maneuver - Opposite Direction	
22	Following Vehicle Making a Maneuver	Rear-End
23	Lead Vehicle Accelerating	
24	Lead Vehicle Moving at Lower Constant Speed	
25	Lead Vehicle Decelerating	
26	Lead Vehicle Stopped	
27	LTAP/OD at Signalized Junctions	Crossing Paths
28	Vehicle Turning Right at Signalized Junctions	
29	LTAP/OD at Non-Signalized Junctions	
30	Straight Crossing Paths at Non-Signalized Junctions	
31	Vehicle(s) Turning at Non-Signalized Junctions	
32	Evasive Action With Prior Vehicle Maneuver	Run-Off-Road
33	Evasive Action Without Prior Vehicle Maneuver	
34	Non-Collision Incident	Non-Collision
35	Object Crash With Prior Vehicle Maneuver	Object
36	Object Crash Without Prior Vehicle Maneuver	
37	Other	Other

Monetary and Non-Monetary Measure of the Pre-Crash Scenario Loss

Economic cost is a common term in transportation engineering to estimate the monetary loss of crashes and related events. Functional-years lost, a measure that provides a non-monetary measure of time lost as a result of motor vehicle crashes, represents the sum of the years of life lost to fatal injuries and years of functional capacity (much like a reasonable quality of life) lost to non-fatal injuries (Miller, 1991). Economic costs are defined as goods and services that must be purchased or productivity that is lost as a result of motor vehicle crashes (Blincoe, 2015). This includes lost productivity (at paid work and at home, for example), medical costs, legal and court costs, emergency service costs, insurance administration costs, travel delay, property damage, and workplace losses.

With Najm's (2007) identification codes of pre-crash scenarios used in the 2004 GES crash database, the frequency of each pre-crash scenario and the injury severity rating to a person be derived using the KABCO scale in year-2013 GES crash records. The KABCO scale records injury severity as resulting in a death (K, for killed), an incapacitating injury (A), a non-incapacitating injury (B), a possible injury (C), or no apparent injury/property-damage only (O).

The KABCO scale must be translated into the Maximum Abbreviated Injury Scale (MAIS) to estimate economic costs and functional-years lost. MAIS levels of injury severity (for the crash victim who suffered the greatest injury) have seven categories, ranging from uninjured (MAIS0) to fatal (MAIS6), thus differing somewhat from the KABCO scale, which has six categories from fatal (K) to injury severity unknown (ISU). Here, Blincoe's (2015) KABCO/MAIS translator, designed on the basis of 2000-2008 NASS CDS data, was employed, to convert all GES injury severities from KABCO to MAIS.

The economic unit costs of reported and unreported crashes were calculated in U.S. dollars for the year 2010 for each level of MAIS injury severity, and these were used to convert the MAIS injury severity to economic costs. Because the economic costs estimates in our study are based on the 2013 GES crash database, a cumulative rate of inflation between 2010 and 2013 was used (6.8% over 3 years). In total, the unit costs of a crash where no one is injured (MAIS0) thus becomes $3,042 in 2013 dollars, a crash victim suffering minor injury (MAIS1) is valued at $19,057, one experiencing moderate injury crash (MAIS2) is valued at $59,643, a serious injury (MAIS3) is valued at $194,662, a severe injury (MAIS4) is $422,231, and a critical injury (MAIS5) is $1,071,165, and fatal injury (MAIS6) is estimated to represent $1,496,840 in economic loss.

Functional-years lost is a non-monetary measure that calculates the years of life lost due to fatal injury and the years of functional capacity lost due to non-fatal injuries (Najm, 2007). This assigns a different value to the relative severity of injuries suffered from motor vehicle crashes. The numbers between injury severity on the basis of MAIS scale and the functional-years lost are 0.07, 1.1, 6.5, 16.5, 33.3, and 42.7 functional-years lost, corresponding to the MAIS0 through MAIS6.

Mapping the Advanced Safety Applications to the Specific Pre-Crash Scenarios

The first step of this estimation process involves mapping each advanced safety application to specific, applicable pre-crash scenarios. Najm et al. (2013) recently mapped many safety applications using V2V technology, including Forward Collision Warning (FCW), Intersection Movement Assist (IMA), Blind Spot Warning and Lane Changing Warning (BSW and LCW), Do Not Pass Warning (DNPW) and Control Loss Warning (CLW), to 17 pre-crash scenarios that can be somewhat addressed by V2V technology. For example, FCW can reduce the frequency of read-end crash types, including the pre-crash scenarios of Following Vehicle Making a Maneuver, Lead Vehicle Accelerating, Lead Vehicle Moving at Lower Constant Speed, Lead Vehicle Decelerating and Lead Vehicle Stopped. With the help of Automatic Emergency Braking, the injury severity of rear-end crashes can be further mitigated by slowing the vehicle in time.

Intersection Movement Assist (IMA) can be mapped to certain crossing-paths crash types, including the pre-crash scenarios of Left Turn Across Path of Opposite Direction (LTAP/OD) at

Non-Signalized Junctions, Straight Crossing Paths at Non-Signalized Junctions and Vehicle(s) Turning at Non-Signalized Junctions. CICAS' objectives is a cooperative intersection collision avoidance system to warn drivers of impending violations at traffic signals and stop signs (Maile and Delgrossi, 2009). Compared with IMA, CICAS has a more powerful function, which warns drivers of running a red light or stop sign or of red-right or stop-sign runners; CICAS can also coordinate intersection movements, and thus take the place of the IMA, Red Light Violation Warning (RLVW), and Stop Sign Violation Warning (SSVW) systems. Therefore, CICAS addresses the following pre-crash scenarios: Running Red Light, Running Stop Sign, LTAP/OD at Signalized Junctions, Vehicle Turning Right at Signalized Junctions, LTAP/OD at Non-Signalized Junctions, Straight Crossing Paths at Non-Signalized Junctions, and Vehicle(s) Turning at Non-Signalized Junctions.

BSW and LCW technologies will benefit the Vehicle(s) Turning - Same Direction, Vehicle(s) Changing Lanes - Same Direction and Vehicle(s) Drifting - Same Direction pre-crash scenarios. DNPW should improve safety in Vehicle(s) Making a Maneuver - Opposite Direction and Vehicle(s) Not Making a Maneuver - Opposite Direction pre-crash situations. CLW can help avoid or mitigate the severity of Vehicle Failure, Control Loss With Prior Vehicle Action and Control Loss Without Prior Vehicle Action pre-crash situations.

Road Departure Crash Warning (RDCW) is a combined application of Lateral Drift Warning (LDW) and Curve Speed Warning (CSW), which can warn drivers of impending road departure (Wilson et al., 2007). The major function of the LDW is to monitor the vehicle's lane position, lateral speed, and available maneuvering room by using a video camera to estimate the distances between the vehicle and the left and right lane boundaries, and is able to alert a driver when it appears the vehicle was likely to depart the lane of the road. The main contrition of CSW is to monitor vehicle speed and upcoming road curvature and able to alert a driver when the vehicle was approaching the upcoming curve at an unsafe speed. The RDCW application has the potential to improve the traffic safety of the pre-crash scenarios of Road Edge Departure With Prior Vehicle Maneuver, Road Edge Departure Without Prior Vehicle Maneuver and Road Edge Departure While Backing Up according to the their definitions.

The Vehicle-to-Pedestrian (V2Pedestrian) and Vehicle-to-Pedalcyclist (V2Pedalcyclist) communication safety application have the potential to detect a pedestrian in a possible crash situation with a vehicle and warn the driver (Harding et al., 2014). To be more specific, the pedestrians can carry devices (such as mobile phones) that can send out a safety signal using Dedicated Short Range Communications (DSRC) and communicate with DSRC devices that would be used in vehicles, so both the pedestrian and the driver could be warned if a possible conflict arises. Four pre-crash scenarios, Pedestrian Crash With Prior Vehicle Maneuver, Pedestrian Crash Without Prior Vehicle Maneuver, Pedalcyclist Crash With Prior Vehicle Maneuver and Pedalcyclist Crash Without Prior Vehicle Maneuver can be addressed by this safety application.

The safety applications described above emphasize connected-vehicle technologies, such as V2V and V2I. Automated Vehicle (AV) technology is rapidly advancing and will also play a key safety role by reducing or even eliminating many human-related factors leading to crashes, and greatly improve warning response times and response decisions.

Cooperative Adaptive Cruise Control (CACC), an extension of ACC, uses Radar and LIDAR measurements to derive the range to the vehicle in front, the preceding vehicle's acceleration is used in a feed-forward loop (Jones, 2013) This enhanced safety application, associated with FCW, can further reduce the number of rear end crashes, including the pre-crash scenarios of Following Vehicle Making a Maneuver, Lead Vehicle Accelerating, Lead Vehicle Moving at Lower Constant Speed, Lead Vehicle Decelerating and Lead Vehicle Stopped. Therefore, a combination of V2V and AV technologies (FCW & CACC) has been identified to address pre-crash scenarios of Following Vehicle Making a Maneuver, Lead Vehicle Accelerating, Lead Vehicle Moving at Lower Constant Speed, Lead Vehicle Decelerating and Lead Vehicle Stopped.

Lane Keeping Assist (LKA) technology alerts the driver when lane deviations are detected in his/her vehicle. The system can also work in conjunction with the Radar Cruise Control system to help the driver steer and keep the vehicle on course (Bishop, 2005). The LKA technology maps to pre-crash scenarios of Road Edge Departure With Prior Vehicle Maneuver, Road Edge Departure Without Prior Vehicle Maneuver and Road Edge Departure While Backing Up, which are also addressed by the RDCW. Therefore, a combination of V2I and AV technologies (RDCW and LKA) has been mapped to these pre-crash scenarios.

Electronic Stability Control (ESC) is another important AV safety application technology. The ESC is an on-board car safety system, which enables the stability of a car to be maintained during critical maneuvering and to correct potential under steering or over steering, which can help avoid crashes that result due to loss of control(Lie et al., 2006). Automatic Emergency Braking (AEB) can use radar, laser or video to detect when obstructions or pedestrians are present and be automatically applied to avoid the collision or at least to mitigate the effects on the situation that a collision is imminent involving the host and target vehicles. According to their function, the pre-crash scenarios of Animal Crash With Prior Vehicle Maneuver, Animal Crash Without Prior Vehicle Maneuver, Evasive Action With Prior Vehicle Maneuver, Evasive Action Without Prior Vehicle Maneuver, Object Crash With Prior Vehicle Maneuver and Object Crash Without Prior Vehicle Maneuver could be mapped to the ESC and AEB. Although other pre-crash scenarios (e.g., scenarios involving pedestrian) may be also related to these safety applications, in order to avoid double counting, the combination of ESC and AEB only be mapped to the six pre-crash scenarios mentioned above.

The pre-crash scenario, Backing Up Into Another Vehicle, can be addressed by the Backup Collision Intervention (BCI) that intelligently senses what the driver may miss when backing up and can even apply the brakes momentarily to get driver’s attention.

Not all of Table 1’s pre-crash scenarios have been mapped to specific safety applications on the basis of connected vehicle (CV) and AV technologies. Due to the uncertain characteristics of the pre-crash scenarios of Non-Collision Incident and Other, there is no corresponding safety application to address. As for the Non-Collision Incident, a typical scenario is that vehicle is going straight in a rural area, in daylight, under clear weather conditions, at a non-junction location with a posted speed limit of over 55 mph; and then fire starts. According to this situation, none of the safety applications mentioned above can benefit to avoid the accident or mitigate the accident severity. On the other hand, the Other pre-crash scenario may obtain benefit from those safety applications, so the combination impacts of the CV and AV based safety applications will be exerted on this scenario.

Table 2 lists all the pre-crash scenarios and their corresponding safety applications on the basis of CV and AV technologies, with the exception of Non-Collision Incident.

Table 2 Mapping Pre-crash Scenarios to CAV Technologies

No.	Pre-Crash Scenario	Mapping Safety Applications
1	Vehicle Failure	CLW
2	Control Loss With Prior Vehicle Action	
3	Control Loss Without Prior Vehicle Action	
4	Running Red Light	CICAS
5	Running Stop Sign	
6	Road Edge Departure With Prior Vehicle Maneuver	RDCW+LKA
7	Road Edge Departure Without Prior Vehicle Maneuver	
8	Road Edge Departure While Backing Up	
9	Animal Crash With Prior Vehicle Maneuver	AEB+ESC
10	Animal Crash Without Prior Vehicle Maneuver	
11	Pedestrian Crash With Prior Vehicle Maneuver	V2Pedestrian
12	Pedestrian Crash Without Prior Vehicle Maneuver	
13	Pedalcyclist Crash With Prior Vehicle Maneuver	V2Pedalcyclist
14	Pedalcyclist Crash Without Prior Vehicle Maneuver	
15	Backing Up Into Another Vehicle	BCI
16	Vehicle(s) Turning - Same Direction	BSW+LCW
17	Vehicle(s) Changing Lanes - Same Direction	
18	Vehicle(s) Drifting - Same Direction	
19	Vehicle(s) Parking - Same Direction	SPVS
20	Vehicle(s) Making a Maneuver - Opposite Direction	DNPW
21	Vehicle(s) Not Making a Maneuver - Opposite Direction	
22	Following Vehicle Making a Maneuver	FCW+CACC
23	Lead Vehicle Accelerating	
24	Lead Vehicle Moving at Lower Constant Speed	
25	Lead Vehicle Decelerating	
26	Lead Vehicle Stopped	
27	LTAP/OD at Signalized Junctions	CICAS
28	Vehicle Turning Right at Signalized Junctions	
29	LTAP/OD at Non-Signalized Junctions	
30	Straight Crossing Paths at Non-Signalized Junctions	
31	Vehicle(s) Turning at Non-Signalized Junctions	
32	Evasive Action With Prior Vehicle Maneuver	AEB+ESC
33	Evasive Action Without Prior Vehicle Maneuver	
34	Non-Collision Incident	None
35	Object Crash With Prior Vehicle Maneuver	AEB+ESC
36	Object Crash Without Prior Vehicle Maneuver	
37	Other	Combined Impacts of Safety Applications

Effectiveness Assumptions of Safety Applications

Mapping the technologies to the target pre-crash scenarios is not enough to estimate the safety benefits of them. Effectiveness of each technology on corresponding pre-crash scenario/scenarios is needed to complete the safety benefits analysis. The most ideal way to obtain the actual effectiveness of technologies is to take advantage of field test and collect data from the real life operation. However, the usage of those technologies mentioned above is rare at this moment, let alone the available field test data to conduct related research. Therefore, assumptions of effectiveness of safety applications on related pre-crash scenarios are made.

The meaning of effectiveness discussed here is the rate of fatal crashes (K) decreased based on the KABCO scale with 90 percent market penetration of all CV and AV technologies. The effectiveness of safety applications for other severity types will be increased by 10 percent compared with their next higher injury severity levels. The maximum effectiveness is 1. The effectiveness of safety applications on Injury Severity Unknown (ISU) will be set up to a constant rate, as well as on the Other pre-crash scenario. Three different scenarios are considered, including conservative, moderate, and aggressive effectiveness scenarios.

For example, in the conservative scenario, the effectiveness of the combination of FCW and CACC on rear-end crashes is assumed to be 0.7 in terms of fatal crashes. According to our regulation, its effectiveness for the incapacitating injury (A), non-incapacitating injury (B), possible injury (C), or uninjured (O) is 0.8, 0.9, 1 and 1, respectively. In addition, the effectiveness of the safety applications on their corresponding pre-crash scenarios' ISU is uniformly set up to 0.3 in the conservative effectiveness scenario, as well as the combination effectiveness of all technologies on Other pre-crash scenario.

Table 3 presents the effectiveness assumptions of three scenarios.

Table 3 Effectiveness Assumptions of Safety Application in Three Scenarios

Safety Application	Conservative						Moderate						Aggressive					
	K	A	B	C	O	U	K	A	B	C	O	U	K	A	B	C	O	U
FCW+CACC	0.7	0.8	0.9	1	1	0.3	0.8	0.9	1	1	1	0.4	0.9	1	1	1	1	0.5
CICAS	0.5	0.6	0.7	0.8	0.9	0.3	0.6	0.7	0.8	0.9	1	0.4	0.8	0.9	1	1	1	0.5
CLW	0.4	0.5	0.6	0.7	0.8	0.3	0.5	0.6	0.7	0.8	0.9	0.4	0.6	0.7	0.8	0.9	1	0.5
RDCW+LKA	0.3	0.4	0.5	0.6	0.7	0.3	0.5	0.6	0.7	0.8	0.9	0.4	0.7	0.8	0.9	1	1	0.5
SPVS	0.6	0.7	0.8	0.9	1	0.3	0.7	0.8	0.9	1	1	0.4	0.8	0.9	1	1	1	0.5
BSW+LCW	0.7	0.8	0.9	1	1	0.3	0.8	0.9	1	1	1	0.4	0.9	1	1	1	1	0.5
DNPW	0.6	0.7	0.8	0.9	1	0.3	0.7	0.8	0.9	1	1	0.4	0.8	0.9	1	1	1	0.5
AEB+ESC	0.3	0.4	0.5	0.6	0.7	0.3	0.4	0.5	0.6	0.7	0.8	0.4	0.5	0.6	0.7	0.8	0.9	0.5
V2Pedestrian	0.4	0.5	0.6	0.7	0.8	0.3	0.5	0.6	0.7	0.8	0.9	0.4	0.6	0.7	0.8	0.9	1	0.5
BCI	0.7	0.8	0.9	1	1	0.3	0.8	0.9	1	1	1	0.4	0.9	1	1	1	1	0.5
V2Pedalcyclist	0.3	0.4	0.5	0.6	0.7	0.3	0.4	0.5	0.6	0.7	0.8	0.4	0.5	0.6	0.7	0.8	0.9	0.5
Combined Impacts of Safety Applications	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5

The effectiveness assumptions will be applied to the original frequency of severity in terms of KABCO scale, and then translates the KABCO scale to the MAIS scale to complete the safety benefits estimate.

RESULTS

Table 4 lists pre-crash scenarios of all light-vehicle crashes by occurrence frequency. 36 pre-crash scenarios represent 99.8 percent of all 2013 GES passenger-vehicle crashes. The top-five (most common) pre-crash scenarios are Lead Vehicle Moving at Lower Constant Speed, Road

Edge Departure Without Prior Vehicle Maneuver, Control Loss Without Prior Vehicle Action, Evasive Action Without Prior Vehicle Maneuver, and Non-Collision Incident, accounting for 47.0 percent of all police-reported, light-duty-vehicle crashes.

Table 5 shows the pre-crash scenarios, in terms of the resulting loss: $170 billion in total economic cost and 2,318,000 functional-years lost. Tables 6 through 8 present the safety benefits of all smart-vehicle-technology applications, according to each pre-crash scenarios under each of the three different effectiveness scenarios.

Advanced transport technologies are estimated to save from $127 to $151 billion in economic costs each year in the U.S., and as much as 1,422,600 to 1,652,200 functional human-years. Among the eleven safety application combinations, the FCW associated with CACC is estimated to have the greatest potential to reduce crash costs, by prevent or mitigate the severity of crossing-path crashes, resulting in an estimated annual (economic) savings of at least $53 billion, alongside 497,100 functional years. This technology is followed by CICAS, in terms of savings benefits. Taken together, they comprise 60%, 57% and 55% of total economic costs from crashes, under the in conservative, moderate and aggressive effectiveness scenarios, respectively.

Table 4 Frequency of Pre-Crash Scenarios of All Light-Vehicle Crashes Based on 2013 GES Crash Records

No.	Pre-Crash Scenario	Frequency	Relative Frequency
1	Vehicle Failure	44,000	0.80%
2	Control Loss With Prior Vehicle Action	65,000	1.18%
3	Control Loss Without Prior Vehicle Action	393,000	7.14%
4	Running Red Light	192,000	3.49%
5	Running Stop Sign	36,000	0.65%
6	Road Edge Departure With Prior Vehicle Maneuver	85,000	1.54%
7	Road Edge Departure Without Prior Vehicle Maneuver	441,000	8.01%
8	Road Edge Departure While Backing Up	77,000	1.40%
9	Animal Crash With Prior Vehicle Maneuver	3,000	0.05%
10	Animal Crash Without Prior Vehicle Maneuver	297,000	5.39%
11	Pedestrian Crash With Prior Vehicle Maneuver	27,000	0.49%
12	Pedestrian Crash Without Prior Vehicle Maneuver	42,000	0.76%
13	Pedalcyclist Crash With Prior Vehicle Maneuver	127,000	2.31%
14	Pedalcyclist Crash Without Prior Vehicle Maneuver	120,000	2.18%
15	Backing Up Into Another Vehicle	22,000	0.40%
16	Vehicle(s) Turning - Same Direction	279,000	5.07%
17	Vehicle(s) Parking - Same Direction	247,000	4.48%
18	Vehicle(s) Changing Lanes - Same Direction	4,000	0.07%
19	Vehicle(s) Drifting - Same Direction	95,000	1.72%
20	Vehicle(s) Making a Maneuver - Opposite Direction	91,000	1.65%
21	Vehicle(s) Not Making a Maneuver - Opposite Direction	1,113,000	20.21%
22	Following Vehicle Making a Maneuver	202,000	3.67%
23	Lead Vehicle Accelerating	268,000	4.87%
24	Lead Vehicle Moving at Lower Constant Speed	202,000	3.67%
25	Lead Vehicle Decelerating	47,000	0.85%
26	Lead Vehicle Stopped	136,000	2.47%
27	LTAP/OD at Signalized Junctions	321,000	5.83%

28	Vehicle Turning Right at Signalized Junctions	320,000	5.81%
29	LTAP/OD at Non-Signalized Junctions	125,000	2.27%
30	Straight Crossing Paths at Non-Signalized Junctions	78,000	1.42%
31	Vehicle(s) Turning at Non-Signalized Junctions	9,000	0.16%
32	Evasive Action With Prior Vehicle Maneuver	44,000	0.80%
33	Evasive Action Without Prior Vehicle Maneuver	65,000	1.18%
34	Non-Collision Incident	393,000	7.14%
35	Object Crash With Prior Vehicle Maneuver	192,000	3.49%
36	Object Crash Without Prior Vehicle Maneuver	36,000	0.65%
37	Other	85,000	1.54%
	Totals	***5,508,000***	***100%***

Table 5 Economic Costs and Functional-years lost of All Pre-Crash Scenarios Based on 2013 GES Crash Records

No.	Pre-Crash Scenario	Economic Costs (Millions of 2013 Dollars)	Functional-years lost (Years)
1	Vehicle Failure	$1,585	25,000
2	Control Loss With Prior Vehicle Action	$14,425	290,000
3	Control Loss Without Prior Vehicle Action	$7,570	103,000
4	Running Red Light	$1,194	14,000
5	Running Stop Sign	$1,958	34,000
6	Road Edge Departure With Prior Vehicle Maneuver	$13,419	264,000
7	Road Edge Departure Without Prior Vehicle Maneuver	$667	5,000
8	Road Edge Departure While Backing Up	$27	1,000
9	Animal Crash With Prior Vehicle Maneuver	$3,359	29,000
10	Animal Crash Without Prior Vehicle Maneuver	$2,653	62,000
11	Pedestrian Crash With Prior Vehicle Maneuver	$5,086	125,000
12	Pedestrian Crash Without Prior Vehicle Maneuver	$925	15,000
13	Pedalcyclist Crash With Prior Vehicle Maneuver	$1,221	24,000
14	Pedalcyclist Crash Without Prior Vehicle Maneuver	$2,094	14,000
15	Backing Up Into Another Vehicle	$2,983	38,000
16	Vehicle(s) Turning - Same Direction	$550	6,000
17	Vehicle(s) Parking - Same Direction	$6,948	60,000
18	Vehicle(s) Changing Lanes - Same Direction	$5,222	41,000
19	Vehicle(s) Drifting - Same Direction	$952	26,000
20	Vehicle(s) Making a Maneuver - Opposite Direction	$6,087	124,000
21	Vehicle(s) Not Making a Maneuver - Opposite Direction	$24	1,000
22	Following Vehicle Making a Maneuver	$2,496	29,000
23	Lead Vehicle Accelerating	$32,399	300,000
24	Lead Vehicle Moving at Lower Constant Speed	$6,320	72,000
25	Lead Vehicle Decelerating	$7,167	62,000
26	Lead Vehicle Stopped	$8,172	116,000
27	LTAP/OD at Signalized Junctions	$884	6,000
28	Vehicle Turning Right at Signalized Junctions	$5,102	70,000

29	LTAP/OD at Non-Signalized Junctions	$11,065	145,000
30	Straight Crossing Paths at Non-Signalized Junctions	$9,151	103,000
31	Vehicle(s) Turning at Non-Signalized Junctions	$8	1,000
32	Evasive Action With Prior Vehicle Maneuver	$177	3,000
33	Evasive Action Without Prior Vehicle Maneuver	$106	3,000
34	Non-Collision Incident	$174	2,000
35	Object Crash With Prior Vehicle Maneuver	$1,413	23,000
36	Object Crash Without Prior Vehicle Maneuver	$5	1,000
37	Other	$5,423	81,000
	Totals	***$ 169,011***	***2,318,000***

Table 6 Annual Economic Cost and Functional-years lost Savings Estimates from Safety Benefits of CAV Technologies under Conservative Effectiveness Scenario (per year, based on 2013 GES Crash Records)

No.	Combination of Safety Applications	Pre-Crash Scenario	Economic Costs Saved ($1M in 2013USD)	Saved Functional-years lost (Years)
1	FCW+CACC	Following Vehicle Making a Maneuver Lead Vehicle Accelerating Lead Vehicle Moving at Lower Constant Speed Lead Vehicle Decelerating Lead Vehicle Stopped	$53,311	497,100
2	CICAS	Running Red Light Running Stop Sign LTAP/OD at Signalized Junctions Vehicle Turning Right at Signalized Junctions LTAP/OD at Non-Signalized Junctions Straight Crossing Paths at Non-Signalized Junctions Vehicle(s) Turning at Non-Signalized Junctions	$22,512	241,900
3	CLW	Vehicle Failure Control Loss With Prior Vehicle Action Control Loss Without Prior Vehicle Action	$13,899	208,200
4	RDCW+LKA	Road Edge Departure With Prior Vehicle Maneuver Road Edge Departure Without Prior Vehicle Maneuver Road Edge Departure While Backing Up	$6,645	104,300
5	SPVS	Vehicle(s) Parking - Same Direction	$6,397	47,100
6	BSW+LCW	Vehicle(s) Turning - Same Direction Vehicle(s) Changing Lanes - Same Direction Vehicle(s) Drifting - Same Direction	$6,196	58,600
7	DNPW	Vehicle(s) Making a Maneuver - Opposite Direction Vehicle(s) Not Making a Maneuver - Opposite Direction	$4,536	82,700
8	AEB+ESC	Animal Crash With Prior Vehicle Maneuver Animal Crash Without Prior Vehicle Maneuver	$4,049	47,400

		Evasive Action With Prior Vehicle Maneuver		
		Evasive Action Without Prior Vehicle Maneuver		
		Object Crash With Prior Vehicle Maneuver		
		Object Crash Without Prior Vehicle Maneuver		
9	V2Pedestrian	Pedestrian Crash With Prior Vehicle Maneuver	$3,043	64,700
		Pedestrian Crash Without Prior Vehicle Maneuver		
10	BCI	Backing Up Into Another Vehicle	$2,678	29,300
11	V2Pedalcyclist	Pedalcyclist Crash With Prior Vehicle Maneuver	$1,950	17,100
		Pedalcyclist Crash Without Prior Vehicle Maneuver		
12	Combined Impacts of Safety Applications	Other	$1,628	24,200
	Totals		***$126,838***	***1,422,600***

Table 7 Annual Economic Cost and Functional-years lost Savings Estimates from Safety Benefits of CAV Technologies under Moderate Effectiveness Scenario (per year, based on 2013 GES Crash Records)

No.	Combination of Safety Applications	Pre-Crash Scenario	Economic Costs Saved ($1M in 2013USD)	Saved Functional-years lost (Years)
1	FCW+CACC	Following Vehicle Making a Maneuver	$54,890	533,500
		Lead Vehicle Accelerating		
		Lead Vehicle Moving at Lower Constant Speed		
		Lead Vehicle Decelerating		
		Lead Vehicle Stopped		
2	CICAS	Running Red Light	$25,206	275,600
		Running Stop Sign		
		LTAP/OD at Signalized Junctions		
		Vehicle Turning Right at Signalized Junctions		
		LTAP/OD at Non-Signalized Junctions		
		Straight Crossing Paths at Non-Signalized Junctions		
		Vehicle(s) Turning at Non-Signalized Junctions		
3	CLW	Vehicle Failure	$16,300	250,900
		Control Loss With Prior Vehicle Action		
		Control Loss Without Prior Vehicle Action		
4	RDCW+LKA	Road Edge Departure With Prior Vehicle Maneuver	$9,468	157,800
		Road Edge Departure Without Prior Vehicle Maneuver		
		Road Edge Departure While Backing Up		
5	SPVS	Vehicle(s) Parking - Same Direction	$6,649	51,800
6	BSW+LCW	Vehicle(s) Turning - Same Direction	$6,407	64,000
		Vehicle(s) Changing Lanes - Same Direction		
		Vehicle(s) Drifting - Same Direction		
7	DNPW	Vehicle(s) Making a Maneuver - Opposite Direction	$5,042	94,900

		Vehicle(s) Not Making a Maneuver - Opposite Direction		
8	AEB+ESC	Animal Crash With Prior Vehicle Maneuver	$4,836	59,500
		Animal Crash Without Prior Vehicle Maneuver		
		Evasive Action With Prior Vehicle Maneuver		
		Evasive Action Without Prior Vehicle Maneuver		
		Object Crash With Prior Vehicle Maneuver		
		Object Crash Without Prior Vehicle Maneuver		
9	V2Pedestrian	Pedestrian Crash With Prior Vehicle Maneuver	$3,649	78,700
		Pedestrian Crash Without Prior Vehicle Maneuver		
10	BCI	Backing Up Into Another Vehicle	$2,792	32,300
11	V2Pedalcyclist	Pedalcyclist Crash With Prior Vehicle Maneuver	$2,289	21,000
		Pedalcyclist Crash Without Prior Vehicle Maneuver		
12	Combined Impacts of Safety Applications	Other	$2,170	32,200
	Totals		***$139,694***	***1,652,200***

Table 8 Annual Economic Cost and Functional-years lost Savings Estimates from Safety Benefits of CAV Technologies under Aggressive Effectiveness Scenario (per year, based on 2013 GES Crash Records)

No.	Combination of Safety Applications	Pre-Crash Scenario	Economic Costs Saved ($1M in 2013USD)	Saved Functional-years lost (Years)
1	FCW+CACC	Following Vehicle Making a Maneuver	$55,792	533,500
		Lead Vehicle Accelerating		
		Lead Vehicle Moving at Lower Constant Speed		
		Lead Vehicle Decelerating		
		Lead Vehicle Stopped		
2	CICAS	Running Red Light	$27,615	275,600
		Running Stop Sign		
		LTAP/OD at Signalized Junctions		
		Vehicle Turning Right at Signalized Junctions		
		LTAP/OD at Non-Signalized Junctions		
		Straight Crossing Paths at Non-Signalized Junctions		
		Vehicle(s) Turning at Non-Signalized Junctions		
3	CLW	Vehicle Failure	$18,702	250,900
		Control Loss With Prior Vehicle Action		
		Control Loss Without Prior Vehicle Action		
4	RDCW+LKA	Road Edge Departure With Prior Vehicle Maneuver	$11,977	157,800
		Road Edge Departure Without Prior Vehicle Maneuver		
		Road Edge Departure While Backing Up		
5	SPVS	Vehicle(s) Parking - Same Direction	$6,807	51,800
6	BSW+LCW	Vehicle(s) Turning - Same Direction	$6,575	64,000

		Vehicle(s) Changing Lanes - Same Direction		
		Vehicle(s) Drifting - Same Direction		
7	DNPW	Vehicle(s) Making a Maneuver - Opposite Direction	$5,477	94,900
		Vehicle(s) Not Making a Maneuver - Opposite Direction		
8	AEB+ESC	Animal Crash With Prior Vehicle Maneuver	$5,622	59,500
		Animal Crash Without Prior Vehicle Maneuver		
		Evasive Action With Prior Vehicle Maneuver		
		Evasive Action Without Prior Vehicle Maneuver		
		Object Crash With Prior Vehicle Maneuver		
		Object Crash Without Prior Vehicle Maneuver		
9	V2Pedestrian	Pedestrian Crash With Prior Vehicle Maneuver	$4,254	78,700
		Pedestrian Crash Without Prior Vehicle Maneuver		
10	BCI	Backing Up Into Another Vehicle	$2,892	32,300
11	V2Pedalcyclist	Pedalcyclist Crash With Prior Vehicle Maneuver	$2,627	21,000
		Pedalcyclist Crash Without Prior Vehicle Maneuver		
12	Combined Impacts of Safety Applications	Other	$2,712	32,200
	Totals		***$151,046***	***1,652,200***

CONCLUSIONS

This study attempts to comprehensively anticipate the safety benefits of various CV and AV technologies, in combination, and in terms of economic costs and functional life-years saved in the U.S. The most recently available U.S. crash database (the 2013 NASS GES) was used, and results suggest that advanced CAV technologies may reduce current US crash costs at least by $126 billion per year (not including pain and suffering damages, and other non-economic costs) and functional human-years lost by nearly 2 million (per year). These results rely on the three different effectiveness scenarios with market penetration rate of 90 percent of all CV and AV based safety applications.

Of the eleven safety applications or combinations of safety applications, the one with the greatest potential to avoid or mitigate crashes is FCW associated with CACC. CICAS also offer substantial safety rewards, with total economic savings over $22 billion each year (and almost 1.24 million years saved). These two safety applications are estimated here to represent over 55 percent of the total economic costs saved by all eleven combinations of CV and AV technologies, suggesting important directions for government agencies and transportation system designers and planners. These two technologies may most merit priority deployment, incentives policies, and driver/traveler adoption.

There is little doubt that CAV technologies will offer some significant safety benefits to transportation system users. However, the actual effectiveness of these technologies will not be known until sufficient real-world data have been collected and analyzed. Here, their effectiveness assumes 90-percent market access and use (so technologies are available to all motorized vehicle occupants and are not disabled by those occupants), as well as different success rates under several assumption scenarios. Such assumptions come with great uncertainty, and the interaction between CAV systems and drivers/travelers. More on-road deployment and testing will be helpful, alongside simulated driving situations. It is also important to mention that connectivity is not needed in many cases, when AV cameras will suffice. But CICAS does require a roadside device able to communicate quickly with all vehicles. And NHTSA is likely to require DSRC on all new vehicles in model year 2020 and forward (Harding et al., 2014), so connectivity may come much more quickly than high levels of automation, in terms of fleet mix over time. Older vehicles may be made connected soon after, when costs are low (e.g., $100 for add-ons to existing vehicles (Bansal and Kockelman, 2015 and the benefits of connectivity more evident to the nation).

It is also useful to note that GES crash records have more attributes than those used here, including road types and weather conditions at time of crash. Future work may do well to focus on anticipating technology-specific safety benefits with more hierarchical pre-crash scenarios, combined with road types and weather conditions. Furthermore, the database used in this study only contains GES crash records, representing only U.S. driving context. For more detailed results, local crash databases, and databases in other countries, can be mined, which may suggest different benefit rankings and magnitudes.

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LIST OF ACRONYMS

ACC	Adaptive Cruise Control
ACAT	Advanced Crash Avoidance Technologies
AEB	Automatic Emergency Braking
AV	Automated Vehicle
BCI	Backup Collision Intervention
BSW	Blind Spot Warning
CACC	Cooperative Adaptive Cruise Control
CAV	Connected and Automated Vehicle
CICAS	Cooperative Intersection Collision Avoidance Systems
CLW	Control Lost Warning
CSW	Curve Speed Warning
CV	Connected Vehicle
DNPW	Do Not Pass Warning
DSRC	Dedicated Short Range Communications
ESC	Electronic Stability Control
FCW	Forward Collision Warning
GES	General Estimate System
IMA	Intersection Movement Assist

ISU	Injury Severity Unknown
LCW	Lane Changing Warning
LDW	Lateral Drift Warning
LKA	Lane Keeping Assist
LTAP/OD	Left Turn Across Path of Opposite Direction
MAIS	Maximum Abbreviated Injury Scale
NASS-CDS	National Automotive Sampling System: Crashworthiness Data System
NASS-GES	National Automotive Sampling System: General Estimate System
NHTSA	National Highway Transportation Safety Administration
RDCW	Road Departure Crash Warning
RLVW	Red Light Violation Warning
SSVW	Stop Sign Violation Warning
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2Pedalcyclist	Vehicle-to-Pedalcyclist
V2Pedestrian	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle