ESTIMATING THE CONTRIBUTIONS OF AUTOMATIC EMERGENCY BRAKING AND LANE SUPPORT SYSTEMS TO ACHIEVING VISION ZERO

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ABSTRACT

Vision Zero is an approach to transportation safety that aims to eliminate all traffic-related fatalities and lifelong injuries. A common strategy to achieving Vision Zero is the safe system approach, which employs a multitude of transportation-related branches to create a safe system for all road users. The design and implementation of advanced driver assist systems (ADAS) is one way to contribute to Vision Zero. This study used real-world nationally representative crash data from the Crash Investigation Sampling System to estimate the contributions of two ADAS to achieving Vision Zero in the United States: an advanced automatic emergency braking system (A-AEB) and lane support systems (LSS). It was assumed A-AEB has crash avoidance capabilities for rear-end crashes, left turn across path opposite direction and lateral direction crashes, and straight crossing path crashes, as well as injury mitigation capabilities due to prevented crashes as well as due to delta-v reduction due to system-induced braking. It was assumed LSS has crash avoidance capabilities for head-on crashes, road departure crashes, and opposite direction sideswipe crashes. The combined contributions were estimated to prevent a cumulative 7,054,894 crashes and 869,456 moderate to fatal injuries by 2050. Despite this, over 125,000 moderate to fatal injuries are still estimated to occur each year, and the total number of crashes is not expected to decline. This emphasizes the need for continuous future contributions from all branches of transportation if the US is to someday achieve Vision Zero.

INTRODUCTION

Vision Zero

Vision Zero, officially adopted by the United States (US) Department of Transportation in 2022, is an approach to road safety that aims to eliminate all traffic-induced fatalities and lifelong injuries [1][2]. To achieve Vision Zero, a common strategy is the safe system approach, which considers the limitations and capabilities of human drivers [3]. Many factors contribute to achieving a safe system, including but not limited to: vehicle design, road design, traffic-related laws, and regulatory standards. One approach to Vision Zero is the development of advanced driver assist systems (ADAS), that are designed to assist drivers in performing normal driving and evasive maneuver actions.

Advanced Driver Assist Systems

ADAS are one way vehicle safety is improving to help achieve a safe system. ADAS are vehicle-mounted systems designed to aid the driver in performing driving tasks and reduce the occurrence and severity of crashes [4]. One example of an ADAS is automatic emergency braking (AEB) which uses forward-facing sensors to prevent and mitigate frontal crashes [5]. Similarly, lane support systems (LSS) systems are designed to assist drivers in staying within the lane boundaries. One LSS system, lane departure warning (LDW) uses a combination of auditory, visual, and haptic warnings to alert the drive they are encroaching upon the lane boundary and need to make a corrective maneuver [5]. A second LSS system, lane keep assistance (LKA) is an active safety system that makes minor steering adjustments, without driver input, to correct the vehicle's trajectory to prevent the vehicle from departing the lane boundaries [5]. Like LDW, LKA may also provide a combination of warnings to alert the drive the vehicle is encroaching upon lane boundaries. Additionally, some LKA systems assist the vehicle in remaining centered within the lane. AEB, LDW, and LKA all have the ability to help avoid crashes, while AEB and LDW have the additional ability to mitigate the severity of a crash by assisting or encouraging the driver to make corrective maneuvers.

Previous Work

Previous research has shown AEB [6]–[9] to be a very effective system in terms of crash prevention, such that several manufacturers have voluntarily committed to standardizing AEB on their vehicles by 2022 [10]. In addition to investigating the effectiveness of current AEB systems, some work has investigated the potential effectiveness of a future advanced AEB (A-AEB) system: an intersection advanced driver assist system (I-ADAS), equipped with AEB capabilities [11]–[13]. Similar to assessing AEB and A-AEB effectiveness, various approaches have been taken to assess the effectiveness of LSS [6], [14], [15]. To successfully achieve Vision Zero, it is necessary to understand the combined effect of AEB and LSS in not only crash prevention, but also in injury mitiation. Some of the aforementioned studies have estimated injury mitigation effectiveness of these systems using the KABCO scale [6][7]. The KABCO scale is a five-level injury scale developed by the Federal Highways Administration (FHWA) and is used by law enforcement to record injuries for persons involved in vehicle crashes [16]. Other studies used the abbreviated injury scale (AIS) to estimate injury mitigation effectiveness for AEB in various crash modes [9], [11]–[13]. The abbreviated injury scale (AIS) is a medically relevant scale designed by medical professionals that divides injuries into six levels [17]. Due to the medical relevance and the detail used to assign AIS scores, it is a more reliable injury scale than KABCO [18].

Automatic Emergency Braking Bareiss et al. [13] investigated the crash avoidance and injury mitigation effectiveness of an A-AEB system in left turn across path opposite direction (LTAP/OD) crashes. Injury mitigation effectiveness was estimated for occupants who sustained a serious injury: a maximum AIS (MAIS) score of 3 or greater, including fatalities (MAIS3+F). However, it is possible for permanent medical impairment to occur at the moderate injury level (MAIS2+F) [19], [20], so it is critical to investigate the ability of systems to mitigate MAIS2+F injuries to achieve Vision Zero. In a separate study, Bareiss et al. [12] assessed the crash avoidance and MAIS2+F injury mitigation effectiveness of an A-AEB system in straight crossing path (SCP) crashes. Prior to Bareiss et al.'s [12] study, Scanlon et al. [11] reported crash and MAIS3+F injury effectiveness values for an A-AEB system in SCP and left turn across path lateral direction (LTAP/LD) crashes. Two studies, one by Cicchino [7] and one by Kusano and Gabler [9] reported crash and injury effectiveness values for a traditional AEB system in rear-end crashes. Cicchino's study used the KABCO scale to assess occupant injury, while Kusano and Gabler assessed injury mitigation at the MAIS2+F level. Finally, like Cicchino, a study by Jermakian looked at crash and injury mitigation effectiveness of AEB using the KABCO scale [6].

Lane Support Systems Braking Dean and Riexinger [14] investigated both LKA and LDW real-world crash avoidance effectiveness but did not investigate injury mitigation effectiveness associated with the systems. Similarly, Riexinger et al. [15] investigated LKA crash avoidance capabilities but did not investigate injury mitigation effectiveness. Finally, Jermakian [6] investigated LKA crash avoidance effectiveness as well as injury mitigation effectiveness using the KABCO scale. Two additional studies, like Dean and Riexinger [14], investigated LDW crash avoidance effectiveness but did not investigate injury mitigation effectiveness: Holmes et al. [21] and Cicchino [22]. The study by Dean and Riexinger [14] investigated LKA and LDW effectiveness using the quasi-induced exposure method to obtain retrospective real-world effectiveness values. This method was similar to Jermakian's [6] study, as both used nationally representative data to form target populations and assess system relevance in various crash configurations. The work by Riexinger et al. [15] and Holmes et al. [21] employed a different method, using vehicle trajectory data to simulate crash scenarios with and without system intervention.

Table 1.
Crash and injury prevention effectiveness values for AEB and LSS computed in previous studies.

Safety System	Configuration	Effectivness	
		Crash	Injury
Automatic Emergency Braking			
AEB	Rear-End and Single Vehicle	20% [6]	9% (AB) 2% (F) [6]
	Rear-End	50% [7]	56% (KABC) [7]
	Rear-End	7.7% [9]	50% (2+F) [9]
A-AEB	SCP, LTAP/LD	25%-59% [11]	38%-79% (3+F) [11]
	SCP (one vehicle equipped)	57% [12]	75% (2+F) [12]
	SCP (both vehicles equipped)	63% [12]	85% (2+F) [12]
	LTAP/OD (one vehicle equipped)	18%-73% [13]	47%-86% (2+F) [13]
	LTAP/OD (both vehicles equipped)	36%-84% [13]	65%-93% (2+F) [13]
Lane Support Systems			
LKA	ROR, HO, SS (opposite and same direction)	3% [6]	5% (AB) 23% (F) [6]
	ROR, HO, SS (opposite direction)	60% ± 16% [14]	--
	ROR	51.1% [15]	--
LDW	ROR, HO, SS (opposite direction)	3% ± 33% [14]	--
	ROR	17.3%-37.3% [15]	--
	ROR, HO, SS	11% [22]	--
	Cross-centerline	22% [21]	--

Objective

The objective of this study was to use real-world crash data and two previously developed injury prediction models to estimate the potential contribution of A-AEB and LSS crash reduction and MAIS2+F injury mitigation capabilities to achieving Vision Zero in the US. The A-AEB system is assumed to function in both traditional AEB scenarios, such as rear-end collisions, and in intersection crash configurations, such as LTAP/OD crashes.

METHODS

Data Sources

In-depth, nationally representative, real-word crash data was selected from the Crash Investigation Sampling System (CISS) case year 2020. CISS is a probability sample of all US tow-away passenger vehicle crashes and records in-depth occupant and vehicle information that was necessary for this analysis, e.g., occupant age, occupant injury outcomes using the 2015 AIS, location of vehicle damage, and vehicle delta-v [23]. Delta-v in CISS is estimated using WinSmash, the crash reconstruction software developed by the National Highway Traffic Safety Administration [24]. To be nationally representative, cases in CISS are assigned weight values that can be used to estimate the national incidence of crashes. These weighted values were used in this analysis. The 2015 AIS is used to code injuries in CISS and was used in this study to define occupant injury severity [17].

Target Population

Distinct target populations were selected for the A-AEB and LSS analyses (Table 2). For both analysis datasets, only drivers and right-front passengers at least 13 years old [25] in tracking passenger vehicles were included. Vehicles needed to be tracking prior to the crash to be included in the analysis because it was assumed ADAS and/or the driver would not be able to regain control of a non-tracking vehicle. Additionally, vehicles were only included if the vehicle did not rollover, and occupants were only included if the occupant was not ejected. This is because the injury prediction models used to estimate A-AEB and LSS injury mitigation effectiveness were not trained to be able to predict injuries for ejected occupants and occupants in vehicles that rolled over. Additionally, the total delta-v of the vehicle must have been recorded in CISS for the vehicle to be included in the analysis, as this value is necessary to run the injury prediction models. Finally, cases with a weight value of 5,000 or greater were removed from the analysis so that a few cases with large weight values would not dictate the results for the subset of cases used in this study. While this is not typical practice for data selection within the CISS database, the injury prediction model was trained on NASS/CDS for which this was a common step [26]. If multiple occupants were in one vehicle, the vehicle was only counted once in the crash prevention analysis while every occupant was included in the injury mitigation analysis.

Automatic Emergency Braking Four two-vehicle A-AEB-applicable crash configurations were analyzed in this study: rear-end crashes, left turn across path opposite direction and lateral direction (LTAP/OD and LTAP/LD, respectively) crashes, and straight crossing path (SCP) crashes. These four crash configurations typically comprise the majority of front row occupant multi-vehicle crashes. In 2019, they comprised 75% of all front row occupants involved in multi-vehicle crashes. The front-striking vehicle in rear-end crashes was considered for analysis, as it was assumed an A-AEB system would not apply to vehicle being struck in this configuration. For the LTAP/OD, LTAP/LD, and SCP crash configurations, both vehicles were considered for analysis. This is because there is a potential increase in system effectiveness if both vehicles in these configurations are equipped with A-AEB [12], [13]. For an occupant to be included in the injury mitigation analysis, occupant belt status and age must have been known if the general area of damage was at the front of the vehicle. Occupant belt status only must have been known if the general area of damage was at the side of the vehicle. This is because belt status and age are significant predictors in the frontal and side crash injury prediction models used to estimate injury mitigation effectiveness.

Lane Departure Prevention Three LSS-applicable crash configurations were analyzed in this study: right and left side road departure (RD) crashes, head-on (HO) crashes, and opposite direction sideswipe (OD/SS) crashes. These crash modes were chosen for analysis because it is assumed the driver did not intend to leave their lane of travel. Same direction sideswipe crashes were excluded, as this crash scenario may present overlap between LSS and blind spot monitoring systems. The location of the damage on these vehicles was not restricted, since the LSS sensors are not responsible for detecting potential collision partners. No specific occupant information was required to be available for the LSS target population cases. This is because LSS does not have crash severity mitigation capabilities, and so an injury prediction model was not used on this population to determine injury mitigation effectiveness.

Table 2.
Case selection criteria for the analysis.

Inclusion Criteria	Remaining Occupants	
	A-AEB	LSS
CISS 2020 passenger vehicles towed for damage	3,432,288	
Drivers and right-front passengers	3,080,597	
At least 13 years old	3,062,195	
Vehicle tracking before crash	2,576,554	
Vehicle did not rollover	2,445,529	
Occupant was not ejected	2,442,182	
Relevant crash type	992,025	295,990
Two-vehicle crash	860,252	--
Recorded DV	608,852	93,551
Weight < 5,000	410,710	75,061
Unique vehicles within occupant population	345,004	60,487
Crash Analysis Dataset	**345,004**	**60,487**
Known occupant predictor variables	293,500	56,572
Occupant Analysis Dataset	**293,500**	**56,572**

Estimating Crash Prevention

The residual number of target population crashes for a given year ($RTP_{Y,C}$), after system intervention, was considered to be a function of vehicle miles travelled (VMT), system crash prevention effectiveness (E_p), and system market penetration (MP) (Eq. 1). In 2020, traditional AEB and LSS both had a non-zero market penetration, so the number of actual crashes was lower than the number of hypothetical crashes that would have occurred with no AEB or LSS intervention. To adjust for this, the hypothetical number of crashes in 2020 was included in the denominator of the estimated residual target population calculation (Eq. 1). $RTP_{Y,C}$ was computed once for each crash configuration, using independent system effectiveness values and TP_{2020} values. The sum of the $RTP_{Y,C}$ values for each configuration represented the total residual crash population.

$$RTP_{Y,C} = \frac{TP_Y(1 - E_P * MP_Y)}{(1 - E_P * MP_{20})} \#(1)$$

$$TP_Y = TP_{2020} * 1.0101^{Y-2020} \#(2)$$

It was assumed VMT increases 1.01% annually and therefore the number of target population crashes (TP_Y) increases 1.01% annually (Eq. 2) [27]. Predicted AEB and LSS market penetration was obtained from the IIHS-HLDI 2020 annual report that outlines predicted availability and prevalence of safety systems within the US vehicle fleet [10]. IIHS-HLDI's definition of LSS includes both warning systems (LDW) and lane keeping systems (LKA). It is expected that AEB will reach 50% and 95% market penetration by 2029 and 2046, respectively. LSS is expected to reach 50% and 95% market penetration by 2028 and 2045, respectively. A-AEB and LSS crash prevention effectiveness values (E_P) from previous studies were used (Table 3). Crash avoidance effectiveness was assessed separately for LDW and LKA. When confidence intervals were presented for an effectiveness value, the average effectiveness was implemented in the study.

Table 3.
Crash avoidance effectiveness values for A-AEB and LSS computed in previous studies used for this analysis.

System	Configuration	Crash Avoidance Effectiveness (E_P)
A-AEB	Rear-End	0.50 [7]
	SCP+LTAP/LD (one vehicle equipped)	0.57 [12]
	SCP+LTAP/LD (both vehicles equipped)	0.63 [12]
	LTAP/OD (one vehicle equipped)	0.45 [13]
	LTAP/OD (both vehicles equipped)	0.60 [13]
LKA	Head-on, road departure, opposite direction sideswipe	0.60 [14]
LDW	Head-on, road departure, opposite direction sideswipe	0.03 [14]

The number of A-AEB and LSS target population crashes in 2020 were used to compute the future residual crash population for each crash configuration (Table 4). When computing $RTP_{Y,C}$ for the LTAP/OD, LTAP/LD, and SCP crash modes, the possibility of both vehicles being equipped with A-AEB needed to be considered. The probability of one vehicle being equipped with AEB is expressed in Eq. 3. The probability of both vehicles being equipped with A-AEB is expressed in Eq. 4. The addition of both probabilities (Eq. 5) was substituted for the E_P*MP term when computing $RTP_{Y,C}$ for the specified crash configurations (Eq. 6).

$$\mathrm{P(1\ Vehicle\ Equipped)} = 2 * (\mathrm{MP})(1 - \mathrm{MP})\left(\mathrm{E_{p,one}}\right) \#(3)$$

$$\mathrm{P(2\ Vehicles\ Equipped)} = (\mathrm{MP})^2\left(\mathrm{E_{p,two}}\right) \#(4)$$

$$\mathrm{P(1) + P(2)} = 2 * (\mathrm{MP} - \mathrm{MP}^2)\left(\mathrm{E_{p,one}}\right) + (\mathrm{MP})^2\left(\mathrm{E_{p,two}}\right) \#(5)$$

$$\mathrm{RTP_{Y,C}} = \frac{\mathrm{TP_Y}\left(1 - \left(2 * (\mathrm{MP_Y} - \mathrm{MP_Y^2})\left(\mathrm{E_{p,one}}\right) + (\mathrm{MP_Y})^2\left(\mathrm{E_{p,two}}\right)\right)\right)}{\left(1 - \left(2 * (\mathrm{MP_{2020}} - \mathrm{MP_{2020}^2})\left(\mathrm{E_{p,one}}\right) + (\mathrm{MP_{2020}})^2\left(\mathrm{E_{p,two}}\right)\right)\right)} \#(6)$$

Table 4.
Number of A-AEB- and LSS-applicable crashes and MAIS2+F injuries in 2020.

System	Crash Type	2020 Crashes	2020 MAIS2+F Injuries
A-AEB	Rear-End	84,213	2,353
	SCP	78,749	3,196
	LTAP/OD (one vehicle equipped)	132,034	4,944
	LTAP/OD (both vehicles equipped)		
	LTAP/LD	50,008	1,333
	AEB Total	**345,004**	**11,826**
LSS	Head-On	11,760	3,060
	Left Road Departure	18,062	4,531
	Right Road Departure	28,788	9,824
	Opposite Direction Sideswipe	1,877	1,062
	LSS Total	**60,486**	**18,477**
Both	**Total**	**405,490**	**30,303**

Estimating Injury Mitigation

Both A-AEB and LSS are capable of reducing the occurrence of injuries by avoiding potential collisions. To estimate the number of residual MAIS2+F injuries after accounting for crash avoidance effectiveness, the crash avoidance effectiveness values computed in previous studies (Table 3) were used alongside the number of target population MAIS2+F injuries in 2020 (Table 4) to compute a residual number of MAIS2+F injuries for each crash configuration (Eq. 7).

$$\mathrm{RTP}_{\mathrm{Y,I}} = \frac{\mathrm{TP}_{\mathrm{Y}}(1 - \mathrm{E}_{\mathrm{P}} * \mathrm{MP}_{\mathrm{Y}})}{(1 - \mathrm{E}_{\mathrm{P}} * \mathrm{MP}_{20})} \#(7)$$

In addition to injury mitigation due to crash avoidance, A-AEB has the ability to reduce the severity of a crash by reducing the vehicle's maximum delta-v. This in turn has the potential to reduce the maximum injury severity sustained by an occupant. To estimate the number of MAIS2+F injuries after accounting for both A-AEB crash avoidance and crash severity reduction, an injury mitigation effectiveness (E_M) value needed to be computed. An MAIS2+F injury mitigation effectiveness value (E_M) for A-AEB was computed for this study using two logistic regression (Eq. 8) crash injury prediction models previously developed by the authors: one for frontal crashes (Eq. 9) and one for side crashes (E. 10). The models were trained using real-world crash data from the National Automotive Sampling System Crashworthiness Data System (NASS/CDS), the predecessor database to CISS [28]. The frontal model uses maximum delta-v, occupant belt status (B), and occupant age (A) to quantify occupant risk. B was set equal to 0 or 1 if the occupant was unbelted or belted, respectively. A was set equal to 0 or 1 if the occupant was less than 65 or at least 65 years old, respectively. The side model uses maximum delta-v, belt status, and side impact type (ST) to quantify occupant risk. ST was set equal to 0 or 1 if the occupant was in a far-side or near-side impact, respectively. A far-side impact was defined as when the primary plane of damage is on the opposite side of the vehicle as where the occupant is seated. A near-side impact was defined as when the occupant is seated on the same side of the vehicle as where the primary damage occurs. Primary damage plane was determined using the CDCPLANE variable in CISS. Occupants in vehicles with frontal damage were evaluated using the frontal model. Occupants in vehicles with side damage were evaluated using the side model. The models were first run on the A-AEB target population occupants using the total delta-v recorded in CISS. Then, the models were run again on the same set of occupants with all the total delta-v values reduced by 34%, as this is the median delta-v reduction due to AEB [9]. The injury mitigation effectiveness was set equal to one minus the ratio of predicted injuries after the delta-v reduction to predicted injuries before the delta-v reduction (Eq. 11). The computed effectiveness value was then used to compute the residual number of A-AEB-applicable MAIS2+F injuries over time ($\mathrm{RTP}_{\mathrm{Y,I}}$) (Eq. 12). The sum of the $\mathrm{RTP}_{\mathrm{Y,I}}$ values for each A-AEB-application crash configuration represented the total residual injury population. LKA and LDW were considered to have injury mitigation capabilities due to crash avoidance only. They were not considered to have injury mitigation capabilities due to crash severity reduction.

$$\mathrm{P}(\mathrm{MAIS2 + F}) = \frac{1}{1 + \mathrm{e}^{\mathrm{logit}}} \#(8)$$

$$\mathrm{P}(\mathrm{MAIS2 + F})_{\mathrm{Front}} = \frac{1}{1 + \mathrm{e}^{-(-8.44 + 0.67(\mathrm{Max.DeltaV}) - 1.81(\mathrm{B}) + 3.47(\mathrm{A}))\#}} \#(9)$$

$$\mathrm{P}(\mathrm{MAIS2 + F})_{\mathrm{Side}} = \frac{1}{1 + \mathrm{e}^{-2.95 + 0.39(\mathrm{Max.DeltaV}) - 2.60(\mathrm{B}) + 1.63(\mathrm{ST})\#}} \#(10)$$

$$\mathrm{E}_{\mathrm{M}} = 1 - \left(\frac{\text{Predicted After MDV Reduction}}{\text{Predicted Before MDV Reduction}}\right) \#(11)$$

$$\mathrm{RTP}_{\mathrm{Y,I}} = \frac{\mathrm{TP}_{\mathrm{Y}}(1 - \mathrm{E}_{\mathrm{P}} * \mathrm{MP}_{\mathrm{Y}})(1 - \mathrm{E}_{\mathrm{M}} * \mathrm{MP}_{\mathrm{Y}})}{(1 - \mathrm{E}_{\mathrm{P}} * \mathrm{MP}_{20})(1 - \mathrm{E}_{\mathrm{M}} * \mathrm{MP}_{20})} \#(12)$$

RESULTS

Crash Prevention

The estimated number of A-AEB-applicable crashes with and without A-AEB intervention was plotted over time from 2020 to 2055 (Figure 1). The estimated number of LSS-applicable crashes with and without LSS intervention was plotted for the same range of years (Figure 2). The LSS plot depicts residual crashes after LDW and LKA intervention independently. Black vertical lines indicate when the system is expected to reach 95% market penetration. Since the A-AEB target population was much larger than the LSS target population, A-AEB is projected to prevent over 200,000 crashes in some years, while the maximum annual crash prevention due to LSS is approximately 40,000 crashes. While A-AEB and LKA had significant crash avoidance effects within their target population crashes, LDW had little to no crash avoidance effect. When looking at the combined effect of LKA and A-AEB on the total crash population, the scale of their contribution is much smaller than when looking at the system-applicable target populations (Figure 3). Their combined effect does not result in a decrease in the number of annual crashes for any of the projected years.

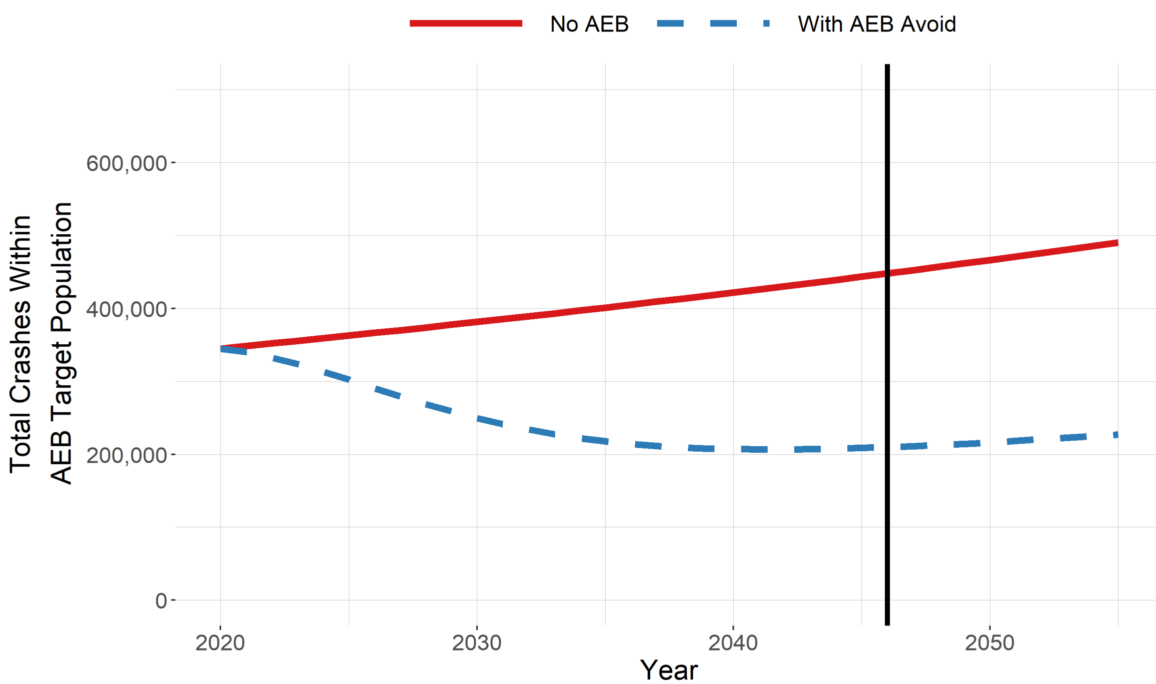

Figure 1. Total predicted A-AEB target population crashes over time with and without A-AEB crash avoidance effectiveness.

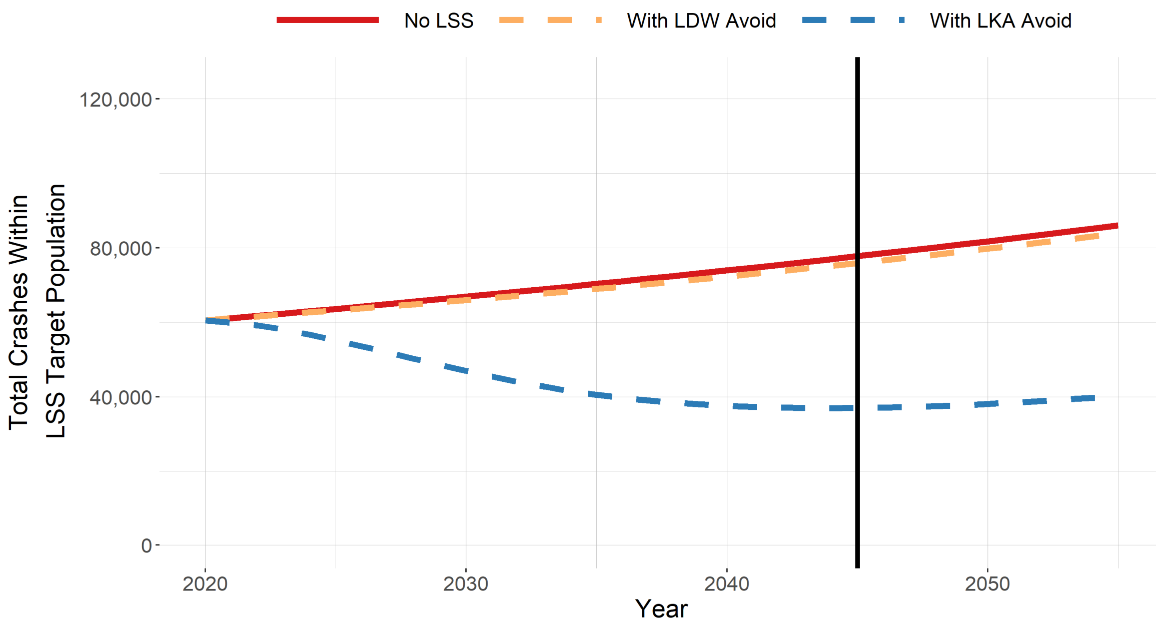

Figure 2. Total predicted LSS target population crashes over time without LSS, with LDW crash avoidance effectiveness, and with LKA crash avoidance effectiveness.

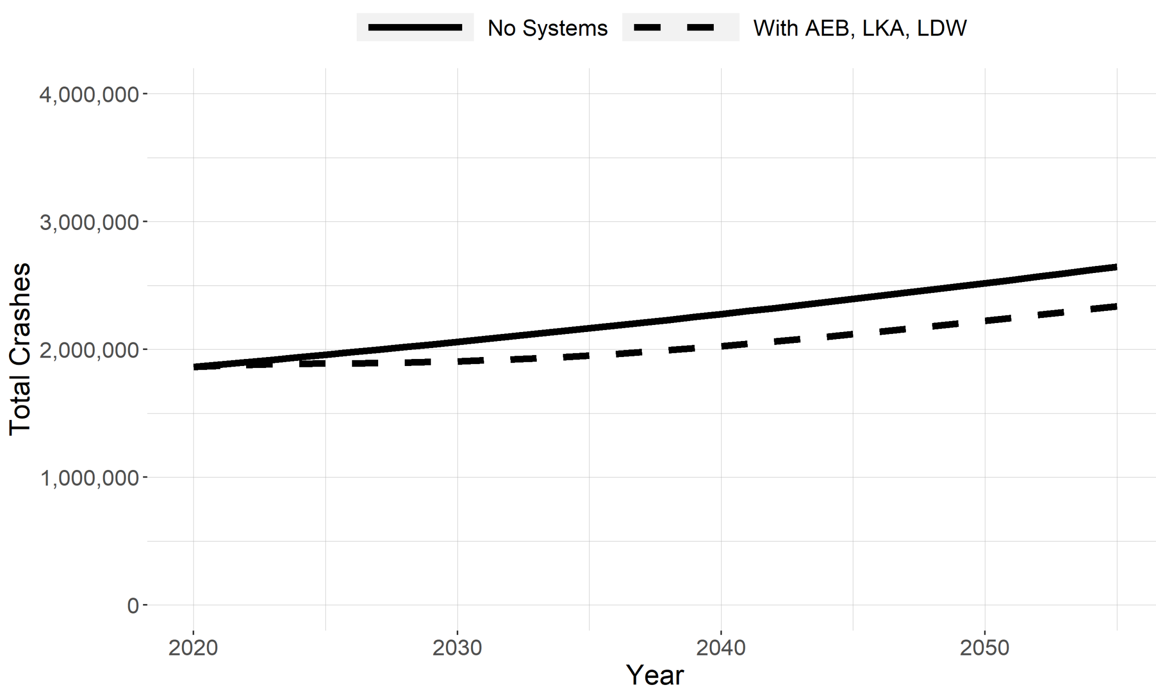

Figure 3. Total number of MAIS2+F injuries over time with and without AEB, LKA, and LDW.

Injury Mitigation

Within the A-AEB occupant target population, there were 15,163 ± 1,831 predicted injuries before the delta-v reduction and 5,802 ± 1,163 predicted injuries after the delta-v reduction (Table 5). The average predicted number of injuries using the recorded delta-v values overpredicted the number of injuries by approximately 3,000. The computed injury mitigation effectiveness was 62% ± 9% and the average effectiveness value, 62%, was used for analysis. The estimated number of A-AEB- (Figure 4) and LSS-applicable (Figure 5) MAIS2+F with and without A-AEB intervention were plotted over time from 2020 to 2055. A black vertical line indicates when the system is expected to reach 95% market penetration. Like seen with the crash avoidance analysis, LDW has little to no effect on injury mitigation, while A-AEB and LKA make significant injury mitigation contributions within their respective target populations. A-AEB is able to mitigate a larger overall number of injuries than LKA due to 1) the A-AEB target population being larger than that of LKA and 2) A-AEB is able to mitigate injuries through both crash avoidance and reducing crash severity. On the other hand, LSS only mitigate injuries via crash avoidance. Given these differences, A-AEB is able to prevent up to approximately 15,000 MAIS2+F injuries in a year, where the maximum number of prevented injuries due to LKA is approximately 13,000. Like seen with the crash avoidance analysis, the combined relative effect of these systems on the overall number of injuries is significantly smaller than the relative effect within the target populations (Figure 6). The total number of annual injuries is expected to remain mostly constant until the year 2040, when the number of injuries will begin to increase again.

Table 5.
Actual and predicted A-AEB-applicable MAIS2+F injuries and the computed A-AEB injury mitigation effectiveness.

Actual MAIS2+F Injuries	Delta-V	Predicted MAIS2+F Injuries	Injury Mitigation Effectiveness	Injury Mitigation Effectiveness Used in Analysis
11,827	Recorded	15,163 ± 1,831	62% ± 9%	0.62
	Reduced	5,802 ± 1,163		

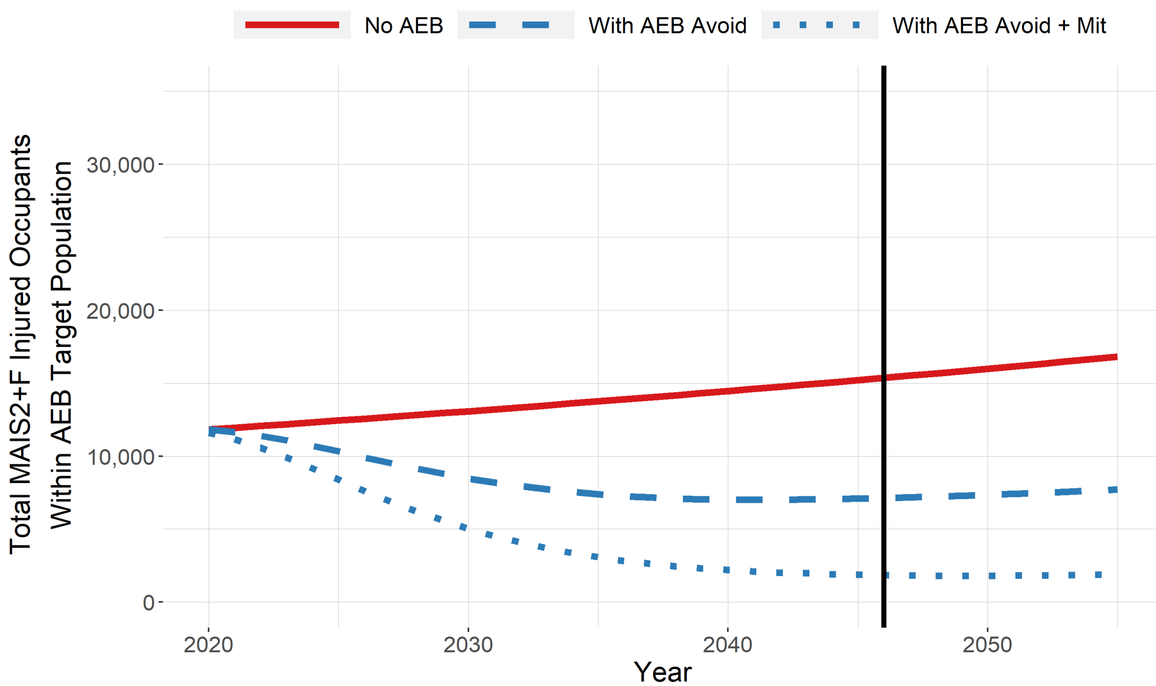

Figure 4. Total predicted AEB target population MAIS2+F injuries over time without A-AEB, with A-AEB injury avoidance effectiveness, and with A-AEB crash avoidance and injury mitigation effectiveness.

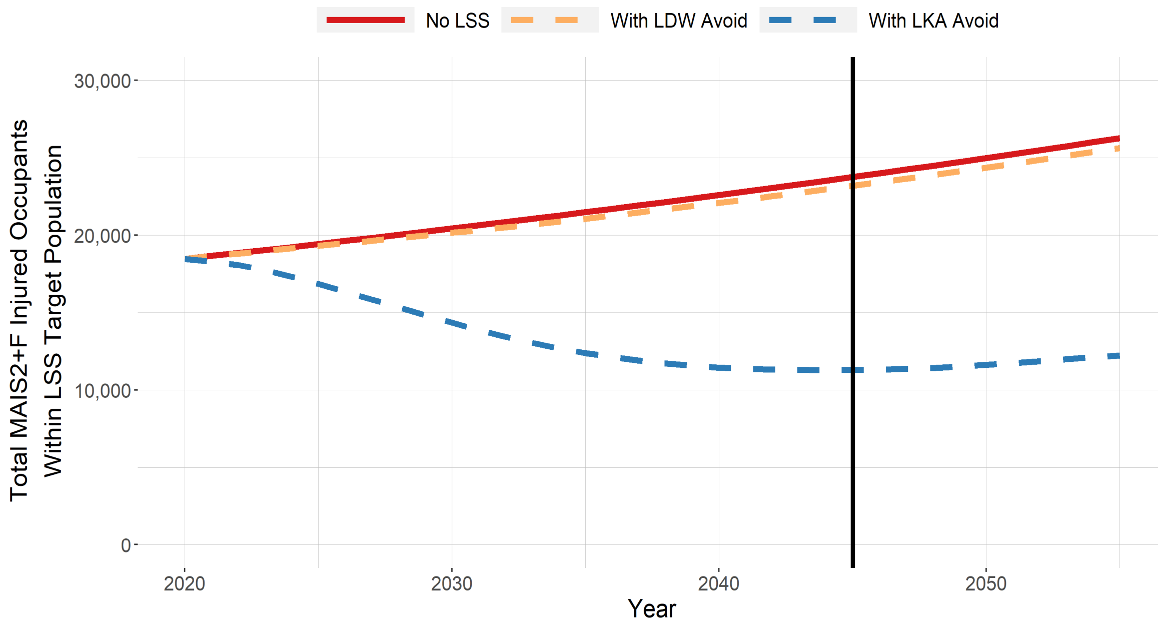

Figure 5. Total predicted LSS target population MAIS2+F injuries over time without LSS, with LDW injury avoidance effectiveness, and with LKA injury avoidance effectiveness.

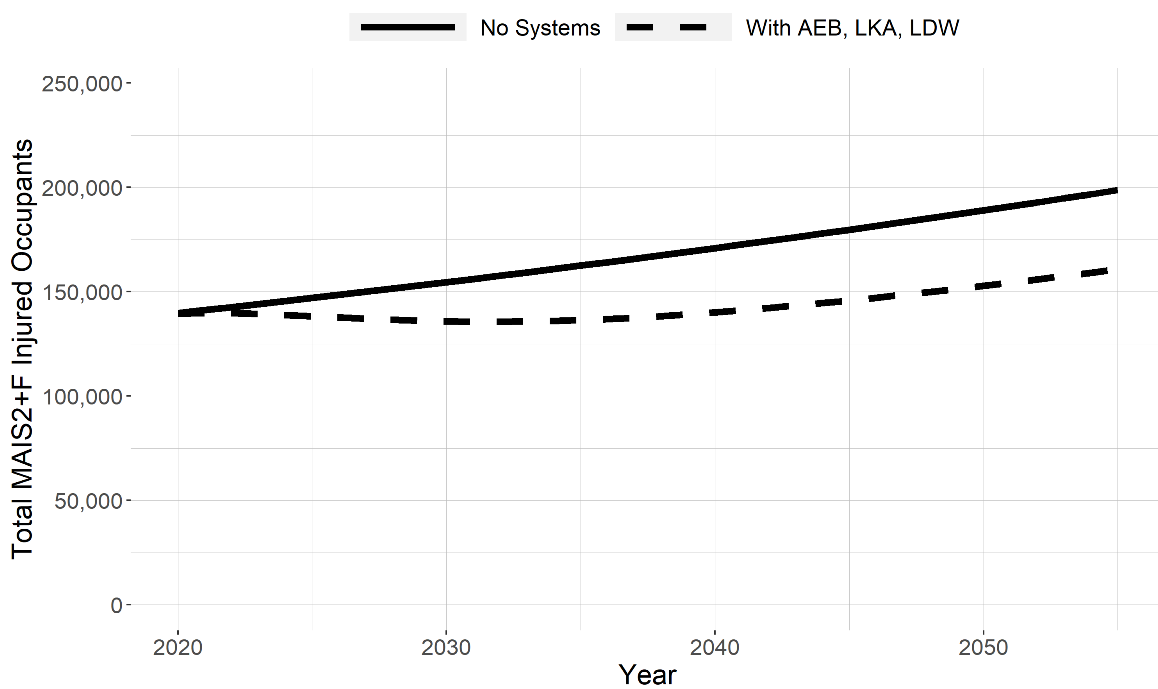

Figure 6. Total number of crashes over time with and without A-AEB, LKA, and LDW.

Overall, the combined effect of A-AEB and LSS are estimated to be able to prevent a cumulative 7,000,000 crashes and 869,000 MAIS2+F injuries by the year 2055 (Table 6).

Table 6. Predicted cumulative crash and MAIS2+F injury reductions due to A-AEB and LSS crash avoidance and injury mitigation effectiveness.

Year	Number Prevented	
	Crashes	MAIS2+F Injuries
2035	1,633,762	202,908
2045	4,121,638	508,438
2055	7,054,894	869,456

DISCUSSION

Due to the assumption that each crash configuration increases in incidence by 1.01% annually, the residual crash and MAIS2+F injury curves will always eventually trend upward again, assuming system effectiveness is less than perfect. Despite this, the number of injuries within the A-AEB target population are projected to level out around 2045 and remain constant until at least 2055. A similar trend is observed for the LKA target population between 2040 and 2050. Despite these significant contributions within each target population, the overall number of MAIS2+F injuries is expected to never dip below 125,000 and is to begin rising steadily again sometime between 2035 and 2040. This emphasizes the need for crash avoidance and injury mitigation strategies outside of just A-AEB and LSS development. Within LSS development, LKA advances and implementation should be prioritized over LDW since real-world LKA effectiveness for both crash avoidance and injury mitigation is significantly higher than that of LDW [14]. This low LDW system effectiveness is largely due to drivers deactiving the system [14], [29].

Additional active safety system development, traffic laws, and vehicle and infrastructure standards and design are all avenues for contribution to the safe system approach to meet the goal of Vision Zero. For example, shoulder, edge line, and center line rumble strips are effective in reducing lane departure crashes [30], [31]. Additionally, setting safe speed limits is one way to mitigate crash severity in all crash configurations and therefore mitigate occupant injury outcomes. Implementing traffic safety cameras, even when not active, has also been an effective method in reducing fatalities and injuries in Sweden, where Vision Zero was first conceptualized [32]. Further, designing roadside infrastructure to handle impact speeds relevant to the set speed limits is a necessary step in improving occupant safety. Currently, roadside hardware is crash tested at a maximum impact speed of 62 mph (100 km/h) [33], despite the maximum speed limit in the US being 85 mph (135 km/h) [34].

Limitations

One limitation of this study is that the A-AEB portion of the analysis assumes an advanced AEB system capable sensing and emergency braking for imminent collisions in typical intersection crash configurations (LTAP/OD, LTAP/LD, and SCP). Therefore, this study assumes that current traditional AEB technology will continue to advanced and merge with I-ADAS system. Additionally, this study uses the total delta-v value recorded in CISS to compute injury mitigation effectiveness. Total delta-v recorded in CISS is computed using WinSmash, NHTSA's crash reconstruction software. WinSmash is known to underpredict delta-v by up to 23% [35] prior to the 2008 version, which increased by only 8.1% for frontal crashes in the 2008 version [36]. The injury prediction model used to estimate injury mitigation effectiveness was trained using delta-v time series data from NASS/CDS vehicle EDRs, which would have been a more accurate representation of the true delta-v. This likely contributes to the model underestimating the actual number of MAIS2+F injuries in the CISS 2020 A-AEB target population. Further, since this analysis uses varying crash avoidance effectiveness values for the A-AEB crash configurations, this analysis assumes the proportions of the crash configurations within the A-AEB target population remains constant over time. Looking at CISS 2017 through CISS 2020 reveals this to be a reasonable assumption (Table 7). The most variation in any of the crash configurations analyzed is in head-on crashes, which comprised a low of 10.0% of the LSS target population crashes in 2019 and a high of 19.4% in 2020. However, since the same effectiveness value is used for all the LSS-applicable crashes, this does not alter the validity of the current results.

Table 7.
Comparison of A-AEB and LSS vehicle crash configuration proportions from CISS 2017 to CISS 2020.

CISS Case Year	A-AEB-Applicable Crash Configurations			LSS-Applicable Crash Configurations		
	Rear-End	SCP and LTAP/LD	LTAP/OD	Head-On	Road Departure	Opposite Direction Sideswipe
2017	23.9%	42.4%	33.7%	13.6%	81.5%	4.9%
2018	23.6%	41.2%	35.2%	10.6%	85.3%	4.1%
2019	21.5%	41.7%	36.8%	10.0%	85.9%	4.1%
2020	24.4%	39.5%	38.3%	19.4%	77.5%	3.1%

CONCLUSIONS

The crash avoidance and injury mitigation contributions of A-AEB and LSS have the ability to prevent 7,054,894 crashes and 869,456 MAIS2+F injuries by 2050. These are significant contributions within the A-AEB and LSS target populations, but a large number of crashes and injuries will still comprise the overall total residual crash and injury population. Contributions from other branches of the safe system approach will be necessary to achieve Vision Zero, in addition to the constant development and improvement of current and new ADAS.

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