

THE ESTIMATED POTENTIAL EFFECTIVENESS OF AEB AND LKA SYSTEMS FOR HEAD-ON CRASHES

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ABSTRACT

Research Question/Objective

In 2019, there were over 3,600 fatal head-on crashes in the US. This represents 10.9% of all fatal crashes despite accounting for 2.7% of all police-reported crashes. Lane departure warning (LDW) and lane keeping assist (LKA) systems could help address cross-centerline crashes. We consider LDW systems to be those that alert the driver prior to the lane crossing event while LKA systems might perform automated steering that may help prevent the vehicle from departing the lane. Automatic emergency braking (AEB) has been effective in preventing or mitigating front-to-rear crashes by providing significant crash-imminent braking. The purpose of this study was to estimate the effectiveness of a simulated LDW or LKA system with a hypothetical AEB system that could activate in cross-centerline head-on crashes.

Methods

The National Automotive Sampling System Crashworthiness Data System (NASS/CDS) is a representative sample of tow-away passenger vehicle crashes in the U.S. containing in-depth crash data. Trajectory data was extracted from scaled scene diagrams for 232 cross-centerline NASS/CDS cases with available event data recorder (EDR) information. There were 111 cross-centerline crashes reconstructed based on the trajectory and EDR recorded crash pulse. This effort to predict the benefits of LDW and LKA systems for cross-centerline crashes, involved modeling the crash, including the road geometry and vehicle dynamics. The encroaching vehicle that crossed the centerline was simulated with hypothetical LDW and LKA systems and the impacted vehicle was simulated with and without an AEB system. The outcomes of the simulations were combined to estimate the potential crash reduction of a hypothetical LDW and LKA combined with AEB. For simulations that resulted in a crash, a frontal injury model was used to predict the probability of the occupants sustaining a moderate to fatal injury (MAIS2+F).

Results

The hypothetical LDW system had an estimated crash benefit between 7.5% and 10.8% and the hypothetical LKA system had a higher estimated benefit of 32%. With the AEB system in the impacted vehicle, the estimated benefit for LDW increased to 13% to 15%, but the estimated benefit for LKA remained the same. The AEB system with the LDW system resulted in an estimated 50.8% to 54.3% reduction of MAIS2+F injured occupants and an estimated 68.4% reduction with the LKA system.

Discussion and Limitations

The simulations indicated that AEB has only a small effect on preventing head-on crashes. However, AEB can mitigate the crash by rapidly reducing the speed of the impacted vehicle prior to the collision. While the hypothetical

AEB system does not prevent many additional simulated head-on crashes, it can assist in reducing the likelihood of passengers sustaining a moderate to fatal injury.

Conclusion and Relevance to Session Submitted

Previous studies have investigated the benefit of LDW and LKA systems for road departure and head-on crashes. This is the first study to investigate the combined benefit of a hypothetical AEB and lane keeping systems for head-on crashes. This paper is relevant to the session because it evaluates the estimated safety benefits of these systems using EDR pre-crash and crash data.

INTRODUCTION

Every year, approximately 34,000 individuals are fatally injured in crashes on roads in the US [1]. These fatalities occur across many types of crash scenarios, each of which has its own set of causation factors. One way to prioritize research on a preventive technology for a specific crash scenario is to look at number of occupant fatalities relative to the total number of occupants involved in this crash scenario. According to Kusano, four crash modes are overrepresented among fatalities: single vehicle road departure crashes, control loss crashes, cross-centerline head-on crashes, and pedestrian/cyclist crashes [2]. Interestingly, two of these crash scenarios require the subject vehicle to depart from the initial lane of travel before the crash occurs. Another method of prioritizing research is to determine factors common among the fatal crashes. Head-on crashes comprise of only 4% of non-intersection crashes but account for 49% of fatalities in non-intersection crashes [3]. Cross-centerline head-on crashes consist of a vehicle crossing the centerline and colliding with a vehicle traveling the opposite direction. Head-on crashes can be dangerous due to the large deceleration experienced upon impact since the vehicles were moving in opposite directions.

The potentially high severity head-on crashes and road departure crashes has been a motivation for the development of active safety systems, such as lane departure warning (LDW) systems. LDW systems are designed to alert the driver, through audible, visual or haptic signals, that the vehicle has inadvertently left the lane of travel [4]. Ideally, the driver reacts to the warning and returns to the lane, preventing an impact (Figure 1). However, the effectiveness of an operational warning system is limited by the reaction time of the driver and the ability of the driver to return to the road without impacting any roadside objects [4]. The reaction time of a driver to a haptic or audible LDW system can vary from as low as 0.38s to 1.36s [5]. Additionally, LDW effectiveness is dependent on the evasive action taken by the driver. Lane departure prevention (LDP) systems may not need the driver to react by automatically steering the vehicle back toward the original lane. Some LDP systems can provide steering input before departing the lane and may also be referred to as lane keeping assist (LKA) systems.

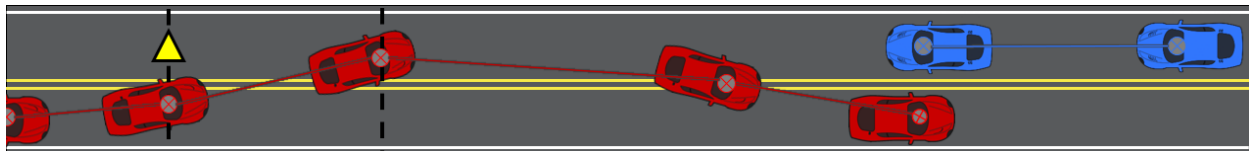


Figure 1. Visual representation of a hypothetical LDW and LKA system. LDW systems may alert the driver that the vehicle has departed its lane of travel. LKA operate similar to the LDW systems, except the LKA system might provide an automated steering response.

Assuming there were no system limitations present, from 2011 to 2015, almost 50% of the moderate to fatal injury crashes that could theoretically benefit from LDW/LKA systems [6]. Over 65% of these LDW/LKA applicable scenarios were drift-out-of-lane (DROOL) road departure crashes. Riexinger found from crash data that roughly 80% of drivers in DROOL road departure crashes responded with a steering maneuver [6]. Several studies have estimated the effectiveness of LDW in road departures, however due to the higher relative speed that the subject vehicles approach each other during a head-on collision, the estimated effectiveness of LDW and LKA systems may be different for head-on than in road departures (Table 1). Cicchino estimated the number of lane departure crashes, including head-on crashes, that were prevented by LDW/LKA systems using insurance claim information. The estimated benefit is lower than other simulated studies since drivers can disable the LDW system and it combines the effect of many system types. The purpose of this study is to estimate the benefit of LDW/LKA systems in head-on crashes.

Table 1. Summary of LDW/LKA effectiveness estimates in the literature.

| Source | System Type | Estimated Effectiveness |
|----------------------|--|---|
| Cicchino 2018 [7] | Single vehicle road departure, head-on, sideswipe crashes in US | 11% (LDW/LKA) |
| Sternlund 2017 [108] | Single vehicle road departure, head-on crashes on high-speed roads in Sweden | 53% (LDW/LKA) |
| Riexinger 2018 [4] | Single Vehicle Road Departure crashes in US | 16.7%-21.5% (LDW) 24.3% (LKA) (Assuming that the system is activated) |

APPROACH

Datasets

NASS/CDS and CISS The National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) data set is a nationally representative sample of all crashes in which at least one passenger vehicle was towed away [9]. Every case in NASS/CDS is assigned a weight to represent the total number of similar crashes that occurred in the US during that case year. NASS/CDS provides detailed information on each case including vehicle deformation, crash causation factors, a scaled scene diagram of the crash, and occupant injury information records. Each case in the data set includes a scaled scene diagram with the vehicle trajectory and impact locations. If possible, the vehicle delta-v is calculated from an energy reconstruction based on the crush profile of the vehicle using Win-Smash [10-12].

EDR Database The Virginia Tech Event Data Recorder (EDR) Database is a collection of the information retrieved from EDRs in vehicles involved in real-world crashes that were investigated in NASS/CDS. The EDR database is continuing to expand to also include cases from the Crash Investigation Sampling System (CISS). Most recently manufactured vehicles have an EDR installed, which records basic vehicle information in the event of a crash. The EDR database is a unique source of direct measurements of vehicle speed before and during a crash. The EDR records data, such as delta-v, during the crash to capture the crash pulse. Additionally, five seconds of pre-crash information, such as vehicle speed, throttle position, brake activation and engine RPM, are also recorded. Some advanced EDRs record information such as the steering-wheel position, the activation of electronic stability control (ESC) and the activation of the antilock brakes system (ABS). EDRs have been shown to accurately measure the crash delta-v within 14% [11] and are frequently used to understand driver precrash behavior [13, 14].

Cross-Centerline Crash Database The cross-centerline crash database contains additional data elements extracted from NASS/CDS scene diagrams and scene photographs by the authors. This dataset follows the same methodology used to extract information on roadside crashes as a part of the National Cooperative Highway Research Program Project 17-43 database [15]. The crashes in the cross-centerline crash database were selected from NASS/CDS case years 2011 to 2015. This dataset contains the trajectory positions and headings of every vehicle involved in the 232 NASS/CDS cross-centerline crashes where at least one passenger vehicle had EDR information available. The road geometry for each road segment was also recorded in this dataset.

Data Selection

NASS/CDS cross-centerline head-on crashes from 2011 to 2015 were selected for estimating the effectiveness of LDW/LKA systems. This is the most recent five years available in NASS/CDS. The cross-centerline crash database was used to provide the coded trajectory of the vehicle before the crash. The EDR pre-crash velocity data was used to determine the vehicle's speed at each point along the trajectory. To be included in the study, the first event for the encroaching vehicle had to be the head-on crash in NASS/CDS (ACCTYPE = 50, 51). Additionally, the EDR needed to record either an airbag deployment or a delta-v greater than 8kph (5mph) for the encroaching vehicle [13]. The bag deployment locks the EDR data preventing subsequent events from overwriting EDR data. In cases where the airbag did not deploy, the 8 kph delta-v requirement increases the likelihood that the event stored in the EDR

corresponds to the NASS/CDS case rather than a minor impact. A crash of at least 8 kph will produce significant damage and would be unlikely to be overwritten by a post-crash event, e.g., hitting a pothole while being towed from the scene. Finally, the EDR must have recorded values for the pre-crash velocity to be used in this study.

In the dataset, there were three cases in which the encroaching vehicle departed the road at least once before the head-on crash. In each of these cases, the encroaching vehicle departed the road to the right, overcorrected, crossed the centerline, and impacted a vehicle travelling in the opposite direction. The first intervention opportunity for this particular scenario involves activating the LDW or LKA system during the road departure rather than when the vehicle crosses the centerline. Therefore, the three cases where a road departure occurred before the cross-centerline crash were removed from the dataset. Although these cases were excluded from this study, it is still possible that implementing avoidance countermeasures may have mitigated or prevented the impact. Overall, there were 111 encroaching vehicles in the simulation dataset. After applying NASS/CDS sampling weights, this represents 35,677 real-world crashes used in this study (Table 2).

Table 2. Case selection criteria.

| | Number of Cases | Weighted Cases |
|--|------------------------|-----------------------|
| Vehicles with EDR information and in the cross-centerline database | 183 | 58,298 |
| Air bag deployment or delta-v > 8 kph | 165 | 48,728 |
| Valid pre-crash data | 164 | 48,641 |
| First event | 164 | 48,641 |
| Single departure cases | 161 | 47,885 |
| Remove large trucks | 148 | 46,509 |
| Valid crash delta-v | 134 | 44,991 |
| Valid pre-crash velocity | 111 | 33,677 |

Crash Reconstruction

Often the EDR was only available in one of the vehicles involved in the cross-centerline head-on collision. To accurately model both vehicles in the crash, the speed of the vehicle without the EDR was reconstructed. Using the delta-v of one vehicle from the EDR, the mass of both vehicles, and the impact angle of both vehicles, the delta-v of the other vehicle was computed based on the conservation of momentum. The delta-v of the other vehicle was computed in both the x and y directions. This assumes that all of the vehicle motion was planar and there was no rotation of the vehicles from the impact. The mass of each vehicle was the sum of the curb weight and cargo weight reported in NASS/CDS. The reconstructed delta-v for the vehicle without an EDR was compared with the WinSmash reconstructed delta-v [10]. Our reconstructed delta-v overestimated the WinSmash delta-v by about 17 percent on average (Figure 2) because it does not account for the rebound velocity of the vehicle and because it does not consider rotation of either vehicle. These assumptions were particularly highlighted by case 717020839, which had a reconstructed delta-v of 122 kph but a WinSmash delta-v of 55 kph. Our estimate was higher than the WinSmash because the small sedan experienced extreme deformation to the occupant compartment. However, WinSmash underestimates the true crash delta-v by roughly 10%, which may indicate that our delta-v estimates are close to the true delta-v [11].

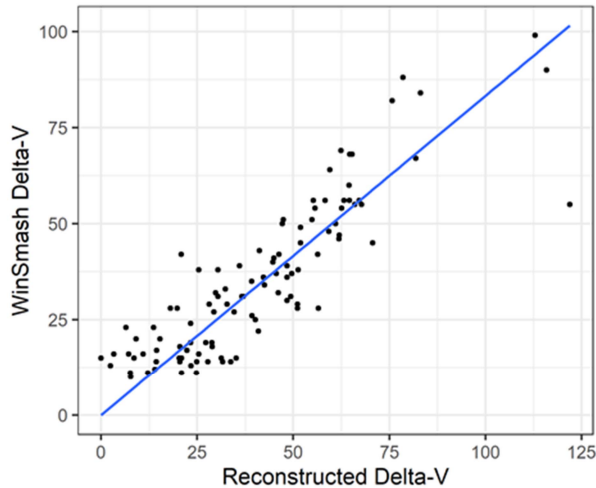


Figure 2. Validation of the delta-v reconstruction.

The velocity of the vehicle after impact was approximated based on the linear distance (D) to the final rest position from the point of impact. The energy absorbed during that distance was estimated from a 0.2g deceleration along the distance to the final rest position. This value was chosen to maximize the agreement between the predicted and actual impact velocities. From the delta-v and the velocity immediately following the impact, the impact velocity was computed. Depending on which vehicle, encroaching, or impacted, contained the EDR information, the initial travel speed changed. For cases in which the impacted vehicle contained an EDR, the first recorded speed was assumed to be its travel speed. For cases in which the encroaching vehicle contained an EDR, the velocity measurements were mapped onto the vehicle trajectory assuming a linear acceleration between measurements [4, 16]. The travel speed was the speed of the vehicle when its center of mass crossed the centerline. The impact velocity reconstructed from the delta-v was compared with the last recorded pre-crash velocity of the vehicle (Figure 3). A linear regression between the reconstructed and last pre-crash velocity determined that the predicted impact speed was on average 9.6% below the last pre-crash velocity with an r^2 value of 0.85. Because many EDRs do not record the exact impact velocity, the last recorded pre-crash velocity does not capture any decrease in speed due to braking before impact.

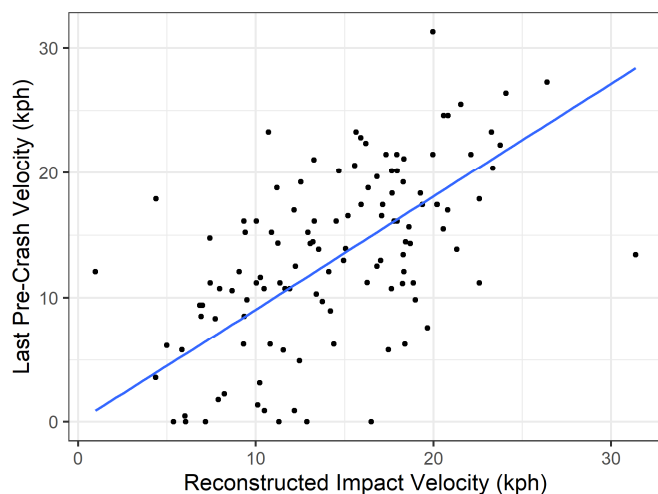


Figure 3. Validation of the delta-v reconstruction.

Vehicle Model

The vehicles in the crash were represented by a rectangle with a length and width equivalent to the overall length and width from NASS/CDS of each vehicle. The vehicle dynamics were modeled as a point with a time step of 0.01s. The total force exerted by the tires was limited to the force available from friction. Therefore, any

combination of steering and acceleration could not exceed 1g. If the 1g limit was exceeded, then the braking force was maintained, and the steering was scaled down such that the magnitude was equal to 1g.

Driver Model

The encroaching vehicle follows its original crash trajectory, but the impacted vehicle was simulated to follow the road by remaining centered in its lane. The vehicle steering was controlled by a theoretical proportional-integral-derivative (PID) controller with the following assumed parameters: $K_p = 743.5$, $K_i = 0.1$, $K_d = 0$. The PID controller was minimizing the distance between the predicted vehicle center in half a second to the intended path of the vehicle. The 0.5s look-ahead was used to more closely resemble how humans drive; drivers do not steer based on their current position but where they will be [19]. Additional length equal to 0.5s of travel was added to the end of the trajectory because the steering model looked ahead 0.5s.

Encroaching Vehicle The encroaching vehicle follows its original crash trajectory. When the LDW system activates, there is an estimated reaction period during which the vehicle continues travelling as before until the driver is estimated to react. Our model considered three different reaction times: 0.0s, 0.38s, and 1.36s [5]. This represents the fastest possible response, a fast response and a slow response to haptic or audible warnings based on simulator studies. We also used two different theoretical braking magnitudes (0.0g and 0.41g) and three different maximum turning rates (0 deg/s, 11.4 deg/s, and 34.1 deg/s) based on EDR data [18]. The steering maneuver was governed by the PID controller, which tried to steer back into the original lane of travel. Thus, there were six different possible maneuvers (Table 3).

Table 3. Probability of simulated encroaching vehicle evasive actions.

| | No Braking | Braking |
|----------------|------------|---------|
| No Steering | 16.5% | 5.1% |
| Light Steering | 11.4% | 27.8% |
| Heavy Steering | 11.4% | 27.8% |

Impacted Vehicle The impacted vehicle begins the simulation traveling at the reconstructed initial velocity. The impacted vehicle had a constant deceleration such that it would be traveling at the reconstructed impact velocity at the point of impact. The model assumed that the driver of the impacted vehicle was paying attention to the road and anticipated the encroachment of the other vehicle. While this assumption is not valid for all real-world cases, an analysis of EDRs in cross-centerline crashes showed that every impacted vehicle in the sample performed an evasive action prior to impact [20]. Therefore, as soon as the encroaching vehicle touched the lane line, the driver of the impacted vehicle was simulated to perform a braking maneuver with a magnitude of either 0.0g or 0.27g [18]. The driver was assumed to follow their intended path by remaining centered in their lane. There were two possible options for the impacted vehicle and the frequency of the braking responses were based on EDR data [18] (Table 4).

Table 4. Probability of simulated impacted vehicle evasive action.

| | No Braking | Braking |
|----------------|------------|---------|
| Lane Centering | 6.4% | 93.6% |

Hypothetical Active Safety Operation Criteria

Our model investigated hypothetical LDW and LKA systems with an activation speed of 50 kph [21]. The time to lane crossing (TTLC) activation threshold of the systems ranged from 0 to 1.2 s. AEB systems are typically for car following scenarios. Although not the typical use case, our hypothetical AEB system could be used to identify vehicles that have crossed the centerline. Due to the vehicle approaching from the side, the AEB parameters were chosen to be similar to other studies of Intersection advanced driver assist systems (I-ADAS) [7, 19-20].

LDW/LKA Estimated Effectiveness

The LDW's estimated effectiveness was determined by calculating the total possible permutations of LDW activation speeds, time to lane crossing (TTLC) of warning activation, reaction times, steering types, and braking types for both vehicles which resulted in a total of 16,539 simulations of cross-centerline collisions. These simulations were performed on multiple CPU cores by a custom python script. Each simulation was weighted based on the frequency of each driver evasive action if the system was of the LDW model or weighted based on the case weight if the system was of the LKA model. A crash was predicted to be prevented with an LDW/LKA system if the vehicle continued driving without striking the opposing vehicle or came to a stop. A crash was predicted to not be prevented if both vehicles impacted each other or the vehicle took no evasive action and departed the road.

Residual Injury Computation

The probability of front occupant injury for cross-centerline crashes was estimated using the injury model developed in by Bareiss in 2019 [20]. The logistic injury model has seven inputs: delta-v, belt use, sex, age, crash compatibility, BMI, and striking location (Table 5). Delta-v and BMI were continuous covariates and all other injury model parameters were binary. The injury model was constructed based on the injury data of front seat occupants that were at least 12 years old and involved in a frontal crash with another vehicle. For cross-centerline crashes, the rear of a vehicle is not struck and therefore the striking location was zero for all cases. Of the 111 simulated cases, 101 cases involving 182 occupants contained all the information necessary to utilize the injury model and estimate the injury benefit. If the vehicle stopped or returned to the lane, the probability of an occupant sustaining a MAIS2+F injury was assumed to be zero. For crashed and parted simulation outcomes, the last velocity was assumed to be the impact velocity.

Table 5. Frontal impact injury model

| Variable | Parameter | Estimate | Standard Error | p-value |
|---------------------|--------------------------|----------|----------------|---------|
| Intercept | -- | -6.516 | 0.863 | <0.001 |
| Total Delta-V | Delta-V (kph) | 0.090 | 0.019 | <0.001 |
| Belt Use | Belted | -0.769 | 0.396 | 0.054 |
| Sex | Male | -0.891 | 0.333 | 0.008 |
| Age | ≥65 | 1.070 | 0.492 | 0.031 |
| Crash Compatibility | Car Struck LTV | 1.222 | 0.368 | 0.001 |
| BMI | BMI (kg/m ²) | 0.084 | 0.021 | <0.001 |
| Striking Location | Rear | -1.455 | 0.501 | 0.004 |

The delta-v was estimated based on the computed final velocity (Equation 2-3). The final velocity was computed based on the mass of each vehicle (m_1, m_2), and the impact velocity of each vehicle (V_{1i}, V_{2i}). The coefficient of restitution (C_R) was assumed to be 1 which follows an assumption used in WinSmash [4]. Often, the two vehicles in cross-centerline crashes are not perfectly aligned and much of the energy is transferred into rotational energy. In order to match the actual crash injury outcomes with the predicted injury outcomes for the baseline configuration and account for any rotation after impact, we assumed that 29.5% of the total delta-v was longitudinal.

$$V_{1f} = \frac{m_1 V_{1i} + m_2 V_{2i} + m_2 C_R (V_{2i} - V_{1i})}{m_1 + m_2} \quad \#(2)$$

$$V_{2f} = \frac{m_1 V_{1i} + m_2 V_{2i} + m_1 C_R (V_{1i} - V_{2i})}{m_1 + m_2} \quad \#(3)$$

For each simulated system configuration, the estimated number of injuries was computed using Equation 4 below. The standard errors from the logistic model was used in the calculation to compute 95th percentile confidence intervals of all estimates. The estimated injury reduction for each system configuration was computed relative to the predicted number of injured occupants in the baseline configuration.

$$Predicted\ Injuries = \sum_{i=1}^{111} Probability\ of\ Injury * Case\ Weight \quad \#(4)$$

RESULTS

Crash Benefit

The overall system benefit was defined to be the percentage of cases in which the system successfully avoided a crash, compared to the percentage of cases in which the crash still occurred. The baseline model was defined as a vehicle without an LDW or LKA system in which the encroaching vehicle followed the original crash trajectory. The benefit of different system type is shown in Figure 4. The crash avoidance benefit of the LDW system increased for systems that delivered an earlier warning. LKA systems that automatically steered produced a greater estimated crash reduction than LDW systems. The speed models that worked at a lower speed showed a higher estimated benefit than the same model with a higher activation speed.

With AEB, the LDW systems had a 5.2% increase in benefit and the LKA system received no increase in benefit. An interesting trend was that the additional benefit due to an AEB system in the impacted vehicle diminished as the system activated earlier. This is because the AEB system allowed the impacted vehicle to brake harder, which granted the driver of the encroaching vehicle more time to respond to the situation. A quicker response time from the driver showed higher estimated benefit for the vehicles with the basic LDW model because the warning was delivered as soon as the vehicle crosses the lane line. The LDW with lower activation speed and earlier TTLC had almost the same increase in benefit because they depend on the driver input. No additional estimated benefit was seen for the LKA system. The benefit due to the LKA system is independent of the driver's reaction time because the LKA system produces an immediate automated evasive maneuver. The extra time available due to the AEB system in the impacted vehicle produced no additional estimated benefit.

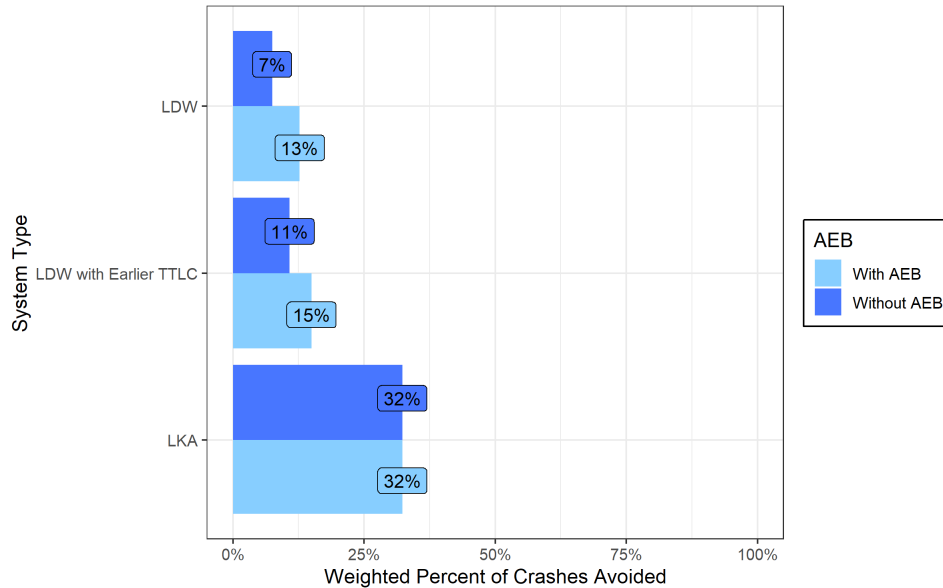


Figure 4. Weighted percent of crashes avoided for each system model and activation speed.

Injury Benefit

The predicted injury benefit for each LDW/LKA system was higher than the crash benefit (Table 6). As expected, systems with an estimated larger crash reduction benefit also had a larger injury benefit. Therefore, each expanded activation speed system performed better than its basic counterpart and systems with an earlier activation also performed better. All LDW/LKA systems showed a higher estimated injury benefit when the impacted vehicle was equipped with an AEB system. The AEB system, if activated, might be able to slow the impacted vehicle down which can lower the delta-v for all crash occupants. However, the increase in injury benefit from the AEB system diminished as a higher proportion of crashes were estimated to be avoided. The LKA system with a lower activation speed is estimated to have the highest crash avoidance and injury mitigation.

Table 6. Estimated injury reduction for each LDW/LKA system

| System Design | No AEB in the Impacted Vehicle | | AEB in the Impacted Vehicle | |
|---------------------|--------------------------------|------------------------|-----------------------------|-----------------|
| | Number of Injured Occupants | Percent Injury Benefit | Number of Injured Occupants | Percent Benefit |
| Baseline | 6,320 ± 680 | 0.0% | - | - |
| LDW | 4,970 ± 200 | 21.4% ± 9.0% | 3,110 ± 150 | 50.8% ± 5.8% |
| LDW with Early TTLC | 4,560 ± 200 | 27.8% ± 8.3% | 2,890 ± 150 | 54.3% ± 5.4% |
| LKA | 3,070 ± 500 | 47.3% ± 9.7% | 2,000 ± 380 | 68.4% ± 6.9% |

DISCUSSION

The basic LDW model provided the smallest benefit since it activated much later than the other systems, a TTLC of 0.0s. For the base LDW system, the predicted crash benefit was 7% and more advanced LKA systems had predicted crash benefit up to 51%. The range of these benefits encompass estimates by Cicchino and Sternlund that combined the analysis LDW and LKA systems in road departure, sideswipe, and head-on crashes [7, 8] (Table 7).

Table 7. Summary of previous LDW studies with head-on crashes.

| Study | Case Selection | LDW/LKA Injury Benefit |
|--------------------|--|---|
| Cicchino 2018 [7] | Single vehicle road departure, head-on, sideswipe crashes in US | Reduction of minor injurious crashes 21% (LDW/LKA) |
| Sternlund 2017 [8] | Single vehicle road departure, head-on crashes on high-speed roads in Sweden | Reduction of minor injurious crashes 30% (LDW/LKA) |
| Present Study | Cross-centerline head-on crashes in the US | 7%-17% (LDW) 32%-51% (LKA) |
| | | 13%-25% (LDW+AEB) 32%-51% (LKA+AEB) |

The basic LDW model provided the smallest benefit since it activated much later than the other systems. For the base LDW system, the predicted crash benefit was 13%. No warning was delivered to the driver in 62% of LDW cases because the encroaching vehicle was travelling below the activation speed when crossing the lane line. After accounting for the NASS/CDS case weights, it was determined that the maximum additional benefit to the lower activation speed is 20.0%. The LDW system with earlier TTLC activation predicted a benefit of 15%. This is a 2% increase in benefit compared to the base LDW model. Previous studies have shown that the highest benefits are to be expected when driver reaction times are the fastest [4, 16]. For the LKA system, the vehicle responds immediately and automatically provides steering input without any driver input. Therefore, the LKA system had the greatest crash benefit.

Due to the nature of cross-centerline crashes, many road departure crashes were not avoided in the simulations because there was very little time for the driver to respond. The fastest driver reaction time (0.38s) and even an early warning of 0.5s TTLC often left very little time for the driver to steer or brake to avoid the object. The time available for the driver of the encroaching vehicle to respond is related to the distance from the departure to the impact location and the speed of the vehicle. Slower moving vehicles with larger distances to travel before impact will have more time to respond than fast moving vehicles with smaller distances to travel before impact. Figure 5 shows the simulation outcome based on the encroaching vehicle's speed and distance between the impact location and point of departure for the two different reaction times for the LDW system and the LDW system with early TTLC activation. For the cases without the expanded activation speed, there was a clear boundary at 50 kph, below which the vehicle crashed in the simulation.

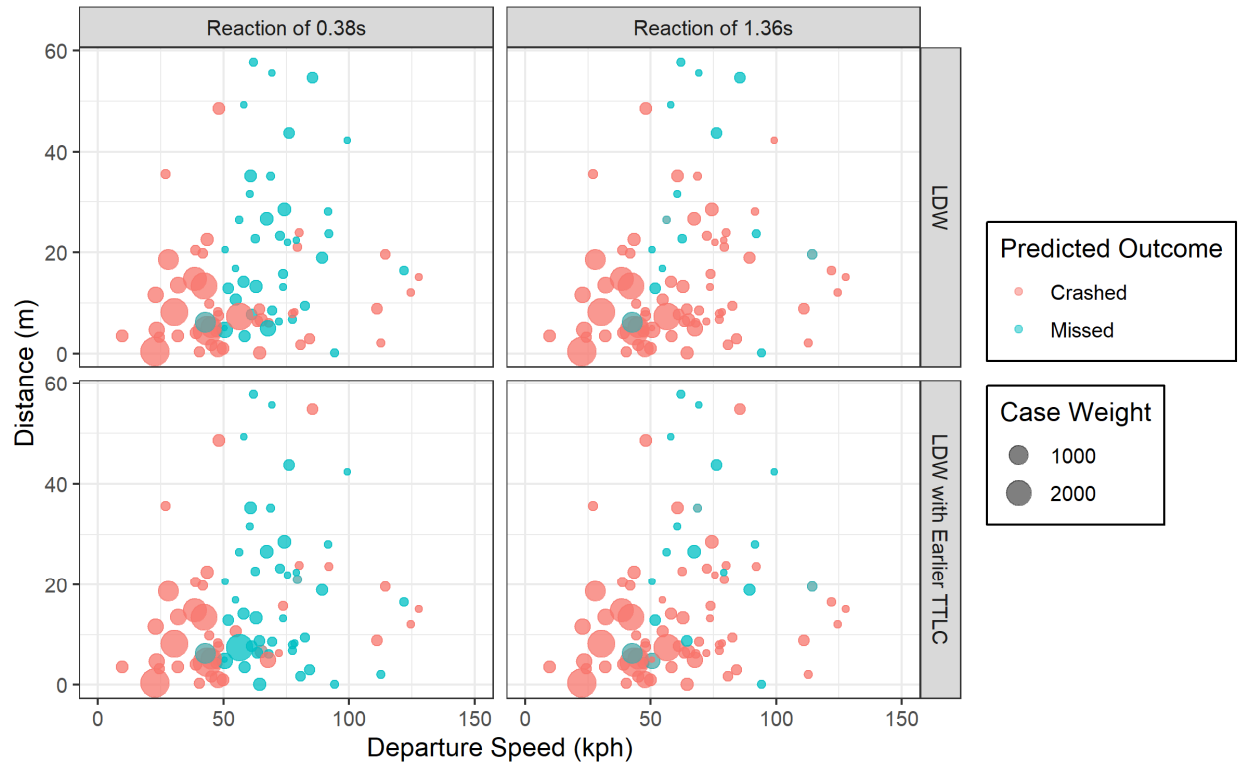


Figure 5. Crash outcome based on the departure speed and the straight-line distance to the impact point from the point of departure. The crash outcome is shown for each reaction time for Advanced LDW and Advanced LDW with Expanded Speed simulations with AEB. The encroaching driver model involved heavy steering (34.1 deg/s) and no braking (0.0 g), and the impacted driver model involved following the intended path and braking (0.27 g)

Limitations

This study used the road geometries and vehicle speeds from real-world head-on crashes to estimate the effectiveness of LDW/LKA and a hypothetical AEB system. The vehicles were simulated in an idealized environment with simplified driver behavior models and simple active safety activation criteria. While the limitations detailed below influence the effectiveness of these systems in the real-world, the trends found from the simulations can provide insight into the potential benefits of these systems.

In many cases, an EDR was present for one of the involved vehicles. While the delta-v was recorded for one vehicle, the delta-v of the other vehicle was reconstructed. This reconstruction assumed that all the vehicle motion was planar and there was no rotation of the vehicles from the impact, which may not always be the case for an oblique frontal crash. Additionally, this study assumed that there were no other vehicles or objects to be avoided, which may increase the effectiveness estimates. Another limitation to the study was that the friction coefficient is assumed to be constant for every case regardless of the weather and road conditions. This would affect a select few cases where road conditions, such as rain and snow, decrease the turning/braking effects. This study did not account for the grade of the road which could alter the deceleration of the simulated vehicles. However, this effect is likely overcome by any braking performed by the driver. The vehicle model limited the acceleration to 1 g. This represents the upper limit of the tire force available for a maneuver. Due to tire tread, the driving surface, and the shape of the vehicle, the actual tire force is likely much lower.

Additionally, this model assumed that the driver of the impacted vehicle was fully attentive and anticipated the encroachment of the other vehicle because drivers in the impacted vehicle always performed an evasive action [36]. However, this may not be true if the driver of the impacted vehicle was also distracted, the road was curved, or the view was obstructed such that the encroaching vehicle approached from a blind turn. The driver of the impacted vehicle did not perform an evasive steering maneuver. Instead, the driver of the impacted vehicle braked and followed their intended path by remaining centered in their lane. These simulated behaviors are derived from analysis of EDR data on pre-crash behavior in cross-centerline crashes [18]. This study did not account for driver

actions throughout the lane crossing event that could disable the LDW/LKA system. Our study did not consider cases with multiple departures and assumed that the drivers may not overcorrect after the initial lane departure event.

CONCLUSIONS

The purpose of this study was to estimate the safety benefits of LDW/LKA systems and hypothetical AEB systems for cross-centerline crashes. AEB improved the crash benefit for LDW systems, but the effect diminished as LDW/LKA system activated earlier. The AEB system reduced the delta-v in the residual crashes which significantly increased the injury benefit for all LDW/LKA systems. Future iterations of this study should analyze if there is a significant change in crash prevention benefits if the trajectory of the impacted vehicle deviates from the center of their lane or if the impacted vehicle performs a steering evasive maneuver.

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