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Active Vehicle Safety Systems: A Review of Crash Evidence

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ABSTRACT

Active safety systems in cars assist in preventing crashes and protect the driver. With the development of self-driving cars and the addition of more safety features in modern vehicles, cars are becoming safer. As many of these systems have been used as standard equipment in vehicles, it is important to understand their operating principles and determine which systems have been shown to be effective in reducing crashes in practice. This paper reviews studies published since 2000 on vehicle safety systems, including anti-lock braking systems (ABS), electronic stability control (ESC), autonomous emergency braking (AEB), lane keeping assistance (LKA), and adaptive headlights. Their operations, development history, and outcomes in practical applications have been reviewed and discussed. The progress of each active safety system is also discussed. Crash statistics for vehicles with and without these systems have been reviewed. ESC shows consistent evidence for reducing crashes involving loss of control, run-off-road, and rollover, while AEB reduces rear-end crashes. LKA reduces relevant lane-departure crashes. ABS reduces braking-related crashes but has not demonstrated a clear reduction in overall crash frequency. Adaptive headlights are supported by insurance-claim evidence, while police-reported crash evaluations remain inconclusive. Because the reviewed studies differ in country, study period, and crash types, the reported percentage reductions are not directly comparable. For this reason, this paper does not attempt to rank these system.

INTRODUCTION

Traditional cars rely on drivers being able to stay attentive on the road, process the information, react accordingly, and make the correct choices to keep the roads safe. As self-driving and assisted-driving cars gain popularity, they shift from reliance on drivers to more automated technologies. This shift aims to increase the safety of roads for drivers, pedestrians, bikers, etc. Commercially, cars are mostly limited to automatic acceleration, braking, or steering while the driver remains mostly in control (National Highway Traffic Safety Administration, 2025). Assisted driving cars can remove human error from crashes and replace it with automated technology that often detects and reacts faster than humans (National Highway Traffic Safety Administration, 2025). The potential for these kinds of cars to reduce deaths is great; however, it is important to understand that technology can still make mistakes.

Cars have caused many crashes each year since their invention, and over time, several safety systems have been implemented to reduce deaths caused by accidents. These are called active or passive safety

systems. Active safety systems attempt to prevent accidents, and passive safety systems attempt to reduce the damage during accidents. Active safety systems assist the driver in braking, acceleration, steering, parking, etc., and often do so better than the driver can (National Highway Traffic Safety Administration, 2025). The fatality rate per 100 million vehicle miles has been declining over the years. In 1923, the fatality rate was 18.65 deaths for every 100 million miles driven, while in 2024, it was 1.3 (National Safety Council, 2024). Vehicle technology is one of the contributions. Road engineering, driver licensing, seat belt laws, drink-driving enforcement, and so on are other contributions leading to reduced deaths.

Passive safety systems, such as seat belts and airbags, mitigate the injury caused by crashes, whereas active safety systems aim to prevent crashes. Therefore, improving active safety systems reduces the number of crashes in which passive safety systems are needed. Understanding the effectiveness of the newer active safety systems could lead to insights on how to improve them, or where improvement would prevent the greatest number of crashes.

This paper reviews several studies about anti-lock braking systems (ABS), electronic stability control (ESC), autonomous emergency braking (AEB), lane keeping assistance (LKA), and adaptive headlights. They are to be analyzed for their effectiveness in preventing crashes. The analysis supports that ESC, AEB, and LKA are effective in preventing crashes.

METHODS

This paper presents a review and comparative study of relevant sources from publications and reports. The sources were identified through Google Scholar and publisher databases by searching using the keywords of safety systems combined with crash and evaluation. The search strings combined the system's name and "effectiveness in crashes", for example, "anti-lock braking system effectiveness in crashes" and "adaptive headlights effectiveness in crashes". These searches occurred around July 2026.

The articles were screened based on their crash analysis in developed countries with road infrastructure. Articles based on modeling, theory, tests, or simulations were not considered for the effectiveness of an active safety system. Due to the limited number of articles analyzing such circumstances, older articles, such as Dang (2007), were used.

The data include Khorasani-Zavareh et al. (2013) for ABS; Dang (2007) and Lyckegaard et al. (2015) for ESC; Cicchino (2017) for AEB; Utriainen et al. (2020) for LKA; and Highway Loss Data Institute (2012) for adaptive headlights. The reviewed data in journal articles and reports are based on police-reported crashes, fatal-crash databases, or other real-world crash data and identify whether the vehicles involved were equipped with the system being evaluated. Priority was given to peer-reviewed articles and government reports. Percentage reductions reported from different studies may not be comparable because the studies differ in country, time period, crash type, vehicle class, and statistical adjustment methods.

RESULTS

Anti-lock Braking System (ABS)

If a driver brakes too hard, the wheels of the car could potentially lock up and result in the wheels sliding instead of slowing the car down. This potentially leads to loss of control, and the tyre can be flat-spotted. ABS prevents the wheels from locking up when a car brakes (Ribbens, 2017). ABS works by automatically adjusting the pressure applied to a car's brakes to ensure that steering control is maintained (Ribbens, 2017). This allows the wheels to continue rotating and not slip while the vehicle slows down.

As shown in Figure 1, each wheel is equipped with a speed sensor and connected to a central pump/valve that regulates the brake pressure applied to it (Ribbens, 2017). The ABS uses the speed sensors to determine whether a wheel is about to lock up. When a potential lock-up is detected, the computer automatically adjusts the brake pressure to the affected wheel through the pump/valve. This mechanism effectively prevents wheel lockup and reduces the risk of skidding. Situations such as rainy roads or sudden stops can cause panic braking, but ABS, regardless of the pressure on the brake pedal, tries to ensure that the wheels will not lock up, reducing the required skill of the driver and preventing more accidents in inclement conditions. However, on loose surfaces such as gravel or fresh snow, a locked wheel can build a wedge of material in front of the tyre that shortens stopping distance, potentially making it harder to stop even with ABS. This is a design trade-off in favour of steering control (Ribbens, 2017).

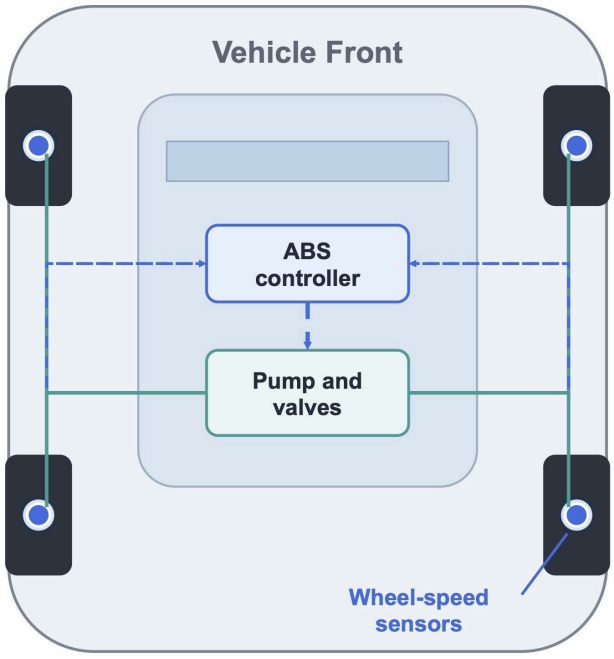


Figure 1: Major Components of an ABS System. The diagram shows the wheel-speed sensors, which monitor wheel rotation, and the pump-valve system, which regulates brake pressure.

ABS was initially created to solve the problem of wheels locking up for planes in the 1920s (Ribbens, 2017). It had the same functions as ABS does for cars (Ribbens, 2017). ABS for cars began in premium cars around the 1970s (Ribbens, 2017). Since then, improvements to the system have made it cheaper and more effective, to the point where it became standard in the 1990s and greatly reduced accidents (Ribbens, 2017).

A self-reported telephone survey in Iran from March 2007 to March 2008 analyzed the rate of fatal road traffic crashes for vehicles with and without ABS (Khorasani-Zavareh et al., 2013). It found that the annual incidence rate of fatal road traffic crashes involving another vehicle was 145.1 (134.8-155.9) per 1000 vehicle-years, but there was not a statistically significant difference between study groups (Khorasani-Zavareh et al., 2013). But the study found that, in crashes attributed to brake failure, vehicles without ABS had 50.3 (42.9-58.5) crashes per 1,000 vehicle-years, whereas vehicles with ABS had 30.0 (21.2-41.2) crashes per 1,000 vehicle-years (Khorasani-Zavareh et al., 2013). The difference was statistically significant after adjustment for the driver's and vehicle's age and the daily driving time (Khorasani-Zavareh et al., 2013). However, it has not demonstrated a statistically significant effect on the overall frequency of crashes involving another vehicle (Khorasani-Zavareh et al., 2013). These findings suggest that, although ABS is effective at reducing crashes associated with wheel lockup or loss of control during braking, its effect on overall crash rates remains unclear. The self-reported nature of the study does bring up bias that could skew the data when adjusting the data when people reported the driver's and vehicle's age and the daily driving time.

Electronic Stability Control (ESC)

ESC is a computer program that tracks the car’s intended and actual positions (National Safety Council, 2015). Sensors read the car’s position, and the program automatically adjusts the car’s brakes to get back on course, preventing steering issues, rollovers, and crashes. ESC aims to prevent unintentional skidding. The ESC system estimates the intended path of the vehicle by using the steering angle and brake positions. At the same time, yaw rate, lateral acceleration, and wheel-speed sensors measure the vehicle’s actual motion. By comparing the intended path with the vehicle’s actual path, ESC can detect oversteering or understeering and apply braking pressure to the wheels to correct the path.

In Figure 2, the gray car and path represent the driver’s intended course, while the red car shows the route that the car is actually on, potentially because of slippery road conditions. In the oversteering example, as shown on the left of Figure 2, ESC applies the brakes to the right-front wheel to help return the vehicle to its intended course. In the understeering example, as shown on the right in Figure 2, ESC instead applies the brakes to the right-rear wheel.

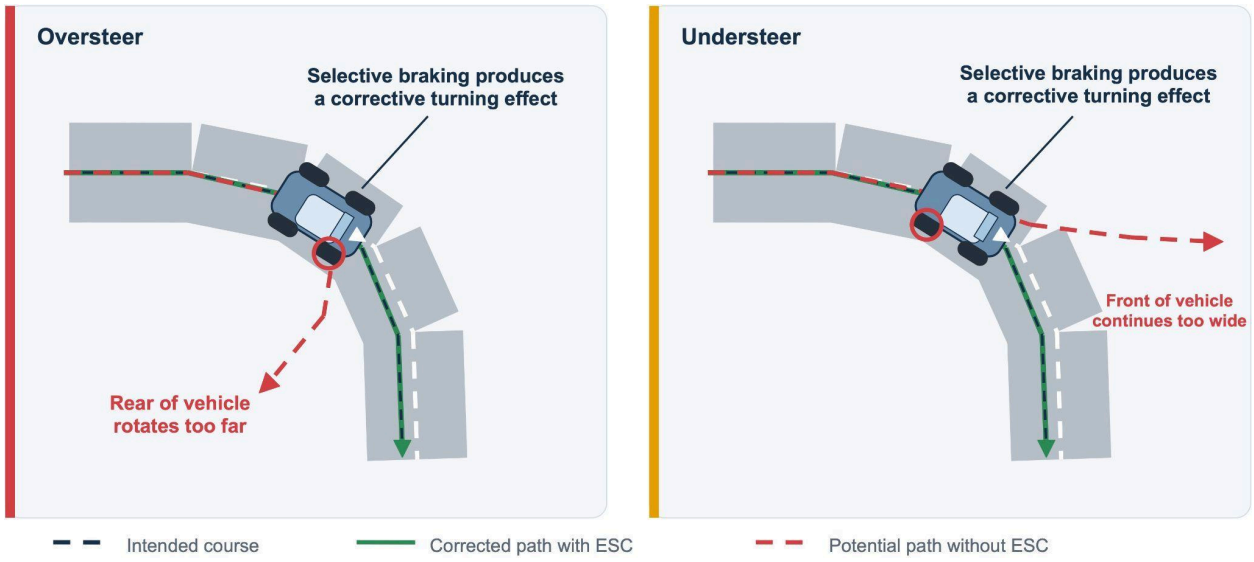


Figure 2: Schematic of ESC Correction of Oversteer and Understeer. The left figure shows how ESC corrects oversteer by applying the right-front brake, and the right figure shows how ESC corrects understeer by applying the right-rear brake. The gray vehicles represent the corrected paths with ESC. The red vehicles represent the potential paths without ESC.

Many popular car manufacturers started producing cars with ESC as an idea to reduce instability when drivers panicked and lost control (Ribbens, 2017). Continued development of the system, along with studies demonstrating its risk reduction, convinced more companies and government agencies of the system's utility (Ribbens, 2017).

A study in Denmark used police-registered injury accidents from 2004 to 2011 in Denmark with cars manufactured in the period 1998 to 2011 and the principle of induced exposure to measure the effectiveness of ESC (Lyckegaard et al., 2015). It found the crude odds ratio and the adjusted odds ratio, the latter through logistic regression controlled for confounding factors: age, gender, driving experience, valid driving license, seat belt use, the vehicle's year of registration, vehicle weight, ESC, the speed limit, and road conditions. The study calculated the crude odds ratio for ESC-equipped cars of getting in a single-vehicle injury accident as 0.40 (95% confidence interval [CI], 0.34–0.47) and the adjusted odds ratio as 0.69 (95% CI, 0.54–0.88). No difference was found in the effectiveness of ESC across slight, severe, and fatal injuries (Lyckegaard et al., 2015). Overall, this study found that ESC reduces single-vehicle injury accidents by 31% when controlling for various confounding factors related to the driver, the car, and the accident surroundings.

In the United States, Dang (2007) used statistical analyses of 1997-2004 crash data from the Fatality Analysis Reporting System (FARS) and 1997-2003 crash data from the State data files to analyze ESC effectiveness. Through 2x2 contingency table analysis and logistic regression analysis, they found that

fatal single-vehicle crashes decreased by 36% in passenger cars and 63% in light trucks and vans. It was adjusted to account for the difference in reporting from state to state and imbalances in the make-models of vehicles with ESC versus those of similar make-models without ESC Dang (2007). There were statistically significant reductions in fatal run-off-road, single-vehicle, and rollover crashes Dang (2007). These findings indicate that ESC is effective in reducing crashes involving loss of vehicle control.

Overall, the studies reviewed indicate that ESC has had a substantial impact on preventing crashes. It can also make use of other active safety systems. Since ESC works in conjunction with other vehicle systems, improvements to other safety systems, such as brakes or sensors, through better sensor accuracy, brake response, and control algorithms, could potentially improve its effectiveness. For example, when a car begins to lose stability during a turn, ESC can apply the brakes to maintain the car's intended path.

Autonomous Emergency Braking (AEB)

AEB is a system for both parking and driving (Jeong, 2022). It aims to prevent any collisions between the car and its surroundings, mainly in the forward and backward directions (Jeong, 2022). It uses cameras and sensors to detect potential obstacles in the car's path, such as pedestrians, vehicles, walls, cyclists, cones, and sidewalks (Jeong, 2022). Developments in sensors and computer programs have improved AEB's ability to avoid collisions (Yang et al., 2022).

AEB works by attempting to prevent and reduce damage by initially warning the driver of the obstacle or tightening the seat belt (Yang et al., 2022). Once a camera detects an obstacle in the car's path that the driver has not addressed, AEB attempts to apply braking pressure that will prevent or at least reduce the crash (Yang et al., 2022).

A study of low-speed AEB in the U.S. used Poisson regression and a 95% confidence interval to compare rates of police-reported crash involvements per insured vehicle year in 22 U.S. states Cicchino (2017). It compared 2010–2014 data between passenger vehicles with and without AEB, controlling for other factors affecting crash risk, such as the in drivers who spent extra money to buy AEB Cicchino (2017). Their results showed that low-speed autonomous emergency braking (AEB) reduced front-to-rear crash rates by 43% and front-to-rear injury crash rates by 45% Cicchino (2017). This indicates that for low-speed areas, there is a substantial reduction in crashes.

Lane Keeping Assistance (LKA)

In 2024, in the U.S., close to two million single-vehicle crashes involved road departures, causing around 470,000 injuries and 20,000 deaths (National Highway Traffic Safety Administration, 2024, Table 28). Drivers leaving their lane or the road is a major problem. LKA revolves around keeping the driver in their lane and on the road. A front-facing camera tracks the lane markings, and if the car drifts too close to the markings without activating a turn signal, LKA alerts the driver through vibrations, visual signals, or audio signals (Ribbens, 2017). LKA goes a step further and automatically steers or brakes to keep the car

in the lane (Ribbens, 2017). This system relies on the markings being visible, meaning inclement weather conditions such as fog or poor road quality reduce the effectiveness of these safety systems. Proper infrastructure is required as well for these systems to be effective.

In the beginning, camera sensors were used to warn the driver when they were about to depart their lane (Jeong, 2022). Early LKA acted like AEB but for lane departure. However, it only actively steered the vehicle when it was about to leave the lane (Jeong, 2022). Recent autonomous driving developments have given the car more control to dictate the car's position in the lane (Jeong, 2022).

A study on LKA thoroughly analyzed 364 fatal head-on and single-vehicle crashes in Finland (Utriainen et al., 2020). By analyzing the markings' visibility, infrastructure, weather, and driver-related risks in each crash to rationalise the results, they found that 27% could've been prevented had commercially available LKA been used (Utriainen et al., 2020). LKA at that time couldn't entirely drive the car, relying on the driver to actively make decisions (Utriainen et al., 2020).

Adaptive Headlights

Adaptive headlights, or adaptive frontlight systems, address the issue of poor visibility around turns at night. Adaptive headlights change the headlights' intensity and direction to achieve this (Toney & Bhargava, 2021). This safety system depends on using the trajectory of the car and the steering wheel to adjust the headlights (Toney & Bhargava, 2021). However, these do not cover all the possibilities for when adaptive headlights can be applied, such as intersections at night (Toney & Bhargava, 2021). Therefore, there is work to also use changes in visibility, lane markings, other cars, and identifiable street signs to direct the headlights (Toney & Bhargava, 2021).

Adaptive headlights in the U.S. can work well due to the easily recognizable markings, but will need further study, as many of the recent innovations on this have focused on addressing one speed or environment, and not general road conditions (Toney & Bhargava, 2021). While adaptive headlights work to give more information and control to the driver, heavy snow on road markings, fog, or poor road signs greatly reduce their effectiveness. Improving adaptive headlights to adapt to situations without infrastructure can improve their effectiveness.

Figure 3 depicts how headlights could give more visibility to the driver. The brightness and angle of the beams could be changed according to the lane and road markings or the direction of the steering wheel and trajectory (Toney & Bhargava, 2021).

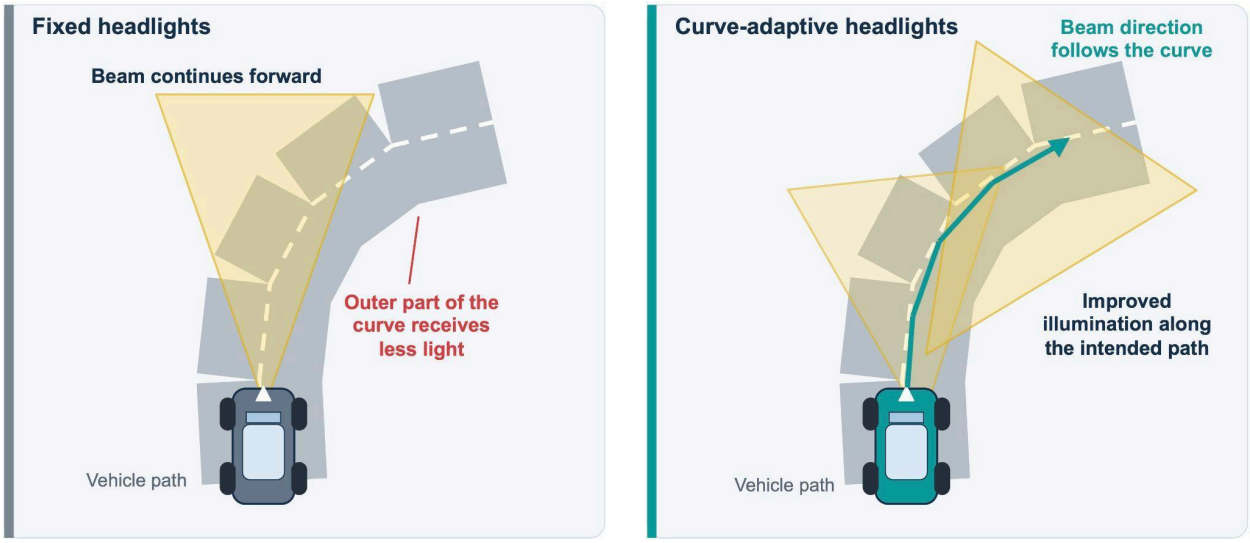


Figure 3: Road Illumination With and Without an Adaptive Frontlight System. The left panel shows how an adaptive frontlight system (AFS) redirects the headlight beam toward the curve, improving illumination along the vehicle's intended path. The right panel shows how a traditional lighting system partially illuminates the curved roadway.

Highway Loss Data Institute (HLDI) (2012) provides the information for Volvo's Active Bending Lights, a curve-adaptive headlight system which turns the headlamps by up to 15 degrees based on vehicle speed and steering angle. Using regression analysis (after adjusting for calendar year, model year, garaging state, vehicle density [number of registered vehicles per square mile], rated driver age group, rated driver gender, rated driver marital status, deductible range [collision coverage only], and risk), vehicles equipped with the system have a 9.0% reduction in property-damage-liability claim frequency and a 16.8% reduction in bodily-injury-liability claim frequency, while collision claim frequency decreased by only 0.7%. However, the claims are not limited to headlights-related crashes only, and further study is needed to identify which crash types are prevented.

In summary, adaptive headlights have moderate insurance-claim evidence of reducing crashes and indirect crash evidence through visibility ratings. No police-reported crash evaluation of curve-adaptive systems was identified. The absence of such studies is an evidence gap, not evidence that the systems are ineffective.

DISCUSSION

Table 1 summarizes the previously reported results for different systems as discussed above. The percentages in the table are not a ranking. The evidence comes from different countries, time periods, vehicle classes, crash definitions, and statistical models, so a 31% ESC reduction and a 43% AEB reduction cannot be compared.

System	Study	Design	Sample	Variables Adjusted for
ABS	Khorasani-Zavareh et al. (2013)	Incidence-rate estimates using a 95% confidence interval.	Self-reported telephone survey in Iran from March 2007 to March 2008. 1232 ABS and 3123 non-ABS vehicles.	The driver's and vehicle's age and the daily driving time.
ESC	Lyckegaard et al. (2015)	Crude odds ratio and the adjusted odds ratio, the latter through logistic regression.	Police-registered injury accidents in Denmark from 2004 to 2011 with cars manufactured in the period 1998 to 2011.	Age, gender, driving experience, year of registration, vehicle weight, ESC, speed limit, and road conditions.
ESC	Dang (2007)	2x2 contingency table analysis and logistic regression analysis	1997-2004 crash data from the Fatality Analysis Reporting System (FARS) and 1997-2003 crash data from the State data files.	Differences in reporting from state to state. Imbalances in the make-models of vehicles with ESC versus those of similar make-models without ESC.
AEB	Cicchino (2017)	Poisson regression and a 95% confidence interval.	2010–2014 police-reported crash data between passenger vehicles with and without AEB in 22 U.S. states.	Difference in drivers who spent extra money to buy AEB.
LKA	Utriainen et al. (2020)	Indefinite analysis for risk ratio	364 fatal head-on and single-vehicle crashes in Finland in 2014-2016.	Markings' visibility, infrastructure, weather, and driver-related risks
Adaptive Headlights	Highway Loss Data Institute (2012)	Regression analysis and Poisson distribution.	Volvo supplied vehicle identification numbers.	Calendar year, model year, garaging state, vehicle density, rated driver age group, rated driver gender, rated driver marital status, deductible range, and risk.

Table 1: Summary of results in practical applications

Among the sources reviewed, ESC has consistent crash evidence. Dang (2007) found large reductions in fatal single-vehicle crashes in the United States (36% in passenger cars and 63% in light trucks and vans). Lyckegaard et al. (2015) found a smaller but still significant reduction of about 31% in single-vehicle injury accidents in Denmark (adjusted odds ratio 0.69). Both studies point to the same crash type: loss of

control. ESC shows consistently reduced crashes involving loss of control, run-off-road, and rollover, while AEB reduces rear-end crashes.

ABS reduces braking-related crashes but has not demonstrated a clear reduction in overall crash frequency. Khorasani-Zavareh et al. (2013) found no overall difference in self-reported crashes, but fewer crashes due to brake failure. Cicchino (2017) found that low-speed AEB reduced front-to-rear crashes by 43% and front-to-rear injury crashes by 45%.

LKA and adaptive headlights do not have the same kind of crash evidence. Utriainen et al. (2020) concluded that 27% of 364 fatal head-on and single-vehicle crashes in Finland in 2014-2016 might have been prevented if LKA had been fitted. HLDI (2012) found a 9.0% reduction in property-damage-liability claims for Volvo Active Bending Lights. Police-reported crash evaluations remain inconclusive.

It should be noted that it is difficult to cleanly separate one system from another. For example, ESC uses the same equipment as ABS (Ribbens, 2017; National Safety Council, 2015); therefore, it is not a standalone ESC-equipped vehicle. AEB, LKA, and adaptive headlights are also often added as options on the same vehicle. The paper does not attempt to rank these systems and does not add a new meta-analysis. The strongest crash evidence is for ESC in single-vehicle loss-of-control crashes (Dang, 2007; Lyckegaard et al., 2015) and for low-speed AEB in rear-end crashes (Cicchino, 2017).

LIMITATIONS

This paper reviewed references across five system categories and has several limitations, including the limited number of studies. The studies include information from different countries, road environments, vehicle classes, crash definitions, and statistical methods, and some rely on self-reported crashes or insurance claims. There isn't a unified statistic to compare these systems to each other in this paper. The absence of proper screening in this paper gives rise to some bias. There is likely English-language and publication bias as well that likely overestimates the effectiveness of each system globally, due to the difference in infrastructure between developed and undeveloped countries. The technology has also changed greatly from 2007 to 2026. These indicate limitations in giving a review of the overall effectiveness of a modern equivalent of an active safety system.

CONCLUSION

Among the systems reviewed, demonstrated crash-reduction evidence is strongest and most consistent for ESC in single-vehicle loss-of-control crashes. ABS can preserve control during braking, but its influence on the result varies depending on driver behavior and crash types. AEB has replicated evidence for reducing rear-end crashes. While some insurance claims show curved-adaptive headlights help in reducing accidents, the evidence of crash prevention is limited. In contrast, ESC manages the brakes of the individual wheels to correct oversteer or understeer by detecting differences between the driver's intended path and the vehicle's actual motion. This reduces crashes involving loss of control,

run-off-road, and rollover. LKA reduces lane-departure crashes by warning drivers or automatically correcting a vehicle's path. Instead of relying on the driver to notice the warning and react accordingly, LKA can directly control and guide the car, therefore reducing relevant crashes. For future research and development on these safety systems, the effectiveness overall for every active safety system should be considered.

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