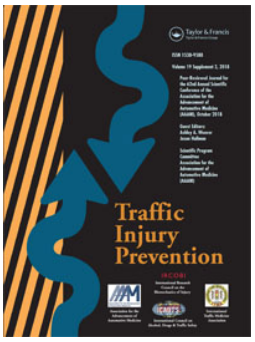

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Field effectiveness evaluation of advanced driver assistance systems

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ABSTRACT

Objective: Advanced driver assistance systems (ADAS) are a class of vehicle technologies designed to increase safety by providing drivers with timely warnings and autonomously intervening to avoid hazardous situations. Though laboratory testing suggests that ADAS technologies will greatly impact crash involvement rates, real-world evidence that characterizes their effectiveness is still limited. This study evaluates and quantifies the association of ADAS technologies with the likelihood of a moderate or severe crash for new-model BMWs in the United States.

Methods: Vehicle ADAS option information for the cohort of model year 2014 and later BMW passenger vehicles sold after January 1, 2014 ($n = 1{,}063{,}503$), was coded using VIN-identified options data. ADAS technologies of interest include frontal collision warning with autonomous emergency braking, lane departure warning, and blind spot detection. BMW Automated Crash Notification system data (from January 2014 to November 2017) were merged with vehicle data by VIN to identify crashed vehicles ($n = 15{,}507$), including date, crash severity (delta V), and area of impact. Using Cox proportional hazards regression modeling, the study calculates the adjusted hazard ratio for crashing among BMW passenger vehicles with versus without ADAS technologies. The adjusted percentage reduction in moderate and severe crashes associated with ADAS is interpreted as one minus the hazard ratio.

Results: Vehicles equipped with both autonomous emergency braking and lane departure warning were 23% less likely to crash than those not equipped (hazard ratio [HR] = 0.77; 95% confidence interval [CI], 0.73–0.81), controlling for model year, vehicle size and body type. Autonomous emergency braking and lane departure warning generally occur together, making it difficult to tease apart their individual effects. Blind spot detection was associated with a 14% reduction in crashes after controlling for the presence of autonomous emergency braking and lane departure warning (HR =0.86; 95% CI, 0.744–0.99). Differences were observed by vehicle type and crash type. The combined effect of autonomous emergency braking and lane departure warning was greater in newer model vehicles: Equipped vehicles were 13% less likely to crash (HR =0.87; 95% CI, 0.79–0.95) among 2014 model year vehicles versus 34% less likely to crash (HR =0.66; 95% CI, 0.57–0.77) among 2017 model year vehicles.

Conclusion: This robust cohort study contributes to the growing evidence on the effectiveness of ADAS technologies.

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Introduction

Although the driver is one of the "best sensors in the car" and can avoid many crashes, a large proportion of crashes are still attributed to driver error. The National Motor Vehicle Crash Causation Survey examined a national sample of U.S. crashes from 2005 to 2007 and identified the critical reason for each crash, defined as the last event in the causal chain (Singh 2015). Driver error was noted as the critical reason in 94% of crashes. These errors included recognition error (e.g., driver inattention and inadequate surveillance), decision error (e.g., driving too fast for conditions, misjudgment of gap or other's speed), and performance (e.g., overcompensation, poor directional control) and nonperformance (e.g., falling asleep) error.

New in-vehicle technologies are being developed and deployed to counteract these driver errors and support the driver to prevent crashes. Advanced driver assistance systems (ADAS) are a class of vehicle technologies that provide drivers with timely warnings. Some ADAS actively and automatically intervene to avoid hazardous situations or when the system detects that a crash is imminent. Examples of ADAS technologies include lane departure warning (LDW) and active lane-keeping assistance (LKA), blind spot detection (BSD), forward collision warning and autonomous emergency braking (AEB), and adaptive cruise control. Many manufacturers offer these technologies as options on some or all of their vehicles and may offer these systems standard in the future. ADAS technologies are the precursor to autonomous vehicles and, depending on

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the combination of ADAS equipment installed in a vehicle, can allow level 1 to level 2 autonomous driving at the present time (SAE International 2014).

Though laboratory testing suggests that ADAS technologies will greatly impact crash involvement rates, real-world evidence that characterizes their effectiveness is still limited. Previous evaluations of AEB and other ADAS have found reductions in both injury-involved and, to a lesser extent, all-severity (injury and noninjury) crashes.

A meta-analysis of pooled data from multiple countries determined that low-speed AEB was associated with a 38% reduction in real-world rear-end crashes (Fildes et al. 2015). Similar reductions were found in an evaluation of police-reported crashes in the United States: Vehicles equipped with AEB experienced a 56% reduction in injury front-to-rear crashes and a 50% reduction in all-severity front-to-rear crashes compared to nonequipped vehicles (Cicchino 2017).

A related study by Cicchino (2018) using police-reported crashes to evaluate LDW found a significant but smaller reduction in single-vehicle, sideswipe, and head-on crashes among equipped vehicles versus nonequipped vehicles and a 21% reduction in injury crashes and a 14% reduction in all-severity crashes. By contrast, a small European study of Volvo passenger cars found a 53% reduction in injury-involved head-on or single-vehicle crashes on roads with speed limits greater than 70 km/h among vehicles equipped with LDW/LKA compared to nonequipped vehicles (Sternlund et al. 2017).

This study evaluates and quantifies the reductions in moderate and severe crashes associated with ADAS technologies in BMWs in the United States using data on a cohort of newer model vehicles linked to a census of crashes.

Methods

This retrospective cohort study uses survival analysis to determine the effectiveness of ADAS technologies in preventing crashes. Model year 2014 and later BMW passenger vehicles sold in the United States between January 1, 2014, and May 18, 2017, were included in the study ($n = 1{,}063{,}503$). BMW is a luxury auto brand of passenger vehicles that includes small to large sedans, SUVs, and electric vehicles. This study does not include motorcycles or the MINI brand. Vehicle ADAS option information for all study vehicles was coded by linking VIN-level options data. ADAS technologies of interest for this study include the following.

Frontal collision warning with autonomous emergency braking

The driver is alerted if the speed of the vehicle and the distance from the vehicle or object in front indicates that a collision is possible. AEB will prevent the collision by applying the brakes if the driver's response is not adequate and there is a high possibility of a crash. Two levels of AEB option are offered. The first (basic) is camera-based with braking at low (city) speeds. The second (premier) level is camera and radar based, adding automatic braking at highway speeds and stronger braking pressure.

Lane departure warning

LDW is camera based and monitors driving lane markings to alert drivers to move back to the middle of the lane if they drift in either direction. LDW functions above 70 kmh up to 210 kmh.

Blind spot detection

BSD is radar based and warns the driver if a vehicle is detected in the blind spot or is approaching fast from the rear.

Lane-keeping assistance and new generation technologies

The newest generation of BMW vehicles (large- and mid-sized sedans introduced in model years 2016 and 2018, respectively) are equipped with ADAS technologies that are improved in both individual hardware and combined functionality. Improved hardware includes stereo camera for LDW and AEB. Four short-range radar sensors improve the abilities of BSD and allow for active steering intervention above 20 kmh to keep the vehicle in the lane with LKA. Coordination of radar and stereo camera further enhances ADAS functionality for all systems.

Typically, these ADAS technologies are offered within packages rather than as individual options. The percentage of buyers who opt for ADAS technologies (take-rate) varies by model and model year. Take-rates were lowest among the small and mid-size sedans and highest among the larger sedans and SUVs.

All crashes captured by BMW's Automated Crash Notification (ACN) system over a nearly 4-year period in the United States (from January 1, 2014, to November 10, 2017) were included in the study. This vehicle-installed crash notification system signals for help in the instance of a crash where a restraint system (i.e., airbag, seat belt pretensioner) is activated and the vehicle telemetry data are consistent with a high risk of injury based on a combination of area of impact on the BMW vehicle, crash severity (measured by change in velocity, delta V), and belt use of occupants. All BMW vehicles are equipped with the ACN system for the first 4 years after first purchase. The ACN system does not capture crashes where a restraint system was not activated. Therefore, the cohort of crashes identified by the ACN system is more likely moderate or severe with a high probability of injury than the overall crash population. The median delta V of these crashes was 17 kmh. Further, because the site of impact is important in risk of injury and restraint system activation, the median delta V of side impact crashes was lower (median 12 kmh) and that of rear impact crashes was higher (21 kmh) than that of front impact crashes (18 kmh). The study does not include the less severe crashes not captured by the ACN.

The crash cases were merged with vehicle configuration data by VIN to identify crashed vehicles ($n = 15{,}507$), including date, crash severity (delta V), and area of impact along with safety technologies present within the vehicle.

Vehicle months (months of follow-up from time of purchase) was used as the exposure measure to compute crash rates and in survival analysis. Vehicle months were computed separately for crashed and noncrashed vehicles. For vehicles that did not crash during the follow-up period, exposure was computed as the number of months between date of retail and the end of the study period (November 10, 2017). For vehicles that crashed, exposure was computed as the number of months between date of retail and crash date.

This study uses survival analysis to compare crash rates among ADAS-equipped versus nonequipped vehicles, controlling for exposure and time of entry into fleet (i.e., vehicles that are 1 month old are compared to each other, vehicles that are 1 year old are compared to each other). Another advantage of survival modeling in the context of this study is the ability to estimate risk (the hazard function) in the presence of staggered observations; in this case, the staggered way in which vehicles entered the fleet on the road over the 4-year period. Survival analysis uses both nonparametric and multivariate regression modeling techniques to compare time to failure (in this case, crash) among one group versus another. In this study, Cox proportional hazards regression models calculate adjusted hazard ratios (HRs) for crashes among BMW passenger vehicles with versus without ADAS technologies over a 4-year period. The hazard ratio can be interpreted as the relative risk of crashing with versus without ADAS. The adjusted percentage reduction in crashes associated with ADAS is therefore interpreted as one minus the HR. The analysis was conducted in SAS using the "proc phreg" procedure.

Results

Within the study cohort of vehicles, 22.5% were equipped with at least one of these ADAS technologies (Table 1). AEB and LDW were the most prevalent ADAS present and, because they are offered as a package, occurred together 99% of the time. BSD also frequently appeared together with AEB and LDW. LKA is offered in only 3 of the most recent vehicle models.

Between January 1, 2014, and November 10, 2017, the ACN system registered 15,507 crashes among the study cohort of vehicles. Thus, on average, these vehicles crashed at a rate of 54.5 crashes per 100 vehicle-months. This rate varied by vehicle size and body type. Two thirds (62.3%) of these crashes involved initial impact on the front of the vehicle (front impact), 21.8% involved initial impact to the side of the vehicle (side impact), 10.6% were rear impacts, and the remaining 5.3% were rollover crashes or no location was noted.

Figure 1 displays the life table estimator for the crashes, a nonparametric method to visualize the survivor function, stratified by ADAS presence. ADAS-equipped vehicles over

Table 1. Study cohort of vehicles and percentage with any ADAS, model year 2014 and later.

	Number of vehicles	Percentage with ADASS
Total	1,063,503	23
By model year		
2014	221,528	14
2015	353,982	20
2016	311,607	26
2017	173,026	31
2018	3,360	30

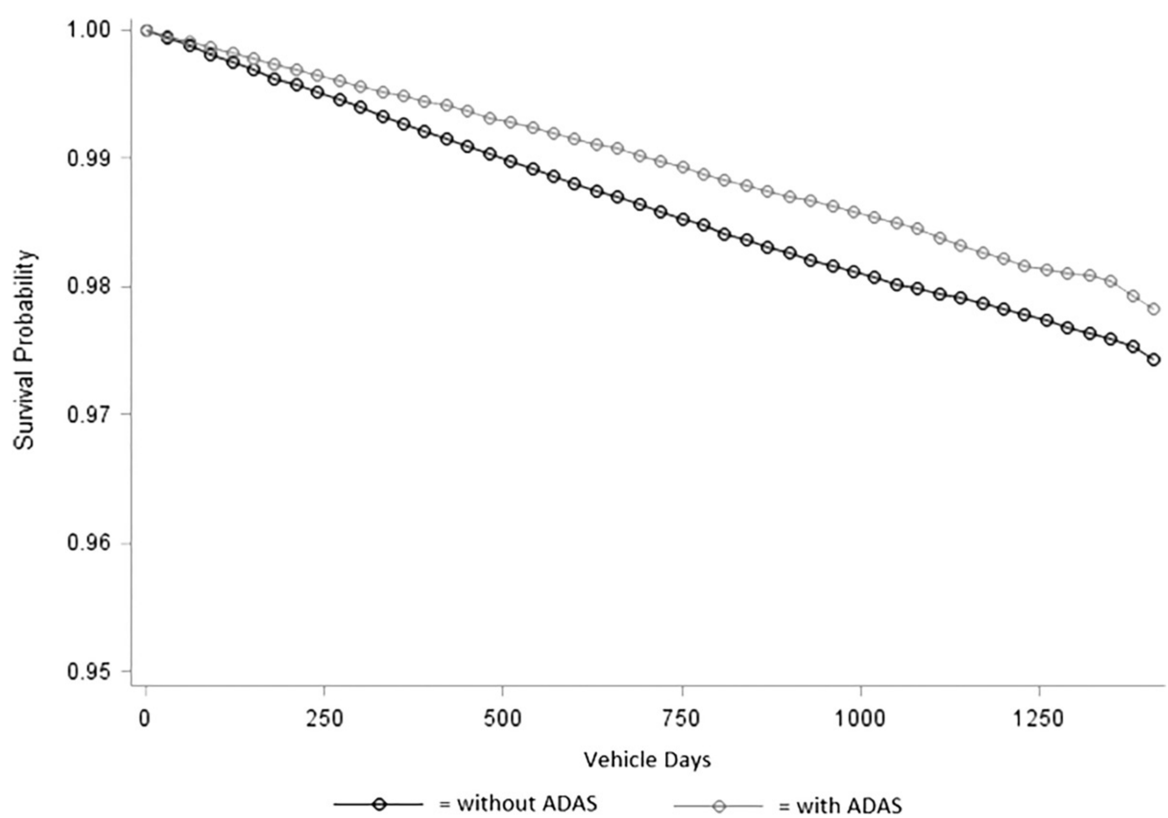

Figure 1. Life table estimator of the survival function, at 30-day intervals.

Table 2. Hazard ratios for crashes, comparing vehicles equipped with frontal crash warning with AEB and LDW to nonequipped vehicles.

	Hazard ratio[a]	95% Confidence interval	
Overall, all EACN crashes[b]	0.77	0.733	0.809
Overall, front impact crash[b]	0.74	0.693	0.783
Overall, side impact crash[b]	0.85	0.771	0.929
By model year[c]			
2014	0.92	0.83	1.025
2015	**0.79**	0.729	0.853
2016	**0.69**	0.625	0.752
2017	**0.69**	0.584	0.811
By vehicle series[d]			
Small to mid-size sedan	**0.62**	0.549	0.69
Large sedan	**0.61**	0.556	0.672
Small to mid-size SUV	**0.85**	0.746	0.969
Large SUV	0.90	0.803	1.011
Electric	1.08	0.859	1.358
Performance	0.91	0.789	1.045

[a]Hazard ratios in bold are significant, $P \leq .05$.
[b]Controlling for vehicle model year and vehicle size/body type.
[c]Controlling for vehicle size/body type.
[d]Controlling for vehicle model year.
EACN: Automated Crash Notification.

the study period have a better survival experience than nonequipped vehicles, with the cumulative probability of surviving to the end of the study period without a crash at 0.979 for ADAS-equipped vehicles compared to 0.975 for nonequipped vehicles.

AEB and LDW mostly occur together, making it difficult to tease apart their individual effects. Vehicles equipped with the optional package that includes any AEB (low and high speed) and LDW were 23% less likely to crash than vehicles not equipped (HR = 0.77; Table 2), controlling for model year and vehicle size/body type. Vehicles equipped with high-speed AEB (HR = 0.79; 95% confidence interval [CI], 0.75 to 0.84) were not significantly more likely to prevent crash than those equipped with low-speed AEB (HR = 0.78; 95% CI, 0.73 to 0.84).

Vehicles equipped with BSD were less likely to be involved in a crash compared to nonequipped vehicles, after controlling for model year and vehicle size/body type (not shown in table). The impact is reduced, but still significant, after controlling for the presence of LDW and AEB (HR = 0.0.86; 95% CI, 0.744, 0.993). This suggests that BSD alone is a less protective factor.

The association of combined AEB and LDW with crash reductions was greater for front impact crashes compared to side impact crashes (HR = 0.74 vs. HR = 0.85, respectively; Table 2). Combined AEB- and LDW-equipped vehicles are 27% less likely (HR = 0.74) to have a front impact crash compared to nonequipped vehicles, controlling for model year and vehicle size/body type. Later model year vehicles showed greater effect in reducing front impact crashes. Differences between vehicle size/body type were not significant.

The analysis indicates that combined AEB and LDW was associated with reductions in side impact crashes but to a lesser degree. Equipped vehicles are 15% less likely to have a side impact crash than nonequipped vehicles, controlling for model year and vehicle size/body type (Table 2). Smaller sample sizes limited this analysis from further stratification by model year and vehicle size/body type.

The association of combined AEB and LDW with reductions in crashes was greater in newer model vehicles: 13% less likely to crash (HR = 0.87) for 2014 model year vehicles versus 34% less likely to crash (HR = 0.66) for 2017 model year vehicles, controlling for vehicle size/body type. The sample of 2018 vehicles in service to date was too small to test.

Stratifying the Cox proportional hazards models by vehicle size/body type found that adjusted hazard rate ratios varied, even after controlling for model year. Reductions in crashes were greatest in small to mid-size and large sedans. Those equipped with combined AEB and LDW were 38 and 39% less likely to crash, respectively (HR = 0.62 and HR = 0.63), than those not equipped, controlling for model year. Large SUVs equipped with AEB and LDW were 10% less likely to crash, though this effect was only marginally significant ($p = .076$). Electric and performance vehicles equipped with these ADAS technologies did not show a significant difference in crash rates, though small sample sizes for these vehicle categories limited this analysis.

The effect of combined AEB and LDW was greatest in the most recent model year large sedan vehicles: Equipped vehicles were 53% less likely to crash than nonequipped vehicles (HR = 0.47). Compared to other models, these vehicles include LKA, with an autonomous steering intervention to keep the vehicle in its lane.

Discussion

This robust cohort study contributes to the growing evidence of the effectiveness of ADAS. The current study found that vehicles equipped with both AEB and LDW were 23% less likely to experience a moderate to severe crash than those not equipped, controlling for model year and vehicle size/body type. This study did not find a significantly different reduction in crashes associated with low-speed AEB compared to high-speed AEB. BSD alone was associated with a small but significant reduction in crashes.

Depending on vehicle type and crash type, AEB/LDW were associated with between 13 and 63% fewer crashes. Because AEB and LDW technologies are, for the most part, offered together in packages, it was not possible to tease apart their individual effects.

Though BMW is a luxury brand, it is not known whether BMW vehicles and their drivers have different crash risks and characteristics compared to other manufacturers. Any differences would limit the generalizability of the findings with the general vehicle population. However, the current study findings are similar to those of previous studies that found that AEB-equipped and LDW-equipped vehicles experience 14 to 56% fewer crashes (Cicchino 2017, 2018; Fildes et al. 2015; Sternlund et al. 2017). Cicchino (2017, 2018) looked at a broad spectrum of crashes from police reports but also limited the analysis to injury crashes, an outcome more similar in severity to the crashes in this study. Cicchino (2017, 2018) found that the impacts of AEB and LDW were higher for injury crashes than for all crashes (adjusted percentage reductions of 56 and 21%, respectively). These percentage reductions are consistent with those found in the current study.

The current study found that much of the protective effect is in frontal impact crash prevention, with a smaller but significant effect on side impact crashes. This is reasonable given that AEB and LDW are, for the most part, developed to prevent front to rear crashes and crashes where a roadway or lane departure occurs where a subsequent frontal impact results. Theoretically, there are crash scenarios where the initial impact is to the side of the vehicle that are relevant to LDW. These include single-vehicle run-off-road crashes or sideswipe impacts that involve side damage.

The newest models incorporate more advanced underlying technologies that may have an enhanced effect. This may explain why AEB/LKA-equipped new-model large sedans are associated with the largest reductions in crashes. LKA includes automatic active mitigation to prevent a crash, whereas other models are equipped with LDW alone, which provides a warning but does not actively intervene.

This study uses real-world data of a cohort of BMW vehicles linked to crash events. The strengths of this study include the large sample size of a well-defined vehicle cohort (over a million vehicles), the long follow-up (4 years), the ability to identify the individual options for each vehicle, and a well-defined outcome measure. The outcome, a census of crashes captured by the ACN system, included information on area of impact and severity (delta V).

A limitation of the study is that the findings are not generalizable to the full spectrum of crash severities. The cohort of crashes analyzed in this study is more likely moderate or severe with a high probability of injury compared to the overall crash population.

An additional limitation of the current study is the challenge of proving causality due to the quasi-experimental design necessitated by using real-world data. By using real-world data, the exposure (ADAS technology) could not be randomly assigned and therefore the observed reductions in crashes cannot be definitively attributed to the ADAS technology. Differential impacts of combined AEB and LDW by vehicle size/body type may be due to factors unrelated to the vehicle, including differences in the way the vehicle is used or driver characteristics (e.g., age, gender, vehicle use patterns). It may also be due to a buyer bias, where buyers who choose to pay more for ADAS options are consumers who value safety and take fewer risks. The role of these nonvehicle factors in ADAS effectiveness merits future study.

This study uses vehicle-months (follow-up from date of purchase). Some exposure bias may remain because vehicles with the same time (months) exposure but greater vehicle miles traveled per month will inherently have greater exposure on the road. However, a measure of mileage was not available at the time of the study.

Based on the findings of this study, ADAS technologies are a promising countermeasure to prevent crashes. Further study is merited to identify nonvehicle factors that might mitigate effectiveness (e.g., driver type). Though the development of autonomous vehicles continues, they will not become a significant proportion of the U.S. vehicle fleet for several decades. In the meantime, if ADAS technologies prevent, conservatively, between 15 and 25% of the 5 million annual crashes as this study suggests, widespread deployment of ADAS technologies could prevent thousands of related deaths and injuries every year. To that end, 20 automakers, including BMW, reached a voluntary agreement with the NHTSA to make autonomous emergency braking systems standard equipment by 2022.

Funding

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References

Cicchino JB. Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates. *Accid Anal Prev*. 2017;99(Pt A):142–S152.

Cicchino JB. Effects of lane departure warning on police-reported crash rates. *J Safety Res*. 2018;66:61–S70.

Fildes B, Keall M, Bos N, et al. Effectiveness of low speed autonomous emergency braking in real-world rear-end crashes. *Accid Anal Prev*. 2015;81:24–S29.

SAE International. *Standard J3016 Titled Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems*. Warrendale, PA: SAE 2014.

Singh S. *Critical reasons for crashes investigated in the National Motor Vehicle Crash Causation Survey*. Washington, DC: NHTSA; 2015. Report No. DOT HS 812 115.

Sternlund S, Strandroth J, Rizzi M, Lie A, Tingvall C. The effectiveness of lane departure warning systems—a reduction in real-world passenger car injury crashes. *Traffic Inj Prev*. 2017;18:225–S229.