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Estimating Effectiveness of Lane Keeping Assist Systems in Fatal Road Departure Crashes

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16. Abstract

This study evaluates the effectiveness of lane keeping assist (LKA) systems in reducing fatal single-vehicle road departure crashes, based on Fatality Analysis Reporting System data from 2016 to 2022. Using a regression model to control for confounding variables, LKA-equipped vehicle models in the sample were estimated to be 24 percent (95% CI: 2-42%) less likely to be involved in fatal road departure crashes than non-equipped models.

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lane keeping assist, LKA, FARS, fatal single-vehicle crashes, single-vehicle crashes, road departure crashes

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List of Acronyms

AEB	automatic emergency braking
ADAS	advanced driver assistance systems
BSW	blind spot warning
FARS	Fatality Analysis Reporting System
LCA	lane centering assist
LDW	lane departure warning
LKA	lane keeping assist
NCSA	NHTSA’s National Center for Statistics and Analysis
NCAP	New Car Assessment Program
OR	odds ratio
PARTS	Partnership for Analytics Research in Traffic Safety[1]
VIN	Vehicle Identification Number
VMT	vehicle miles traveled
vPIC	NHTSA’s Product Information Catalog and Vehicle Listing

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[1] The Partnership for Research Analytics in Traffic Safety, called PARTS, represents GM, Honda, Mazda, Mitsubishi, Nissan, NHTSA, Stellantis, Subaru, Toyota, the U.S. DOT's Volpe Center, UMTRI, and the nonprofit Mitre Corporation.

Executive Summary

This study examines the effectiveness of lane keeping assist systems[2] in reducing fatal road departure crashes. In 2022 there were 6,836 fatal single-vehicle road departure crashes among passenger vehicles in the United States, resulting in 7,279 fatalities.[3] Of these crashes, 5,178 occurred in speed limit zones of at least 40 mph, corresponding to the minimum activation speed for many LKA systems.[4] While previous studies have found that LKA systems are somewhat effective in averting road departure crashes of any severity, the National Highway Traffic Safety Administration is not aware of previous research that has focused exclusively on effectiveness in fatal crashes.

To assess the effectiveness of LKA systems in this context, the relative odds of being involved in a fatal road departure crash for LKA-equipped vehicle models relative to non-equipped models were calculated using the quasi-induced exposure method and random effects regressions. Random effects for vehicle models were included to control for vehicle features and driving behaviors that may correlate with particular models. This study uses Fatality Analysis Reporting System data from 2016 to 2022 combined with LKA system information from *Ward's Automotive Yearbook* (Norris, 2017 to 2022[5]).

The results indicate that LKA-equipped models are 24 percent less likely to be involved in fatal single-vehicle road departure crashes compared to non-equipped models, with a 95 percent confidence interval of 2 to 42 percent. (Note that other LKA-relevant crash types, including multivehicle sideswipe and head-on crashes, are not included in this estimate.) This estimate is higher than previous estimates of LKA effectiveness in single-vehicle road departure crashes, which may reflect this study's focus on fatal crashes, differences in crash definitions, differences in manufacturers included in the studies, or methodological differences. Given the wide confidence interval, this study's results should be interpreted with caution.

Studying LKA effectiveness using crash data has significant benefits in assessing the performance of these systems in the real world, but there are also limitations. The data used in this study indicates only whether a vehicle is equipped with LKA but not whether the system was enabled at the time of the crash, so these results represent the effectiveness of systems as used. If a significant share of LKA systems are disabled, this analysis would tend to underestimate the actual effectiveness of LKA when enabled. This study also treats LKA as a single entity, though actual systems differ in performance across vehicle make, models, and MYs. However, it was not possible to account for these differences in this study. This study also treats LKA as a single entity, though actual systems differ in performance across vehicle make, models, and MYs.

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[2] In this study LKA is used as a shorthand to refer to advanced driver assistance systems that include both lane keeping assist and lane departure warning systems.

[3] Crash and fatality statistics were obtained from Fatality Analysis Reporting System 2022 data. Single-vehicle road departures are defined as crashes in which the *VE_TOTAL* variable equals 1 (one vehicle involved in the crash) and the *ACC_TYPE* variable is either 01 (drive off road to the right) or 06 (drive off road to the left). This definition excludes roadside departure crashes due to control/traction loss; roadside departure crashes caused by attempts to avoid collision with a vehicle, pedestrian, or animal; and roadside departures where the specifics are unknown.

[4] Based on NHTSA's New Car Assessment Program data on LKA status and projected sales volume for MY 2023 vehicles, the sales-weighted average minimum operating speed for LKA systems is 36 mph (58 kph), with a low of 28 mph (45 kph) and a high of 47 mph (70 kph).

[5] All reference citations to *Ward's* are (Norris, 2017 to 2022), but are hereafter just referred to as *Ward's Automotive Handbook*, or just *Ward's*. See reference page.

However, it was not possible to account for these differences in this study. Despite attempts to control for confounding variables, it is also possible that the effect attributed to LKA stems partly from other vehicle technologies or features that tend to co-exist with LKA, such as automatic emergency braking or blind spot warning systems, and such correlations would render the estimates too high. Finally, small sample sizes lead to relatively large margins of error in the results.

Introduction

Background

Advanced driver assistance systems that may prevent or reduce lane departure crashes, including lane departure warning, lane keeping assist, and lane centering assist systems,[6] have become increasingly prevalent in the past decade.[7] According to *Ward's Automotive Yearbook* data, LDW market penetration in the U.S. passenger vehicle fleet increased from 20 percent to 88 percent from MYs 2016 to 2023, and LKA increased from 9 percent to 79 percent over the same period.

To better understand the potential benefits of lane keeping technologies, this study estimates the real-world effectiveness of combination lane keeping assist with lane departure warning (LKA+LDW) systems in preventing fatal road departure crashes using U.S. data from 2016 to 2022. This study focuses on fatal crashes due to the high costs of fatalities and the lack of existing data on the effectiveness of LKA in fatal crash avoidance. It focuses on single-vehicle road departure crashes—where a vehicle departs its lane and drives off the road—due to their overrepresentation among fatal crashes relative to non-fatal crashes and because effectiveness estimates from single-vehicle crashes tend to be more reliable. In multivehicle lane departure crashes, such as sideswipes or head-on crashes, it is not possible to accurately assess from crash data which vehicle initially left its lane, muddying attempts to infer LKA effectiveness for these crash types. Results for two-vehicle lane departure crash types are therefore included only in the appendix section for reference.

This study focuses on combined LKA+LDW systems. Previous studies have assessed LDW, LKA+LDW, and, in one case, LCA+LKA+LDW systems separately.[8] The *Ward's Automotive Yearbook* data used for ADAS system information in this study does not track LCA, and the number of vehicles in the dataset (from MY 2016 to 2023) that have LDW without LKA lead to samples too small for inference. On the other hand, all vehicles in the dataset with LKA also have LDW, so *in this study, LKA is used as a shorthand to refer to ADAS systems that include both lane departure warnings and lane keeping assist*. The vehicles in this study are equipped with both LKA and LDW, but it cannot be discerned from the data whether one or both systems were engaged for any given vehicle at the time of the crash. In addition, because LCA status is not available, it is not known whether an LCA system may have been engaged in some of the vehicles with LKA. The implications of this uncertainty will be discussed further below.

Literature Review

Table 1 presents findings from three other studies that have estimated the real-world effectiveness of LKA systems in preventing lane-departure crashes, including a study stemming

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[6] LDW systems monitor a vehicle's position within the driving lane and alert the driver as the vehicle approaches or crosses lane markers, using haptic, visual, auditory, or a combination of warnings. LKA and LCA are active support technologies that generally use steering assistance to prevent a driver from departing the lane, by providing momentary support when a vehicle approaches a lane marking in the case of LKA or by providing ongoing support to keep a vehicle centered in the lane in the case of LCA.

[7] While some ADAS features may enhance safety, others—such as adaptive cruise control or parking assistance—may primarily serve to increase convenience.

[8] See, for example, Cicchino (2018), Spicer et al. (2021), St. Lawrence et al., (2022), and Leslie et al. (2023).

from the Partnership for Analytics Research in Traffic Safety (St. Lawrence et al., 2022[9]), a study of GM vehicles by UMTRI researchers (Leslie et al., 2023), and a study of Toyota vehicles (Spicer et al., 2021).[10] All three studies used large samples of vehicles matched by VIN to State-level police-recorded crash data. These studies generally found modest benefits of LKA for at least some lane departure crash types, with the effectiveness estimates for preventing single-vehicle road departure crashes ranging from 8 to 15 percent.

None of the estimates in Table 1 measured the effectiveness of LKA systems in *fatal* road departure crashes, so they are not directly comparable to the results presented in this study, though the estimates in bold come closest. The PARTS (2022) analysis found that vehicles with LKA systems were 13 percent less likely to be involved in road departure crashes with serious or fatal injuries (A or higher on KABCO[11]), though this estimate was not quite statistically significant ($\alpha=0.05$). The UMTRI study (Leslie et al., 2023) found that GM vehicle models with LKA were 22 percent less likely than vehicle models without LKA to be involved in road departure crashes with fatal, serious, or suspected possible injuries (B or higher on KABCO). While they are measuring slightly different things, both estimates come from large samples and provide a signal that LKA systems could be effective in preventing some road departure crashes with bodily injury.

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[9] St, Lawrence et al. is hereafter referred to as PARTS or PARTS report; see the reference citation.

[10] There are several other studies of LKA effectiveness using real-world crash data, including Sternlund et al. (2017), Dean and Reixinger (2022), and Peiris et al. (2022). Because these studies have relatively small sample sizes or a lack of controls for confounding variables, the results may not be generalizable and were therefore not included in Table 1.

[11] Crash data used in these studies come from police crash reports, which use the KABCO injury severity scale: K=Fatal Injury, A=Suspected Serious Injury, B=Suspected Possible Injury, C=Possible Injury, and O=No Apparent Injury.

Table 1. LKA effectiveness estimates from other studies

Source	Population	LKA+LDW Effectiveness	Data	Exposure Measure / Estimation Method
PARTS (2022)	Road departure	8%* (5-12%)	Vehicles from MY 2015-2020 (93 models; 8 OEMs) matched by VIN to 2.7 M police-reported crash records from 2016-2021 from 13 states. In the biggest road departure sample, there were 63,507 vehicles in road departures crashes, 9,417 with LKA.	Quasi-induced exposure. Logistic regression w/ fixed effect controls for various confounders, including vehicle models.
	Road departure; A+ on KABCO	**13% (-1-24%)**		
	Same-direction sideswipe	5%* (3-7%)		
	Same-direction sideswipe; A+ on KABCO	-5% (-28-13%)		
	Opposite direction	8%* (4-11%)		
	Opposite direction; A+ on KABCO	-1% (-13-10%)		
UMTRI Leslie et al., (2023)	Road departure (>30 mph)	15%*	GM vehicles from MY 2017-2021 matched by VIN to 600 K police crash reports from 14 states. In the biggest road departure sample, there were 15,669 vehicles in road departure crashes, 3,599 with LKA.	Quasi-induced exposure. Mixed effects logistic regression w/ fixed effect controls for various confounders and random effects for vehicle models.
	Road departure (>30 mph); B+ on KABCO	**22%***		
	Same-direction sideswipe (>30 mph)	8%*		
	Same-direction sideswipe (>30 mph); B+ on KABCO	9%		
	Opposite direction (>30 mph)	7%*		
	Opposite direction (>30 mph); B+ on KABCO	2%		
Spicer et al., (2021)	Road departure	9%* (1-16%)	Toyota vehicles from MY 2015-2018 matched by VIN to 308K police crash reports from 8 states. In road departure sample, 6,489 vehicles in road departure crashes, 2,077 with LKA.	"Vehicle days" from date of purchase. Survival analysis using Cox proportional-hazards regression w/ fixed effects controls for model, MY, and retail state.
	Same direction sideswipe	6% (-3-13%)		
	Head-on	-4% (-67-35%)		

Notes: (1) Estimates with an asterisk (*) indicate that the effectiveness estimate was statistically significant at a 95% confidence level. (2) In PARTS (2022), vehicles with LDW+LKA excluded vehicles with LCA (the effectiveness of LDW+LKA+LCA was estimated separately). In Leslie et al., (2023) and Spicer et al., (2021), there are no mentions of lane centering assist, so it is unknown whether some of the vehicles with LDW+LKA also had LCA. 3) Since drivers can disable these features, estimates provide the effectiveness of having an LKA-equipped vehicle, rather than the effectiveness of the technology when it is enabled.

It is worth noting that even estimates that appear to be measuring the same thing—the effectiveness of LKA in preventing road departure crashes, for example—are not entirely comparable, due to differences in sample composition and method choices. For example, while the PARTS (2022) study included LKA systems from eight different vehicle manufacturers, the

UMTRI study (Leslie et al., 2023) included only GM vehicles and the Spicer et al., (2021) study included only Toyota vehicles. If the effectiveness of LKA systems vary across vehicle makes or models, effectiveness estimates will naturally vary as well. Additionally, PARTS excluded vehicles with LCA in estimating the effect of LKA, but the UMTRI and Spicer studies did not specify whether some of the vehicles with LKA also had LCA. Crash type definitions also differ across the studies, leading to further variation in estimates. For example, while the PARTS study included rollovers in its definition of road departure crashes, the UMTRI study did not.[12] Other sources of variation in estimates include differences in crash years and MYs included in the analysis, differences in the states from which crash reports are taken, and differences in the regression model and control variables included. While the range of estimates can provide clues about the effectiveness of LKA systems in lane departure crashes, it is important to remember that individual estimates are specific to the crash definitions, LKA system specifications, and other conditions represented in the analysis and may not be fully generalizable to other contexts. The confidence bands are also very wide for most of these estimates, which limits the strength of claims that we can make about LKA effectiveness based on this research.

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[12] See Appendix B for a comparison of the road departure crash definitions used in these studies.

Data and Method

Data for this analysis comes from two sources: (1) FARS records from 2016 to 2022 and (2) *Ward's Automotive Yearbook* data tables for vehicle MYs 2016 to 2023. FARS is an annual census of fatal crashes in the United States[13] and provides data for the main dependent variable in this study—an indicator of whether a vehicle was involved in a "target crash" (a crash that might have been avoided with LKA) or a "control crash" (being the struck vehicle in a rear-end crash)—as well as for environmental, vehicle, and driver control variables. *Wards* data provides the information needed to create the main explanatory variable in this study: an indicator for whether a vehicle was equipped with LKA[14] technology.

FARS Crash Data and Target Population

Table 2. FARS crash type definitions

Crash Type	FARS Filter	Narrative Definition
Single-Vehicle Road Departure	VE_TOTAL=1 & ACC_TYPE in (01,06)	One passenger vehicle involved in crash Single Driver-Right Roadside Departure-Drive Off Road (01) or Single Driver-Left Roadside Departure-Drive Off Road (06)
Rear-Struck (control crash)	ACC_TYPE in (21:23, 25:27, 29:31) & P_CRASH2 not in (10,11)	Passenger vehicles described as "Same Trafficway, Same Direction-Rear End." Includes struck vehicles that were stopped, going slower than striking vehicle, or decelerating. Excludes struck vehicles where "critical event that made this crash imminent" for subject vehicle is "over the lane line on the left side of travel lane" or "over the lane line on the right side of travel lane."

Table 2 shows how road departure crashes were defined using the FARS Crash Type (*ACC_TYPE*) variable. This group includes crashes involving one passenger vehicle in which the driver departed the road to the right or left.[15] Other single-driver crashes, including crashes due to control or traction loss and those resulting from an intentional maneuver to avoid a collision, are not included in the target crash type, since lane keeping systems would not be expected to help prevent these crashes. Since this analysis requires a control crash group, Table 2 also provides the FARS definition of the rear-struck control crash group. This group includes passenger vehicles that were rear-ended, though vehicles for which the critical pre-crash event was traveling over the lane line to the right or left are excluded. These vehicles are excluded because LKA systems may help prevent this type of rear-end crash, and as explained further below, it is desirable to have LKA-equipped vehicles in the sample experience control crashes at the same rate as non-equipped vehicles.

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[13] To qualify as a FARS case, a crash must involve a motor vehicle traveling on a trafficway customarily open to the public and must have resulted in the death of a motorist or a non-motorist within 30 days of the crash.

[14] Recall that all the vehicles in this sample with LKA also had LDW, so the effectiveness estimates measure the effectiveness of both features together. *Wards* defines LKA as follows: "When sensors detect the vehicle is drifting from its designated lane at high speeds without the use of a turn signal, the vehicle will steer back into its lane." *Wards* defines LDW as follows: "When sensors detect the vehicle is drifting from its designated lane without the use of a turn signal, (1) an audible alert will chime or (2) the steering wheel or driver seat will vibrate."

[15] As in the PARTS study, this study does not exclude rollovers from its definition of road departure crashes.

Table 3 shows the annual average number of fatal single-vehicle road departure crashes and fatalities, based on FARS data from 2018 to 2022.[16] To further align the target population of crashes with the capabilities of LKA systems, crashes that occurred on roadways with posted speed limits of less than 40 mph were excluded, since this is close to the average minimum operating speed of LKA systems,[17] as were crashes on roads that were covered with anything other than rain[18] since LKA sensors may not be able to "see" lane markings on roads covered with snow, slush, etc. With these exclusions, potentially LKA-system-relevant road departure crashes account for 4,593 crashes and 4,889 fatalities annually, over the five-year period from 2018 to 2022.[19]

Table 3. Fatal road departure crashes and fatalities, 5-year annual average (2018-2022)

Crash Characteristics	Fatal Crashes	Fatalities
Passenger vehicles involved in fatal road-departure crashes (single vehicle)	6,115	6,511
+ Speed limit ≥ 40mph	4,705	5,009
+ Road surface dry or wet (i.e., not snow or slush-covered, etc.)	4,593	4,889

Ward's Automotive Yearbook Data

Information on LKA from *Wards* was appended to the FARS crash data in order to separate vehicles into LKA-equipped and non-LKA-equipped groups. *Wards* began tracking LKA for MY 2016 vehicles, so this analysis includes only vehicles from MYs 2016 to 2023. The *Wards* data were matched to FARS records by make-model-year, and only make-model-year vehicles for which LKA was standard or not available were retained in the analysis.[20] For example, the analysis includes 2022 Hyundai Elantras (100% LKA-equipped) and 2022 Hyundai Accents (0% LKA-equipped), but not 2022 Nissan Maximas (45% LKA-equipped), since it is uncertain whether an individual vehicle of that model in the FARS data is equipped with LKA.

Table 4 shows the number of vehicles by MY that meet the criteria for the 2016- to 2022 road departure sample, along with the shares for which LKA status is certain (i.e., equipped; these are

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[16] Passenger vehicles were identified using NCSA body type classification from 2016 to 2019 and, due to a change in classification practices, vPIC body type classification from 2020 to 2022. A sensitivity analysis showed that using NCSA body type classification for all years 2016 to 2022 resulted in changes in annual average fatal crash and fatality counts of less than half of one percentage point.

[17] Based on NCAP data on LKA status and projected sales volume for MY 2023 vehicles, the sales-weighted average minimum operating speed for LKA systems is 36 mph (58 kph), and the highest minimum operating speed among vehicles in the data was 43 mph (70 kph).

[18] Specifically, vehicles involved in crashes where the FARS *Roadway Surface Condition* variable (*VSURCOND*) was snow; ice/frost; sand; water (standing or moving); oil; slush; mud, dirt, or gravel; or other were excluded.

[19] Other environmental and crash conditions that may interact with LKA system effectiveness—such as road curvature, whether the crash happened at an interchange, number of lanes, and driver impaired status—were not used as exclusion criteria in the main sample, since LKA may still be expected to function in these conditions. See Table 7 includes results from sensitivity analyses that (1) include crashes at speed limits of at least 30 mph, (2) include all road surface conditions, (3) exclude crashes at interchanges, (4) exclude crashes on curves, and 5) separate effects on urban and rural roads.

[20] Ideally, vehicles that also have LCA would be excluded from the analysis to isolate the effects of LDW+LKA, but because the *Wards* data does not provide information on LCA, some of the LKA vehicles in the sample may also have LCA.

in the sample) versus vehicles with uncertain LKA status (i.e., optionally equipped or unknown; not in the sample). For most model years, more than half the vehicles meeting the road departure sample criteria have known LKA status (i.e., either LKA is standard equipment or not), and overall, about 58 percent of relevant vehicles (3,509 vehicles) have known LKA status and are included in the sample.

Table 4. Vehicles in sample by MY and LKA match status

Vehicle Model Year	**Passenger Vehicles in Full Sample** (Road Departures, 40+MPH, wet/dry + Rear-Struck Control Crashes)	**% with LKA standard (in sample)**	**% without LKA (in sample)**	**% with LKA optional (not in sample)**	**% LKA equipped unknown (not in sample)**
2016	1,631	0%	65%	35%	1%
2017	1,424	5%	48%	46%	1%
2018	1,123	11%	37%	51%	1%
2019	857	24%	35%	41%	1%
2020	596	36%	22%	40%	1%
2021	370	45%	19%	35%	1%
2022	101	53%	11%	34%	2%
2023	8	63%	25%	13%	0%
TOTAL	**6,110**	**14%**	**44%**	**42%**	**1%**

The sample thus includes 3,509 MY16-MY23 passenger vehicles involved in road departure or rear-struck crashes from 2016 to 2022,[21] on dry or wet roads and in speed zones of at least 40 mph, with the further constraint that LKA was standard or not an option on the model. Figure 1 shows how the 3,509 vehicles in the sample are distributed across vehicle makes. Toyota vehicles comprise the largest segment of the sample, at around 19 percent, followed by Nissan (15%), Chevrolet (10%), Ford (9%), and Kia (7%).

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[21] The years in the sample span changes in traffic and crash patterns prompted by the COVID-19 pandemic. Year-level controls included in the regressions should help separate any related time-based effects from the effects of LKA.

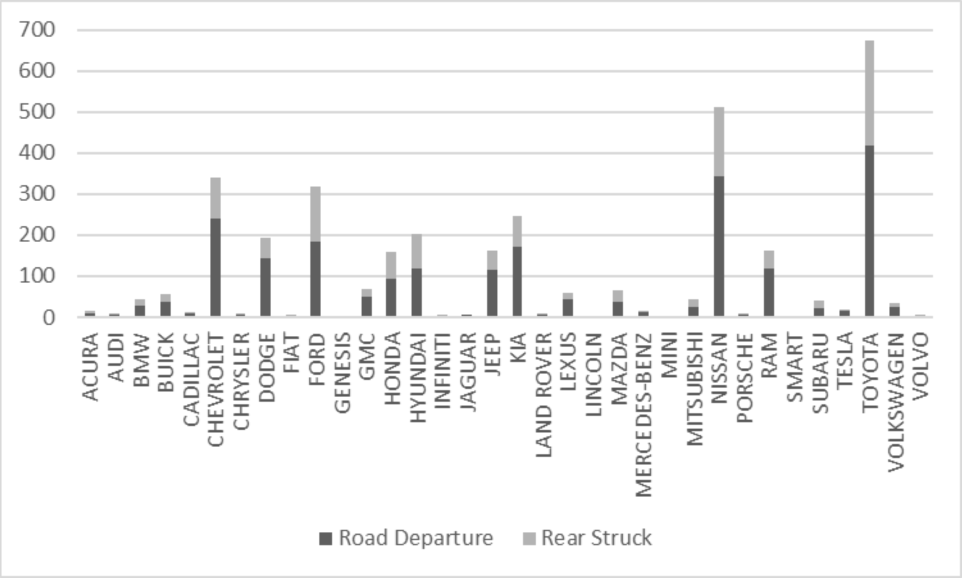

Figure 1. Vehicle makes in main sample

Figure 2 compares the distribution of vehicle makes represented in the main sample of 3,509 vehicles (including only vehicles for which LKA is standard or not an option) to the distribution of makes in the full sample of 6,110 vehicles that would be included if LKA status were known for each vehicle. Recall that the latter sample includes MY16 to MY23 passenger vehicles involved in either (1) a fatal single-vehicle road departure crash on wet or dry roads in a speed zone of at least 40 MPH or (2) a vehicle that was struck from behind in a fatal rear-end crash. There are five vehicle makes that are over- or under-represented by at least 2 percentage points in the study sample after filtering for known LKA: Toyota (8 percentage points higher in the study sample), Nissan (4 p.p. higher), Ford (4 p.p. lower), Chevrolet (4 p.p. lower), and Honda (2 p.p. lower). The LKA effectiveness estimates presented below thus reflect a slight underrepresentation of Ford, Chevrolet, and Honda and an overrepresentation of Toyota and Nissan vehicles.

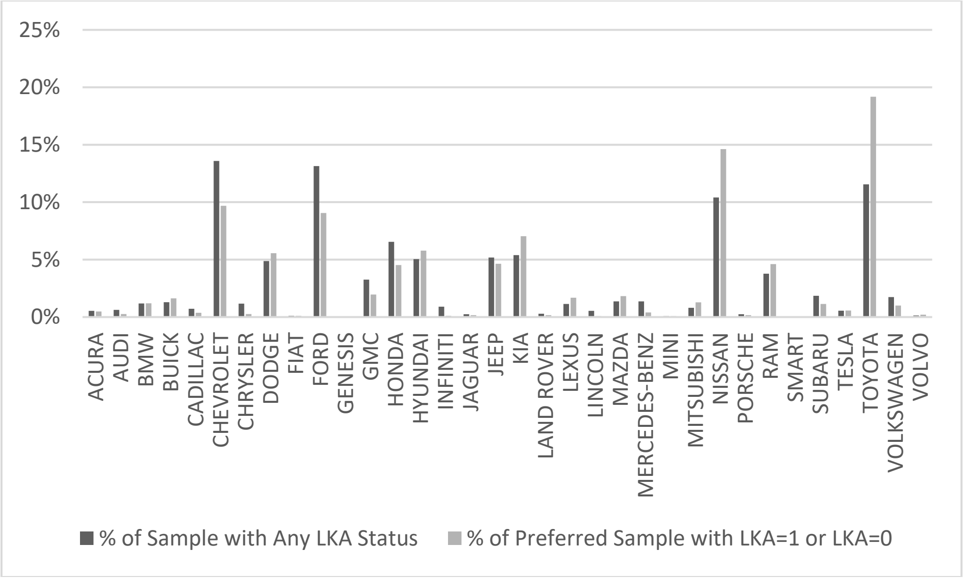

Figure 2. Share of vehicle makes in main sample versus sample with no LKA restrictions

Method

To find the relative rate of fatal crash involvement for LKA-equipped vehicles compared to non-equipped vehicles, the number of fatal crashes in each group would ideally be divided by a corresponding measure of exposure, such as vehicle miles traveled. Since exposure data is not available, this analysis follows the PARTS and UMTRI studies in using the quasi-induced exposure method, which employs "control crashes" assumed to be unaffected by the presence of LKA as a proxy for exposure.

Table 5 illustrates the information needed to calculate the crude relative odds of an LKA-equipped vehicle being involved in a fatal road departure crash, using the quasi-induced exposure method. First, the ratio of road departure crashes to rear-struck crashes is calculated for LKA-equipped vehicles (*A/B=150/100=1.5)* and non-LKA-equipped vehicles (*C/D=2000/1000=2).* The relative odds of LKA-equipped vehicles being in a fatal road departure crash is then found by dividing the LKA ratio by the non-LKA ratio (*1.5/2=0.75)*.

Table 5. Quasi-induced exposure – example calculation

	LKA-Equipped Vehicles	**Non-Equipped Vehicles**
Road Departure Crashes	A = 150	C = 2000
Rear-Struck ("Control") Crashes	B = 100	D = 1000

To account for differences across crash scenarios, vehicles, and drivers that may vary systematically with LKA status, adjusted odds ratios were found using logistic regressions with control variables. Following previous LKA effectiveness studies, controls were included for speed limit, age category, gender, driver alcohol involvement,[22] weather, road surface condition, and light levels. To account for changes over time, controls for crash year and MY were included. A random effect for make-model was also included to account for vehicle model features that may be constant across MYs in the sample and for driver behavior that may covary with model types.[23] [24] The SAS command PROC GLIMMIX was used to estimate the logistic models with the control variables listed and random effects for make-model.

Descriptive Statistics by Crash Type and LKA Status

For the quasi-induced exposure method to approximate exposure-based estimates, the rate of rear-struck crashes to VMT among LKA-equipped vehicles should be the same as the corresponding rate for non-LKA-equipped vehicles. Without VMT information, it is not possible to know if this assumption holds, but following Keall and Newstead (2009), it is possible to compare control crash samples and infer whether other variables associated with rear-struck/VMT ratios vary in a systematic way.

Table 6 shows the size of the road departure and rear-struck crash groups along with control variable summary statistics, by LKA status. Ideally, the rear-struck LKA group should have similar characteristics to the rear-struck non-LKA group, since this would increase confidence in the quasi-induced exposure estimates. In Keall and Newstead (2009), which compared New Zealand crash data in 2005 and 2006 with VMT, females were found to be overrepresented in rear-struck crashes relative to miles driven. If this correlation holds true in this study's sample, then the higher share of female drivers in the LKA group in rear-struck crashes would tend to overestimate exposure in the LKA-control-crash group. This, in turn, would tend to underestimate the LKA odds ratio and overestimate effectiveness. Likewise, vehicle body types differ significantly across the LKA and no-LKA groups, though it is unclear how this may bias the results, since the vehicle groups in Keall and Newstead (2009) are different from those in the

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[22] Beyond driver alcohol involvement, other types of driver impairment and driver distraction are important causal factors in fatal crashes. However, according to Blincoe et al. (2023), distraction and non-alcohol-related impairment are unreliably recorded in the police crash reports that comprise FARS data. Therefore, they are not included as control variables in this study. This omission should not affect the effectiveness results unless distraction and other forms of impairment tend to differ significantly across drivers of LKA versus non-LKA vehicles. Table 6 shows that alcohol involvement is not significantly different across these groups.

[23] A random coefficient model, also known as a hierarchical or mixed model, was used here, since vehicles are nested into make-model categories. This type of model accounts for the clustering of vehicles into make-model categories (rather than assuming their independence) when calculating variation. This method also preserves degrees of freedom in a relatively small sample. See Dai et al. (2006).

[24] The random effects model provides subject-specific odds ratios, which estimate the average odds of being in a fatal crash for a vehicle model that has LKA relative to the same model without LKA. This provides slightly different information from a population-average odds ratio estimate produced by regular logistic or GEE models, which estimate the odds of being in a fatal crash for the population of vehicle models with LKA relative to models without LKA. The interpretation of the odds ratios from the random effects model is suitable for our purposes, since it directly measures the benefit of specific models changing from "No LKA" to "LKA" status, either due to manufacturers updating their models or users enabling it in vehicles where it had been disabled. For reference, Table 15 in Appendix C provides a comparison of subject-specific and population-average point estimates, with effectiveness estimates differing by less than 2 percentage points for each model.

FARS data. Overall, they found that smaller vehicle crash counts overestimated exposure and vice versa. To the extent that this correlation holds in this study's sample, a higher share of smaller vehicles in the LKA rear-struck group would again tend to inflate effectiveness estimates.

Table 6. Descriptive statistics by crash type and LKA status, FARS 2016-2022 main sample

	Road Departure		**Rear-Struck (Control Crash)**	
	No LKA	**LKA**	**No LKA**	**LKA**
Number of vehicles	1775	519	897	318
Mean age	45.2	44.1	45.7	46.7
Female %	26.3	28.9	42.1**	51.6**
Passenger car %	52.1	54.3	47.0	44.3
Utility Vehicle %	23.5**	42.8**	27.6**	51.9**
Pickup %	19.3**	1.0**	14.6**	0.3**
Van %	5.2**	1.9**	10.7**	3.5**
Mean speed limit	54.9	55.4	56.0	55.0
Alcohol-involved %	39.8	38.3	3.3	3.1
Daylight %	41.8*	37.8*	60.2	57.9
Clear/cloudy %	86.0	86.3	91.1	88.4
Dry road surface %	86.0	86.9	92.1*	88.7*

Notes: Both samples include passenger vehicles (MY16-23) with known LKA fitment from FARS 2016-2022 data. Road Departure sample includes vehicles coded as ACC_TYPE 01 and 06, from crashes on wet or dry roads in 40+MPH speed limit zones. Rear-Struck (Control Crash) sample includes all rear-struck vehicles not coded as being over a lane line as the critical pre-crash event. * indicates that the mean/share for LKA-equipped vehicles is different from that for non-LKA-equipped vehicles at the 10% level, ** at the 5% level.

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Results

Table 7 shows the relative odds of an LKA-equipped model being involved in a fatal road departure crash (defined as in Table 2), using the data and methods described above, along with the results from several alternate specifications. The rightmost two columns in the table show the total sample size (N), as well as the number of LKA-equipped vehicles in the target crash group. The dependent variable is vehicle involvement in a fatal road departure crash, the main explanatory variable is whether the vehicle was equipped with LKA, and the control variables include age, sex, driver alcohol involvement, speed limit, weather, road surface condition, light condition, MY, crash year, and random effects for vehicle make-model.

Table 7. Relative odds of LKA-equipped model being involved in fatal road departure crash

Sample description		Odds ratio (95% CI)	Sample size (N)	# with LKA in target crash group
RD0	Includes MY16-23 passenger vehicles from 2016-2022 fatal crashes. Road departure crashes limited to ≥40 mph speed limit zones on dry/wet roads only. Rear-struck as control crash.	0.756 (0.58,0.98)	3,509	519
RD1	Like RD0, but speed limit ≥ 30mph	0.773 (0.60,1.00)	4,012	664
RD2	Like RD0, but all road surface conditions	0.738 (0.57,0.96)	3,552	527
RD3	Like RD0, excluding crashes at interchanges	0.755 (0.58,0.99)	3,323	467
RD4	Like RD0, but straight roads only (no curves)	0.762 (0.57,1.01)	2,546	291
RD5	Like RD0, but urban only	0.711 (0.52,0.97)	2,434	249
RD6	Like RD0, but rural only	0.791 (0.57,1.09)	2,289	270

All estimates include continuous control for speed limit; categorical controls for Age (<25, 25-64, 65+, Unk), Sex (M, F, Unk), Driver alcohol (Y, N), Weather (Clear/Cloudy, Not Clear/Cloudy, Unk), Road Surface (Wet, Dry, Other, Unk), Light (Daylight, Dark Unlit, Dark Lit, Dawn/Dusk, Other/Unk), Model Year, Crash Year; and random effects for vehicle make-model. Sample sizes for rural and urban samples (RD5 and RD6) do not sum to the original sample size (RD0) because all rear-struck control crashes were included in each sample.

The odds ratio of 0.756 for sample RD0 in Table 7 indicates that, after controlling for the potentially confounding variables, the average LKA-equipped model in the sample was about 76 percent as likely as a comparable non-equipped model to be in a fatal road departure crash, implying an effectiveness rate of 24 percent. These estimates were just statistically significant at the .05 level, with a relatively large confidence interval of 2 to 42 percent.

Alternate Specifications

The alternate specification rows in Table 7 provide estimates from samples that differ slightly from the main sample to assess whether LKA effectiveness appears to change when the crash context changes in LKA-relevant ways. In samples RD1 and RD2 the speed limit and road surface condition constraints were relaxed as noted in the table. These changes do not substantially alter the results; estimated effectiveness decreases as expected when the sample expands to include speed limits below the activation speed of some LKA systems, though effectiveness increases when a broader range of road surface conditions are included, which is unexpected. This could be due to the difference between speed limits and actual driving speeds, though the differences in estimates are so small relative to the confidence bands that the changes here do not provide a great deal of information.

Alternate specification RD3 in Table 7 excludes around 200 crashes from the sample that occurred at interchanges, since the functioning of LKA systems may be undermined in areas that lack clear lane lines or road edges, though removing these cases has almost no effect on the results. Alternate specification RD4 removes about 1,000 crashes that occurred on non-straight road segments, and the effectiveness estimate decreases as expected, but by less than 1 percentage point. While this may provide some support for the idea that LKA does not significantly underperform on curved roads, it is again difficult to make confident claims based on the relatively small samples and wide confidence bands.

Alternate specifications RD5 and RD6 stratify the sample based on whether the road departure happened in a rural or urban area (sample sizes for rural and urban samples do not sum to the original sample size because all rear-struck control crashes were included in both samples). The point estimates indicate that LKA may be slightly more effective in urban than rural environments, though the confidence intervals mostly overlap here as well.

Appendix A contains results from similar regressions for same-direction sideswipe and opposite-direction crashes. As noted above, the inability to determine which vehicle departed its lane in a multivehicle crash make LKA effectiveness estimates for these crash types less reliable. Yet, since LKA systems are designed to help prevent these types of lane departure crashes as well, it may be useful to have even rough estimates of their effectiveness in these crash types.

Discussion

The results presented above indicate that the average LKA-equipped model in the sample was 24 percent less likely than a comparable non-equipped model to be involved in a fatal road departure crash from 2016 to 2022 (95% CI: 2-42%). The large confidence interval is similar to that found in other studies and may reflect the relatively small sample and/or the variation in effectiveness of LKA systems across vehicles, time, or crash conditions. It should be noted that this estimate—and those presented in the literature review—represent the effectiveness of *driving an LKA-equipped vehicle* rather than the effectiveness of LKA when it is enabled, as it is not known from the data whether LKA is enabled or activated at the time of the crash. Some research has indicated that a substantial portion of drivers—perhaps 50 percent—deactivate or do not enable LDW and LKA features.[25] If the goal is to assess the effectiveness of LKA systems as they are actually used, in the current real-world scenario in which drivers can choose whether they are enabled, then existing estimates provide useful information about the overall effectiveness of LKA. If, on the other hand, the goal is to estimate the effectiveness of LKA systems assuming they are engaged, then the existing estimates should be divided by current use rates (which would result in increased effectiveness estimates).

The 24 percent effectiveness point estimate is high compared to most road departure estimates from previous studies, and though the confidence interval is large, it will be useful to explore possible explanations for the relatively high estimate:

- LKA systems could be more effective in preventing fatal crashes than non-fatal crashes. The results from the UMTRI study indicated that this phenomenon was happening in injury crashes versus all crashes, at least in the case of road departures, though this trend was less clear in the PARTS study and for other crash types.
- While the adjusted odds ratios come from regressions that control for a variety of variables that may be correlated with LKA status and influence fatal crash likelihood, including individual vehicle models and behavior of drivers who purchase them, they may not capture other aspects of models that change over time and affect safety. Prominently, LCA information was not available for the vehicles in this sample, so the LKA estimates could be picking up some benefits of LCA. Additionally, most vehicles in the sample that had LKA also had AEB. While AEB is not designed to prevent lateral-move crashes, it is possible that it influenced the severity of crashes in this sample if, for example, the severity of a road departure crash was reduced due to emergency braking before striking an object. It is also possible that both LKA and AEB are proxies for other safety-enhancing crash avoidance or crashworthiness features. Table 12 in Appendix A shows the results of regressions assessing the effect of AEB on the probability of lane-departure crashes in samples containing no LKA-equipped vehicles. These samples were small and the results have wide confidence bands, but the point estimates provide some

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[25] Reagan et al. (2018) found that LKA systems (referred to as lane departure prevention in their study) were enabled in 55 percent of 358 LKA-equipped vehicles brought to 14 dealerships in the Washington, DC, metro area in 2016. The rate of LKA use was higher than the rate for LDW (45%, n=547), and use rates varied significantly across manufacturer (Chevrolet, Lexus/Toyota, and Volvo had LKA use rates of 72%, 74%, and 87%, respectively). Higher mileage was also significantly correlated with lower use rates.

initial evidence that AEB has little effect in road departure crashes but may have some effect in head-on crashes.[26]

- As discussed above, LKA effectiveness estimates may be inflated if the LKA-equipped vehicles in the sample experience rear-struck ("control") crashes at a higher rate than non-equipped vehicles. In the quasi-induced exposure method, this would tend to overestimate exposure in the LKA-equipped group, thereby reducing the LKA odds ratio and biasing effectiveness estimates upwards. Without exposure data, it is not possible to know definitively whether this is the case in this study. The LKA-equipped vehicles in the sample were more likely to be models in which BSW technology was standard (22%) or optional (69%) compared to non-equipped vehicles (1% and 63%, respectively). If the BSW feature helps avert being rear-struck, and LKA correlates with BSW, then LKA-equipped vehicles may be underrepresented among rear-struck crashes. This would bias estimates of LKA effectiveness downward. On the other hand, if female drivers and smaller vehicles are more likely to be in rear-struck crashes in the United States, as was true in the Keall and Newstead (2009) New Zealand study, then the LKA control crash subsample may overestimate exposure, since it appears that the rear-struck LKA-equipped vehicles in this sample are smaller and have more female drivers (see Table 6). This would tend to bias estimates of LKA effectiveness upward.
- While FARS is representative in the sense that it includes all fatal crashes in the United States, the sample used here—which includes only vehicle models for which LKA was either standard or not an option from MYs 2016 to 2023—is nonetheless quite small and may not be representative of all vehicles with LKA technology. While this would not tend to bias the results in one direction or another, it is possible that a larger sample would provide different estimates.

Several other limitations, common across real-world effectiveness studies, are worth noting:

- An LKA system is treated here as a single entity, when in reality, there is a great deal of variation across manufacturers, models, MYs, and driver options. For example, systems vary in the types of sensors they use, the type of warnings given (e.g., auditory, haptic, visual, or a combination), the default setting when the vehicle is turned on (off, on, or the same as the last trip), and the sensitivity setting options given to drivers. Some instantiations of LKA may be more effective than others, though this study is not able to assess such differences. The results presented in the UMTRI study (Leslie et al., 2023) and in Spicer et al., (2021) are based on LKA systems from single manufacturers (GM and Toyota, respectively), so these studies may come closer to assessing the effectiveness of a single system.
- While this study controls for variables that may be correlated with driving behaviors, such as vehicle model, age, and gender, it cannot control for driver behavior directly. If driving behavior correlates with LKA status in a way that is not controlled for with these variables, then effectiveness estimates may be biased.

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[26] There is little published research on the effectiveness of AEB systems in head-on crashes. In simulation results presented in Riexinger et al. (2023), the presence of AEB in the struck vehicle in a fatal head-on collision was predicted to increase the effectiveness of LDW in the striking vehicle by increasing the time-to-crash and effectively giving the driver of the striking vehicle more time to respond to the lane departure warning.

- Many of the FARS variables in this analysis come from police crash reports, so the ways that some of the control variables are defined (especially driver alcohol involvement, weather, light status, and road surface condition) may be inconsistent across reports. The binary dependent variable for involvement in fatal crash, however, is likely to be quite consistent (e.g., compared to injury categories defined by police-assessed rating on the KABCO scale.)

In conclusion, this study contributed to the body of research on LKA effectiveness by providing the first estimate of effectiveness in fatal road departure crashes. These results provide further evidence that LKA is effective in preventing or reducing the severity of some lane-departure crashes, though as the share of vehicles with LKA on the road increases, the ability to statistically assess the effectiveness of the technology should improve as well.

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[27] The Partnership for Research Analytics in Traffic Safety, called PARTS, represents GM, Honda, Mazda, Mitsubishi, Nissan, NHTSA, Stellantis, Subaru, Toyota, the U.S. DOT's Volpe Center, UMTRI, and the nonprofit Mitre Corporation.

Appendix A: Effectiveness of LKA in Same-Direction Sideswipes and Opposite-Direction Crashes

In the main analysis only estimates of LKA effectiveness in single-vehicle road departure crashes were presented, since estimates for multivehicle lane departure crashes are complicated by the inability to accurately assess the LKA status of the lane-departing vehicle within a crash. Still, real-world effectiveness is not limited to single-vehicle road departure cases, and it is within the operational design domain of LKA systems to prevent (or reduce in severity) other types of lane departure crashes as well. In this section, effectiveness estimates for same-direction sideswipe and opposite-direction crashes (including head-on crashes) between two vehicles are presented, with the caveat that estimates are likely to be less reliable.

Table 8. FARS crash-type definitions for same-direction and opposite-direction crashes

Crash Type	FARS Filter	Narrative Definition
Same-Direction Sideswipe	ACC_TYPE in (44:47) & VE_FORMS=2	Same Trafficway, Same Direction-Angle, Sideswipe-Straight Ahead on Left (44) Same Trafficway, Same Direction-Angle, Sideswipe-Straight Ahead on Left/Right (45) Same Trafficway, Same Direction-Angle, Sideswipe-Changing Lanes to the Right (46) Same Trafficway, Same Direction-Angle, Sideswipe-Changing Lanes to the Left (47) Crashes involving two in-transport vehicles
Opposite-Direction	ACC_TYPE in (50,64) & VE_FORMS=2	Same Trafficway, Opposite Direction-Head-On-Lateral Move (Left/Right) (50) Same Trafficway, Opposite Direction-Angle, Sideswipe-Lateral Move (Left/Right) (64) Crashes involving two in-transport vehicles
Rear-Struck (control crash)	ACC_TYPE in (21:23, 25:27, 29:31) & P_CRASH2 not in (10,11)	All psgr vehicles described as "Same Trafficway, Same Direction-Rear End." Includes struck vehicles that were stopped, going slower than striking vehicle, or decelerating. Excludes struck vehicles where "critical event that made this crash imminent" for subject vehicle is "over the lane line on the left side of travel lane" or "over the lane line on the left side of travel lane."

Table 8 provides working definitions of same-direction sideswipe crashes and opposite-direction crashes, using the FARS *ACC_TYPE* variable. Note that crashes with more than two vehicles were excluded, to make it somewhat more likely that LKA effectiveness estimates are based on information from the lane-departing vehicle in the crash.[28] These analyses also include rear-struck crashes as the control crash, and the definition is the same here as in the road departure regressions.

Table 9 presents estimates of the relative odds of an LKA-equipped model being involved in a fatal same-direction sideswipe crash, along with the results from alternate specifications. The rightmost two columns in the table show that sample sizes are lower here than in the road departure regressions, due to there being fewer fatal sideswipe crashes.

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[28] There are 358 vehicles involved in same-direction sideswipes in the main sample when crashes with more than two vehicles are excluded and 559 vehicles in a comparable sample with no restriction on the number of vehicles in involved the crash. Likewise, there are 1,362 vehicles involved in opposite-direction crashes in the main sample when limited to two-vehicle crashes and 1,598 vehicles in a comparable sample without the two-vehicle limitation.

Table 9. Relative odds of LKA-equipped model being involved in fatal same-direction sideswipe

Sample description		Odds ratio (95% CI)	Sample size (*N*)	# with LKA in target crash group
SD0	Includes MY16-23 passenger vehicles from 2016-2022 fatal crashes. Same-direction sideswipe crashes limited to ≥40 mph speed limit zones on dry/wet roads only. Rear-struck as control crash.	0.987 (0.66,1.47)	1,573	104
SD1	Like SD0, but speed limit ≥ 30mph	0.972 (0.67,1.42)	1,616	117
SD2	Like SD0, but all road surface conditions	0.978 (0.66,1.45)	1,578	105
SD3	Like SD0, excluding crashes at interchanges	0.897 (0.60,1.34)	1,526	87
SD4	Like SD0, but straight roads only (no curves)	0.937 (0.62,1.42)	1,513	87
SD5	Like SD0, but urban only	0.823 (0.37,1.81)	1,310	24
SD6	Like SD0, but rural only	1.116 (0.71,1.75)	1,477	80

All estimates include continuous control for speed limit; categorical controls for Age (<25, 25-64, 65+, Unk), Sex (M, F, Unk), Driver alcohol (Y, N), Weather (Clear/Cloudy, Not Clear/Cloudy, Unk), Road Surface (Wet, Dry, Other, Unk), Light (Daylight, Dark Unlit, DarkLit, Dawn/Dusk, Other/Unk), Model Year, Crash Year; and random effects for vehicle make-model.

The estimates presented in Table 9 indicate that LKA may not be effective in preventing fatal same-direction sideswipe crashes, though sample sizes are relatively small. The odds ratio point estimate of 0.987 from sample SD0 corresponds to an effectiveness rate of about 1 percent, though the 95 percent confidence interval spans effectiveness estimates from -47 percent to 34 percent.

Regressions using samples SD1 through SD6 also produce effectiveness estimates that are generally quite close to zero, with similarly wide confidence bands. The estimate from sample SD3, which excludes 47 sideswipe crashes that occurred at an interchange, suggests an effectiveness point estimate of around 10 percent, but the 95 percent confidence interval ranges from -34 percent to 40 percent. Similarly, the “urban-only” stratification represented by sample SD5 produced a slightly higher effectiveness estimate, but this sample included a very small number of LKA-equipped vehicles and also had a wide confidence band.

Among the real-world LKA effectiveness studies represented in Table 1, the PARTS and UMTRI studies found positive, statistically significant effectiveness rates for LKA in same-direction sideswipe crashes (5 and 8 percent, respectively). When the samples were limited to crashes with injuries, however, the estimates were not statistically different from zero, which aligns with the findings here. It is difficult to know whether this is a signal of ineffectiveness in fatal crashes or an artifact of the sample sizes or other measurement issues.

Table 10. Relative odds of LKA-equipped model being involved in fatal opposite-direction crash

Sample description		Odds ratio (95% CI)	Sample size (N)	# with LKA in target crash group
OD0	Includes MY16-23 passenger vehicles from 2016-2022 fatal crashes. Opposite direction crashes limited to ≥40 mph speed limit zones on dry/wet roads only. Rear-struck as control crash.	0.673 (0.51,0.89)	2,577	295
OD1	Like OD0, but speed limit ≥ 30mph	0.648 (0.49,0.85)	2,721	319
OD2	Like OD0, but all road surface conditions	0.671 (0.51,0.89)	2,619	305
OD3	Like OD0, excluding crashes at interchanges	0.672 (0.51,0.89)	2,571	293
OD4	Like OD0, but straight roads only (no curves)	0.676 (0.50,0.91)	2,146	204
OD5	Like OD0, but urban only	0.678 (0.50,0.92)	2,134	195
OD6	Like OD0, but rural only	0.671 (0.45,1.00)	1,657	100

All estimates include continuous control for speed limit; categorical controls for Age (<25, 25-64, 65+, Unk), Sex (M, F, Unk), Driver alcohol (Y, N), Weather (Clear/Cloudy, Not Clear/Cloudy, Unk), Road Surface (Wet, Dry, Other, Unk), Light (Daylight, Dark Unlit, DarkLit, Dawn/Dusk, Other/Unk), Model Year, Crash Year; and random effects for vehicle make-model.

Table 10 provides analogous estimates for fatal opposite-direction crashes. The odds ratio of 0.673 associated with sample OD0 indicates that LKA-equipped models are 33 percent less likely to be involved in fatal opposite-direction crashes than their non-equipped counterparts, with a 95 percent confidence interval of 11 to 49 percent. The opposite-direction crash sample is bigger than the same-direction sideswipe sample but smaller than the road departure sample. Estimates from alternate specification samples OD1 to OD6 did not vary substantially from the main estimate.

These effectiveness estimates are substantially higher than the opposite-direction crash estimates from other studies shown in Table 1. The PARTS and UMTRI studies found LKA to be 8 and 7 percent effective at preventing opposite-direction crashes, respectively, though the estimates of effectiveness in preventing opposite-direction crashes with injuries in these studies were not statistically different from zero. Similarly, the Spicer et al., (2021) estimate of LKA effectiveness in head-on crashes was not statistically different from zero. Because this study differs from others on several dimensions, it is difficult to pinpoint why the 33 percent effectiveness estimate is so much higher than these other estimates.

As discussed above, the vehicles in the sample with LKA also had AEB, so it is possible that some of the effectiveness being attributed here to LKA may be stemming from AEB, if emergency braking reduced the impact speed (and therefore probability of fatality) in an opposite-direction crash. Since there were no vehicles in the LKA sample without AEB, the latter could not be controlled for in the main regressions. However, it was possible to isolate a small sample of vehicles with AEB that did not also have LKA, and this sample was used to separately estimate the effectiveness of AEB in lane-departure-type crashes.

Table 11. Relative odds of AEB-equipped model being involved in fatal lane-departure crash, from sample of vehicles without LKA

Sample description		**Odds ratio (95% CI)**	**Sample size (*N*)**	**# with LKA in target crash group**
RD_AEB	Road Departure Sample with AEB as main explanatory variable	0.961 (0.59,1.56)	1,791	133
OP_AEB	Opposite Direction Crash Sample with AEB as main explanatory variable	0.842 (0.51,1.40)	1,341	85
SD_AEB	Same Direction Sideswipe Sample with AEB as main explanatory variable	1.026 (0.49,2.14)	7,60	23

Estimates from generalized linear mixed model (GLMM) with make-model random effects. All estimates also include continuous control for speed limit and categorical controls for Age (<25, 25-64, 65+, Unk), Sex (M, F, Unk), Driver alcohol (Y, N), Weather (Clear/Cloudy, Not Clear/Cloudy, Unk), Road Surface (Wet, Dry, Other, Unk), Light (Daylight, Dark Unlit, DarkLit, Dawn/Dusk, Other/Unk), Model Year, Crash Year.

Table 11 presents estimates of the effectiveness of AEB in fatal lane-departure crashes. Though these are not the primary crash types AEB is designed to prevent, AEB could lessen the severity of a lane departure crash followed by a collision with an object, as in a road departure crash, or a head-on crash with another vehicle, if AEB is engaged in the subject or struck vehicle. The sample sizes are relatively small, and none of the effectiveness estimates are significantly different from zero. Yet, while the point estimates for the effectiveness of AEB in fatal road departure and same-direction sideswipe crashes are close to zero (with odds ratios close to 1), the point estimate in the opposite-direction sample hints at possible effectiveness in that context. The odds ratio of 0.842 in this sample corresponds to AEB effectiveness of about 16 percent in fatal opposite-direction crashes, though it is important to note that the 95 percent confidence interval ranges from -40 percent to 49 percent.

To the extent that AEB is independently effective in fatal opposite-direction crashes, then the estimated effectiveness of LKA in opposite-direction crashes should be reduced by that amount. For example, the data in Table 10 indicated that models with LKA were 33 percent less likely to be involved in a fatal opposite-direction crash, but if AEB is responsible for about 16 percent of that effectiveness (hypothetical only, given wide confidence intervals), then the actual effectiveness of LKA may be closer to 17 percent.

Appendix B: LKA Effectiveness Estimates From Samples With Alternate Road Departure Definitions

In this section, effectiveness estimates from the main road departure regression are compared with estimates obtained using the road departure definitions from the other studies described above (PARTS, 2022; Leslie et al., 2023; and Spicer et al., 2021). While there are numerous reasons for the variation in effectiveness estimates across studies, this analysis will help determine to what extent—if any—the differences are caused by differences in the road departure definition.

Table 12. Road departure and rear-struck crash definitions from other studies

Crash Type	**PARTS (2022) study of ADAS effectiveness from 8 OEMs**	**UMTRI (Leslie et al., 2023) study of ADAS effectiveness in GM vehicles**	**Spicer et al., (2021) study of ADAS effectiveness in Toyota vehicles**
Road Departure Definition from original study	"• Crashes where exactly one vehicle was reported. • First event reported was ran off the road, cross centerline, cross median, collision with fixed objects, or rollover. • Vehicle maneuver at the time of crash was either: going straight, negotiating a curve, leaving traffic lane, or ran off road." (p. 16)	"Single Vehicle AND Harmful Event IN {Run off road, Cross centerline, Cross median, Fixed object}" (p. 21)	"…single-vehicle crashes where the first harmful event was coded 's 'run off the road'" (p. 1698)
Road Departure SAS code used to filter FARS	VE_TOTAL=1 AND VEVENTNUM=1 AND SOE IN (1,17,19:21,23:26,30:35, 38:43,46,48,50,52:53,57:59,63:65,68,79) AND P_CRASH1 IN (1,14,15)	VE_TOTAL=1 AND SOE IN (17,19:21,23:26,30:35,38:43, 46,48,50,52:53,57:59, 63:65,68,79)	VE_TOTAL=1 AND VEVENTNUM=1 AND SOE IN (63,64,79)
Rear-Struck (Control Crash) Definition from original study	"• Manner of crash was identified as front-to-rear. • Initial point of contact on the rear end of the vehicle. • Not a non-standard front-to-rear crash, such as vehicles that were reported to be backing up or parked (to remove these edge cases). • Not crashes where more than two vehicles were reported (to reduce the potential for misattribution of striking and struck vehicle")." (p. 1")	"Manner of Crash = Rear-end AND Initial Contact Point on Vehicle = Rear" (p. 2")	"...vehicles involved in multivehicle crashes coded as "front-to-rear" or "rear end" where the Toyota/Lexus was coded with rear-end damage." (p. 1698)
Rear-Struck (Control Crash) SAS code used to filter FARS	MAN_COLL=1 AND IMPACT1=6 AND PCRASH_1 NOT IN (7,13) AND VE_TOTAL<=2	MAN_COLL=1 AND IMPACT1=6	MAN_COLL=1 AND IMPACT1=6

Table 12 provides the road departure crash type definitions from the PARTS, UMTRI, and Spicer et al. studies, along with their rear-struck control crash definitions. The table also shows how the definitions were translated to FARS variable filters, though this reflects best guesses and may not exactly match the filters used to select vehicles from police crash reports in these studies. The Spicer et al. (2021) study seems to have the most restrictive definition of road departure, including only crashes in which the first harmful event was "run off the road." The PARTS and UMTRI studies include a broader swath of single-vehicle crash types; PARTS includes rollovers, while UMTRI does not, but PARTS also filters by pre-crash maneuvers.

Table 13. Relative odds of LKA-equipped model being involved in fatal lane-departure crash, using alternate road departure crash-type definitions

Sample description		Odds ratio (95% CI)	Sample size (*N*)	# with LKA in target crash group
RD0	Includes MY16-23 passenger vehicles from 2016-2022 fatal crashes. Road departure crashes limited to ≥40 mph speed limit zones on dry/wet roads only. Rear-struck as control crash.	0.756 (0.58,0.98)	3,509	519
RD7	Like RD0, with PARTS-like Road Departure & Rear-Struck definitions	0.726 (0.54,0.97)	3,651	645
RD8	Like RD0, with UMTRI-like Road Departure & Rear-Struck definitions	0.700 (0.56,0.88)	5,022	672
RD9	Like RD0, with Spicer-like Road Departure & Rear-Struck definitions	0.714 (0.56,0.91)	4,457	559

All estimates include continuous control for speed limit; categorical controls for Age (<25, 25-64, 65+, Unk), Sex (M, F, Unk), Driver alcohol (Y, N), Weather (Clear/Cloudy, Not Clear/Cloudy, Unk), Road Surface (Wet, Dry, Other, Unk), Light (Daylight, Dark Unlit, DarkLit, Dawn/Dusk, Other/Unk), Model Year, Crash Year; and random effects for vehicle make-model.

Table 13 shows the results of the comparison, with the main road departure results presented in the RD0 row and results from regressions using the alternate crash type definitions in rows RD7, RD8, and RD9. Recall that the only differences across these models were the definitions of road departure and rear-struck crashes; the sample still included MY16-23 vehicles with known LKA status from 2016 to 2022 FARS data, with only crashes that occurred on dry or wet roads in speed zones of at least 40 mph.

As expected, changing the inclusion criteria for the samples led to variation in sample sizes; the relatively broad UMTRI road departure definition results in the largest sample (5,022 vehicles) and the definition using the FARS *ACC_TYPE* variable results in the smallest (3,509). There is substantial overlap in the confidence intervals presented here, and the point estimates imply effectiveness estimates ranging from 24 percent (RD0, the main estimate presented in this paper) to 30 percent (RD8, UMTRI-like definition).

It is perhaps surprising that the UMTRI-like crash definition (RD8) produced the highest effectiveness estimate, since it was the most inclusive and would therefore theoretically capture a greater number of non-LKA-relevant crashes. One possible explanation is that LKA is actually more effective in the additional crash types captured in the UMTRI definition. Another is that a broader definition included more crash types that could be addressed by technologies or other factors that tend to coexist with LKA, such as AEB. To the extent that the latter is true, caution should be exercised in attributing effectiveness to LKA per se.

Notably, these effectiveness estimates are all higher than the road departure estimates presented in the original studies (see Table 1). From this, it can be concluded that the road departure definition used in the main analysis is not responsible for the relatively high effectiveness estimate, since using alternate definitions resulted in even higher point estimates. As explored above, it could be that LKA is relatively more effective in reducing the severity of crashes than preventing them altogether, or it could be an artifact of other sample or methodological differences.

Appendix C: Comparison of Subject-Specific and Population-Average Estimates

In this section, effectiveness estimates obtained using the random effects model (a GLMM with make-model random effects, as in the main analysis above) are compared with estimates obtained using a generalized estimating equations (GEE) model. Both models account for clustering of vehicle models within makes, but the estimates they produce have different meanings. Estimates from the random effects model are subject-specific; in this context, they tell us the average odds of being in a fatal crash for a vehicle *model* that has LKA relative to the *same model* without LKA. Estimates from a GEE model are population-averaged; they would tell us the average odds of being in a fatal crash for a vehicle with LKA relative to a vehicle without LKA, capturing differences both between and within models.

This study uses a random effects model, as does the UMTRI (Leslie et al., 2023) study of GM vehicles, which produce subject-specific estimates. The PARTS (2022) study appears to use regular logistic regression with vehicle model fixed effects, which would not account for clustering but would produce population-average estimates. The Spicer et al. (2021) study uses a Cox proportional hazards regression with fixed effects for vehicle model, which should also produce population-average estimates. This represents another possible source of variation in the estimates.

The interpretation of the odds ratios from the random effects model is suitable for our purposes, since it directly measures the benefit of specific models changing from "No LKA" to "LKA" status, either due to manufacturers updating their models or users enabling it in vehicles where it had been disabled. Still, it may be useful to know how much the subject-specific estimates differ from the population-average estimates, to confirm that this modeling choice is not having an outsized effect on the results.

Table 14. Relative odds of LKA-equipped model being involved in fatal lane-departure crash, subject-specific versus population-average estimate comparison

Sample description		**(a) Subject-specific odds ratio** from GLMM with make-model random effects	**(b) Population-average odds ratio** from GEE model clustered at make-model level	**Sample size (*N*)**	**# with LKA in target crash group**
RD0	Main Road Departure Sample	0.756	0.739	3,509	519
OP0	Main Opposite Direction Crash Sample	0.673	0.664	2,577	295
SD0	Main Same Direction Sideswipe Sample	0.987	0.968	1,573	104

All estimates include continuous control for speed limit and categorical controls for Age (<25, 25-64, 65+, Unk), Sex (M, F, Unk), Driver alcohol (Y, N), Weather (Clear/Cloudy, Not Clear/Cloudy, Unk), Road Surface (Wet, Dry, Other, Unk), Light (Daylight, Dark Unlit, DarkLit, Dawn/Dusk, Other/Unk), Model Year, Crash Year.
The GEE model produced point estimates but was not able to converge on standard error estimates, likely due to sample size.

Table 14 shows subject-specific point estimates[29] from the main random-effects model in column (a) and population-average estimates from a GEE model in column (b). The odds ratio point estimates vary by less than two percentage points in each case. For example, implied LKA

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[29] The GEE model was not able to converge on confidence interval estimates due to small sample sizes, so only point estimates are provided here.

effectiveness in fatal road departures is 26 percent in the population-average case versus 24 percent in the preferred subject-specific estimate. This indicates that a vehicle with LKA is 26 percent less likely than a vehicle without LKA to be involved in a fatal road departure crash, and a vehicle model with LKA is 24 percent less likely than the same model without LKA to be involved in a fatal road departure crash.

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