APPLYING LANE KEEPING SUPPORT TEST TRACK PERFORMANCE TO REAL-WORD CRASH DATA

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ABSTRACT

Lane Keeping Support (LKS) is an advanced driver assistance system (ADAS) technology intended to prevent a vehicle from drifting out of its travel lane. To assess the potential for LKS to reduce real-world crashes where the driver drifts out of their travel lane, test track performance was compared with the real-world crash data.

Five light vehicles equipped with LKS were evaluated on the test track using Lane Keeping Assist (LKA) test methods contained within the Euro NCAP Test Protocol - Lane Support Systems. Specifically, the procedures to evaluate a vehicle's response to an imminent departure over a solid white line were used; tests to evaluate LKS system response to an unmarked road edge were not performed. These tests identified performance differences between the vehicles, and were somewhat dependent on the lateral velocity used during test conduct.

Results from these tests were compared to relevant fatal crashes in the National Motor Vehicle Crash Causation Survey (NMVCCS) survey conducted by the National Highway Traffic Safety Administration from 2005-2007, and the agency's new Crash Investigation Sampling System (CISS). A review of the fatal 2005 – 2007 NMVCCS and 2017 CISS lane/roadway departure cases was performed to classify the shoulder type present on the side of the roadway from which the subject vehicle first departed from, and to estimate the shoulder width just after the departure, where applicable. The objective of this effort was to estimate whether LKS interventions could have potentially amended the real-world pre-crash path of the subject vehicle in the vicinity of the lane departure, given the system performance observed on the test track.

When the test track performance of the vehicles was considered in the context of the road shoulder widths and road/lane/shoulder characteristics present in the 43 fatal NMVCCS and 50 CISS crashes analyzed for this paper, estimating whether LKS could have affected the crash outcome was found to depend on a number of factors. From an input perspective, the lateral velocity of the vehicle as it is directed toward the boundary of the lane, and whether that boundary is comprised of a clearly defined painted line or simply a pavement edge, has the potential to affect whether an LKS intervention can even be expected.

Even if the input conditions are such that a vehicle's LKS activation criteria are satisfied, then the ability of the system to effectively address the pre-crash scenario is relevant, yet can depend on a number of factors. The amount of lateral deviation before or beyond the lane line and/or road edge, and the implications of it being too large, are important considerations. In the case of a right-side departure away from the travel lane, excessive lateral deviation may result in at least part of the vehicle leaving the paved roadway. Similarly, left-side departures with excessive lateral deviation have the potential to increase the risk of a head-on crash.

INTRODUCTION

Lane Departure Warning (LDW), Lane Keeping Support (LKS), and Lane Centering Control (LCC) are three advanced driver assistance system (ADAS) technologies intended to prevent vehicles from drifting out of their travel lane. All three systems utilize a camera-based vision system to monitor the vehicle's lateral position with respect to the roadway. Depending on the system design and system's level of intervention authority, the technology is intended to warn the driver that they are leaving the travel lane, redirect the lateral path of the vehicle to stay in the lane, or continuously maintain the lateral position of the vehicle within the lane of travel.

The run-out-of-lane pre-crash scenarios identified by Swanson, et al were used to estimate the target crash population of the ADAS systems discussed in this paper [Swanson, 2018]. In this work, a combination of the National Automotive Sampling System (NASS) General Estimates System (GES) and Fatality Analysis Reporting System (FARS) 2011-2015 crash databases were used to examine all police-reported crashes involving a light vehicle in the critical event of the crash or in the event that occurred which made the crash imminent. Light vehicles include all passenger cars, vans, minivans, sport utility vehicles, or light pickup trucks with gross vehicle weight ratings less than or equal to 10,000 pounds. Common crash types were analyzed to produce a list of representative pre-crash scenarios based upon NHTSA pre-crash variables (i.e., the pre-crash movement or the vehicle's action prior to an impending critical event or prior to impact if the driver did not make any action). From the pre-crash scenarios identified in the report, Table 1 lists those relevant to the inadvertent run-out-of-lane crash problem. This approach identified, on average, over 760,000 run-out-of-lane crashes annually; over 9,600 of which were fatal.

Table 1.
2011 – 2015 FARS and GES run-out-of-lane light vehicle target population

Scenario	Avg FARS	Avg GES
Road edge departure/No Maneuver	6,284	472,182
Opposite Direction/No Maneuver	2,983	96,095
Drifting/Same Direction	196	120,223
Object/No Maneuver	151	80,088
Total	9,615	768,588

To assess the potential effectiveness of countermeasures intended to prevent run-out-of-lane crashes, Wiacek, et al performed a study to better understand why drivers depart the roadway and under what conditions and circumstances the crashes occur [Wiacek, 2017]. Using fatal crashes from the National Motor Vehicle Crash Causation Survey (NMVCCS), this study identified 72 cases where the result of a subject vehicle departing the travel lane resulted in a crash where an occupant in an involved vehicle sustained fatal injuries. Of these, 43 cases where the subject vehicle drifted out of the lane and crashed were used to assess the real-world applicability of LDW/LKS/LCC crash avoidance technologies.

The study concluded that a robust LKS/LCC system with sufficiently high lateral control authority could have effectively prevented many of the 43 cases reviewed. In other words, unless there were other factors present which prevented the driver from reengaging in the driving task, a robust LKS/LCC system would likely have prevented the driver from running out of the lane, which started the chain of events that led to the fatal crashes. The study suggested that LKS/LCC systems appear to have more potential in crash reduction than LDW since the systems do not rely on alert modality effectiveness or driver responsiveness. Additionally, the mentioned the environmental and roadway conditions at the time of the crash would likely not have compromised the performance of the vision system to detect the roadway boundary at the moment the vehicle left the lane.

This paper builds upon the earlier work by comparing measured test track performance of vehicles equipped with LKS systems with the real-world crash data. The purpose was to measure the performance of the LKS systems under controlled conditions and estimate how the systems may have addressed the driving conditions preceding known crashes. The goal in doing this is to assess the efficacy.

Five light vehicles from different manufacturers were tested using Lane Keep Assist (LKA) test methods contained within the European New Car Assessment Programmed (Euro NCAP) Test Protocol - Lane Support Systems [Euro NCAP, 2015] to assess technology implementation differences. Euro NCAP uses LKA to describe systems NHTSA would describe as having LKS. For the sake of this paper, the terms can be used interchangeably. The following vehicles were tested:

- 2017 Cadillac CTS
- 2017 Ford Fusion
- 2017 Mercedes Benz C300
- 2017 Toyota Prius Prime
- 2017 Volvo XC90

For each vehicle, the test track performance was used to assess if the vehicles' LKS systems intervened, whether the interventions corrected the vehicle's heading back to the travel lane, and the maximum lateral deviation from the test lane line marking.

In addition to the vehicle tests, the crash data were also surveyed to assess how the technology would apply to the real-world. First, the 43 fatal NMVCCS cases from the previous study were reanalyzed. For each crash, on the side of the lane or roadway departure, the shoulder width of the road was estimated. To be consistent with the Euro NCAP LKA test procedure, the shoulder width measurement was estimated from the inside edge of the lane marking to the edge of the road surface. In those crashes where the shoulder width was not relevant because of the crash type or roadway surface, the side of the roadway or lane of travel was characterized.

Lastly, using the same methodology, a review of the run out of the lane fatal data was also analyzed using the 2017 NHTSA Crash Investigation Sampling System (CISS). CISS, which began pilot data collection is 2016, replaced the retired National Automotive Sampling System Crashworthiness Data System (NASS-CDS) as NHTSA's nationally-representative investigation-based data collection program. For these 50 cases, the shoulder width was measured or the side of the lane/roadway departure or was characterized. The results of this analysis will be presented and discussed in the context of the five vehicles tested.

VEHICLE TESTING

Test Procedure

The Euro NCAP LKA test procedure uses a series of trials performed with iteratively increasing lateral velocities towards the desired lane line. For all tests, a robotic steering controller was utilized to increase the repeatability of the procedure and reduce variability associated with manual steering inputs. Although the Euro NCAP LKA test protocol does not specify use of robotic steering controller, it does require tight path tolerances be satisfied by the vehicle as it approaches the desired lane marking during testing.

Pretest conditions

For each subject vehicle (SV), prior to testing, the vehicle manufacturers were asked to complete pre-test forms that included information to determine if any system initiation testing must take place prior to conducting the performance testing. If system initialization testing was needed, the vehicle manufacturer provided the recommended instruction to initialize the system.

Once the system was initialized, the SV's tires and brakes were pre-conditioned using a series of start and stops at predefined speeds and brake decelerations.

Test Maneuver

Each LKS trial began with the SV being driven at 72 km/h down a straight lane delineated by solid white and dashed white lines. The SV path was initially parallel to the lane lines, with an offset from the solid white line that depended on what lateral velocity would be used later in the maneuver (Figure 1).

After a short period of steady state driving, the steering machine was used to adjust the heading of the SV towards the solid white lane line using a path defined by a 1200 m radius curve. The amount of time the SV path remained on this curve depended on the lateral velocity desired for the test trial, and the heading angle associated with it. Once these parameters had been achieved, the steering machine returned the handwheel angle to zero, and was decoupled from the SV so as to allow the SV handwheel to move freely and independently.

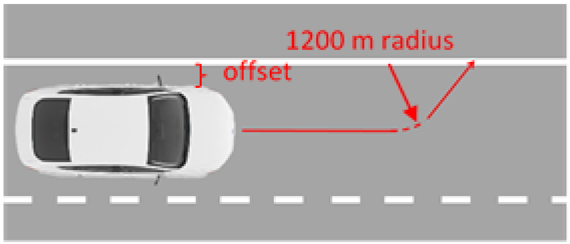

Figure 1. Left lane departure for LKS test

The lateral velocity of the SV approach towards the solid lane line (from both the left and right directions) was iteratively increased from 0.1 m/s. If acceptable LKS performance was realized, the lateral velocity used for the next trial was increased by 0.1 m/s. This continued until the SV was no longer able to satisfy the LKS performance criteria or until a maximum lateral velocity of 1.0 m/s was reached. The tests performed with lateral velocities from 0.1 - 0.5 m/s were used for the Euro NCAP performance assessment protocol, whereas those >0.5 m/s were used for research purposes. [Euro NCAP, 2015]

LKS Validity Criteria

The following validity criteria were applied to each test trial to insure the tests were properly performed:

- SV Speed: 72 km/h ± 1.0 km/h
- Lateral deviation from test path: ± 0.05 m
- Lane departure lateral velocity: ± 0.05 m/s from target lateral velocity
- Steering wheel velocity: ±15 deg/sec

LKS Performance Criteria

Acceptable LKS performance occurred when SV did not cross the inboard leading edge of the solid lane line by more than 0.4 m.

Results

The results from the five vehicles tested under the conditions described above will be presented. A summary of the data by vehicle and test condition is presented in Table 2. Per the test condition, the maximum lateral deviation is noted. Positive values indicate the maximum lateral deviation occurred prior to the vehicle crossing the inboard edge of the lane line. A negative value indicates the maximum lateral deviation occurred after the vehicle crossed the inboard line edge. No LKS intervention (No LKS) is noted on the summary table, as well as if a vehicle was not tested under a given condition (NDT).

Tests Performed with Lateral Velocities from 0.1 – 0.5 m/s

Of the five vehicles tested, only the Cadillac CTS and the Volvo XC90 satisfied the performance criteria for the first five lateral velocity iterations during both the left- and right-side lane line approaches. In the case of the Volvo XC90, the maximum lateral deviation occurred prior to the vehicle crossing the lane line, as indicated by the positive values in Table 2.

The Mercedes C300 satisfied the performance criteria during tests conducted with lateral velocities up to 0.3 m/s during left- and right-side approaches.

The Ford Fusion and Toyota Prius had asymmetrical performance where, under certain test conditions, the vehicles satisfied the performance criteria on one side but not the other for the same lateral velocity.

The Ford Fusion did not satisfy the performance criteria on the left-side approaches when lateral velocities of 0.1 and 0.4 m/s were used, but did for each right-side approach. For this vehicle, LKS did not activate during trials performed with a lateral velocity of 0.1 m/s (three repeated trials were performed, each with the same outcome) and while LKS did activate during the test performed with a 0.4 m/s lateral velocity, maximum lateral displacement exceeded 0.4 m.

The Toyota Prius satisfied the performance criteria at 0.2 m/s and 0.3 m/s on the right side, but exceeded the maximum lane deviation limit of 0.4 m on the left side.

Tests Performed with Lateral Velocities from ≥0.6 m/s

LKS interventions were observed during tests performed with lateral velocities of 0.6 to 0.9 m/s for three of the five vehicles tested in this paper. The Volvo XC90 satisfied the LKS performance criteria during left- and right-side approaches for lateral velocities up to 0.7 m/s, and only on the left side at 0.8 m/s. No further testing was conducted with the Volvo XC90.

The Cadillac CTS satisfied the LKS performance criteria during left- and right-side approaches performed with a lateral velocity of 0.6 m/s. Although LKS interventions were observed during left- and right-side approaches using lateral velocities up to 0.9 m/s, the vehicle exceeded the maximum lateral deviation threshold.

The LKS system on the Ford Fusion intervened when tested at the lateral velocity of 0.5 m/s, but the vehicle exceeded the maximum lateral deviation threshold on both the left- and right-side approaches. No further testing was conducted at higher lateral velocities.

For the Toyota Prius, testing at higher lateral velocities was only conducted on the right side because the performance criteria was not satisfied at lower lateral velocities during left-side approaches. The vehicle satisfied the maximum lateral deviation at 0.6 m/s, exceeded the criteria at higher lateral velocities on the left-side approach tests.

The Mercedes C300 was only tested on the right side at the lateral velocity of 0.5 m/s. The LKS did not engage during this trial, and no further testing was conducted. No vehicles were tested with lateral velocities at or above 1.0 m/s.

Figures 2 and 3 illustrate the performance differences among the five test vehicles during tests performed with the various lateral velocities. Lateral deviations greater than those specified by the LKS performance criteria are shaded in blue.

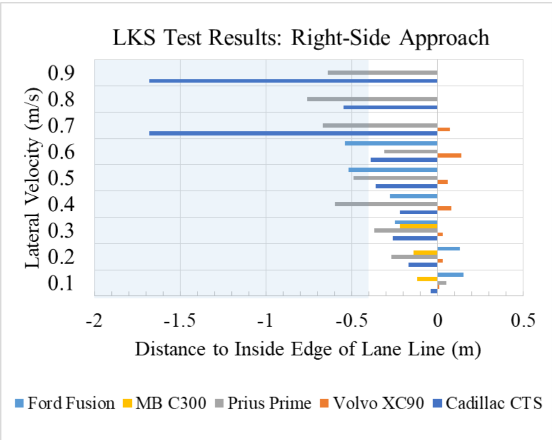

Figure 2. LKS test results – right side departure

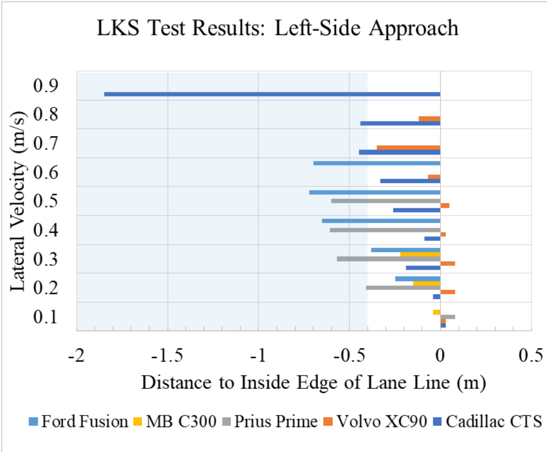

Figure 3. LKS test results – left side departure

Table 2.
Summary of test results by vehicle and test conditions

Maximum Lateral Deviation (m)	Lateral Velocity (m/s) 0.1 L	0.1 R	0.2 L	0.2 R	0.3 L	0.3 R	0.4 L	0.4 R	0.5 L	0.5 R
Cadillac CTS	0.03	-0.04	-0.04	-0.17	-0.19	-0.26	-0.09	-0.22	-0.26	-0.36
Ford Fusion	**No LKS**	0.15	-0.25	0.13	-0.38	-0.25	**-0.65**	-0.28	**-0.72**	**-0.52**
Mercedes Benz C300	-0.04	-0.12	-0.15	-0.14	-0.22	-0.22	**No LKS**	**No LKS**	**No LKS**	**No LKS**
Toyota Prius Prime	0.08	0.05	**-0.41**	-0.27	**-0.57**	-0.37	**-0.61**	**-0.6**	**-0.6**	**-0.49**
Volvo XC90	0.03	0.01	0.08	0.03	0.08	0.03	0.03	0.08	0.05	0.06

Maximum Lateral Deviation (m)	0.6 L	0.6 R	0.7 L	0.7 R	0.8 L	0.8 R	0.9 L	0.9 R	1.0 L	1.0 R
Cadillac CTS	-0.33	-0.39	**-0.45**	**-1.68**	**-0.44**	**-0.55**	**-1.85**	**-1.68**	DNT	DNT
Ford Fusion	**-0.7**	**-0.54**	DNT	DNT	DNT	DNT	DNT	DNT	DNT	DNT
Mercedes Benz C300	DNT	**No LKS**	DNT	DNT	DNT	DNT	DNT	DNT	DNT	DNT
Toyota Prius Prime	DNT	-0.31	DNT	**-0.67**	DNT	**-0.76**	DNT	**-0.64**	DNT	DNT
Volvo XC90	-0.07	0.14	-0.35	0.07	-0.12	DNT	DNT	DNT	DNT	DNT

Figures 4 and 5 are screen shots from test video recorded during right-side approaches performed with a lateral velocity of 0.7 m/s, for the Volvo XC90 and the Cadillac CTS, respectively. LKS intervened during both trials. The maximum lateral deviation recorded for the Volvo XC90 was 0.07 m from the inboard edge of the lane marking (able to satisfy the LKS performance criteria), whereas it was 1.68 m for the Cadillac CTS (unable to able to satisfy the LKS performance criteria). The white arrows shown in Figures 4 and 5 indicate the reference lane marking.

Figure 4. Point of maximum lateral deviation observed during a right-side approach test performed with the Volvo XC90 and a 0.7 m/s lateral velocity

Figure 5. Point of maximum lateral deviation observed during a right-side approach test performed with the Cadillac CTS LKS and a 0.7 m/s lateral velocity

REAL-WORLD SHOULDER WIDTH ANALYSIS

A review of the fatal 2005 – 2007 NMVCCS and 2017 CISS lane/roadway departure cases was performed to classify the shoulder type present on the side of the roadway the subject vehicle first departed its travel lane, and to estimate the shoulder width just after the departure, where applicable. The objective of this effort was to estimate whether LKS interventions could have potentially amended the real-world pre-crash path of the subject vehicle near the lane departure, given the system performance observed on the test track.

NMVCCS Lane Width Analysis

Method To establish a baseline, the 43 previously analyzed fatal NMVCCS cases were reassessed. For these cases, it was previously established that the subject vehicle drifted out of the lane, resulted in a fatal crash, and was relevant to assessing the real-world applicability of LDW/LKS/LCC crash avoidance technologies. All the cases were reviewed and the side of the initial lane or roadway departure was identified. Once identified, the shoulder width distance was estimated for the side of the roadway departure. Examples will be discussed below followed by the results of the analysis.

To be consistent with the measurement convention used in the Euro NCAP LKA test procedure, and with the data reported in Table 2, the shoulder width estimates extracted from the NMVCCS and CISS cases were referenced from the inside edge of the lane marker to the end of the road surface at the location of the lane departure.

The side of the roadway was also characterized in those cases where a lane marking or shoulder was not present, such as when the vehicle traveled into an adjacent lane, rural or local roads where there were no markings and only a road edge and, intersections or when a curb was present that define the edge of the useable road surface.

Examples In NMVCCS Case Nos. 2006-045-063 and 2007-78-071 the drivers drifted out of the lane on the left side. For these types of cases the road shoulder width measurement was estimated from the inside edge of the lane marker to the end of the road surface. This was conducted by examining the scene diagram and the scene photos, using the lane line width as the reference for the measurement. (Figures 6 and 7)

Figure 6. NMVCCS Case No. 2006-045-063 shoulder width

Figure 7. NMVCCS Case No. 2007-078-071 shoulder width

NMVCCS Case No. 2005-76-035 is an example where the subject vehicle departed the lane of travel into the "adjacent lane." In this case the driver drifted over the center line and departed the road on the left resulting in a rollover (Figure 8).

Figure 8. NMVCCS Case No. 2005-76-035 adjacent lane on the left

NMVCCS Case No. 2005-11-61 is an example of crash where the vehicle was traveling a straight, level, two-way, rural gravel roadway with no painted lines (Figure 9). The subject vehicle drifted and exited the roadway to the right.   This type of roadway was characterized by its “road edge.”

Figure 9. NMVCCS Case No. 2005-11-61 road edge example

NMVCCS Case No. 2007-49-043 is an example of a roadway where there was no lane marking and just a curb at the end of the road surface on the side the vehicle departed the travel lane. In this case the subject vehicle was traveling east in left lane. After traveling through an intersection, the subject vehicle drove off the road to the left onto the curbed median striking a light pole (Figure 10). This crash also has some characteristics similar to the intersection crashes that were identified in the CISS data, and will be discussed later in this paper.

Figure 10. NMVCCS Case No. 2007-49-043 curb example

Results Using the method described above, the results of the analysis of the 43 NMVCCS cases are provided in Figure 11. For this analysis, the shoulder width measurement data was grouped by 0.1 m increments up to 0.4 m.

The data show that in 16 of the 25 crashes where a shoulder was present on the side of the road, and the vehicle departed the lane, the shoulder was greater than 0.4 m. In nine of the crashes, the shoulder width was equally distributed between the "greater than 0.1 m" and "equal to 0.4 m or less" groupings. There were no crashes where the shoulder was 0.1 m or less.

In this data set, there were three crashes where the subject vehicles left the road with no lane markings on the side of the roadway departure. It should be noted that in these cases, there was a clearly-defined road edge. Lastly, in 14 cases the vehicle drifted into the adjacent lane. These crashes resulted in the vehicle leaving the roadway after crossing into the oncoming lane or drifting into oncoming traffic

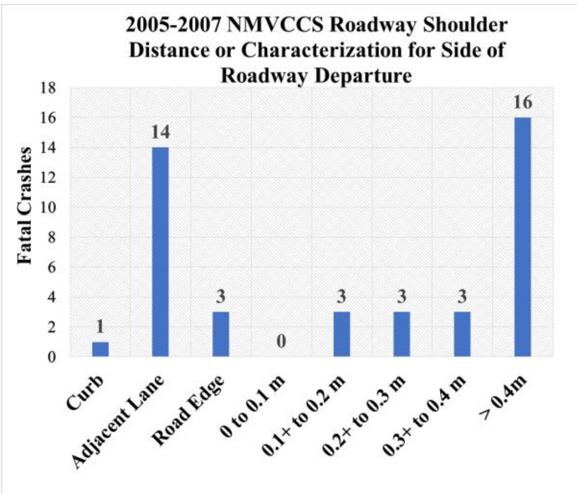

Figure 11. 2005 – 2007 NMVCCS roadway shoulder distance or characterization

CISS Lane Width Analysis

Method A second analysis of the real-world crash data was conducted using NHTSA's CISS. In response to a congressional directive to modernize its nationally representative crash databases, NHTSA concluded that the NASS-Crashworthiness Data System (NASS-CDS) program would be retired and replaced with the CISS. The new CISS program was designed to provide many improvements from its predecessor including, obtaining more accurate scene and vehicle measurements. [Mynatt, 2017] In addition to the improved measurement, the 2017 CISS dataset was the first year collected for the program. Given the NMVCCS data was older, the newer data could provide insight into changes to the roadways with respect to the efficacy of LKS.

As with the NMVCC study, all fatal cases from the 2017 CISS dataset that met the following Crash Type Code were selected: 01, 02, 04, 05, 06, 07, 09, 10, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 64, 65, 66, and 67 (a chart explaining the crash types is provided in the Appendix of this paper). As with the NMVCCS case selection, the intent was to capture fatal crashes resulting from the vehicle leaving the original travel lane. The CISS cases are also provided in the Appendix.

Fifty-seven cases met the criteria, however, upon review of the data, seven cases were excluded from the final analysis because the subject vehicles were traveling the wrong way on a one-way street or the vehicle lost control prior to departing the roadway. There were 50 cases in the final data set.

In CISS, all the crash scene measurements are now collected in three-dimensions using a Nikon Total Station electronic measuring devices, coupled with FARO® Blitz software. [Mynatt, 2017] As discussed in the NMVCC section, the cases were reviewed, and the side of the initial lane or roadway departure was identified. The NMVCCS shoulder width measurements were estimated using the scene diagrams and photos. In CISS, the shoulder widths were measured in the Blitz diagramming software near the roadway departure location. It should be noted that beginning in 2018, shoulder width measurements in CISS are coded in the data file. As with the NMVCCS cases, the side of the roadway departure was also characterized when applicable. Examples of the roadways will be provided below followed by a summary of the results.

Examples CISS Case No. 1-13-2017-127-01, the subject vehicle initially departed its lane of travel on the right side prior to returning and departing the lane on the left side, resulting in a crash with a vehicle traveling in the adjacent lane. (Figure 12). In this case, the lane departure occurred on a highway whose shoulder width was measured from the inboard edge of lane line to the end of the road surface on the far right.

Figure 12. CISS Case No. 1-13-2017-127-01 shoulder width example

CISS Case No. 1-19-2017-113-01 is an example of a vehicle leaving the lane of travel into the adjacent lane. In this case the subject vehicle was traveling east on the highway, departing the lane on the left. The vehicle departed the roadway on the left where it struck a concrete driveway, and rolled over before coming to rest on its side (Figure 13).

Figure 13. CISS Case No. 1-19-2017-113-01 adjacent lane

CISS Case No. 1-32-2017-013-01 was categorized as a vehicle parked on shoulder. In this case the subject vehicle was traveling on a major highway. The vehicle departed the roadway to the right, entering the road shoulder. The front of subject vehicle impacted the rear of a parked vehicle on the shoulder (Figure 14).

Figure 14. CISS Case No. 1-32-2017-013-01 parked vehicle

CISS Case No. 1-33-2017-025-01 is an example of a crash that occurred at an intersection. In this case, the subject vehicle drifted out of the travel lane into the adjacent lane. This occurred at an intersection where there were no lane markings. The vehicle proceeded to travel until it impacted a vehicle traveling in the opposite direction. Figure 15 shows the approach for the subject vehicle and the lack of lane markings at the intersection on the left side.

Figure 15. CISS Case No. 1-33-2017-025-01 intersection example

CISS Case No. 1-28-2017-046-01 is an example where there were no lane markings on a gravel road but a discernable road edge. In this case, the subject vehicle was negotiating a right curve. The vehicle departed the roadway to the left side and impacted a tree on the left side of the vehicle (Figure 16).

Figure 16. CISS Case No. 1-28-2017-046-01 road edge example

Results The results of the shoulder width measurements and roadway departure characterization for the 50 CISS cases are presented in Figure 17. As with the NMVCCS analysis, the shoulder width measurement data were grouped by 0.1 m increments up to 0.4 m.

The data show that in 16 of the 19 crashes where a shoulder was present on the side of the road, and the vehicle departed the lane, the shoulder width was greater than 0.4 m. In three of the crashes, the shoulder was greater than 0.1 m wide but equal to 0.3 m or less. There were no crashes where the shoulder was 0.1 m or less.

In this data set, there were seven crashes where the subject vehicle left the road with no lane markings on the side of the roadway departure. It should be noted that in these cases, there was a clearly defined road edge. There were four cases where the vehicle drifted out of the lane at an intersection where the lane markings were not present. In 18 cases, the vehicle drifted into the adjacent lane. As with the NMVCCS cases, generally these crashes resulted in the vehicle leaving the roadway after crossing into the oncoming lane or drifting into oncoming traffic. Lastly, there were two cases (CISS Case Nos. 1-32-2017-013-01 and 1-28-2017-039-01) where the subject vehicles impacted a vehicle parked on the shoulder.

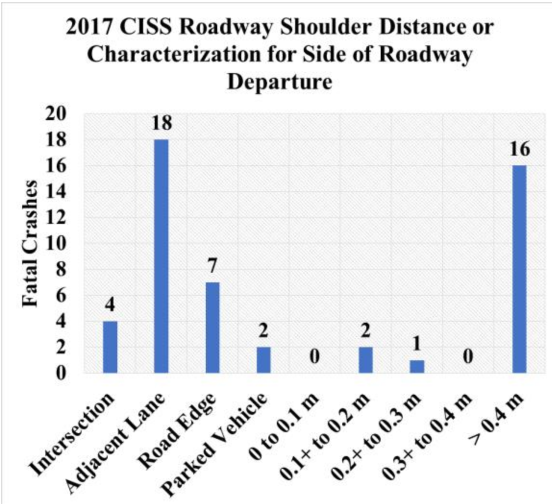

Figure 17. 2017 CISS roadway shoulder distance or characterization

DISCUSSION

This section will discuss the results of five vehicles tested with the Euro NCAP LKA procedure (i.e., those described earlier in this paper) in the context of the analysis of the real-world fatal crashes. Specifically, given the performance of the vehicles under the test conditions, discussion will be focused on whether the fatal crashes could have been potentially prevented for those cases where there was a shoulder, road edge, and adjacent lane.

With respect to the roadway shoulder width, NMVCCS and CISS results (which encompassed 93 fatal crashes that were collected approximately 10 years a part) were consistent and showed similar distributions. For that reason, the combined results are presented in Figure 18.

These real-world data were not assessed for the dynamic state of the vehicle and the lateral velocity of vehicle prior to the roadway departure. Any attempt to correlate that lateral velocity was beyond the scope of the study. It is also assumed that the travel speed of the subject vehicles met or exceeded the minimum activation speed for the LKS. The cases were identified by the vehicle appearing to drift out of the lane, and quantifying the shoulder width when applicable or characterization of the side of the roadway departure.

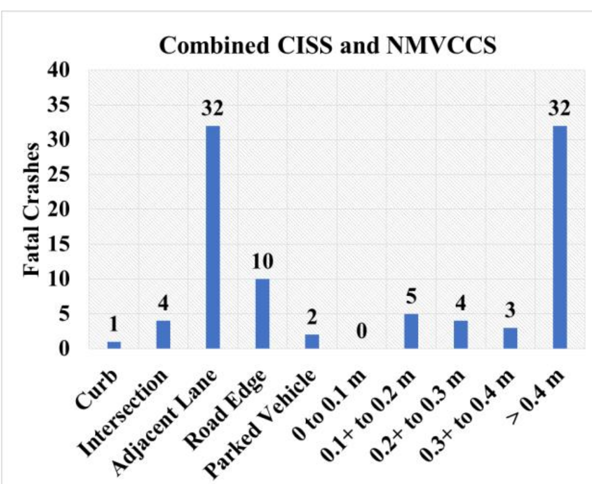

Figure 18. Combined CISS and NMVCCS roadway shoulder distance or characterization.

Lane Departure with Shoulder
CISS Case No. 1-19-2017-041-01, is an example of a roadway with a narrow shoulder that only an LKS that allows very limited lateral deviation from the travel lane would be expected to prevent at least part of the subject vehicle from departing the roadway. The subject vehicle in this example was traveling west and departed the roadway to the right. The vehicle, traveled down an embankment, across an adjacent roadway prior to impacting a tree.

From Figure 19, the shoulder width was measured in CISS to be approximately 0.15 m. The test track data previously presented in Table 2 indicated that only the Volvo XC90 LKS interventions consistently (i.e., over a wide range of lateral velocities) prevented right-side lateral deviations below that distance. Except for the lower lateral velocity conditions, the other test vehicles generally exceeded a lateral deviation of 0.15 m.

Figure 19. CISS Case No. 1-19-2017-041-01 vehicle approach

Lane Departure without Lane Markings
There were 10 crashes identified where there were no lane markings on the road or on the side of the road departure.

It is unknown whether any of the five vehicles tested were equipped with LKS systems capable of intervening in response to a circumstance where a lane departure is imminent, but only a road edge is present (i.e., no lane marker), as such conditions were not evaluated on the test track in this study. Euro NCAP has adopted a test procedure that includes a limit of 0.1 over a road edge, as shown in Figure 20 using a test procedure similar to the LKS test described earlier but without the lane line. [Euro NCAP, 2017]

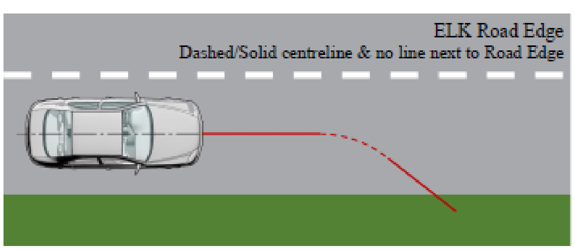

Figure 20. Euro NCAP road edge test condition

CISS Case No. 1-19-2017-097-01 is an example of a road edge case. In this fatal crash, the subject vehicle departed the roadway to the right where there was a disparate lane line and a discernable road edge (Figure 21). After departing the roadway, the vehicle traveled down a steep embankment, striking one or multiple trees and rolling over before coming to final rest. To prevent this type of crash, it is expected the most effective LKS intervention would occur prior to the vehicle leaving the road since pavement provides greater lateral force (turning) capacity than an unpaved deformable surface. With regards to intervention proximity to a lane line, the Volvo XC90 test track performance was indicative of this kind of operation; preventing the vehicle from traveling past the line in each of the right-side approaches. However, and as previously stated, it is unknown whether the Volvo XC90 LKS system has been configured to respond to an imminent road edge departure which, in this case, is essentially a lane departure without a clear marking delineating the right side of the lane. This case provides evidence of why it may be important for an LKS system to address lane and road departures, to maximize the overall potential safety benefits provided by these systems during real-world driving where clear markings are not always present.

Figure 21. CISS Case No. 1-19-2017-097-01 vehicle approach

Lane Departure into Adjacent Lane

Thirty-two of the ninety-three crashes shown in Figure 18 involved the subject vehicle drifting out of the initial travel lane into an adjacent lane. Crashes that involve the subject vehicle drifting out of its lane result in head-on crashes with an oncoming vehicle or a road departure from the adjacent lane.

With respect to LKS and the vehicles tested, it was determined that the roadway width in the adjacent lane was not a limiting factor as it exceeded the 0.4 m performance criteria. Specifically, for the single vehicle crashes where the vehicle departed the road on the right side, many of the same observations that were discussed in the shoulder width section remain true with respect to the performance of the LKS. If the LKS engaged in the test condition, depending on the lateral velocity, the LKS may have been effective in preventing many of these adjacent lane crashes that did not involve another vehicle traveling in the opposite direction.

Of the 32 adjacent lane cases, over half were head-on crashes. Ten were identified in NMVCCS and eight in CISS. The analysis performed for this paper did not explore the location of the vehicles involved in head-on crashes relative to the lane marking at impact. However, assuming the opposing vehicle does not travel into the subject vehicle’s lane, and if it can be assumed that if the subject vehicle’s LKS does not allow the subject vehicle to cross into the adjacent lane, the head-on crash would likely not occur.

CISS Case No. 1-28-2017-032-01 is example where the subject vehicle encroaches into the adjacent lane and is involved in a fatal head-on collision. The subject vehicle was traveling west on a two lane non-divided roadway. A large truck was traveling east on the same roadway. The subject vehicle entered the truck’s lane, and a head-on impact resulted (Figures 22 and 23).

Figure 22. CISS Case No. 1-28-2017-032-01 vehicle approach

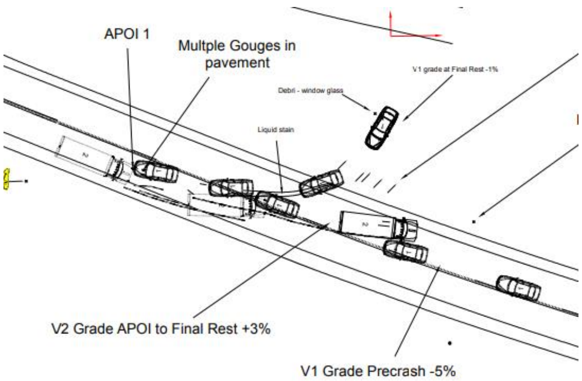

Figure 23. CISS Case No. 1-28-2017-032-01 scene diagram

Figure 24 presents the damage incurred by the subject vehicle. Based upon the crush pattern and interaction with the truck, the subject vehicle likely crossed over the centerline and into the adjacent lane by well over the 0.4 m allowance specified in the Euro NCAP LKA performance criteria.

Figure 24. CISS Case No. 1-28-2017-032-01 front end crush of subject vehicle

Other Lane Departure Cases

There were four crashes that occurred at intersections where there were no lane markings leading up to the location of the lane departure. It was apparent for each case, the subject vehicle was not turning and proceeding through the intersection. Otherwise, lane markings were present leading up to the intersection.

As discussed earlier (NMVCCS Case No. 2007-49-043) there was one crash where there were no lane markings on the side of the roadway departure and the road edge was delineated by a curb, over which the subject vehicle travelled. It is unknown how LKS may have affected the outcome of these crashes where the lane markings are not present.

Lastly, there were two cases (CISS Case Nos. 1-32-2017-013-01 and 1-28-2017-039-01), involving a vehicle parked on the shoulder. The assessment of the LKS performance was similar to the adjacent lane, head-on crashes discussed earlier. The effectiveness of the LKS is dependent on how far the vehicle deviates into the shoulder and the location of the parked vehicle. The only way to assure the crash is avoided during an imminent lane departure is to prevent or minimize how far the vehicle encroaches into the roadway's shoulder.

CONCLUSION

Five light vehicles equipped with LKS were evaluated on the test track using methods from the Euro NCAP LKA test procedure. Specifically, the procedures evaluated a vehicle's response to an imminent departure over a solid white line; tests to evaluate LKS system response to an unmarked road edge were not performed. These tests identified performance differences between the vehicles, and were somewhat dependent on the lateral velocity used during test conduct.

When the test track performance of the vehicles was considered in the context of the road shoulder widths and road/lane/shoulder characteristics present in the 43 fatal NMVCCS and 50 CISS crashes analyzed for this paper, estimating whether LKS could have affected the crash outcome was found to depend on a number of factors.

From an input perspective, the lateral velocity of the vehicle as it is directed toward the boundary of the lane, and whether that boundary is comprised of a clearly defined painted line or simply a pavement edge has the potential to affect whether an LKS intervention can even be expected.

Even if the input conditions are such that a vehicle's LKS activation criteria are satisfied, the ability of the system to effectively address the pre-crash scenario depends on a number of factors. The amount of lateral deviation before or beyond the lane line and/or road edge, and the implications of it being too large, are important considerations. In the case of a right-side departure away from the travel lane, excessive lateral deviation may result in at least part of the vehicle leaving the paved roadway. Similarly, left-side departures with excessive lateral deviation have the potential to increase the risk of a head-on crash.

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Appendix

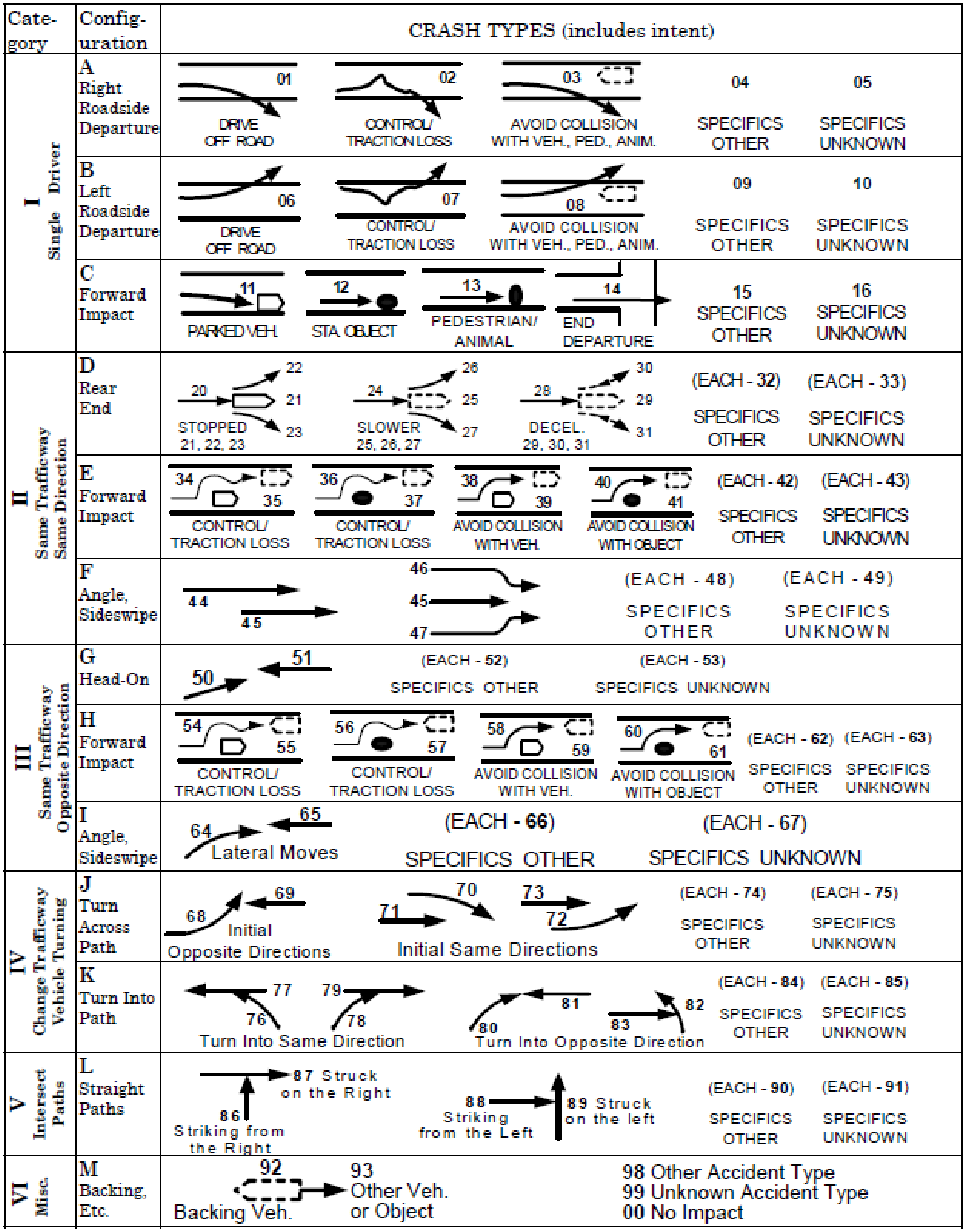

Figure A1. Crash type descriptions.

Table A1. CISS Cases

Case Number	Charcterization	Case Number	Charcterization
1-19-2017-041-01	0.15 m	1-22-2017-036-01	Adjacent lane
1-11-2017-020-01	0.18 m	1-19-2017-048-01	Adjacent lane
1-22-2017-050-01	0.3 m	1-13-2017-008-01	Adjacent lane
1-23-2017-064-01	0.48 m	1-24-2017-014-01	Adjacent lane
1-32-2017-152-01	0.6 m	1-22-2017-046-01	Adjacent lane
1-22-2017-083-01	0.82 m	1-16-2017-048-01	Adjacent lane
1-20-2017-006-01	0.85 m	1-28-2017-032-01	Adjacent lane
1-22-2017-119-01	0.87 m	1-11-2017-033-01	Adjacent lane
1-20-2017-042-01	0.92 m	1-20-2017-084-01	Adjacent lane
1-18-2017-054-01	0.96 m	1-25-2017-024-01	Adjacent lane
1-19-2017-029-01	1.03 m	1-20-2017-103-01	Adjacent lane
1-22-2017-062-01	1.27 m	1-33-2017-090-01	Adjacent lane
1-17-2017-086-01	1.3 m	1-23-2017-102-01	Adjacent lane
1-22-2017-052-01	1.32 m	1-19-2017-113-01	Adjacent lane
1-28-2017-008-01	1.33 m	1-21-2017-074-01	Adjacent lane
1-30-2017-094-01	1.69 m	1-18-2017-073-01	Adjacent lane
1-20-2017-013-01	1.95 m	1-23-2017-130-05	Adjacent lane
1-20-2017-024-01	2.0 m	1-17-2017-095-01	Adjacent lane
1-13-2017-127-01	3.0 m	1-28-2017-046-01	road edge
1-32-2017-013-01	Parked Vehicle	1-28-2017-047-01	road edge
1-28-2017-039-01	Parked Vehicle	1-28-2017-048-01	road edge
1-33-2017-025-01	Intersection	1-19-2017-097-01	road edge
1-24-2017-029-01	Intersection	1-22-2017-104-01	road edge
1-11-2017-017-01	Intersection	1-12-2017-070-01	road edge
1-22-2017-059-01	Intersection	1-19-2017-140-01	road edge