LANE DEPARTURE WARNING SYSTEM RESEARCH AND TEST DEVELOPMENT

Frank S. Barickman
National Highway Traffic Safety Administration
Larry Smith
Robert Jones
Transportation Research Center, Inc.
United States of America
Paper number 07-0495

ABSTRACT

According to Traffic Safety Facts 2005 [1], single-vehicle crashes resulted in over 58% of all vehicular fatalities on the nation's roadways during that year. Of these fatal crashes, almost 15,000 occurred either off of the roadway or on the shoulder. The National Highway Traffic Safety Administration has recognized that technologies such as electronic stability control and other emerging safety technologies can potentially reduce a great number of these fatal crashes.

One emerging technology that the National Highway Traffic Safety Administration believes may have great potential to save lives is lane departure warning. These systems assist the driver by providing a warning (passive or active) that their vehicle is about to depart the road lane. The actual number of lives saved would depend upon the effectiveness of the lane departure warning system.

This paper will discuss both the past and present research that has been conducted by the National Highway Traffic Safety Administration. It will give a general overview of the performance and potential safety benefits of the technology. Information on the type of sensors and performance testing to evaluate lane departure warning systems will be presented, including examples of them. Data from past field operational tests and test track research documenting system performance will be shown.

INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) has long recognized that single-vehicle road departure (SVRD) crashes lead to more fatalities than any other crash type [2]. Lane departure warning (LDW) was a key technology identified at the start of the Intelligent Vehicle Highway System (IVHS) program that could potentially reduce the number of fatalities and injuries associated with SVRD [3]. Based on 1991 General Estimate System and Fatal Accident Recording System data, Wang and Knipling reported that SVRD crashes accounted for almost 1.3 million of the 6.11 million police reported crashes and about 37.4% of all fatal vehicle crashes [2].

Since that time, NHTSA has continued to study the SVRD problem to increase the understanding of the crash problem and to help foster the development of this crash avoidance technology. In the mid and late 1990s, NHTSA developed performance guidelines to eliminate and mitigate road departure crashes [4]. This work ultimately specified performance guidelines for both a LDW system and a curve speed warning (CSW) system. Pomerleau also estimated that approximately 10% of all passenger vehicle road departure crashes can be prevented with LDW technology [4].

In a more recent effort as part of the Intelligent Vehicle Initiative program, NHTSA completed a road departure crash warning system (RDCWS) field operational test (FOT). The RDCWS FOT studied both a lateral drift warning system and a CSW system in an operational test environment. The study observed 78 subjects' driving behavior for 1 month: 1 week baseline without the RDCWS enabled and 3 weeks with the RDCWS enabled. The study found that the LDW function had three major influences on the subjects [5]:

- Turn signal usage per mile driven increased by 9%. (Note, that the system suppressed warnings when the turn signal was activated.)
- The standard deviation of lane position was decreased significantly.
- Vehicles returned to the lane of travel quicker after being issued an imminent alert as compared to lane excursions during the baseline week.

As part of the FOT, the Volpe Center served as the independent evaluator for the project. In a presentation about the preliminary RDCWS findings [6], it was reported that the RDCWS with full deployment and availability could result in 34,000 to 82,000 fewer lane departure crashes.

Crash statistics show that over time, SVRD crashes have remained the largest category of crashes that result in fatalities. From the crash problem description described by Wang and Knipling in 1994, a similar problem remains today as documented by Traffic Safety Facts 2005 (approximately 40%). Data from the FOT demonstrates that this technology has the potential to reduce SVRD crashes.

PERFORMANCE TEST EVALUATION

LDW can be effective in preventing lane departure crashes because the technology can prevent the vehicle from departing the lane by either warning the driver or actively controlling the vehicle. Similarly, ESC is effective in preventing lane departure crashes because the technology can either limit a vehicle's tendency to oversteer, thus preventing it from spinning out of control or mitigate excessive understeer, thereby preventing a vehicle from "plowing" off the road in a sharp curve. Whereas ESC systems assist drivers who do too much steering in a lane departure event, LDW systems assist drivers that do not steer by alerting them. These systems function at opposite ends of the crash spectrum.

LDW systems have recently been introduced as original equipment on late model vehicles in Japan, Europe, and North America. Unfortunately, it is still too early to support any traditional benefit analysis (crashes before technology vs. crashes after technology) due to low market penetration. However, many have been trying to understand if benefits can be estimated through performance tests and objective test development.

In an effort to understand how LDW systems can potentially reduce SVRD crashes, NHTSA has been studying current LDW technology. For an LDW system to reduce crashes, it must operate at a certain level of performance under varying conditions. The purpose of this testing was to identify what objective test procedures could be used to measure the performance of LDW technology.

Exisiting Objective Performance Tests

During recent years, NHTSA researchers and others have been developing performance tests, specifications, and operational requirements for LDW technology. In some cases, these procedures and/or guidelines have been developed for specific programs such as the RDCWS FOT, but in general many of the concepts they test or specify are very similar. The following list of performance tests was reviewed:

1. Recommendations for Objective Test Procedures for Road Departure Crash Warning Systems [7]
2. ISO/CD17361 Lane Departure Warning Systems [8]
3. Development of Test Scenarios for Off-Roadway Crash Countermeasures Based on Crash Statistics [9]
4. Run-Off-Road Collision Avoidance Using IVHS Countermeasures [4]
5. Concept of Operations and Voluntary Operational Requirements for LDWS On-board Commercial Motor Vehicles [10]

Items 1 and 2 in the above list specify detailed test procedures on how LDW performance testing can be conducted. A variety of test scenarios, conditions, and detailed procedures are defined. Item 3 recommends a series of more abstract tests that can be performed to assess LDW performance based on developing tests from statistical crash data. Najm suggests that 96.3% of all road departure crashes stem from just six conflict scenarios [9]. Items 4 and 5 do not necessarily define performance tests, but provide performance specifications and operational requirements that should be met by an LDW system.

A detailed summary comparing and contrasting the above listed efforts is beyond the scope of this paper, but there are many common concepts that are recommended to be tested. They all indicate that an LDW system should be able to function using different roadway delineations. These include both solid and dashed lines, yellow and white lines, and raised pavement markings. They all recommend (or suggest demonstrating via a test) that LDW warnings should be issued for straight roads (>1000m radius of curvature) and curves (various radius of curvature 50m to 1000m) within some time frame (or distance) of the lane marking at a variety of road departure rates. The lateral departure rates vary from 0.1 to 0.8 m/s. Some of the other common concepts include a minimum operational speed (and/or test-specific speeds), tests to determine if the warning is suppressed by turn signal usage, and environment conditions for the tests.

Test Vehicle and Measures

For this testing, a passenger car was instrumented for data collection. The test vehicle was purchased with original equipment (OE) lane departure warning system (LDW) that provided an audible and visual warning when the vehicle departs the lane. Also included on the platform were an aftermarket (AM) LDW and a low-cost lane position measuring system (LPMS) [11].

Both the OE and AM LDW systems use a forward looking video camera. Both systems issue auditory and visual warnings to the driver to indicate lane departure. For this study, a detailed analysis of the user interface was not appropriate. The output signals were used as a means to indicate lane departure electronically. The primary measures that were collected are defined in Table 1.

Raw measurement data were not available from the OE LDW sensor. Derived measures such as warning time onset and lane line crossing had to be determined by fusing the OE LDW departure flag (i.e. data channel marker) with other data. To compute warning time measures, time synchronized video data were manually compared to the onset of the departure flag from the OE LDW. Other metrics for the OE LDW were calculated by comparing the data from the other two sensors and/or the event button and monitoring the output response of the OE LDW system. Unfortunately, the ability to determine if the LDW is tracking the roadway line (availability) cannot be completely assessed this way, but positive warning rates can be calculated (i.e. if we know a lane line boundary was crossed, did the OE LDW warn or not?).

Derived performance measures for the AM LDW were calculated using the lateral position and lane width channels as measured from the sensor. Lane departures and warning times were calculated by comparing the lane bust measure to the AM LDW warning flag. Data from the point of interest (POI) button and other sensors were also compared to ensure that a lane bust actually occurred. For consistency, warning times were also compared manually to the video data. Availability was measured by monitoring the lane position confidence channel.

TABLE 1.
Primary measures collected by the onboard data acquisitions for testing.

System	Measure Description	Units	Sample Rate
OE LDW	Departure Flag	On/Off	30 Hz
AM LDW	Lateral Position	Meters	5 Hz
AM LDW	Lane Width	Meters	5 Hz
AM LDW	Lateral Velocity	M/sec	5 Hz
AM LDW	Line Type	Solid / Dashed / Unknown / None	5 Hz
AM LDW	Lateral Position Confidence	Percent	5 Hz
AM LDW	Warning Flag	On/Off	5 Hz
LPMS Left	Lateral Dist to Left Line	Meters	30 Hz
LPMS Right	Lateral Dist to Right Line	Meters	30 Hz
GPS Position	High Accuracy Position	Northings and Eastings	10 Hz
POI Button	Point of Interest (Experimenter Flag)	On/Off	30 Hz
Video Left	Left Down Looking Video	N/A	30 Hz
Video Right	Right Down Looking Video	N/A	30 Hz
Video Fwd	Forward Looking Video	N/A	30 Hz

Test Track Testing

Performance testing for each system was conducted at the Transportation Research Center, Inc. (TRC) in East Liberty, OH. Tests were conducted to assess how the systems generated warnings on both straight road segments and curves.

The first test was conducted on the straight section of the Winding Road Course (WRC) at the TRC. This test is very similar to the ISO repeatability test and the NIST lateral drift on a straight road test. The purpose of the test is to assess when warnings are given with respect to departing the lane and how repeatably the warnings are issued. To conduct the test, cones mark two different approach angles leading up to a lane line. Using GPS measurements, results are recorded by comparing the vehicle position at the time of the warning to the position of the painted road marking.

A rectangular course was marked 188m long by 3.6m wide, with one long edge of the rectangle being a solid painted line as can be seen in Figure 1. Cones were placed on the solid line at the entry, 54m, and 188m from the entry point. An additional cone was placed 3.6m from the painted line to denote the width of the course. The driver was responsible for aligning the cone 3.6 m out from the painted line with one of the cones at 54m and 188m, depending on desired approach rates. Two calculated angles were used to achieve the two approach rates of 0.3 m/s and 0.8 m/s at the controlled vehicle forward speed of 74 KPH. The exact distance from the painted line to the vehicle at the time the LDWS alarm sounded was determined from GPS data.

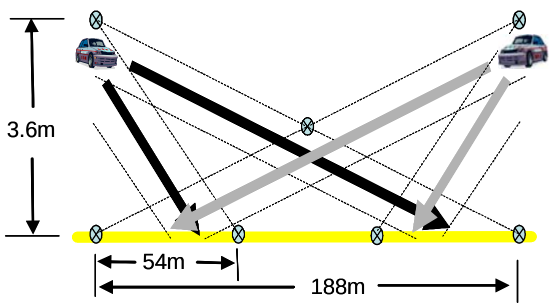

Figure 1. Layout of the straight lateral drift warning scenario (not to scale).

The purpose of the second test was to determine the timeliness and repeatability of the warning during a slow drift while in a curve. A figure displaying the general test scenario is shown in Figure 2. This is similar to the ISO warning generation test and the NIST curved road lateral drift test. The ISO document prescribes that this test be performed in a curve of radius 500m ±50m. No such curve was found in any available test facilities. The warning generation test was attempted on a curve with a radius of 110m, the largest un-banked curve available on TRC property for this test.

The objective of this test was to achieve two different approach rates relative to the lane markings, in two different directions through the curve, and to depart the roadway on both the left and right side of the lane. On a straight section of the roadway approaching the curve, the vehicle is accelerated to 74 KPH. While in the curve, lane changes are performed at an approximate lateral velocity of 0.3 m/sec and 0.8 m/sec. The exact distance from the painted line to the outside edge of the vehicle at the time the LDWS alarm sounded was determined from GPS data.

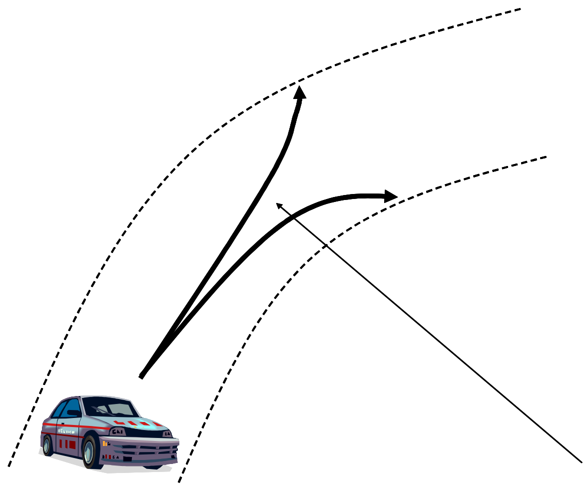

Figure 2. Layout of the curve lateral drift warning scenario.

In the ISO test document, a false alarm test is described. The false alarm test was conducted on the skid pad at the TRC. Straight lanes with painted lines approximately 2km long and 3.6m wide are available. The test was conducted with the car driven directly down the center of the lane. No lane crossings are performed. The objective of the test is to ensure that no false alarms are generated.

Performance Testing Results

The summary results from this testing can be seen in Table 2. Overall, both the OE LDW and the AM LDW systems were able to perform quite well in these tests.

One problem discovered during testing was that the AM LDW was not operating in a warning-enabled state during the lateral drift test in a curve. Although the sensor was functioning (i.e. lateral position was being output) through the curve, the warnings were suppressed because the initial approach did not have lane lines. If the AM LDW senses that there are no lane lines present for some period of time, the system enters a mode where warnings are suppressed. Once the system senses good quality lines for some time period, it automatically enables itself and is able to present warnings to the driver. In the real world, this is done to prevent false alarms; however, from a test standpoint, this can be a problem when using a limited area.

TABLE 2.
Results of the performance testing conducted on the test track.

#	Description	OE LDW			
		Low Lateral Velocity		High Lateral Velocity	
		L	R	L	R
1	Straight Lateral Drift Warning	Pass	Pass	Pass	Pass
2	Curve Lateral Drift Warning	Pass	Pass	Pass	Pass
3	False Alarm Test	Pass			
#	**Description**	**AM LDW**			
		Low Lateral Velocity		**High Lateral Velocity**	
		L	**R**	**L**	**R**
1	Straight Lateral Drift Warning	Pass	Pass	Pass	Pass
2	Curve Lateral Drift Warning	N/A	N/A	N/A	N/A
3	False Alarm Test	Pass			

Both systems were able to correctly generate warnings during the straight lateral drift warning test. Warnings were issued within the given window specified by the ISO test procedure under both lateral drift rates. The alerts were issued within the 'on time' rating as calculated by the NIST test procedure. They were issued prior to the latest warning line and after crossing the earliest warning line determined by the lateral drift velocity. Finally, warnings were issued in a repeatable manner by both systems during all tests.

The OE LDW system was able to pass the curve lateral drift warning tests. Warning generation tests were within the window of the pass criteria set by the ISO test procedure. Warnings were issued prior to the latest warning line and after crossing the earliest warning line determined by the lateral drift velocity. Repeatability was a little more variable than the straight lateral drift tests. It is believed that the variability was caused by the test driver since it is difficult to create the lane departure scenario in the same manner on a curve (i.e., its harder to judge where you cross the lane boundaries on a curved section of road vs. crossing a lane line while driving straight.). Warnings were issued but were sometimes outside of the ISO set +/- 30cm zone for each test group.

Both systems were able to pass the ISO false alarm test. This test is very easy to implement and run, but it may be too simple to yield valuable data. Neither of the systems tested issued a false alarm (i.e., a warning from the LDWS without a lane departure or near-departure).

Functional Testing

Functional testing was performed to determine how the systems functioned under real-world road conditions. This testing is similar to what Najm describes as system robustness testing. The tests are performed on roads that are very similar to the types of roadways described in the crash statistics. Since the tests are conducted on public roadways, the external test conditions cannot be tightly controlled, but they do provide a reasonable amount of variability that may be experienced in the real world.

Functional testing was conducted on State roadways around the Marysville, Ohio area. The roads have a posted speed limit of 72-88kph, are non-freeway / two lanes, rural, and mostly straight with some curves. The road markings appear to be in good condition based on human visual perception. On the right hand side of the road, the edge is delineated by a constant white line. The left or center line of the roadway is delineated by yellow solid and/or dashed lines. The road can further be characterized by mentioning that the surroundings are mostly agricultural and sparsely populated with rural housing.

The test consisted of multiple drives over time. The testing took place over multiple days and is done at different times of the day. During each drive, the experimenter would regularly but randomly depart the roadway as many times as they could on both the left and right sides of the road. The experimenter would indicate a road departure by pressing the POI button every time the vehicle departed the lane. Data were recorded both manually and electronically, recording if the LDW system(s) issued a warning to the driver.

One of the important aspects of functional testing is to negate environmental conditions over time. To negate environmental conditions, tests using the same roadways were conducted over multiple days, times, weather, and lighting conditions. Tests were also conducted using a "double-back" route, where the route return trip is the same route but in the opposite direction, thus having the sensor face 180 degrees from its initial trip. It is believed that the environmental effects are negated using this method because performance can be shown over a period of time verses any one instantaneous moment. The fact that weather, traffic, sunlight, etc. are constantly changing can be negated if performance is consistently poor or good over a given section of roadway.

Functional Testing Results

The results of the functional testing are displayed in Table 3. The results are for a total of 12 test drives. At first look when evaluating the overall performance of both systems, the results are comparable with both systems performing in the 80 – 85% range. One important note is that the systems both operationally perform differently. This is evident in the number of departure attempts. The OE LDW is capable of warning the driver constantly when speeds are over 70kph. The AM LDW is not capable of warning constantly. The AM LDW system suppresses warnings for 5 seconds after it issues a warning. This limits the overall number of departures that can be accomplished during the same segment. This operational difference also makes the AM LDW departure attempts a subset of the OE LDW departure attempts.

Looking at the individual segments, performance differences become more obvious. The OE LDW system performs above 95% of the time on every segment but one, which brings down its overall average. The AM LDW does not perform as high as the OE LDW but never performs lower than 63% (10% higher than the worst OW LDW performance).

The other interesting observation from the data is that the OE LDW's worst performing section is the AM LDW's best performing section. It is unclear as to why this phenomenon was observed. Again, all of these roadway segments had lane markings that looked average or better and they all looked visually very similar. Tests were also conducted using both systems at the same time. Since the AM LDW was able to perform quite well, it is hard to suggest that there is a particular problem with this segment.

TABLE 3.
Results of the functional testing conducted on public roadways.

Segment	Description	OE LDW		
		Depart	**Warn**	**%**
A	TRC Property	106	105	99.1%
B	TRC Gate to Raymond	501	476	95.0%
C	Raymond to SR 31	287	284	99.0%
D	SR 31 to SR 4	520	277	53.3%
E	SR 4 South of SR 347	449	431	96.0%
Totals		1863	1573	84.4%
Segment	**Description**	**AM LDW**		
		Depart	**Warn**	**%**
A	TRC Property	39	32	82.1%
B	TRC Gate to Raymond	441	369	83.7%
C	Raymond to SR 31	264	167	63.3%
D	SR 31 to SR 4	457	419	91.7%
E	SR 4 South of SR 347	381	286	75.1%
Totals		1582	1273	80.4%

DISCUSSION

Unfortunately, detailed data for the OE LDW were not available for this testing. Only the basic inputs (we departed a lane) and outputs (the LDW system warned) were known for testing. If other data such as lateral position within the lane, lane width, line marking type, and measurement confidence were known, a better understanding of why the OE LDW performed poorly during section "D" of the functional test might be known. Looking at the performance from the AM LDW was not helpful since it seemed to perform the best in this section.

Overall, looking at the performance of the AM LDW, the data generally suggest that the sensor sometimes had trouble tracking the roadway markings. This was indicated in the data as either low confidence or the absence of a lane boundary being sensed. This has been discussed by others as "availability".

Similar conclusions were found in the RDCW FOT where they identified that availability was, perhaps, the most important issue in LDW. They found that lane marking quality, camera obstructions, roadway contamination (water, glare, snow, salt, etc.), and ambient lighting conditions can impede the ability of the system to correctly track the lane.

CONCLUSIONS

Assessment of LDW systems is a challenge. There are many external influences that can cause problems and degrade the performance of the system. Although it may be important to characterize the functional characteristics of an LDW system, simply completing performance tests on a test track may not be enough to gain insight into the real-world effectiveness of an LDW system. From the results of this study, it is believed that existing objective test procedures do not adequately characterize real-world performance. Both the OE LDW and AM LDW systems performed quite well during the test track scenarios; however, both systems had various problems when tested on public roadways.

A functional performance test may provide better operational insight about the performance of an LDW system. Using this methodology, external influences can be minimized and real world performance can be measured. Since both systems essentially passed test track testing, it appears both systems are equal in performance. However, when comparing data from the functional test, it becomes obvious that the two systems perform quite differently.

The idea of a functional performance test is quite new, and there are many problems with the concept. One challenge is to make this test repeatable so that similar results can be obtained from any group of similar roadways. Another problem is that roadways are constantly changing over time. Even using the same roadways, the results may differ with the same system. A third challenge for this testing is developing pass/fail criteria for the test. Is it acceptable for an LDW system to perform above 90% and then have a section where it performs at only 50%? Or is it better to have a system that performs at above 80% under all conditions? To help understand these issues and answer these questions, additional testing needs to be completed.

REFERENCES

1. National Center for Statistics and Analysis. *Traffic Safety Facts 2005.* U.S. Department of Transportations, National Highway Traffic Safety Administration.

2. Wang, J., Knipling, R. R. *Single Vehicle Roadway Departure Crashes: Problem Size Assessment and Statistical Description.* DOT HS 808 113, March 1994.

3. Mironer, M., Hendricks, D. *Examination of Single Vehicle Roadway Departure Crashes and Potential IVHS Countermeasures.* DOT HS 808 144, August 1994.

4. Pomerleau, D., Jochem, T., Thorpe, C., Batavia, P., Pape, D., Hadden, J., McMillian, N., Brown, N., Everson, J., *Run-Off-Road Collision Avoidance Using IVHS Countermeasures.* DOT HS 809 170, December 1999.

5. LeBlanc, D., Sayer, J., Winkler, C., Ervin, R., Bogard, S., Devonshire, J. Mefford, M., Hagan, M., Bareket, Z., Goodsell, R., and Gordon, T. *Road Departure Crash Warning System Field Operational Test: Methodology and Results.* UMTRI 2006-9-1, June 2006.

6. Wilson, B. Road Departure Crash Warning System: Preliminary Results of the Independent Evalution. http://www.itsa.org/itsa/files/pdf/RDCW Volpe Evaluation.pdf. ITS America: Public Meeting on the Benefits of Advanced Crash Avoidance Systems. April 2006.

7. Szabo, S., Norcross, R., *Recommendations for Objective Test Procedures for Road Departure Crash Warning Systems.* NISTIR 7288, February 2000.

8. ISO Draft International Standard. *Intelligent Transport Systems – Lane Departure Warning Systems – Performance Requirements and Test Procedures.* Working Document N123.33. ISO/CD17361. Committee ISO/TC204/WG14. June 2003.

9. Najm, W., Koopermann, J. Boyle, L, and Smith, D. *Development of Test Scenarios for Off-Roadway Crash Countermeasures Based on Crash Statistics.* DOT HS 809 505, September 2002.

10. Houser, A., Pierowicz, J., Fuglewicz, D. *Concept of Operations and Voluntary Operational Requirements for Lane Departure Warning System*

(LDWS) On-board Commercial Motor Vehicles. FMCSA-MCRR-05-005. July 2005.

11. Barickman, F., Stoltzfus, D. *A Simple CCD Based Lane Tracking System.* Society of Automotive Engineers. 1999-01-1302. March 1999.