LANE DEPARTURE WARNING (LDW) PERFORMANCE EVALUATION

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ABSTRACT

This paper describes a test track based lane departure warning (LDW) evaluation performed by the National Highway Traffic Safety Administration (NHTSA). NHTSA defines an LDW system as one intended to alert the driver when their vehicle is about to drift beyond a delineated edge line of their current travel lane. LDW system alerts consist of audible, visual, and/or haptic warnings, or any combination thereof. The test maneuver described was designed to emulate a lateral drift while travelling on a straight road. This type of maneuver was chosen because it represents one of the most dominant pre-crash scenarios as reported in the 2004 General Estimates System (GES) database.

LDW performance was quantified by considering the vehicle's proximity and approach rate to the inboard edge of a single lane line at the time of the LDW alert. Variations in how the alerts were presented to the driver, and the manner in which the timing of the alerts changed as a function of the lateral velocity toward the lane line, were observed.

BACKGROUND

During mid to late 2008, NHTSA performed an evaluation of the lane departure warning (LDW) systems installed on three late model passenger cars. All tests were performed by researchers at the agency's Vehicle Research and Test Center (VRTC), located on the Transportation Research Center, Inc. (TRC) proving grounds in East Liberty, OH.

NHTSA defines an LDW system as one intended to alert the driver when their vehicle is about to drift beyond a delineated edge line of their current travel lane. Contemporary LDW systems use forward-looking cameras, in conjunction with algorithms designed to compare predictions of the vehicle path and lane of travel. If a departure is deemed imminent, an LDW alert is presented to the driver. LDW alerts consist of audible, visual, and/or haptic warnings, or any combination thereof.

At the time the work discussed in this paper was performed, the number of US-production light vehicles available with LDW was quite low, with only four vehicle manufacturers known to offer such systems on limited variants of certain vehicle makes and models. Of these manufacturers, only three offered systems able to initialize and perform on a road where only one lane line was present. So as to best evaluate the current state of LDW technology implementation, sample offerings from each of these three vehicle manufacturers were procured: a 2008 BMW 528i, 2009 Buick Lucerne, and a 2008 Infiniti EX35. Although it is believed each of the LDW systems installed in these vehicles have been designed to address the pre-crash scenario described in this paper, the manner in which the respective cues were presented differed, as shown in Table 1.

Table 1.
LDW Alert Modality

Vehicle	LDW Alert		
	Audible	Visual	Haptic
BMW 528i	None	None	Vibrating steering wheel
Buick Lucerne	Repeated tones	Flashing icon on instrument panel (amber)	None
Infiniti EX35	Repeated tones*	Flashing icon on instrument panel (amber)	None

*The Infiniti EX35 LDW alert remains on during the entire lane departure event (not just when it is first detected).

THE ROAD DEPARTURE CRASH PROBLEM

The Early Edition of Traffic Safety Facts 2007 reports that there were 22,054 fatal single vehicle police reported crashes. This represents 59 percent of all fatal police reported crashes in 2007. Of the 22,054 fatal single vehicle crashes, over 15,000 were reported to be off roadway, on the shoulder, or on the median [1]. NHTSA has long recognized that single-vehicle road departure (SVRD) crashes lead to more fatalities than any other crash type [2].

In an analysis of the 2004 General Estimates System (GES) data, Volpe (part of DOT's Research and

Innovative Technology Administration) reported that there were approximately 5,942,000 police reported crashes that involved at least one light vehicle. These crashes involved over 15,000,000 people and resulted in 2,737,000 injuries. From this target population, 36 pre-crash scenarios were identified that attributed to 99.4 percent of all light-vehicle crashes. A 37th pre-crash scenario is recognized as 'other' but accounts for only 0.6 percent of all crashes [3].

One of the most dominant pre-crash scenarios identified by Volpe was "Road Edge Departure without Prior Vehicle Maneuver" (REDPVM). This pre-crash scenario was reported to rank fifth in overall crash frequency attributing to approximately 333,706 crashes. Additionally, REDPVM ranked third highest in direct economic cost to society estimated to cost over $9M and was ranked second highest with 270,000 functional years lost [3]. Volpe defines the typical REDPVM scenario to be associated with a light vehicle travelling straight in a rural area at night, normal weather conditions, at posted speeds of 55 mph or greater, and departing the road edge at a non-junction area. Volpe recognizes that this pre-crash scenario occurs with several dynamic variations. Approximately 26 percent of these crashes were found to occur when the vehicle was negotiating a curve and 27 percent were found to occur at the road shoulder or parking lane. Out of all the REDPVM crashes, two-thirds were found to depart the road edge to the right [3].

Based on the crash frequency, cost, and functional years lost (a measure of harm) data, NHTSA decided that the use of a test maneuver designed to emulate these real-world crash scenarios would provide an appropriate way to evaluate LDW performance. Building on the efforts put forth by previous field operational tests and the Integrated Vehicle-Based Safety Systems (IVBSS) programs, NHTSA researchers subsequently developed an objective test procedure to perform the work described in this paper. The objectives of this work were twofold: (1) identify the US-production based LDW alert criteria as presented to the driver with respect to the road edge line, and (2) refine the test procedures to enhance the accuracy, repeatability, and/or reproducibility by which the LDW system evaluations could be performed.

TEST METHODOLOGY

Overview

The tests described in this paper were designed to evaluate the ability of an LDW system to detect, and alert the driver of, an imminent lane departure. The tests were each performed at a constant speed of 45 mph (72.4 kph), with two departure directions (left, right), and over a range of departure rates. All tests were based on straight road departures made across a single continuous solid white lane line. LDW performance was quantified by considering the vehicle's proximity and approach rate to the inboard edge of the lane line at the time the LDW alert was first presented.

The tests were each performed on the Transportation Research Center Inc. (TRC) Vehicle Dynamics Area (VDA) located in East Liberty, Ohio. The VDA measures 1800 by 1200 ft (549 by 366 m), and is comprised of a flat asphalt surface with a one percent longitudinal grade for drainage. The pavement of the VDA used for the LDW evaluations was in good condition, free from potholes, bumps, and excessive cracks. The north turn-around loop, shown in Figure 1, was used to maximize the length of the LDW test course. All tests were performed during daylight hours with good visibility (no fog, rain, snow). The ambient temperatures and wind speeds present during the BMW 528i and Buick Lucerne evaluations ranged from 75 to 81 ºF (24 to 27 ºC) and 1 to 4 mph (2 to 6 kph), respectively. During tests performed with the Infiniti EX35, the ambient temperatures and wind speeds were 38 to 49ºF (3 to 9 ºC) and 6 to 17 mph (10 to 27 kph), respectively.

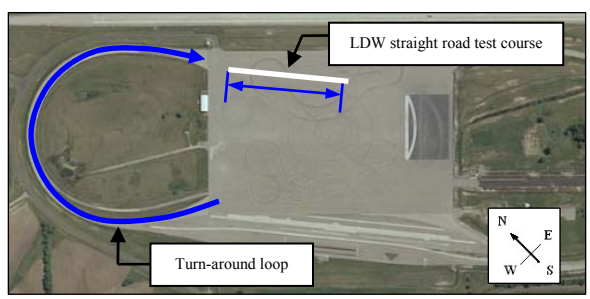

Figure 1. Orientation of the LDW test course on the TRC VDA (not to scale).

Instrumentation

The test vehicles were each equipped with instrumentation and data acquisition systems to monitor and record vehicle speed, lateral and longitudinal position (via GPS), yaw rate, and LDW alert status. All analog data was sampled at 200 Hz. Signal conditioning of these data consisted of amplification, anti-alias filtering, and digitizing. Amplifier gains were selected to maximize the signal-to-noise ratio of the digitized data. GPS data were sampled at 20 Hz, and were differentially

corrected during post-processing. To facilitate comparison of the position of the test vehicle with respect to the inboard lane line edge, GPS-based static surveys of the lines were performed. All data, including the analog and GPS-based data from the test vehicle and a static lane line survey, were then merged into a single data file per trial for the ease of subsequent data analysis. Appendix Table A1 provides a summary of the instrumentation used during the LDW evaluations discussed in this paper. In addition to this equipment, a dashboard-mounted display was used to present the driver with accurate vehicle speed information.

LDW Alert Monitoring

When activated, the LDW systems discussed in this paper provided the driver with auditory, visual, and/or haptic alerts. Recording when these alerts first occurred was important since this information would provide the points in time for which the vehicle's lane position and rate of approach would be reported, the objective measures by which LDW performance was quantified. The methods used to record the LDW alerts differed from vehicle to vehicle, as shown in Table 2.

Table 2.
LDW Alert Monitoring Methods

Vehicle	Monitor
BMW 528i	Direct tap of the motor used to vibrate the steering wheel
Buick Lucerne	Direct tap of the speakers installed behind the left and right a-pillar trim
Infiniti EX35	Direct tap of the piezoelectric speaker mounted to the back of the instrument panel

BMW 528i

Of the vehicles discussed in this paper, only the BMW 528i presented the driver with a haptic alert to warn of an impeding lane departure. This alert, vibrations transmitted to the driver's hands, originated from a small motor attached directly to the steering wheel. To monitor the state of this alert, researchers directly tapped the leads supplying voltage to this motor. Note: Safety precautions required the steering wheel-based airbags be removed prior to installing the programmable steering machine. In the case of the BMW 528i, removing the steering wheel also disabled the LDW alert. Retaining LDW alert functionality while evaluating the vehicle with the steering machine installed required NHTSA researchers to request and receive assistance from BMW.

Buick Lucerne

The LDW installed in the Buick Lucerne presented alerts via small speakers installed behind the left and right a-pillar trim. The alerts were directional; a left lane departure would produce an alert heard predominately from the left speaker, whereas right departures produced alerts most apparent from the right speaker. The speakers were also used as part of the vehicle's audio system; however it was not necessary to have the audio system on for the LDW alert to be heard by the driver.

To monitor the LDW alert during evaluation of the Buick Lucerne, researchers directly tapped the leads of both speakers, collecting data from each speaker independently. Figure 2 presents an example of the LDW alert flag recorded for the Buick Lucerne. Note that while the duration of the alert shown in this figure was believed to be accurate, the data trace does not accurately portray how the alert was presented to the driver (i.e., as it actually consisted of a series of three beeping tones, not a single continuous alert). This is because the speaker tap used to monitor the Buick Lucerne LDW status was not designed to monitor the frequency content of the signal, just to show the speakers received DC voltage, indicating the presence of an alert.

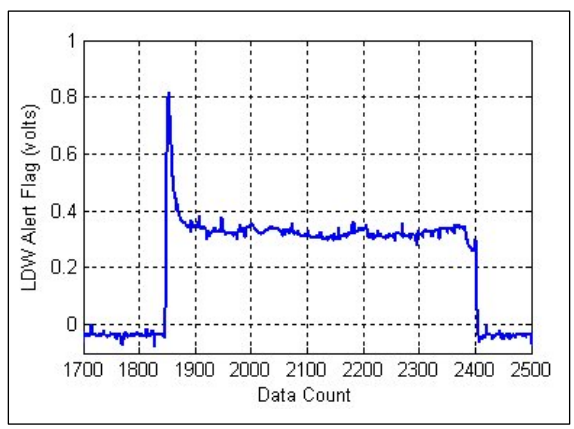

Figure 2. Output from the LDW alert speaker tap during a lane departure performed with the Buick Lucerne.

Infiniti EX35

For the Infiniti EX35, the LDW alert was presented to the driver via a piezoelectric speaker installed behind the center console trim. To access this

speaker, much of the components housed in the console had to be removed (e.g., trim, the radio, navigation and climate controls, etc.). To record the LDW alert, the speaker leads were directly tapped, and the signal that activated the piezoelectric speaker, shown in Figure 3, was recorded. In addition to the LDW alert speaker tap, an external microphone was positioned near the speaker, and its output recorded. In the case of the Infiniti EX35, installation of the external microphone allowed researchers to assess the feasibility of using a microphone to monitor the piezoelectric speaker output (the speaker design was different from that of the Buick Lucerne), and to provide a redundant LDW alert monitor. However, the microphone-based alert data were not used during subsequent data processing or analyses.

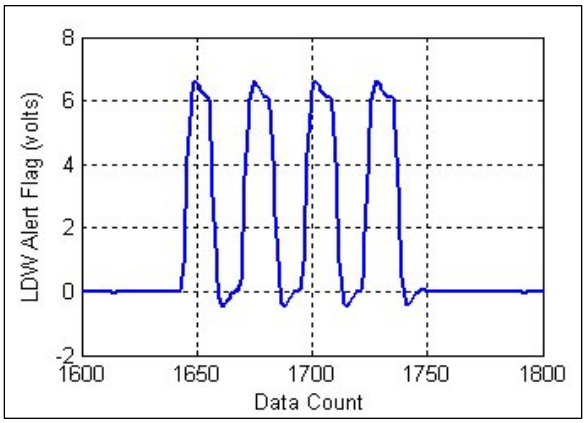

Figure 3. Output from the LDW alert piezoelectric speaker tap during a lane departure performed with the Infiniti EX35.

Lateral Velocity Ranges

The lane departures described in this paper occurred over a range of lateral velocities intended to represent unintended drifts. When considering the severity of these tests, it is important that the reader recognize these are gradual transitions from the lane of travel over the line of interest. In the context of this paper, the term "lane change" should not be confused with the far more severe maneuvers used to assess obstacle avoidance capability, lateral stability, or dynamic rollover resistance.

Lane Line Markings

To insure maximum relevancy, the 4 in. (10.2 cm) lane marker width, marking color and reflectivity, and line styles satisfied the USDOT specifications required by the Manual on Uniform Traffic Control Devices (MUTCD), and were in "very good condition" [4]. The lane departures described in this paper each occurred over a continuous solid white line.

Test Configurations and Conduct

To emulate a common pre-crash lane departure scenario, researchers evaluated LDW performance using a test course based on a straight road. All tests described in this paper were performed with a constant nominal speed of 45 mph (72.4 kph). To be considered a valid test, the vehicle speed was required to remain within ± 1.2 mph (± 2 kph) of the target speed, from the start of the test until any part of the vehicle, as defined by the two dimensional geometry described later in this paper, had crossed a lane line by at least 3.3 ft (1 m). Where possible, cruise control was used; otherwise, the driver modulated the throttle throughout the maneuver. For the BMW 528i and Buick Lucerne, the steering rate for each test was nominally 125 deg/s, and all steering inputs were commanded with a programmable steering machine. In the case of the Infiniti EX35, a skilled test driver manually performed the lane departures.

As previously shown in Figure 1, the LDW straight road course was positioned on the VDA such that the test vehicle could easily reach the 45 mph (72.4 kph) target speed, while also providing approximately 1000 ft (300 m) of pavement over which the departure could take place. To maximize input repeatability, two pylon-delimited gates were used to help guide the driver to the appropriate course[1], and all steering inputs were initiated from a common location. In the case of the tests performed with the BMW 528i and Buick Lucerne, repeatability was further enhanced by automatically initiating these inputs with the programmable steering machine, triggered as the vehicle was driven over a thin metal plate line lined with retro-reflective tape centered within the confines of the second gate. More detailed course specifications are provided in Figure 4. Note that Figure 4 illustrates the test scenario for a left departure. The vehicle was driven on the right side of the lane line to evaluate left-side lane departure warning performance, and on the left side of the lane line for the right-side lane departure tests.

[1] Use of additional gates would have been helpful, however researchers were concerned that visually, the extra pylons would define two distinct rows (i.e., on either side of the travel lane) that could be potentially interpreted as two lane lines by an LDW detection algorithm. If this occurred, it would confound the researchers' ability to confirm whether a particular LDW system could be initialized from, and operated with, the presence of only one lane line.

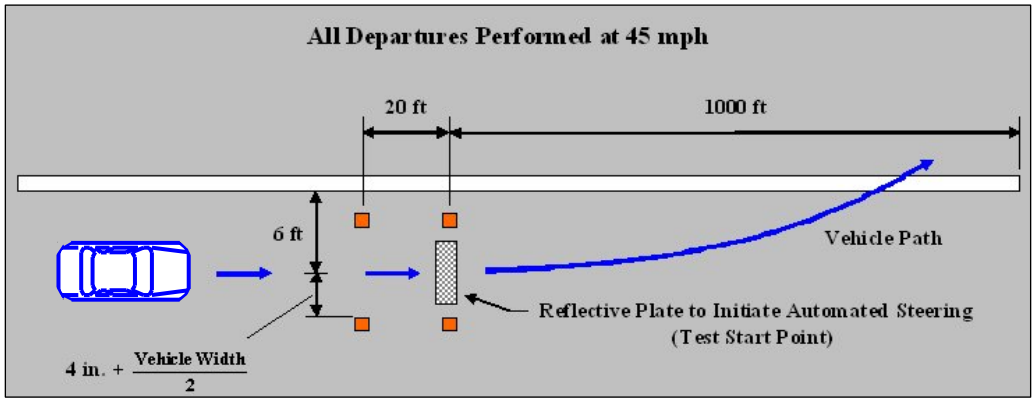

Figure 4. Straight road lane departure test course.

In the case of the BMW 528i and Buick Lucerne, the straight road lane departure tests were performed using steering angles from 1 to 15 degrees, input with an incremental increase of one degree per individual trial. For the Infiniti EX35, the driver was instructed to perform lane departures using a range of steering angles and rates. The subsequent data were processed, and the lateral position and velocity of the vehicle at the time of the LDW alert calculated. In some cases, particularly during the left departure attempts, the combination of open-loop automation and a one-degree steering angle failed to produce a lane departure before the end of the test course. As such, these data were treated as outliers and not used for subsequent analyses.

TEST RESULTS

The test procedures described in this paper were intended to provide NHTSA with the ability to objectively evaluate contemporary LDW systems. To quantify performance, the lateral distance from the vehicle to the lane line, and the lateral velocity of the vehicle with respect to the lane line, at the time of the LDW alert were determined.

To calculate the lateral distance from the vehicle to the lane line during post processing of the data, each test vehicle was first represented by a two dimensional polygon whose length and width were determined by considering the outboard-most contact area of the tires to the ground. Using this representation, the position of the vehicle (calculated with highly accurate differentially corrected GPS data) was compared to the static lane line survey for the straight course of interest. At the instant the LDW alert was initiated, the lateral distance from the closest corner of the polygon to the lane line was determined.

The vehicle's lateral velocity was calculated from the heading angle with respect to the lane line edge and forward velocity. At the onset of the LDW alert, trigonometric Equation 1 was solved [5].

$$V_{lat} = V_{fwd} * \text{Sine}\ \Theta \quad (1)$$

where:

V_{lat} = Lateral velocity perpendicular to the vehicle with respect to the edge of the lane line.

V_{fwd} = Forward velocity of the vehicle.

Θ = Angle between the vehicle heading and the edge of the lane line.

An overall summary of the lateral positions and velocities observed at the time of the LDW alert during straight road departures over a solid white lane line are shown in Figures 5, 6, and 7. In each figure, right departures are shown in red, left departures in blue.

BMW 528i

For the BMW 528i, LDW alerts were presented during 28 of the 30 valid tests performed. For the two tests an alert was not observed (during one departure to the left, and during one to the right), the lateral velocities at the inboard edge of the lane line were 2.6 and 4.0 ft/s, respectively. Figure 5 presents the lateral positions and velocities observed at the time of the LDW alert during 28 straight road departures performed with the BMW 528i.

Figure 5 reveals two interesting trends. First, as the lateral velocity of the approach became higher, the distance from the vehicle to the lane line at the time of the LDW alert increased. Second, tests performed with steering to the right always produced alerts

earlier than those performed with steering to the left (i.e., for the same lateral velocity, the LDW alert occurred when the vehicle was further away from the lane line when a departure to the right was used).

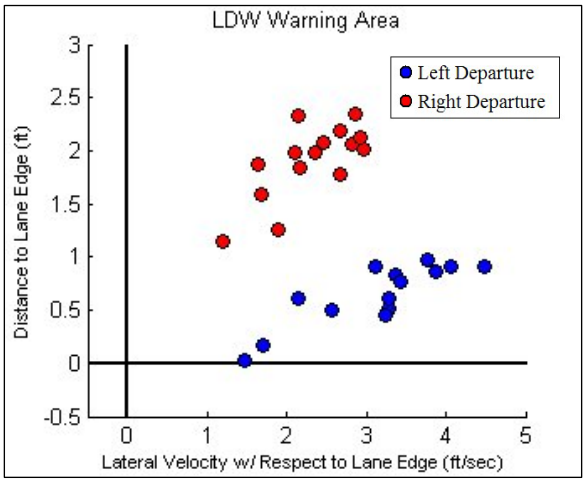

Figure 5. Lateral positions and velocities observed at the time of the LDW alert during lane departures performed with the BMW 528i.

The data presented in Figure 5 imply the BMW 528i LDW algorithms consider lateral velocity when determining when the alert should be presented and not just the proximity of the vehicle to the lane line. Intuitively, this makes sense; as the lateral velocity of an unintended drift increases, the time the driver has before a lane departure occurs is reduced. Presenting alerts earlier in time would be expected to maximize the amount of time the driver has to take corrective action before the lane line is actually breached. Such findings have been documented in research performed in both simulators and on road studies [6,7]. It should also be noted that that careful attention must be made in how the alerts are presented so as to not annoy the driver [7,8,9].

The specific reasons for the apparently asymmetrical alert observed during the BMW 528i evaluation are unknown. On one hand, the crash data do indicate that when a vehicle is involved in a "Road Edge Departure without Prior Vehicle Maneuver" scenario, the vehicle departs the road edge to the right in approximately two-thirds of the cases [3]. Overall, about 2.79 percent of all people involved in this crash scenario suffered high level Maximum Abbreviated Injury Scale (MAIS) 3+ injuries (serious, severe, critical, or fatal).

However, while departing a lane to the right may ultimately evolve into a road departure, departures to the left may result in the driver's vehicle encroaching into another vehicle traveling in the opposite direction. The resulting crashes are often quite serious. Although the frequency of the "Vehicle(s) Not Making a Maneuver – Vehicles Traveling in Opposite Direction" crash scenario is less than that of the "Road Edge Departure without Prior Vehicle Maneuver" crashes, about 2.58 percent of all people involved on this crash scenario suffered high level MAIS 3+ injuries [3].

For these reasons, developing a more complete understanding of the tuning philosophy used for the vehicles like the BMW 528i LDW may be an interesting subject for future research.

Buick Lucerne

In the case of the Buick Lucerne, LDW alerts were presented during 24 of the 30 valid tests performed. When left lane departures were commanded, alerts were not produced during tests performed with lateral velocities of 3.8, 4.0, 4.4, and 4.7 ft/s. When right departures were used, alerts were not produced during tests performed with lateral velocities of 4.6, and 5.6 ft/s. Figure 6 presents the lateral positions and velocities observed at the time of the LDW alert during 24 straight road departures performed with the Buick Lucerne.

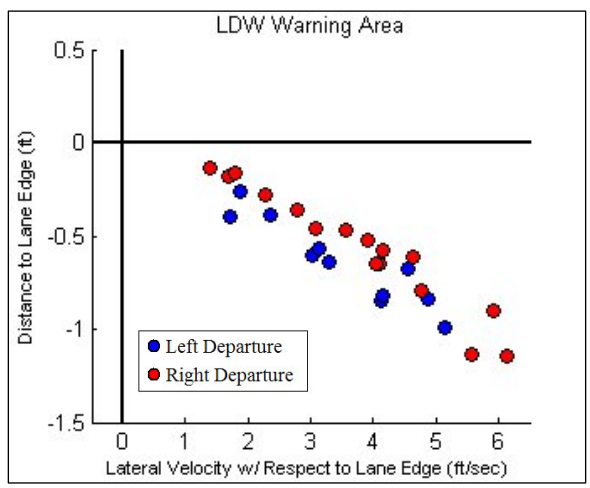

Figure 6. Lateral positions and velocities observed at the time of the LDW alert during lane departures performed with the Buick Lucerne.

For the Buick Lucerne LDW, each alert was observed during[2] (i.e., when lateral displacements was ≤ 4 in)

[2] A lane departure was taken to begin the instant the vehicle crossed the inboard edge of the lane line, and that the lane line was 4 in (10.2 cm) wide.

or after (i.e., when lateral displacements was > 4 in) the lane departures associated with the individual trials. Also, the distance from the vehicle to the lane line generally decreased as the lateral velocity of the approach became higher. The reason for this trend is unclear, but the vehicle's LDW sampling rate, processing speed, and/or alert response time are suspect. For example, as the lateral velocity toward the lane line increases, the amount of time available to establish and report an imminent departure is reduced. If the sample rate is not sufficiently high, the lateral distance traveled between the data points used to predict the likelihood of a departure will increase.

In the case of the Buick Lucerne, the alerts observed during right departures generally occurred sooner than those associated with left departures for a common lateral velocity. However, the effect was subtle; much less apparent than seen during the BMW 528i evaluation.

Infiniti EX35

The tests performed with the Infiniti EX35 indicate LDW evaluations can be successfully executed with a skilled test driver in lieu of a programmable steering machine. However, due to the manner in which the driver input the steering, the number of Infiniti EX35 tests performed with high lateral velocities was more limited than those used to assess the LDW performance of the other vehicles. Figure 7 presents the lateral positions and velocities observed at the time of the LDW alert during 59 straight road departures performed with the Infiniti EX35. LDW alerts were observed during all valid tests.

Despite the limited range of lateral velocities produced by the driver-based lane departures performed with the Infiniti EX35, the authors believe the data produced by these tests were capable of revealing some meaningful trends about the vehicle's LDW operation.

First, although some data outliers were produced, the distance from the vehicle to the lane line remained quite consistent across the limited range of lateral velocities considered. Second, the data shown in Figure 7 indicate the Infiniti EX35 LDW alerts are not asymmetric. For this vehicle, alerts observed during the right departures occurred with nearly equivalent combinations of lateral displacement and lateral velocity as those associated with departures to the left (discounting the outlying data points).

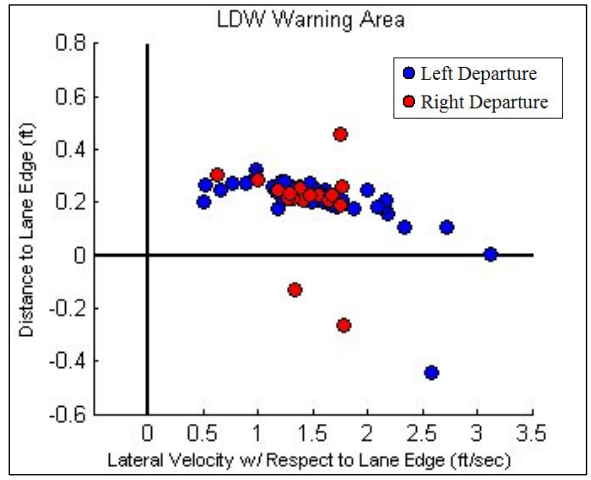

Figure 7. Lateral positions and velocities observed at the time of the LDW alert during lane departures performed with the Infiniti EX35.

CONCLUSION

Lane Departure Warning (LDW) system functionality is of great interest to NHTSA. Given the prevalence of unintended road departures in the crash data, and the high societal costs they impose, better understanding how advanced technologies may be able to assist drivers in mitigating these crashes is an agency priority. This paper has provided details of how NHTSA evaluated the LDW performance of three contemporary passenger cars using a test scenario designed to emulate one of the most commonly occurring pre-crash road departures scenarios. LDW performance was evaluated by considering the vehicle's proximity and approach rate to the inboard edge of a single lane line at the time of the LDW alert.

The LDW systems installed in the vehicles discussed in this paper each had unique performance characteristics. Specifically, variations in how the alerts were presented to the driver, and the manner in which the timing of the alerts changed as a function of the lateral velocity toward the lane line, were observed. How these factors affect the ability of the systems to mitigate unintended lane departures in the real-world will be addressed in future research activities.

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APPENDIX

Table A1.
Instrumentation Used During LDW Evaluation

Type	Output	Range	Resolution	Accuracy
Differentially-corrected GPS data	Vehicle speed	0.3 - 77 mph* (0.5 - 125 kph)	0.001 mph* (0.01 kph)	0.06 mph* (0.1 kph)
	Longitudinal position with respect to the lane line	N/A	2 in (5 cm)	< 3.9 in (10 cm) absolute; 1.6 in (1 cm) static
	Lateral position with respect to the lane line	N/A	2 in (5 cm)	< 3.9 in (10 cm) absolute; 1.6 in (1 cm) static
	Lateral velocity with respect to the lane line	N/A	0.33 ft/s (0.1 m/s)	±0.33 ft/s (±0.1 m/s)
Data Flag (Test Course Gate)	Signal to initiate automated steering inputs when driven over a retro-reflective marker	0 – 10V	N/A	Output response better than 10 ms
Data Flag (LDW Alert)	Signal indicating the LDW alert status	±10V	N/A	Output response better than 10 ms
Vehicle Dimensional Measurements	Location of GPS antenna, vehicle centerlines, and two bumper measurements	N/A	0.05 in (1mm)	0.05 in (1mm)

*Values for the stand alone vehicle speed sensor used to provide output to the dashboard display and for data synchronization.