U.S. Department
of Transportation
National Highway
Traffic Safety
Administration

www.nhtsa.gov

DOT HS 812 078 November 2014

Heavy-Vehicle Lane Departure Warning Test Development

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Suggested APA Format Citation:

Hoover, R. L., Sughosh, J. R., Howe, G., & Barickman, F. S. (2014, November). *Heavy-vehicle lane departure warning test development*. (Report No. DOT HS 812 078). Washington, DC: National Highway Traffic Safety Administration.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. DOT HS 812 078	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Heavy-Vehicle Lane Departure Warning Test Development		5. Report Date November 2014 6. Performing Organization Code NHTSA/NVS-312
7. Author(s) Richard L. (Dick) Hoover, Sughosh J. Rao, Ph.D., and Gavin Howe, Transportation Research Center Inc., and Frank S. Barickman, NHTSA		8. Performing Organization Report No.
9. Performing Organization Name and Address National Highway Traffic Safety Administration Vehicle Research and Test Center P.O. Box B37 East Liberty, OH 43319-0337		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTNH22-070D-00060
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 1200 New Jersey Avenue SE. Washington, DC 20590		13. Type of Report and Period Covered Final Report – 8/12 – 6/14 14. Sponsoring Agency Code NHTSA/NVS-312

15. Supplementary Notes The authors acknowledge the support of Randy Landes, Don Thompson, Guogang Xu, Mark Heitz, Thomas Gerlach Jr., Chris Boday, Bryan O'Harra, Kamel Salaani, and Mike Thompson for assistance with vehicle preparation, data processing, program support, scheduling, data 1092610collection, report review, and test driving.

16. Abstract

This report summarizes findings of a market study on existing lane departure warning systems (LDWS), compares domestic and international standard test procedures, and evaluates a developed test procedure for heavy-vehicle lane departure warning systems.

The performance of two heavy-vehicle LDWS was evaluated for various lane departure scenarios. The performance tests included for left and right side warning activation on two different lane marking types (solid and dashed lines), and on straight and curved lanes. The developed test procedure is based on the existing light vehicle NCAP lane departure warning test procedure with modifications for heavy-vehicle applications. The performance of the LDWS was analyzed and results are reported.

17. Key Words Lane Departure Warning (LDW), Subject Vehicle (SV), Lane Line, Takata, Mobileye		18. Distribution Statement Document is available to the public from the National Technical Information Service www.ntis.gov.	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 97	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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EXECUTIVE SUMMARY

The lane departure warning system (LDWS) is a driver aid that utilizes visual sensors to detect lane markers ahead of the vehicle. The LDWS alerts the driver when the vehicle is laterally approaching a lane boundary marker (indicated by a solid line, a dashed line, or raised reflective indicators such as Botts dots). The LDWS sounds an audible tone or beeps and is often associated with a visual dash lamp or display icon to indicate which side of the vehicle is departing the lane.

This report presents a brief overview of emerging technologies through a market analysis of LDWS and a review of technical standards pertaining to the expansion of LDWS into heavy vehicles.

This report also documents an evaluation of two LDWS. The two systems (Mobileye and Takata) were installed on one test vehicle and evaluated simultaneously for warning capabilities when presented with real-world driving situations in the safety of the test track. Test scenarios included lane change maneuvers for both straight-lane and curved-lane tests.

Both LDWS presented driver alerts when the vehicle was approaching or had just crossed over the lane line. Any false positives that occurred were noted. The straight lane test sequences adapted from the light vehicle New Car Assessment Program (NCAP) LDW [1] test were adequate and only required minor changes such as adjusting lateral or longitudinal spacing to accommodate the larger size of commercial heavy vehicles.

The results of the data analysis indicated that increasing only the base speed of the subject vehicle (SV) did not appear to change the performance of the LDWS. These LDWS did not present out-of-lane alarms at or below 25 mph. The warning threshold speeds specified by the manufacturers were 34.2 mph (55 km/h) for the Mobileye system [2] and 42 mph (67.6 km/h) for the Takata system[3]. Tests were conducted to verify the threshold speed and results show that the Mobileye LDWS unit did warn at 35 mph (56.3 km/h), whereas the Takata LDWS did not warn until the vehicle was tested at the next higher speed increment of 45 mph (72.4 km/h). For most of the camera-based LDW systems identified in this report, the warning threshold speeds ranged from 34 to 42 mph (55 to 68 km/h).

1 INTRODUCTION

NHTSA's Vehicle Research & Test Center has been performing research in the area of lane departure warning and lane departure prevention (LDP) systems for over 20 years. This research has included sensor development, test track characterization, over the road evaluation, and human performance testing. This work, as well as NHTSA's other LDW projects, was important in the development of the "Lane Departure Warning System Confirmation Test" as part of the agency's New Car Assessment Program for crash avoidance technologies. The Lane Departure Warning System Confirmation Test is currently only applicable to light vehicles (LV); however, the test procedure could be applicable to heavy vehicles greater than 10,000 pounds gross vehicle weight rating (GVWR), as well.

During the course of this project, LDW technologies were integrated into an existing VRTC test truck. Test track work was conducted to characterize the performance of original equipment and aftermarket (AM) LDW technology for heavy vehicles. LDW NCAP procedures were performed with a heavy vehicle equipped with LDW products from two vendors, Mobileye and Takata SafeTraK (Meritor WABCO).

1.1 Objectives

The objectives of this Task Order were to:

- Research the state of the industry heavy-vehicle LDWS market;
- Review existing and proposed objective test procedures, U.S. and International;
- Develop a basic LDW test plan for examination of available HT LDWs;
- Prepare the test facility and surfaces for conducting the proposed LDW test plan;
- Retrofit/integrate and test LDW systems for a heavy vehicle (Class 8 Tractor); and
- Summarize test results and provide observations about the evaluated heavy-vehicle LDW objective test procedure.

1.2 Acronyms

AutoVue – Bendix camera-based LDWS (frequently installed as an original equipment manufacturer (OEM) option on some trucks or as an aftermarket add-on unit)

BSW – blind spot warning

IVBSS – Integrated Vehicle-Based Safety Systems

LDW – lane departure warning

LDWS – lane departure warning system – lane tracking system with annunciators (audible, visual, and/or haptic; system does not correct for out-of lane occurrence)

LKS and LKAS – lane keeping support and lane keeping and support – Mobileye – an active steering control system that assists the driver in maintaining the vehicle position within the lane; this system has capabilities beyond the scope of this report

Mobileye – Mobileye camera-based aftermarket LDWS (also installed as an OEM option on some trucks)

NPRM – Notice of Proposed Rulemaking

OEM – original equipment manufacturer

PDW – pedestrian detection warning (unique to Mobileye)

SafeTraK – Meritor WABCO camera-based LDWS (frequently installed as an OEM option on some trucks or as an aftermarket add-on unit) now renamed OnLane

TRC – Transportation Research Center, Inc. (test facilities and support)

TSR – traffic sign recognition (unique to Mobileye)

V2V – vehicle-to-vehicle

V2I – vehicle to infrastructure

VDA – Vehicle Dynamics Area test facility at TRC Inc.

VRTC – Vehicle Research and Test Center (NHTSA research laboratory)

2 BACKGROUND

2.1 Technology

Lane departure warning systems have been in development by industry for over 20 years. LDWS are generally visual devices that look at the lane line markers to compute a predicted moment of lane departure and alert the driver when unintended lane departures are about to occur without causing undue false warnings due to subtle lateral lane position changes. Beginning with simple line scan video, LDW has developed into sophisticated lane marker identification and lane boundary projection systems that provide the driver with a warning if the vehicle has a trajectory that will take it out of lane. While most LDWS apply video techniques, other areas of research include infrared, Lidar, magnetic, and electronic mapping technologies.

2.2 Market Research on State of the Industry for Discrete Heavy-Vehicle LDW Systems

LDWS have been in commercial development for both passenger cars and heavy vehicles for over twenty years. Currently there are five suppliers developing LDWS for heavy vehicles in the United States. These include: Bendix (AutoVue), Meritor WABCO (SafeTraK), Mobileye (C2-270), Continental (LDW); and Delphi Forewarn (LDW). The Société des Automobiles Peugeot (PSA, Peugeot-Citroen in France)/Robert Bosch Co. is in co-development of an infrared LDWS. Two major truck manufacturers are also projecting to release their own OEM versions of LDWS in 2014.

Other than PSA/Bosch, each of these developers uses a camera system to look ahead of the vehicle while it is being driven down the highway. Several companies have developed smart-phone applications which use the camera on the devices, including iOnRoad and MinTron. Additionally, there are numerous LDWS installed in production passenger cars, but they have not been implemented into heavy vehicles. PSA and Bosch are co-developing an infrared LDWS for passenger cars, but currently are not expected to extend licensing to heavy vehicles or other OEMs. This market report will focus on the camera-based LDWS for heavy vehicles and two smart-phone applications.

Initial LDWS development was for standalone systems, but with the pending NPRM mandate [4] for electronic stability control systems on heavy vehicles, OEMs are looking toward future sensor fusion, or combining LDWS, FCW, and BSW with stability controls. The integrated perimeter sensing systems would then provide the driver with warnings from 360-degrees of roadway observations, rather than just a narrow look ahead. Once integrated, the sensor array can be further infused into the stability control systems and future vehicle-to-vehicle and vehicle-to infrastructure intermodal communications. These combined systems would enhance crash avoidance mitigation solutions, and play important roles in setting pre-crash conditions that would reduce crash related injuries.

2.2.1 List of Systems

In 2013, many manufacturers offered LDWS, ranging from integrated systems to aftermarket kits and smart-phone applications. Below is a list of 10 systems, followed by an overview of their capabilities in the subsequent sections.

1. Bendix – AutoVue - formerly known as Iteris by Audiovox
2. Meritor WABCO – SafeTraK – Takata (now called OnLane)
3. Mobileye – ADAS C2-270 (also 560)
4. Continental LDW
5. Delphi Forewarn LDW
6. Bosch LDWS
7. PSA Peugeot - Infrared LDWS
8. iOnRoad – iPhone Application
9. MinTron – iPhone Application
10. Surveillance Video LDWS - BLS-3000

2.2.1.1 AutoVue LDWS

The AutoVue LDWS was developed by Iteris, a subsidiary of AudioVox, and under the parent Voxx Company[5]. In the past few years, Bendix began developing applications with the Iteris system, and in 2011 Bendix purchased the AutoVue line from Iteris (see Figure 2.1 and Figure 2.2).

Figure 2.1 Bendix AutoVue – Camera and ECU

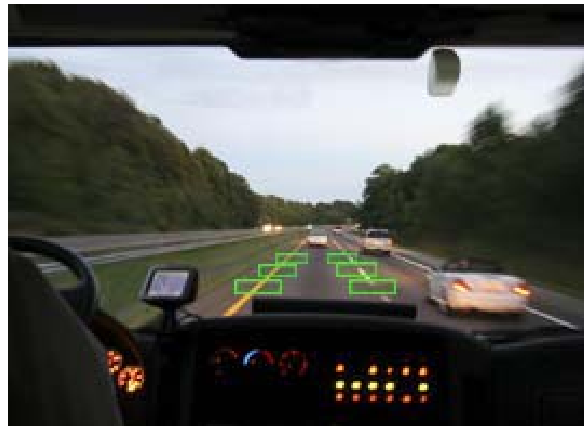

Figure 2.2 Bendix AutoVue – Lane Tracking Road Scene Simulation

AutoVue is a vision-based LDWS that applies a wide-angle camera to view and track visible lane lines. Its on-board computer calculates the vehicle position in the lane and alerts the driver if the vehicle begins to drift out of the lane without applying the turn signal in that direction. The audible warning sounds like a tire passing over a highway rumble strip. This is a driver's aid for maintaining the vehicle in the lane, but does not intervene in the driving function. AutoVue is in use at Daimler and is being tested for potential applications at another large-vehicle OEM.

The AutoVue LDWS is designed to work in most weather conditions, whether daytime or nighttime, rain or fog, as long as lane markings are visible to the camera. The LDWS tracks both solid and dashed lane lines. The AutoVue goes into a disabled mode if the lines are covered over or not visible and then it warns the driver with an orange reduced-function light.

The AutoVue is optimized to reduce false alarms by disabling alarms when the turn signal is applied and when the vehicle speed is less than 37 mph (59.5 km/h). The warning sound is maintained if vehicle drift occurs in the direction opposite to the intended turn[5].

The AutoVue marketing Web site [5] showed the Iteris AutoVue was available as an OEM option that can be installed in any factory modification centers around the world. This LWDS is available on all North American-made Class 8 trucks (i.e., GVWR greater than 33,000 pounds), including Freightliner, Western Star, International, and Peterbilt.

2.2.1.2 SafeTraK LDWS (now called OnLane)

Currently, Meritor WABCO's Takata SafeTraK LDWS is an available option for new Daimler trucks and at Navistar on special request (not yet a standard option)[8]. The vision-based system is contained in a windshield-mounted camera unit. It has separate left and right speakers that produce a low-pitch warning buzz on the side of the truck that is drifting over the lane line (Figure 2.3).

Figure 2.3 WABCO SafeTraK Camera in Overhead Windshield Mount

In November 2013, Meritor WABCO announced the OnLane technology (which uses Takata SafeTrak technology), which applies a camera-based LDWS for heavy vehicles. The system provides visual and acoustic warnings, with an optional seat vibration function.

WABCO's advanced OnLane system was developed specifically for heavy vehicles to reduce incidence of out-of-lane incursion through early driver warning. The OnLane unit combines an electronic control unit (ECU) and lane tracking camera into a single windshield-mounted unit. Functions to be added to the OnLane unit include detection of driver fatigue, traffic signal recognition, and headlight control. When the OnLane data is fused with that from WABCO's "OnGuard" radar-based emergency braking system (EBS), an automatic intervention system will apply the vehicle service brakes upon detection of numerous road hazards, including slower-moving, stopped/stationary, or oncoming objects.

OnLane features include multi-mode warnings for unintentional lane departure events, camera-based tracking of visible lane lines, system activation above 42 mph (68 km/h), dash lights showing system availability and fault conditions, and directional audible warning tones. It is compliant with EU regulation No 351/2012.

2.2.1.3 Mobileye ADAS

Mobileye began in 1999 as a technology company that focused primarily on developing vision-based Advanced Driver Assistance Systems (ADAS) for forward collision warning. In the early 2000's, Mobileye was installed mostly on OEM production cars, but was made available for the aftermarket in 2006[2]. Since then, Mobileye has expanded into pedestrian detection and LDWS. Mobileye systems are now being installed on heavy vehicles and off-road equipment. Select Daimler trucks are pre-wired for Mobileye; others can have it added as an option.

Figure 2.4 Mobileye 560

An example is one large coach OEM (Entegra Coach - Figure 2.5) [9] that currently has a factory option to add Mobileye during vehicle production. The option specifies the "Mobile Eye Lane Departure and Forward Collision Warning System with Car, Motorcycle, Bicycle & Pedestrian Detection" [10].

Figure 2.5. Mobileye as Factory Option in Entegra Coach

2.2.1.4 Continental LDW

The Continental LDWS [11] uses a camera mounted on the front of the vehicle to monitor the road up to 40 m (131 ft) ahead of the vehicle. If the vehicle unintentionally drifts out of the lane, the Continental LDW will warn the driver through acoustical sounds and haptic vibrations. The passive LDW can be made active for steering intervention in lane keeping assistant (LKA) mode, which activates above 37.3 mph (60 km/h). Continental began supplying LDWS to European passenger car and heavy-vehicle markets in 2007.[12]. Continental LDW was introduced into the American market in 2013.

Figure 2.6 Continental: Always in Lane and Accident-Free to the Destination: Lane Departure Warning

2.2.1.5 Delphi Forewarn LDW

The Delphi Forewarn LDWS is an image-processing visual lane tracker that alerts the driver if the vehicle unintentionally departs from the lane. It detects visible lane lines as far as 25 meters in front of the vehicle[13]. The Forewarn LDW provides audible, tactile, or visual alerts (see Figure 2.7). This system is OEM-installed by Volvo in Europe.

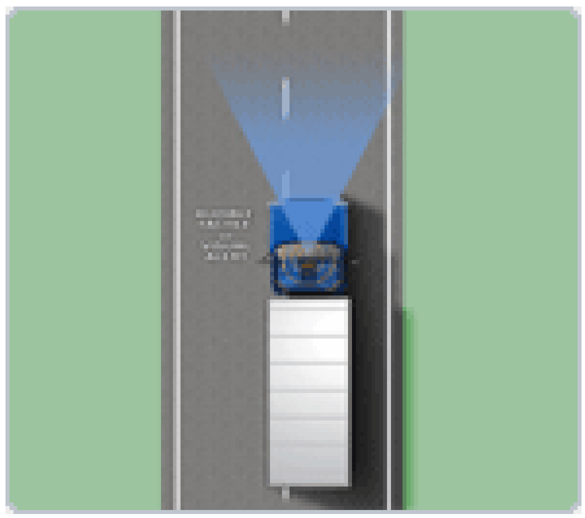

Figure 2.7 Delphi Lane Departure Warning

The Forewarn LDWS provides lane change predictions using lane width and road curvature estimates to determine heading and lane position, and can be integrated with brake and steering controls for lane keeping intervention.

2.2.1.6 Bosch/PSA - Peugeot Citroen LDWS

PSA and Bosch are co-developing an infrared LDWS in Europe [14]. One specification available is the system activates lane tracking when the vehicle exceeds 49.7 mph (80 km/h) and solid or dashed lane markings are present on the roadway. The primary benefits are infrared works well in adverse weather conditions (including night time, fog, and heavy rain) and infrared sensors are much lower cost than other visible light-based camera systems. One drawback is that infrared does not work if the roadway is covered by snow or heavy ice.

2.2.1.7 iOnRoad ADAS

The “iOnRoad” device by Picitup [15] is a combination FCW and LDW smart cellphone application. The iOnRoad Advance Driving Assistance System (ADAS) application merges the cellphone camera with GPS positioning to compute time-to-collision with a vehicle ahead and produces color-coded visual cellphone warnings showing the severity of the warning. In 2013, LDW was added to compute vehicle drift toward visible lane lines with complementary warning levels. Audible warnings are produced for both FCW and LDW danger zones. Being already on-line during operation, the added Road Snap Assistant feature allows the driver to capture and upload to the Web pictures of obstacles or poor road conditions they may encounter. This type of application is one of the lowest cost, low resolution LDW systems on the market. The user needs only to purchase a smart cellphone and an on-windshield mounting cradle.

Figure 2.8 and Figure 2.9 are two pictures of the iOnRoad being used with a roadway simulation video. The first shows the vehicle (the handheld iPhone camera) positioned in the middle of a driving lane. The screen lane is highlighted with a green color and the screen shows no warnings. The second picture shows the street scene blanked out and replaced by a text warning, ”Lane Departure” and a synthesized lane depiction with a red arrow and highlight on the lane line that is being crossed. The iOnRoad device does not interact with the vehicle controls; and therefore, does not prevent lane crossing warnings when the driver turns on the turn signals[16].

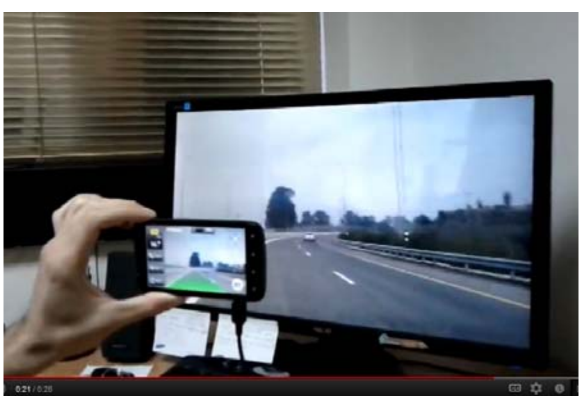

Figure 2.8 iOnRoad Simulation With Vehicle in the Lane

Figure 2.9 iOnRoad Simulation With Vehicle-out-of-the Lane Warning

For an even faster screen update while using the iOnRoad, communications link provider Qualcomm has developed an "app" (software application) that shortens the time delay between video frames, therefore rendering up to 15-percent quicker screen image updates when combined with the iOnRoad app[17].

2.2.1.8 MinTron LDWS

MinTron LDWS is a vision-based lane monitoring system applied for tracking roadway lane lines. It produces audio and visual warnings to the driver if the vehicle departs from the lane without applying the appropriate turn signal[18].

MinTron LDWS gives a modified double-rumble-strip sound when crossing over lane lines, which repeats if you stay over the lines. Screen image shows blue lane lines which turn red when the vehicle runs over it. MinTron is basically a smart-phone application, but no price value was relayed from any source or supplier.

Figure 2.10 and Figure 2.11 show two snapshots from a MinTron YouTube video[19]. Figure 2.10 shows the vehicle traveling in-the-lane by highlighting the lane lines in blue. A blue circle appears in the center of the current lane of travel, indicating safe travel in this lane. A green cross-hatch pattern appears considerably ahead and in the lane to represent traffic that you are following (for FCW alert tracking).

Figure 2.11 shows a blue line on the right, but now, a red line on the left. The red line indicates that the vehicle is driving onto the left lane line. The little blue circle that was previously ahead in your lane now appears as a large red warning circle in the adjacent lane to the left, which shows the driver where the vehicle is headed if no corrective action is taken. This circle, being large and red, is to alert the driver that continued movement into that lane or off-road location may result in a crash if the driver doesn't recover to their initial lane.

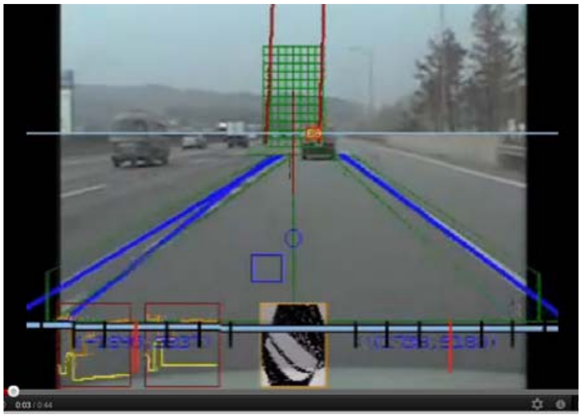

Figure 2.10 MinTron - Blue Lane Lines While "in-the-lane"

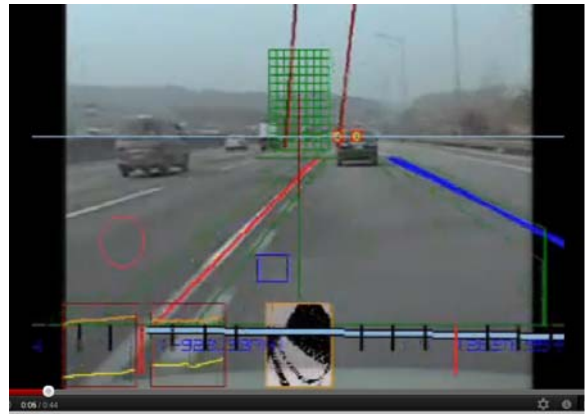

Figure 2.11 MinTron - Red Line Warning When Encroaching on Left Lane Line

The following two MinTron videos show the basis for the improved version seen in the previous video. The first video (Figure 2.12) shows a left lane incursion while driving on a multi-lane highway at 46 mph (74 km/h). The green left arrow shows that the vehicle is drifting into the left lane, the projected green lane lines show in-lane, and pink lines show when crossing the lane line. No audio warning from the system was heard in the video, which may indicate that it is a purely visual warning, however, it is also possible that the system audibly warned, but the video itself does not have any audio output.

The second video (Figure 2.13) shows a less crowded highway under heavy rain/fog conditions, with the vehicle speed at 66 mph (107 km/h). The green arrow now indicates that the vehicle is moving toward the right and that the center of the camera view has crossed over the projected pink lane line on the left, but is not yet fully into the center lane.

Figure 2.12. MINTRON- Imaged-Based Lane Departure Warning System Operating on Highway

Figure 2.13. MinTron Driving in Heavy Rain/Fog

2.2.1.9 Surveillance Video LDWS - BLS-3000

Another camera-based system is the Surveillance Video BLS-3000 (Figure 2.14). The BLS-3000 [22] is a multifunctional system that provides LDW, accident video recording with vehicle data, and self-analysis of recorded data using a built-in digital signal processor (DSP). The 3D G-sensor activates the LDWS when the vehicle swerves or the camera identifies that the vehicle is crossing a lane line, and then the BLS-3000 warns in three modes: a “voice” message on the warning condition, an audible sound on the built-in speaker, and an alpha-numeric warning on the LED display. The warning duration time can be set during system installation. The minimum luminance requirement is 1 Lux. The lane line tracking camera field-of-view is shown in Figure 2.15. Figure 2.16 outlines the basics of the BLS-3000 LDWS operation

Figure 2.14 BLS-3000 LDWS and Accident Recording System

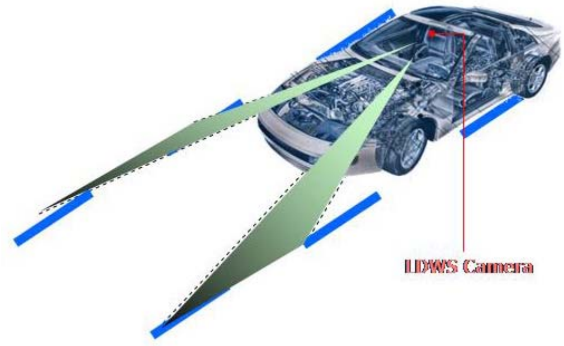

Figure 2.15 BLS-3000 Camera Tracking Lane Lines

Figure 2.16 How BLS-3000 LDWS Works

- High Performance DSP and powerful image processing algorithm detects the lane departure in real time.

- If a driver crosses the driving lane marker, the BLS-3000 will detect it and warn the driver by audible sound voice message or visual LED display.

- If a driver approaches the road edge line, the BLS-3000 gives a pre-warning with voice message.

- The warning duration time can be pre-set at the time of installation.

In compiling this list of LDW systems, additional sources of information were found through contacting OEM and supplier companies; guidance from industry organizations such as the Society of Automotive Engineers, the Technology and Maintenance Council of the American Trucking Association, and the Truck and Engine Manufacturers Association; and extensive Web searches. The research areas included identification of: what LDW systems are available from OEMs and as aftermarket options for heavy vehicles; what systems are available for retrofit to an existing vehicle and/or if they are only offered as an OEM option on a new truck or tractor; what are the associated costs, availability, and feasibility of retrofitting a state of the industry LDWS on a modern class 8 vehicle; and what is projected for next generation LDW technology performance.

2.2.2 Established and Proposed LDW Standards

There are multiple test procedures/standards or proposed standards for the evaluation of LDWS. Specific examples include: NHTSA "NCAP for Light Vehicles" (U.S.); ISO/DIS 17361 "LDWS Intelligent Transport Systems - Lane Departure Warning Systems - Performance Requirements and Test Procedures"; Commission Regulation (EU) No 351/2012 of 23 April 2012 "Type-Approval Requirements for the Installation of Lane Departure Warning Systems in Motor Vehicles" implementing Regulation (EC) No 661/2009 of the European Parliament and of the Council; and FMCSA "Voluntary Requirements for Large Truck LDWS" (U.S.). The performance requirements, warning indications, test conditions, and vehicle conditions specified in these U.S. and foreign test procedures/standards are presented in the following tables.

Performance requirements for the following test procedures are listed in Table 2.1, which include LDW Test Lane Geometry – Straight and Curve, Additional Tests - Long Straight, Suppress Warning on Driver Intention to Change Lanes, Minimum LDW Warning Activation Speed, Manual Reinstatement of LDW at Initiation of Each New Ignition Cycle, and Constant Warning Signal to Driver if LDW Systems Has Been Deactivated.

Table 2.1 Performance Requirements for Proposed and Established LDWS Test Procedures/Standards For both Light and Heavy Vehicles

Reference	NHTSA LV NCAP 2010	EU 351/2012	ISO 17361/2007	FMCSA-MCRR-05_005
Organization and Document Name	National Highway Traffic Safety Administration - LV NCAP - Lane Departure System Confirmation Test	European Parliament and Council □ Requirements for Installation of LDWS in Motor Vehicles	International Organization for Standardization - Intelligent Transport Systems - Lane Departure Warning Systems - Performance Requirements and Test Procedures	Federal Motor Carrier Safety Administration - Concept of Operations and Voluntary Requirements for LDWS On-board Commercial Motor Vehicles
LDW Test Lane Geometry - Straight	straight only; >1246 ft (380 m)	straight	>1000 m or two 500 m straightaways	Straight
LDW Test Lane Geometry - Curve	none	>250 m radius at inside line	>=500 m radius at speed >= 72 km/h (LDWS Class-I); or >=250 m radius at speed >= 61.2 km/h (LDWS Class-II); tolerance +/- 10% of the minimum radius for each LDWS Class	one of two conditions: >=500 m radius at speed >= 20 km/h (Condition 2); or >=250 m radius at speed >= 61 km/h, <72 km/h (Condition1)
Additional Tests - Long Straight	none	none	false-positive; >1000 m	none
Suppress Warning on Driver Intention to Change Lanes	not specified	may be suppressed	may be suppressed by turn signal application, braking, or other high-priority maneuver	should not issue warnings for lane departures when driver uses vehicle turn signal in the intended direction of lane change
Minimum LDW Warning Activation Speed	not specified, but tests conducted at 45 mph (72.4 km/h)	>60 km/h	>=72 km/h (LDWS Class-I); or >= 61.2 km/h (LDWS Class-II)	>=37 mph (>=60 km/h)
Manual Reinstatement of LDW at Initiation of Each New Ignition Cycle	not specified	Yes	not specified	not specified
Constant Warning Signal to Driver if LDW Systems Has Been Deactivated	suppress LDW alerts and indicate less-than ideal operating conditions to the operator	Yellow Light	status indicator to show: on/off; failure; or incapable of warning driver	status indicator to show: on/off; failure; or incapable of warning driver

Vehicle condition specifications for each standard are listed in Table 2.2 including Test Weight, Tire Pressures, Trailer Requirements with Tractors, Transmission Gear Selected, and Reference Point on vehicle that first leaves the lane.

Table 2.2 Vehicle Conditions for Proposed and Established LDWS Standards for Both Light and Heavy Vehicles

Reference	NHTSA LV NCAP 2010	EU 351/2012	ISO 17361/2007	FMCSA-MCRR-05_005
Test Weight	fuel >=75% filled, other fluids at 100% capacity; add only weight of driver and instrumentation	any load condition without exceeding mass limitation on any one axle	between complete vehicle curb mass and maximum authorized total mass	not specified
Tire Pressures	OEM cold inflation pressure specified on vehicle placard	recommended by vehicle OEM	not specified	not specified
Trailer Required with Tractors	car test, no trailer required	not specified	not specified	not specified
Vehicle Gear Selection	automatic transmission in "Drive" or manual transmission in highest gear to sustain desired speed	not specified	not specified	not specified
Specified Vehicle Reference Point Identified as Item Leading Vehicle in Lane Departure	any point on two dimensional polygon measured at outer tire on each axle (points are referenced on the ground beneath centerline of tire bulge)	Outboard Point on Centerline of Steer Tire Bulge	Outside of One of the Front Wheels (steer axle) of vehicle or leading part of an articulated vehicle (tractor or articulated bus)	vehicle departs lane at warning threshold

Test conditions for each standard are listed in Table 2.3 including conditions for the Test Surface, Ambient Air Temperature, Maximum Ambient Wind Speed, Visibility, Test Lane Width, Visible Lane Markings (if position about lane not specified), and Left and Right Edge Lane Markings, and Center Line Markings.

Table 2.3 Test Conditions for Proposed and Established LDWS Standards

Reference	NHTSA LV NCAP 2010	EU 351/2012	ISO 17361/2007	FMCSA-MCRR-05_005
Test Surface	dry, uniform, solid-paved surface with peak coefficient-of friction = 0.9; single roadway lane edge	flat, dry asphalt or concrete	flat, dry asphalt or concrete	all types of roads, at any hours of the day, and in all types of driving conditions
Ambient Air Temperature	between 32° F (0° C) and 100° F (38° C)	between 32° F (0° C) and 113° F (45° C)	10 +/- 30° C	all temperatures
Maximum Ambient Wind Speed	<=22 mph (36 km/h)	not specified	not specified	not specified
Visibility	No inclement weather: meaning no rain, snow, hail, fog, smoke, or ash; sun angle >15 degrees above horizontal; see more than 3 miles (5000 m)	visibility conditions that allow safe driving at the required test speed	distance at which the illuminance of a non-diffusive beam of white light with a color temperature of 2700 K is decreased by 5% of its original light source illuminance; minimum horizontal visibility range = 1 km	daylight (sunny/cloudy); nighttime (with and without streetlight illumination); and twilight (sunrise/sunset)
Test Lane Width	>25 ft; no visible second lane line on vehicle side opposite from intended lane change side	> 3.5 m	not specified; manufacturer predetermined width when visible lane marking exists only on one side of lane	not specified
Visible Lane Markings (if position about lane not specified)	white solid; yellow dashed 10 ft long (3 m) x 30 ft (10 m) spacing; or Botts dots = MUTCD [23]; only one edge line to be seen by LDW system under test	white, dashed or solid	white, dashed or solid	solid and dashed, single and double, yellow and white - painted lines; raised pavement markers (Botts dots); lines with and without reflectors/reflective material
Left Edge Lane Marking	4 to 6 in (10 to 15 cm) width	solid white, width varies by country (10 to 37.5 cm)	solid white, width varies by country (12 to 30 cm)	see Visible Lane Markings above
Center Line Marking	4 to 6 in (10 to 15 cm) width	dashed white, dimensions vary by country (10 to 15 cm wide x 3 to 6 m long x 4.5 to 12 m gap spacing)	dashed white, dimensions vary by country (10 to 20 cm wide x 2 to 6 m long x 7 to 12 m gap spacing)	see Visible Lane Markings above
Right Edge Lane Marking	4 to 6 in (10 to 15 cm) width	solid white, width varies by country (10 to 30 cm { except France uses dashed lines})	solid white, width varies by country (12 to 30 cm { except France uses dashed lines})	see Visible Lane Markings above

Warning indications specified for each standard are listed in Table 2.4 including warning modes and LDW warning lamp visibility.

Table 2.4 Warning Indication for Proposed and Established LDWS Standards

Reference	NHTSA LV NCAP 2010	EU 351/2012	ISO 17361/2007	FMCSA-MCRR-05_005
Warning Modes	auditory alert, visual alert, haptic vibration, or haptic vehicle cue	at least two of: optical, acoustic, or haptic;	easily perceivable haptic or audible warning	audible; visual; or tactile
	OR: any combination thereof	OR: one warning includes: haptic or acoustic, plus spatial indication in direction of unintended drift	OR: if other warning systems equipped on truck: LDW must warn by distinguishable haptic, audible, or visual modality; or any combination thereof	any combination thereof
LDW Warning Lamp Visibility	visible to operator	Day and Night Visibility of Warning Indicator Required	clearly distinguishable	visible

Test parameters for each standard are summarized in Table 2.5 including the following: Vehicle Test Speeds, Lateral Rate of Lane, Departure Direction, Curve Direction, Maximum Yaw Rate, Steer Input Method, Number of Trials, earliest Alert Distance to line, Maximum Out-of-Lane Displacement Before Warning, Test Completion Point, Maximum Width of Warning Zone, Minimum Specification to "Pass" Mode, Total test trials in complete test matrix, and Minimum Specification to "Certify."

Table 2.5. Test Parameters for Proposed and Established LDWS Standards

Reference	NHTSA LV NCAP 2010	EU 351/2012	ISO 17361/2007	FMCSA-MCRR-05_005
Vehicle Test Speeds	45 mph +/- 1.2 mph (72.4 km/h +/- 2 km/h) hold constant	65 km/h +/- 3 km/h hold constant	Straight and Curve: 72 to 79.2 km/h Class I or 61.2 to 68.4 km/h Class II	Straight and Curve: 72 to 79.2 km/h Class I or 61.2 to 68.4 km/h Class II
Lateral Rates of Lane Departure (approach velocity (Vn) at a right angle to the lane boundary at the warning issue point)	Target: 1.64 f/s (0.5 m/s); Range: 0.3 to 2.0 f/t (0.1 to 0.6 m/s)	Range: 0.1 to 0.8 m/s {repeat at two different rates}	For V1 and V2 selected by the manufacturer: Curve: 0<V1<=0.4 m/s and 0.4<V2<=0.8 m/s; Straight: 0.1<(V1+/□ 0.05)<=0.3 m/s and 0.6<V2+/-0.05<=0.8 m/s	<2.6 f/s (<0.8 m/s)
Departure Direction	Left Side	Left Side	Left Side	Left Side
	Right Side	Right Side	Right Side	Right Side
Curve Direction	not tested	curve direction not specified	Left Curve and Right Curve	Left Curve and Right Curve
Maximum Yaw Rate	<1.0 deg/sec	not specified	not specified	not specified
Steer Input Method	driver	driver	driver	driver
Number of Trials	5 reps each mode combination	1 each test mode combination	1 each per 8 curve test; 4 each per 4 straight repeatability tests	not specified
Must Not Alert Before Distance; V=lateral departure rate; D=distance before lane line;	2.5 ft (0.75 m) before crossing inboard edge of lane line	not specified	If 0 < V <= 0.5 m/s, D=0.75m; If 0.5<V<=1.0 m/s, D=1.5s * V; If 1.0m/s< V, D=1.5m	displacement not specified; not warn before earliest warning line
Maximum Out-of-Lane Displacement Before Warning	1.0 ft (0.3 m) beyond the inboard edge of lane marker just crossed	0.3 m beyond the outside edge of lane marker just crossed	0.3 m outside of the lane boundary (marker centerline) for passenger cars and 1 m for trucks and buses	displacement not specified; before latest warning line
Test Complete When Vehicle Crossed Over	lane edge boundary by >= 3.3 ft (1m)	not specified	not specified	vehicle exceeds latest warning line
Maximum Width of Warning Zone	3.5 ft (1.05 m)	not specified	1 ft (30 cm) for each test group	not specified; determine warning threshold, then track within +/- 4 in (0.1 m) of threshold when at specified lane departure rate
Minimum Specification to "Pass" Mode	3 of 5 per test mode (60%)	1 of 1 per test mode (100%)	100%	95% of the time on straight
Total trials	30	8	24	not specified
Minimum Specification to "Certify"	20/30 (67%)	100%	100%	not specified

3 TESTING METHODOLOGY

The heavy-vehicle protocol used to test LDW systems in a test tractor are presented in this chapter. The test procedures for straight and curved lanes are described first, followed by a detailed test matrix for the various lane departure scenarios, and finally test preparations are presented including descriptions of the test vehicle, procurement and installation of LDWS, test site preparation, and instrumentation.

3.1 Test Procedures

After reviewing the results of previous studies and related test procedures, a simplified approach was selected for evaluating the basic functionality of heavy-vehicle LDWS. The basic straight-lane tests from the NHTSA NCAP LDW test procedure for LV was extended to heavy vehicles with some modification for in-lane cone spacing and roadway lengths for longer start-up and stopping distances. A series of curve tests was added to evaluate the sensitivity of LDWS on curved roads. The test procedures for the straight and curved lane tests are discussed below.

3.1.1 Straight Lane Departure Test Maneuver

The straight lane departure test was adapted from the NCAP LDW [1] test procedure with slight modifications for heavy vehicles. A left side lane departure test on a solid lane marking, with the test course layout, is shown in Figure 3.1. This test course is replicated for the dashed line and is laterally inverted for the right side tests. The major modification from the NCAP test procedure was the widening of the spacing between the in-lane guide cones (pylons). Eight inches (20 cm) were allowed on each side of the vehicle for clearance of passage for speeds up to 55 mph (88.5 km/h), compared to 4 inches (10 cm) for light vehicles. This resulted in a net spacing of 114 inches (290 cm) between the “starting gate” cones, where the center of the lane was measured as 6 ft (1.83 m) from the inside edge of the lane line being tested.

Additional cones (comprising the entry gate) were situated on the approach lane to ensure that the vehicle was centered within the lane and a constant test speed was maintained, thus providing more than 2.5 seconds of stabile lane “preview” time for the LDWS prior to beginning the actual lane departure maneuver. Two cones were positioned with their bases 114 inches (290 cm) apart to designate the "entry gate," which was laterally centered on the driving lane and located 200 feet (61 m) before the test start point.

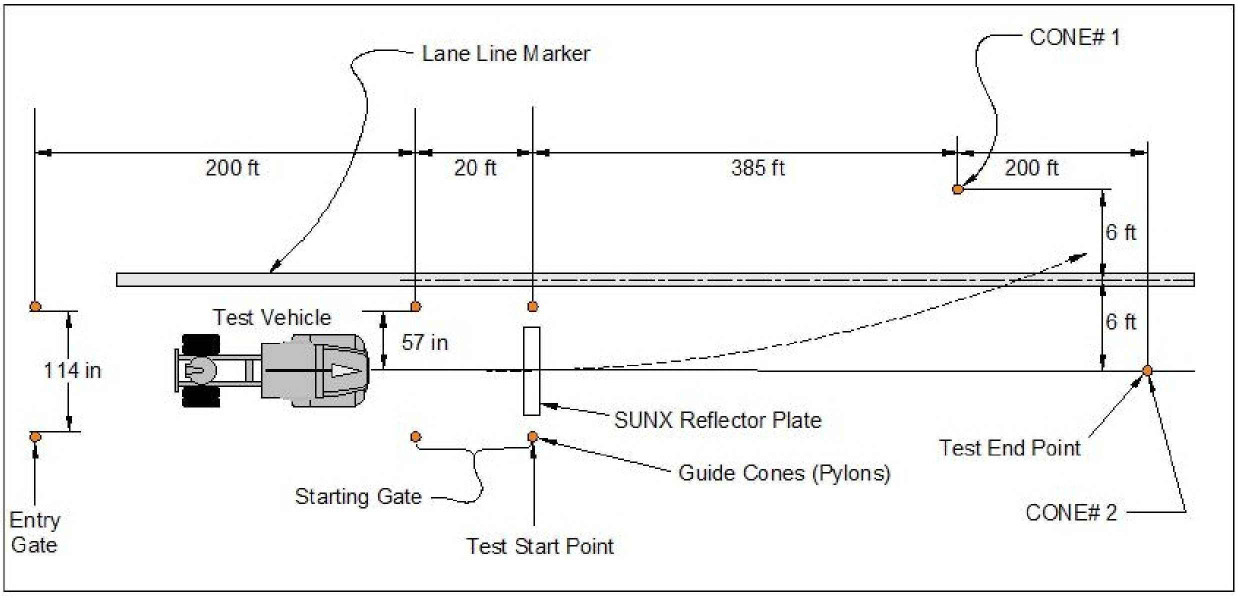

Figure 3.1 Heavy-Vehicle LDW Left Lane-Change Test Procedure and Layout.
Note: For illustration only – not to scale.

In addition to the pylons mentioned above, pylons CONE #1 and CONE #2 were placed on the test track to assist the driver to achieve the proper lateral velocity for the tests. NOTE: These cones are optional and placed 6 ft (1.83 m) outside and inside (respectively) of the inside edge of the lane line marker.

The driver approaches the "entry gate" at the constant test speed, centering the vehicle between the pylons. The test starts once the vehicle passes the SUNX plate, and the driver slowly imparts steering to move the vehicle so that it crosses the lane between CONE #1 and CONE #2. The test ends after any part of the vehicle has crossed the inside edge of the lane line by 1 m (3.3 ft).

A view from the end of the LDW straight lane course is shown in Figure 3.2 including the test lane line and the specified gate and guide cones.

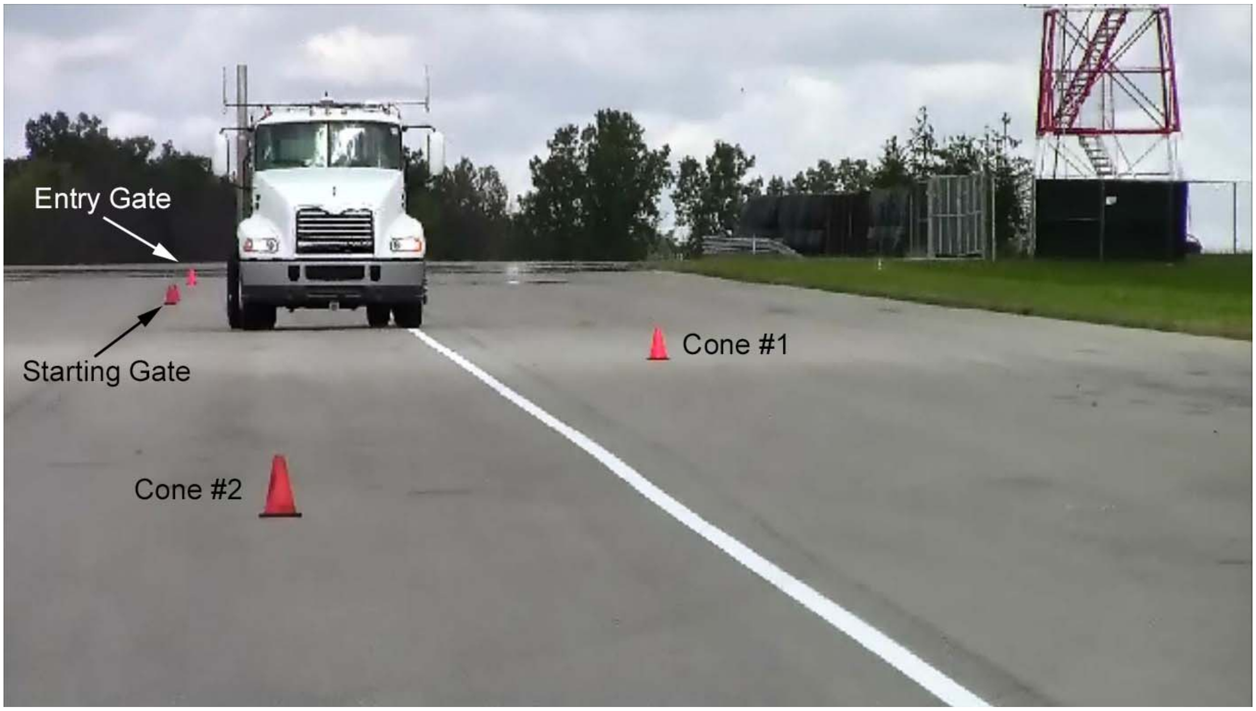

Figure 3.2 Straight-Lane Solid-Line - Lane Change to the Left

3.1.2 Curved Lane LDW Test – Course Layout

The NCAP procedure was adapted for curve testing on the TRC Vehicle Dynamics Area turnaround loops. The same general longitudinal displacements used for the previous straight lane tests were applied to the solid and dashed-lane lines of the curved roadway. The South Loop of the VDA was chosen for curved-lane LDW tests, since it provided LDW lanes comparable to the VDA straight lanes. The major differences to the VDA straight lanes were; the solid white lane line was only 13.33 feet (4 m) laterally from the dashed yellow lane line (inner lane width), there was a guard rail around the outside of the outer lane (second lane width approximately 15.67 ft (4.77 m)), the lanes were banked 11 degrees (19 percent super-elevation) low side on the right (driving clockwise around the roadway curve to the right), and there was an extensive berm lane to the inside of the marked lanes (greater than 20 feet (6 m) wide).

Acceleration, soak, and lane-change zones were configured similar to the straight lane with the longitudinal measurements made along the curved solid lane line. The test scenario for the right lane change for the solid lane marking on the VDA South loop is illustrated in Figure 3.3. All tests on the curved roadway were performed in a clockwise direction only. The vehicle speed of 45 mph (72.4 km/h) was maintained for all tests.

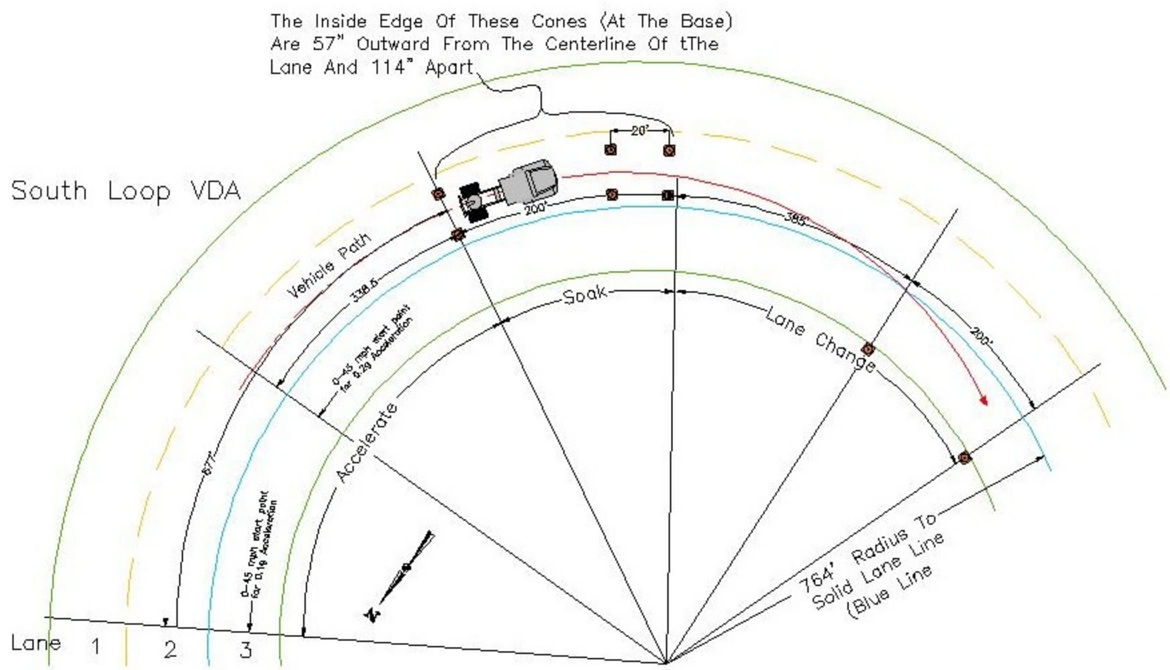

Figure 3.3 Curved Lane Test - Course Layout
Note: For illustration only – not to scale.

LDW curve tests were performed in both North and South Loops sequentially; however, only the South Loop was mapped with the Oxford RT lane survey trolley for differential lane position measurement. Only the data collected for tests in the South Loop was used in the data analysis.

3.2 Test Matrix

Once the test procedures were selected, the various scenarios to be evaluated were determined and a test matrix was drawn up. The test matrices and the purpose of the individual tests are presented in the following sections.

3.2.1 Straight-Lane Test Procedures

The straight-lane test matrix was designed to include LDWS effectiveness, longitudinal speed sensitivity characterization, duration of warning characterization, (partial lane change warning re-activation), warning interrupt or prevention modes with the use of turn signals, and the effect of braking on warning suppression. The lane mode, speeds evaluated, turn signal application and general notes for each test procedures are listed in Table 3.1. The purpose of each of the test procedures is discussed below.

Table 3.1 Solid Line Straight Lane - Tested on Left and Right Sides of Tractor - 26 Tests

Test Procedure	Lane Mode	Speeds (mph)	Turn Signals Applied	Notes
Baseline Test	In-Lane	25, 55	None	
Lane Change Test - Speed Sensitivity Characterization	Change Lane	25, 35, 45, 55	None	
Partial Lane Change - Duration of Warning Characterization	Partial Lane Change	45	None	Drive With Front Tire Continuously Within Warning Zone After Onset
Turn Signal Warning Prevention Capability	Change Lane	35, 45, 55	Apply R-T/S before lane change	
Turn Signal Warning Interrupt Capability	Change Lane	45	Apply L-T/S only after Left-Warning begins	
Opposite (Wrong) Turn Signal	Change Lane	45	Yes, apply Left-T/S before lane change	This Should Not Prevent Valid Lane Departure Warning
Service Brake Warning Interrupt Capability	Change Lane	45	Apply Service Brake after Left-Warning begins	~0.2 g decel

Baseline Test: A baseline test was performed to determine if the LDWS produced any false-positive warnings while the vehicle was driven down the length of the center of the initial driving lane. The test lane line marker was configured on only one side of the vehicle (since the test lane markings were 25 feet apart from each other). Most LDW systems are designed to have an operational threshold at or above 35 mph, therefore baseline tests speeds of 25 and 55 mph were selected to evaluate the LDW systems well above and below this threshold speed. Five test repetitions were performed for each LDW system for each speed, and the procedure was repeated for both left and right sides of the vehicle. No lane departure warnings were expected for this test procedure.

Lane Change Test: A full lane-change test was performed where the vehicle remained centered in the lane until passing through the starting “gate” before initiating the lane-change maneuver. The LDWS was expected to warn the driver when the vehicle moved out of lane. Five repetitions were made for each of four longitudinal speed ranges, which included 25, 35, 45, and 55 mph (speed sensitivity). The procedure was performed for left and right side lane departures. Five repetitions were performed for each speed and lane change direction.

Partial Lane Change Test: For the partial-lane-change test procedure, the vehicle was driven as in the full-lane-change tests, except that when the lead tire approached the lane line, the driver steered the vehicle so the front tire remained on the lane line until the tractor reached Cone #2. This test procedure was designed to determine if the out-of-lane warning would stay on continuously or end after the initial warning. This procedure was performed at 45 mph. with 5 repetitions performed for each lane change direction.

Warning Prevention Test: The turn signal “warning prevention” capability of the LDW systems was evaluated by having the driver apply the appropriate turn signal prior to performing a full-lane change. Here, the LDWS was evaluated as to whether it maintained functionality of the warning capability when the driver signaled prior to initiating an intentional lane change. Speeds tested included: 35, 45, and 55 mph with 5 repetitions performed for each speed and lane change direction.

Warning Interrupt Test (Turn Signal): A turn signal “warning interrupt” test was performed to see if applying the turn signal after the alarm is initiated would cause the alarm to cease. For this test procedure, the driver performs an un-intentional lane change (lane change without applying the turn signal prior to making the maneuver) and once the LDWS activates the warning, the driver quickly applies the corresponding turn signal to identify if the turn signal application interrupts the warning function (or if it has no effect on the warning capability). Five repetitions were performed at 45 mph for both left and right side lane changes.

Opposite Turn Signal Test: For the "opposite turn signal" test procedure, the driver applies the opposite direction turn signal prior to performing a full-lane change. Here, the right turn signal was applied and then the vehicle put into a left lane change maneuver, and visa-versa. The LDWS was expected to maintain full operation and warn upon the left lane line crossing in the event of an unintentional or miscued application of the right turn signal. This scenario was performed at 45 mph with 5 repetitions for each side of the vehicle.

Warning Interrupt Test (Braking): A final test procedure evaluated the interaction between LDW activation and braking to identify if the lane departure warning was interrupted by the driver applying the service brakes. The service brake warning interrupt capability was evaluated by driving the vehicle through the starting gate at 45 mph and, without applying a turn signal, beginning to make a full lane-change maneuver. As soon as the LDW activated, the driver applies the service brakes to a deceleration of 0.2 (+/- 0.5) G.

The dashed-yellow-line straight-lane tests (listed in Table 3.2) were repeated similarly to the solid line tests. However, the array of tests was reduced to include only baseline tests, lane-change speed sensitivity tests, and turn signal warning prevention tests.

Table 3.2 Dashed Line Straight Lane - Tested on Left and Right Sides of Tractor - 16 Tests

Test Procedure	Lane Mode	Speeds (mph)	Turn Signals Applied
Baseline Test	In-Lane	25, 55	None
Lane Change Test - Speed Sensitivity Characterization	Change Lane	25, 35, 45, 55	None
Turn Signal Warning Prevention Capability	Change Lane	35, 45	Apply L-T/S before lane change

3.2.2 Curved-Lane Test Procedures

Three curved lane test procedures were evaluated: baseline, speed sensitivity, and turn signal warning prevention tests. Lane changes to the left and to the right were performed for each test type, and for each lane line marker type. The lane mode, speeds, and turn signal application for each curved roadway tests procedure are listed in Table 3.3. The procedures were the same as those for straight roadways except for test location (VDA South Loop).

Table 3.3 Curved Roadway – Solid and Dashed Lane Lines – Left and Right Side of Tractor

Test Procedure	Lane Mode	Speeds (mph)	Turn Signals Applied
Baseline Test	In-Lane	45	No
Lane Change Test - Speed Sensitivity Characterization	Change Lane	45	No
Turn Signal Warning Prevention Capability	Change Lane	45	Yes, apply L-T/S before lane change

3.3 Test Preparation

Before the LDW tests could be performed, the vehicle and test sites needed to be prepared for testing. This involved various steps which included procurement and installation of commercially available LDW systems, RT-GPS survey of lane lines, and vehicle instrumentation. Details of these activities are discussed in this section.

3.3.1 Test Vehicle

NHTSA provided a low-mileage test vehicle. The over-the-road tractor was a model year 2011, Mack CXU612 4x2 day-cab. The tractor had limited mileage as it had been employed as a test vehicle since new. Total ballast added included approximately 400 lb for driver and instrumentation. Basic vehicle and axle information are listed in Table 3.4 and Table 3.5.

Table 3.4 Vehicle Information, 2011 Mack CXU612 4x2

Model Year, Make, Model	2011 MACK CXU612 4x2
Configuration	Class 8, Truck Tractor
VIN	1M1AW01Y7BM002685
Brake System	Air Drum, 4S/4M
Mileage	4700 miles
GVWR	34,700 lb.
Wheelbase	144 inch
Track - Steer Axle	80 inch
Track - Drive Axles	73 inch
Overall Length	228 inch
Overall Width	100 inch
Overall Height	111 inch
Steering Ratio	18.4
ABS System	Bendix
Front Suspension Type, Make, and Model	Leaf Spring, Solid Axle, Mack FXL12
Rear Suspension Type, Make, and Model	Air Bag, Solid Axle, Meritor GCW45
Steer Axle Tire Size, Make, and Model	295/75R22.5G Bridgestone R250
Drive Axle Tire Size, Make, and Model	295/75R22.5G Bridgestone R250

Table 3.5 Axle Rating and Weights, 2011 Mack CXU612 4x2

Axle	GAWR (lb)	Empty Weight (lb)
Steer	12,000	8,550
Drive Axle	22,700	4,680
Tractor Total	34,700	13,230

3.3.2 Procurement and Installation of Commercially Available LDW Systems

The Mack tractor was not equipped with an LDW systems when initially purchased; therefore, LDW systems were procured and installed prior to testing. Three LDW systems were selected by NHTSA for evaluation, but only two were available at the onset of testing. The LDW systems installed included the Takata SafeTraK LDWS (Takata) [24] {sold exclusively by Meritor WABCO in the United States} and the Mobileye C2-270 Advanced Collision Prevention Systems (Mobileye)[2].

The Takata LDWS was installed by Arvin-Meritor in Troy, MI. The integrated system included a windshield-mounted camera, discrete left and right overhead speakers, and an in-dash dual lamp display/switch unit. The Takata was wired to the vehicle SAE J-1939 Controller Area Network (CAN) interface and was energized upon activation of the ignition key switch.

The Mobileye LDWS was installed at VRTC by Mobileye-trained technicians. This add-on system consisted of a windshield-mounted camera with built-in monophonic speaker and a controllable driver display. The display device indicated vehicle speed, visual left and right lane excursion markers, and a five-level loudness control with sound defeat option. The Mobileye was connected to the vehicle CAN interface, both turn signals, and the headlight high-beam indicator.

3.3.3 Test Site Preparation

Numerous test sites were discussed within the test team and two sites were selected for the LDW tests. The standard NCAP LDW test pad at the TRC VDA was chosen for the straight lane tests and a new course was laid out for curve testing on the North and South Loops at the ends of the VDA (Figure 3.4). For straight-lane tests on the VDA surface, the loops were used for acceleration and deceleration zones between tests. For the curve tests in the loops, the VDA straightaways were used for the acceleration and deceleration zones between tests.

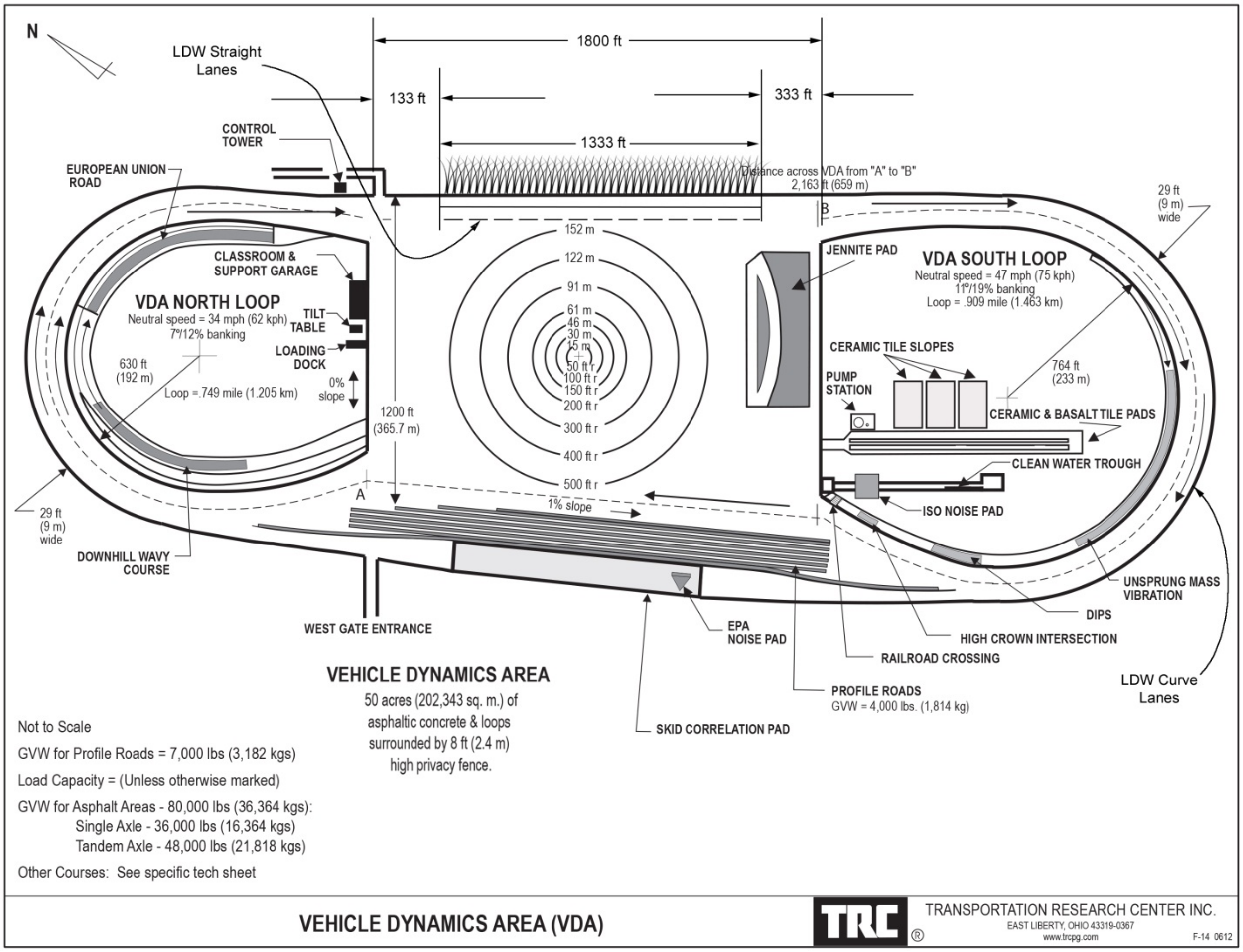

Figure 3.4 TRC VDA – LDW Straight Lanes and LDW Curve Lanes
Note: For illustration only – not to scale.

3.3.4 Test Instrumentation

In-vehicle instrumentation was implemented to collect audible, visual, and digital information obtained during the lane change maneuvers. Off-board instrumentation included video, sunlight monitor, and lane survey equipment. The test tractor was instrumented with several levels of data acquisition equipment, including Controller Area Network (CAN), GPS, digital, analog, and video monitors.

A United Electronic Industries (UEI) "Cube" data acquisition system was installed to collect data from the numerous data sources[25]. The J1939 truck CAN (on Mack tractor) was monitored to identify truck health and activity signals. A second CAN interfaced the Oxford Technologies [26] RT Hunter differential GPS unit, while a third CAN interface merged the independent RT 3003 Inertial Measurement Unit (IMU) [26] data (see APPENDIX A). A fourth CAN input was connected to the output of the Mobileye LDW system [2], where a CAN output was not available from the Takata LDW system[24].

Analog data were collected with the Cube for numerous discrete sensors added to the truck. A test lane starting point location was identified with a retro-reflective SUNX [27] sensor attached to the front bumper. The turn signals and high-beam headlight circuit were monitored while sharing with the Mobileye inputs. Steering wheel input was measured with a potentiometric device added to the steering column. Independent pitch, roll, and yaw rate measurements (along with the three orthogonal accelerations) were obtained with a Systron-Donner [28] Six-Degree of-Freedom MotionPak. Pressure sensors were installed in the supply chambers and service brake foot valve. Data files included 5 seconds of pre-trigger and 30 seconds of post-trigger logging.

A single Novatel [29] ProPak-V3 RT2 Triple-Frequency GNSS Receiver (without IMU) was separately monitored through USB connection to the laptop PC. A magnetically roof-mounted Pinwheel Antenna [30] (GPS-702-GG) combined both L1 and L2 GPS frequencies with GLONASS for signal reception.

Four video cameras were stationed throughout the tractor for observation of lane position and LDWS annunciation. Single cameras were attached to the front fenders above the outboard side of the steering tires to observe the lane excursions for each front tire (the tire-to-outer-edge displacement in each view was 22 inches). Two cameras were installed in the cab where one viewed the activity on the Mobileye display and the yellow and green dash lamps for the Takata LDW systems, and the other camera provided an over-the-driver's-shoulder view of the lanes ahead. All four images were combined in one frame (Figure 3.5) with a quad splitter and recorded on a Sony MiniDV video recorder. The sound from the LDW systems was collected with separate left and right microphones in order to differentiate the left and right warning sounds.

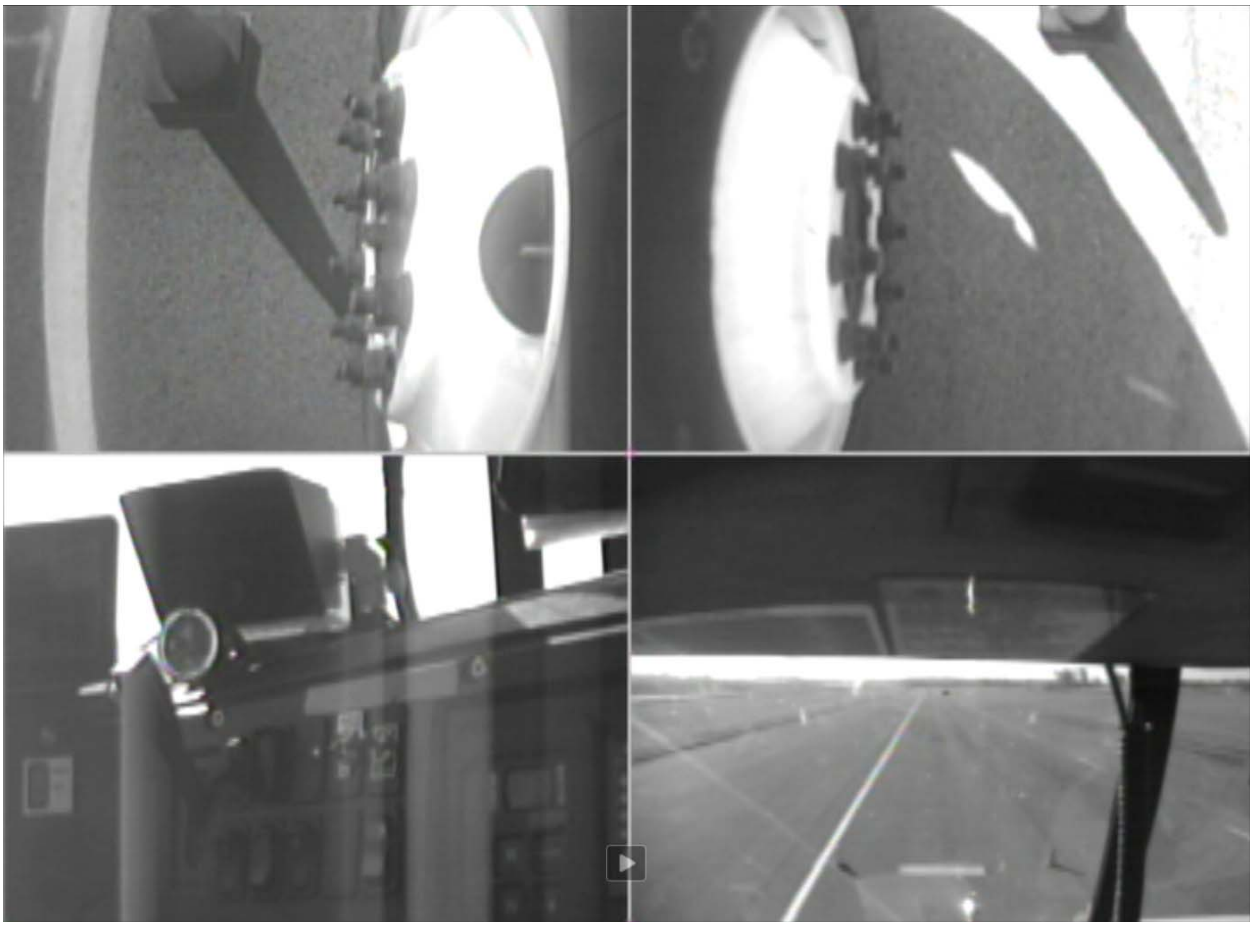

Figure 3.5 Four Onboard Camera Composite Image

Lane excursions were monitored by an on-the-ground observer stationed at the end of the test lane. Video sequences were collected with a tripod-mounted Canon HFR-340 digital video camera.

3.3.5 RT-GPS survey of lane lines

An Oxford RT lane survey trolley with differential GPS was used to survey both the straight lanes (solid and dashed line areas) and the two lanes at the south VDA curve. This survey data was used to create GPS maps of the lane lines which were then loaded onto the onboard RT Hunter system. The RT Hunter system is capable of using the map to measure and output the distance of the vehicle to the lane lines. An additional Novatel GPS unit was used to measure the straight lanes, whose data provided accurate measurements as an alternative to the RT unit.

3.3.6 Illuminance Readings

Periodic illuminance readings were taken of the sunlight impinging upon the test pad. An International Light Model ILL1400 Radiometer/Photometer [31] was elevated to three angles above the horizon and facing in line with the forward direction of the tractor movement. Elevation angles included: 30, 60, and 90 degrees above the plane of the roadway surface.

4 RESULTS

This chapter details the results of the LDW tests outlined in Chapter 3. The results of the straight lane tests are discussed first followed by the results for the curved lane.

4.1 Straight-Lane Test Results

The straight lane tests were conducted on the LDW lanes on the East side of the VDA. The SV participated in 210 straight-lane tests. Half of the tests were performed to test lane departure on the left side and the other half for the right side. The results pertaining to each test type are discussed first, followed by a summary of the tests that produced warnings.

4.1.1 Baseline Tests

The baseline tests involved driving the vehicle within the lane to check for false positive warnings from the LDW systems. Tests were run at speeds of 25 and 55 mph. These speeds were chosen to be well below and above the LDWS activation speed of 35 mph. Five repetitions at each speed were conducted for each lane marking type (solid and dashed) and for each side of the vehicle (left and right) giving a total of 40 tests conducted. No false positive results were observed in any of the tests for either the Mobileye or Takata LDW systems.

4.1.2 Lane Change Tests

The lane change tests are true positive tests and were conducted to test the proper functioning of the LDW systems. The test was conducted at four speeds; 25, 35, 45, and 55 mph with 5 repetitions at each speed, for each side of the vehicle, and for each lane marking type (solid and dashed). Overall, 80 lane change tests were conducted.

The 25 mph speed is below the 35 mph activation speed for both LDW systems (Mobileye and Takata) and no warnings were recorded at this speed for either system. For the 35 mph tests (activation speed), the Mobileye LDWS produced a warning for every trial, while the Takata LDWS did not produce any warnings. For the 45 mph and 55 mph tests, both systems produced warnings for every trial. Comparing the trends also revealed that the Takata LDWS consistently warned earlier than the Mobileye LDWS, except when testing the dashed lane marking on the right side of the vehicle. In this case, the Takata warning did not follow any discernible trend and warnings were observed both before and after the Mobileye warning. The data from these tests are shown in Table 4.1 and Table 4.2 for the left and right side respectively. The range (distance to the lane marking) at which warning occurred and the range rate for both the LDW systems are tabulated. The warning trends are plotted and discussed in Section 4.1.7.

A negative "warning range" value indicates that the warning occurred after the vehicle had crossed over the center line of the lane marker.

Table 4.1 Straight Lane, Left Lane Change Test Data

Test No.	Test Speed (mph)	Lane Type	Mobileye		Takata	
			Warning Range (m)	Range Rate (m/s)	Warning Range (m)	Range Rate (m/s)
1	25	Solid	No Warning	No Warning	No Warning	No Warning
2	25	Solid	No Warning	No Warning	No Warning	No Warning
3	25	Solid	No Warning	No Warning	No Warning	No Warning
4	25	Solid	No Warning	No Warning	No Warning	No Warning
5	25	Solid	No Warning	No Warning	No Warning	No Warning
6	35	Solid	-0.138	0.460	No Warning	No Warning
7	35	Solid	-0.127	0.496	No Warning	No Warning
8	35	Solid	-0.195	0.628	No Warning	No Warning
9	35	Solid	-0.198	0.566	No Warning	No Warning
10	35	Solid	-0.167	0.525	No Warning	No Warning
11	45	Solid	-0.188	0.585	0.019	0.466
12	45	Solid	-0.187	0.646	0.002	0.673
13	45	Solid	-0.168	0.613	0.01	0.601
14	45	Solid	-0.184	0.706	-0.011	0.619
15	45	Solid	-0.205	0.642	0.005	0.550
16	55	Solid	-0.241	0.730	-0.038	0.685
17	55	Solid	-0.175	0.706	-0.351	0.699
18	55	Solid	-0.228	0.882	-0.676	0.841
19	55	Solid	-0.231	0.655	-0.018	0.668
20	55	Solid	-0.266	0.847	-0.036	0.767
21	25	Dashed	No Warning	No Warning	No Warning	No Warning
22	25	Dashed	No Warning	No Warning	No Warning	No Warning
23	25	Dashed	No Warning	No Warning	No Warning	No Warning
24	25	Dashed	No Warning	No Warning	No Warning	No Warning
25	25	Dashed	No Warning	No Warning	No Warning	No Warning
26	35	Dashed	-0.231	0.487	No Warning	No Warning
27	35	Dashed	-0.200	0.324	No Warning	No Warning
28	35	Dashed	-0.256	0.549	No Warning	No Warning
29	35	Dashed	-0.185	0.410	No Warning	No Warning
30	35	Dashed	-0.227	0.507	No Warning	No Warning
31	45	Dashed	-0.220	0.644	-0.042	0.693
32	45	Dashed	-0.201	0.601	-0.128	0.586
33	45	Dashed	-0.180	0.625	0.006	0.499
34	45	Dashed	-0.196	0.536	0.026	0.527
35	45	Dashed	-0.225	0.561	-0.027	0.545
36	55	Dashed	-0.196	0.624	0.006	0.610
37	55	Dashed	-0.193	0.621	0.006	0.581
38	55	Dashed	-0.215	0.634	0.022	0.604
39	55	Dashed	-0.246	0.716	-0.002	0.619
40	55	Dashed	-0.24	0.702	No Warning	No Warning

Table 4.2 Straight Lane, Right Lane Change Test Data

Test No.	Test Speed (mph)	Lane Type	Mobileye		Takata	
			Warning Range (m)	Range Rate (m/s)	Warning Range (m)	Range Rate (m/s)
1	25	Solid	No Warning	No Warning	No Warning	No Warning
2	25	Solid	No Warning	No Warning	No Warning	No Warning
3	25	Solid	No Warning	No Warning	No Warning	No Warning
4	25	Solid	No Warning	No Warning	No Warning	No Warning
5	25	Solid	No Warning	No Warning	No Warning	No Warning
6	35	Solid	-0.224	0.235	No Warning	No Warning
7	35	Solid	-0.232	0.277	No Warning	No Warning
8	35	Solid	-0.218	0.210	No Warning	No Warning
9	35	Solid	-0.229	0.381	No Warning	No Warning
10	35	Solid	-0.224	0.330	No Warning	No Warning
11	45	Solid	-0.267	0.444	-0.05	0.378
12	45	Solid	-0.231	0.352	-0.046	0.259
13	45	Solid	-0.272	0.468	-0.054	0.476
14	45	Solid	-0.267	0.369	-0.03	0.393
15	45	Solid	-0.255	0.330	-0.075	0.390
16	55	Solid	-0.293	0.657	-0.083	0.556
17	55	Solid	-0.207	0.552	-0.035	0.517
18	55	Solid	-0.283	0.562	-0.063	0.511
19	55	Solid	-0.243	0.547	-0.047	0.546
20	55	Solid	-0.275	0.602	-0.067	0.511
21	25	Dashed	No Warning	No Warning	No Warning	No Warning
22	25	Dashed	No Warning	No Warning	No Warning	No Warning
23	25	Dashed	No Warning	No Warning	No Warning	No Warning
24	25	Dashed	No Warning	No Warning	No Warning	No Warning
25	25	Dashed	No Warning	No Warning	No Warning	No Warning
26	35	Dashed	-0.179	0.275	No Warning	No Warning
27	35	Dashed	-0.209	0.396	No Warning	No Warning
28	35	Dashed	-0.209	0.384	No Warning	No Warning
29	35	Dashed	-0.232	0.312	No Warning	No Warning
30	35	Dashed	-0.244	0.464	No Warning	No Warning
31	45	Dashed	-0.248	0.414	-0.184	0.441
32	45	Dashed	-0.301	0.558	-0.438	0.648
33	45	Dashed	-0.259	0.447	-0.580	0.477
34	45	Dashed	-0.242	0.412	-0.067	0.406
35	45	Dashed	-0.253	0.447	-0.258	0.448
36	55	Dashed	-0.278	0.421	0.010	0.431
37	55	Dashed	-0.198	0.376	-0.587	0.543
38	55	Dashed	-0.297	0.620	-0.185	0.596
39	55	Dashed	-0.259	0.650	-0.692	0.744
40	55	Dashed	-0.308	0.531	-0.042	0.550

4.1.3 Partial Lane Change Tests

The partial lane change tests were conducted to observe the duration of warning of the two systems. In this test, the vehicle was driven on or just over the lane marking for an extended period without activating the turn signal to observe the behavior of the LDW systems. The test was conducted at 45 mph, for both sides of the vehicle, only on the solid lane marking, and with 5 repetitions for each condition giving a total of 10 trials. Data for the left and right side trials are shown in Table 4.3 and Table 4.4 respectively. Both the Mobileye and Takata systems produce an initial warning at the time of lane departure (for both sides of the vehicle), but no continued warning was produced by either of the LDW systems. In other words, no change in warning duration was observed compared to the Lane Change results presented in the previous section.

Table 4.3 Left Partial Lane Change Data

Test No.	Test Speed (mph)	Lane Type	Mobileye		Takata	
			Warning Range (m)	Range Rate (m/s)	Warning Range (m)	Range Rate (m/s)
1	45	Solid	-0.231	0.640	0.008	0.524
2	45	Solid	-0.159	0.342	0.032	0.469
3	45	Solid	-0.135	0.385	0.043	0.359
4	45	Solid	-0.14	0.379	0.034	0.458
5	45	Solid	-0.167	0.420	0.012	0.360

Table 4.4 Right Partial Lane Change Data

Test No.	Test Speed (mph)	Lane Type	Mobileye		Takata	
			Warning Range (m)	Range Rate (m/s)	Warning Range (m)	Range Rate (m/s)
1	45	Solid	-0.201	0.258	-0.082	0.325
2	45	Solid	-0.243	0.380	-0.033	0.410
3	45	Solid	-0.232	0.280	-0.073	0.445
4	45	Solid	-0.256	0.342	-0.071	0.468
5	45	Solid	-0.264	0.360	-0.069	0.432

4.1.4 Warning Prevention Tests

The warning prevention tests were conducted to check if the LDW systems produced false warnings when the driver changed lanes intentionally. This test is a standard lane change maneuver, with the appropriate turn signal activated while changing lanes. The test procedure was conducted at 35, 45, and 55 mph speeds on the solid lane marking while only 35 mph and 45 mph trials were conducted on the dashed lines. Five repetitions were conducted at each speed and for each side giving a total of 50 trials. Neither the Mobileye nor the Takata LDWS produced a false positive warning in any trial.

4.1.5 Warning Interrupt Test

Warning interrupt tests were conducted to determine if the duration of the LDW warning was reduced if the driver turned on the appropriate turn signal or applied the brakes once the lane departure warning occurs. This test was conducted at 45 mph on the solid lane marking. Five repetitions were conducted for each side and for each interrupt action (turn signal and braking) giving a total of 20 trials. The warning durations for these tests are compared to the average warning durations of the systems during the Lane Change tests when no interrupt action was taken. The average normal warning durations with no interruptions are shown in Table 4.5. No warnings exceeded 1 s in duration for the Takata or Mobileye units tested.

Table 4.5 Average Normal Warning Duration

Side	Mobileye (s)	Takata (s)
Left	0.89	0.88
Right	0.91	0.81

4.1.5.1 Turn Signal Interrupt

Data detailing the results from the turn signal interrupt left and right side tests are presented in Table 4.6 and Table 4.7. The time at which each system produced a warning, the time at which the turn signal was activated, the duration of the warning for each of the systems, and finally the duration of the warning after interrupt action for both the systems are listed in each table. For the left side trials, it was not determined why the Takata system did not produce any warnings (NW) after it functioned correctly during previous non-intentional lane change tests, while the warnings of the Mobileye system were shortened from a nominal duration of 0.89 s to around 0.70 s depending on when the turn signal was activated.

For the right side trials, no difference in the warning duration was observed for the Takata system (remained around nominal warning duration of 0.81 s), while the Mobileye warning duration was reduced to around 0.35 s. The shorter duration of the Mobileye warning is attributed to the earlier activation of the turn signal by the driver due to the earlier warning from the Takata system. This is confirmed by the observation that the Mobileye warning is consistently interrupted within 0.16 s of turn signal activation in all of the 10 trials.

Table 4.6 Left Side Warning Interrupt Data (Turn Signal)

Test No.	Warning Start Time (s)		Turn Signal Activation Time (s)	Warning Duration (s)		Warning Duration after Interrupt (s)	
	Mobileye	Takata		Mobileye	Takata	Mobileye	Takata
1	16.43	NW	17.01	0.74	NW	0.16	NA
2	16.38	NW	16.87	0.65	NW	0.16	NA
3	14.94	NW	15.52	0.73	NW	0.15	NA
4	16.90	NW	17.40	0.65	NW	0.15	NA
5	15.49	NW	16.01	0.64	NW	0.12	NA

Table 4.7 Right Side Warning Interrupt Data (Turn Signal)

Test No.	Warning Start Time (s)		Turn Signal Activation Time (s)	Warning Duration (s)		Warning Duration after Interrupt (s)	
	Mobileye	Takata		Mobileye	Takata	Mobileye	Takata
1	14.87	14.51	15.07	0.35	0.78	0.15	0.22
2	13.16	12.75	13.37	0.35	0.79	0.14	0.17
3	10.68	10.24	10.79	0.26	0.82	0.15	0.27
4	16.41	15.99	16.64	0.34	0.81	0.11	0.16
5	15.71	15.26	15.90	0.34	0.82	0.15	0.18

4.1.5.2 Brake Interrupt

The results for the left and right side brake interrupt tests are listed in Table 4.8 and Table 4.9 respectively. The warning durations remained unchanged relative to the observed average Lane Change tests durations (Table 4.5) despite the brake application on warning. Unlike the Turn

Signal Interrupt case, no trends regarding change of warning duration due to interrupt action were observed.

Table 4.8 Left Side Warning Interrupt Data (Braking)

Test No.	Warning Start Time (s)		Brake Activation Time (s)	Warning Duration (s)		Warning Duration After Braking (s)	
	Mobileye	Takata		Mobileye	Takata	Mobileye	Takata
1	15.44	15.10	15.59	0.95	0.83	0.80	0.34
2	15.01	14.59	15.01	0.93	0.82	0.93	0.4
3	12.43	12.10	12.50	0.93	0.86	0.86	0.46
4	15.70	15.34	15.81	0.84	0.88	0.73	0.41
5	13.75	13.31	13.83	0.93	0.91	0.85	0.39

Table 4.9 Right Side Warning Interrupt Data (Braking)

Test No.	Warning Start Time (s)		Brake Activation Time (s)	Warning Duration (s)		Warning Duration After Braking (s)	
	Mobileye	Takata		Mobileye	Takata	Mobileye	Takata
1	16.46	16.07	16.68	0.87	0.80	0.65	0.19
2	15.97	15.63	16.08	0.87	0.79	0.76	0.34
3	15.45	15.06	15.48	0.88	0.83	0.85	0.41
4	13.36	12.93	13.42	0.89	0.83	0.83	0.34
5	12.78	12.27	12.66	0.89	0.83	0.89	0.44

4.1.6 Opposite Turn Signal Test

This test is identical to the Warning Prevention test except that the wrong turn signal is applied by the driver during the lane change. This test was conducted at 45 mph on the solid lane marking only. Five repetitions were performed for each side for a total of 10 tests. The last test performed for the right side of the vehicle had incomplete data and hence is not included in any of the analysis.

For the 9 valid tests, the Takata LDWS was not deterred by the wrong turn signal and produced a normal warning each time as expected, whereas the Mobileye LDWS did not produce any warnings. This is because the Mobileye system installed on this particular Mack truck does not read the turn signal status from the vehicle CAN, but instead has analog turn signal inputs. For this configuration the Mobileye system does not differentiate between left and right turn signals and only checks if any turn signal is turned on. Hence the Mobileye system did not produce a warning when the wrong turn signal was turned on.

4.1.7 Warning Range and Range Rate Analysis

Combining all the tests, a total of 50 trials in each direction were true positive tests and produced a LDW from at least one of the systems (49 tests produced a LDW for the right side tests due to one file with incomplete data). All of these tests were combined to examine the warning range for each system.

The scatter plot of the warnings for the left and right side tests are presented in Figure 4.1 and Figure 4.2 respectively. The x-axis denotes test number, with the tests conducted on the solid and dashed lane marking clearly demarcated with different markers on the plots. The y-axis shows the distance to the lane marking of the corresponding SV side when the warning occurs (Warning Range). Positive values for warning range indicate that the vehicle is yet to cross the lane marking and negative numbers indicate that the vehicle has crossed over the center line of the lane marking when warning occurs.

From the plots, there is a trend visible that both of the systems produce a lane departure warning within a consistent range with the Takata system having some scatter. For the right side trials on the dashed lane marking, the Takata warning range data exhibits high variability which was not observed in identical tests for the left side.

Box plots of the warning range data for the left and right side tests are shown in Figure 4.3 and Figure 4.4 respectively. Outliers present in the Takata warning range data are identified with red plus signs in the figures. The Mobileye warning range data does not have any outliers. Key statistics of the warning range data are presented in Table 4.10 and Table 4.11 respectively for the left and right side tests.

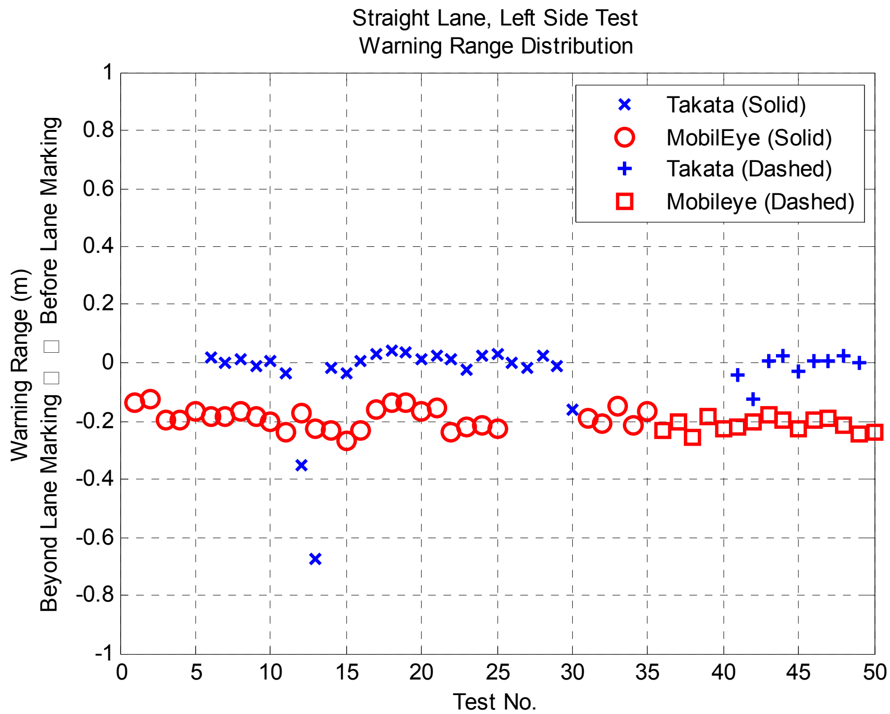

Figure 4.1 Straight Lane, Left Side Test - Warning Range Distribution

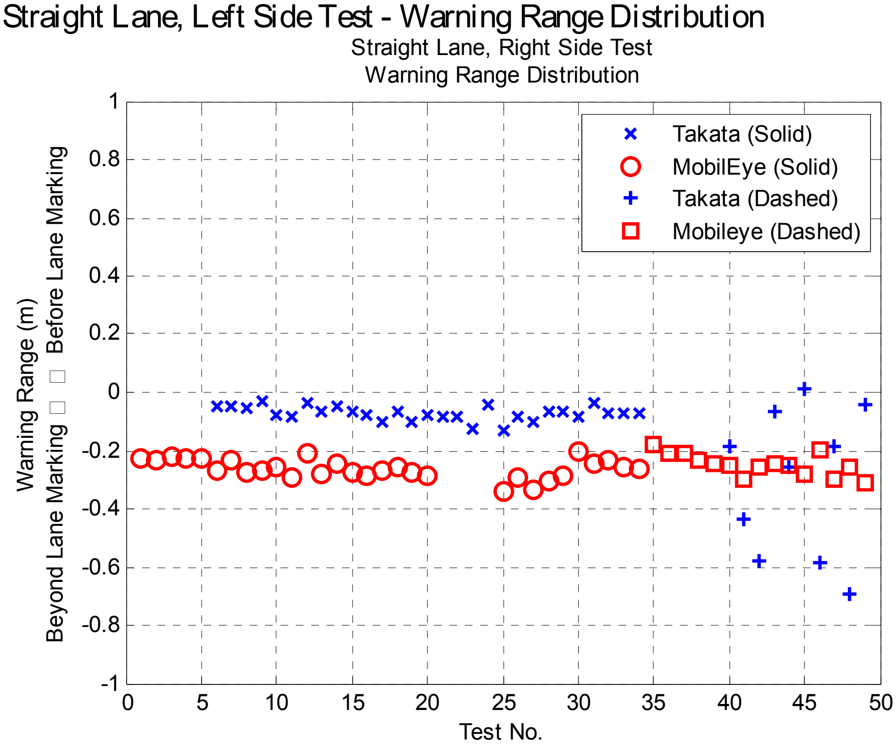

Figure 4.2 Straight Lane, Right Side Test - Warning Range Distribution

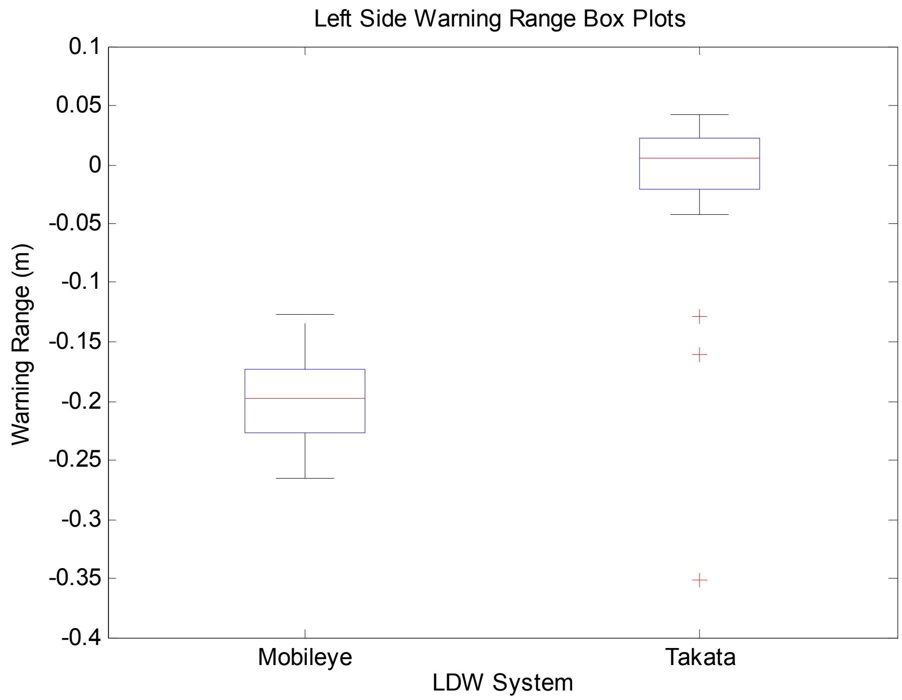

Figure 4.3 Straight Lane, Left Side, Warning Range Box Plot

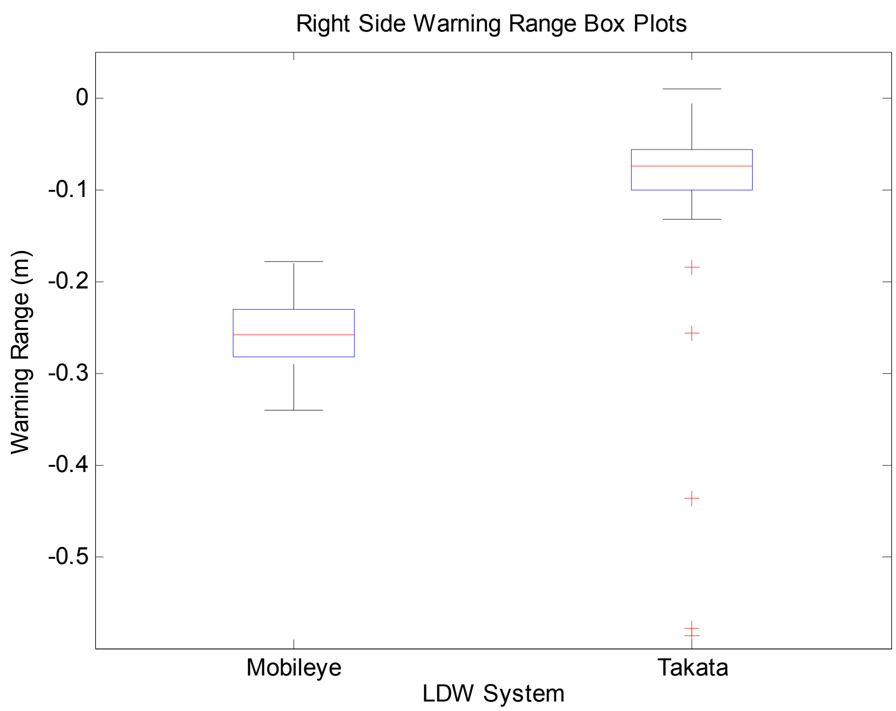

Figure 4.4 Straight Lane, Right Side, Warning Range Box Plot

Table 4.10 Straight Lane, Left Side, Warning Range Statistics

Statistic for Warning Range	Mobileye (m)	Takata (m)
Mean	-0.198	-0.035
Median	-0.198	0.005
Range	0.139	0.719
Standard Deviation	0.034	0.134

Table 4.11 Straight Lane, Right Side, Warning Range Statistics

Statistic for Warning Range	Mobileye (m)	Takata (m)
Mean	-0.257	-0.130
Median	-0.259	-0.075
Range	0.162	0.702
Standard Deviation	0.036	0.161

The relation between warning range and the range rate (rate at which the vehicle is approaching the lane marking) for the left side tests are shown in Figure 4.5. Analyzing the scatter plot reveals that as the range rate increases, the warning occurs later, further into the lane change.

For the left side trials, the negative Pearson's Correlation value (Table 4.12) for both the systems confirms that as the range rate increases, the warning occurs later, further into the lane change maneuver. The correlation values indicate that there is moderate to low correlation between range rate and warning range. The P value of 0.0008 for the Mobileye system indicates that the correlation is statistically significant, whereas the P value of 0.0019 for the Takata system indicates moderate statistical significance.

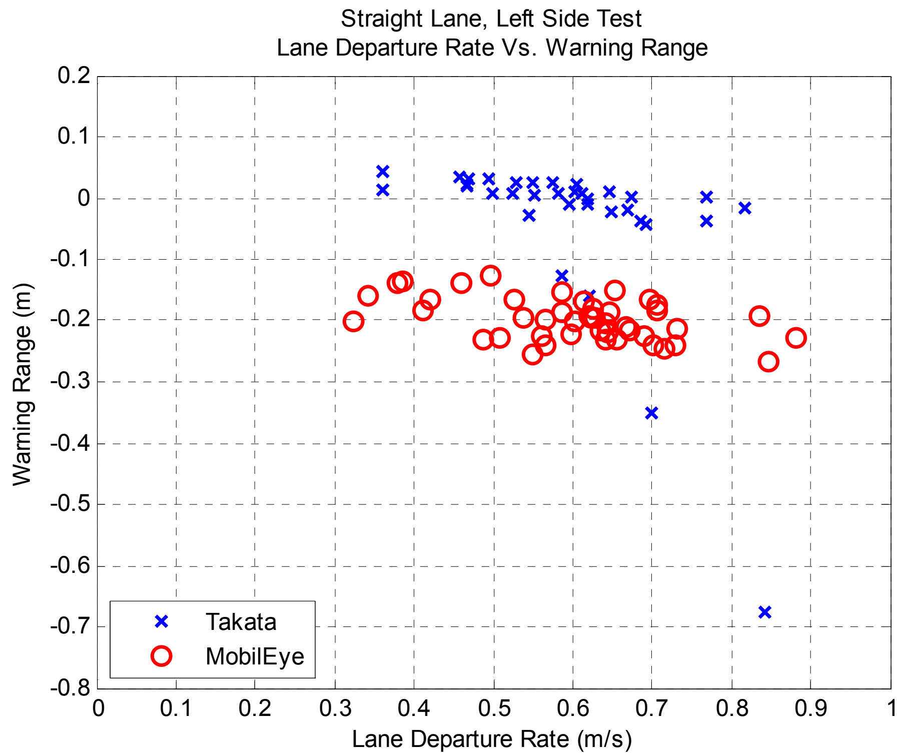

Figure 4.5 Left Side Test – Range Versus Range Rate Plot

Table 4.12 Left Side, Warning Range Versus Range Rate Statistics

Warning Range vs. Range Rate Statistics	Mobileye	Takata
Pearson's Correlation (R)	-0.4817	-0.5136
P value	0.0008	0.0019

The warning range vs. range rate data for the right side trials is shown in Figure 4.6. Data from the statistical analysis of the range vs. range rate data is shown in Table 4.13. The negative Pearson's Correlation value for both the systems confirms that as the range rate increases, the warning occurs later, further into the lane change maneuver. The correlation values indicate that there is moderate correlation between range rate and warning range. The P values of 1.53e-08 and 0.0007 for the Mobileye and Takata systems indicates that the correlation is statistically significant.

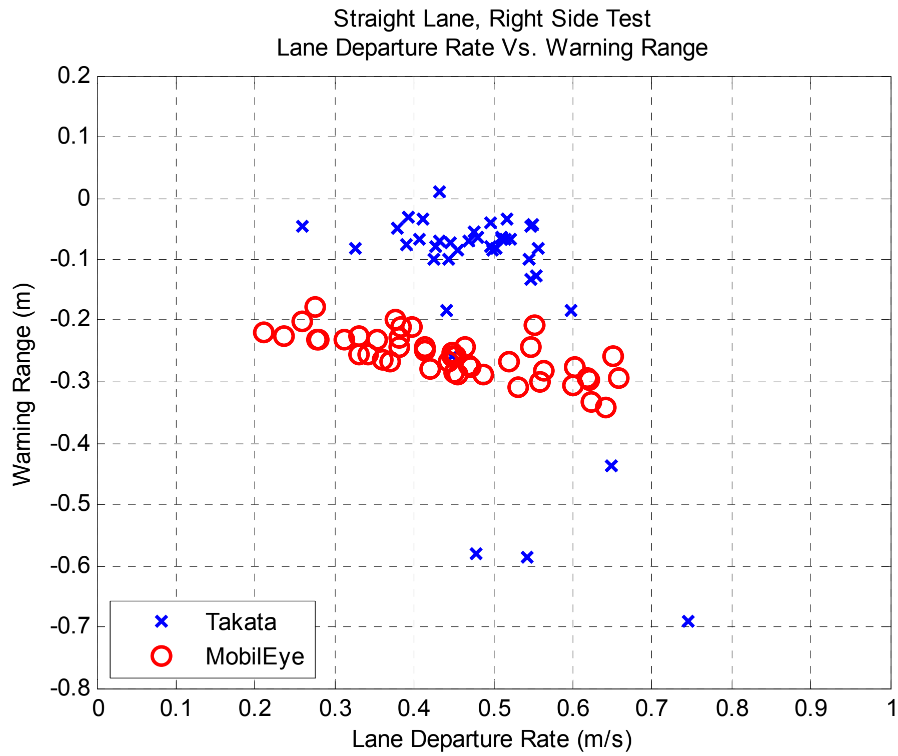

Figure 4.6 Right Side Test – Range Versus Range Rate Plot

Table 4.13 Right Side, Warning Range Versus Range Rate Statistics

Warning Range vs. Range Rate Statistics	Mobileye	Takata
Pearson's Correlation (R)	-0.7272	-0.5196
P value	1.53e-08	0.0007

The warning range, range rate, lane type and test speed for all the left and right side runs discussed in this section are presented in Table 4.14, Table 4.15, Table 4.16, and Table 4.17.

Table 4.14 Straight Solid Lane, Left LDW Tests Summary

Test No.	Test Speed (mph)	Lane Type	Mobileye		Takata	
			Warning Range (m)	Range Rate (m/s)	Warning Range (m)	Range Rate (m/s)
1	35	Solid	-0.138	0.460	No Warning	No Warning
2	35	Solid	-0.127	0.496	No Warning	No Warning
3	35	Solid	-0.195	0.628	No Warning	No Warning
4	35	Solid	-0.198	0.566	No Warning	No Warning
5	35	Solid	-0.167	0.525	No Warning	No Warning
6	45	Solid	-0.188	0.585	0.019	0.466
7	45	Solid	-0.187	0.646	0.002	0.673
8	45	Solid	-0.168	0.613	0.010	0.601
9	45	Solid	-0.184	0.706	-0.011	0.619
10	45	Solid	-0.205	0.642	0.005	0.550
11	55	Solid	-0.241	0.730	-0.038	0.685
12	55	Solid	-0.175	0.706	-0.351	0.699
13	55	Solid	-0.228	0.882	-0.676	0.841
14	55	Solid	-0.231	0.655	-0.018	0.668
15	55	Solid	-0.266	0.847	-0.036	0.767
16	45	Solid	-0.231	0.640	0.008	0.524
17	45	Solid	-0.159	0.342	0.032	0.469
18	45	Solid	-0.135	0.385	0.043	0.359
19	45	Solid	-0.140	0.379	0.034	0.458
20	45	Solid	-0.167	0.420	0.012	0.360
21	45	Solid	-0.155	0.585	0.023	0.465
22	45	Solid	-0.240	0.566	0.009	0.646
23	45	Solid	-0.222	0.597	-0.021	0.648
24	45	Solid	-0.212	0.731	0.025	0.574
25	45	Solid	-0.226	0.689	0.030	0.495
26	45	Solid	No Warning	No Warning	0.001	0.768
27	45	Solid	No Warning	No Warning	-0.017	0.816
28	45	Solid	No Warning	No Warning	0.025	0.550
29	45	Solid	No Warning	No Warning	-0.011	0.595
30	45	Solid	No Warning	No Warning	-0.161	0.621
31	45	Solid	-0.194	0.836	No Warning	No Warning
32	45	Solid	-0.211	0.666	No Warning	No Warning
33	45	Solid	-0.150	0.652	No Warning	No Warning
34	45	Solid	-0.217	0.671	No Warning	No Warning
35	45	Solid	-0.165	0.697	No Warning	No Warning

Table 4.15 Straight Solid Lane, Right LDW Tests Summary

Test No.	Test Speed (mph)	Lane Type	Mobileye		Takata	
			Warning Range (m)	Range Rate (m/s)	Warning Range (m)	Range Rate (m/s)
1	35	Solid	-0.224	0.235	No Warning	No Warning
2	35	Solid	-0.232	0.277	No Warning	No Warning
3	35	Solid	-0.218	0.210	No Warning	No Warning
4	35	Solid	-0.229	0.381	No Warning	No Warning
5	35	Solid	-0.224	0.330	No Warning	No Warning
6	45	Solid	-0.267	0.444	-0.050	0.378
7	45	Solid	-0.231	0.352	-0.046	0.259
8	45	Solid	-0.272	0.468	-0.054	0.476
9	45	Solid	-0.267	0.369	-0.030	0.393
10	45	Solid	-0.255	0.330	-0.075	0.390
11	55	Solid	-0.293	0.657	-0.083	0.556
12	55	Solid	-0.207	0.552	-0.035	0.517
13	55	Solid	-0.283	0.562	-0.063	0.511
14	55	Solid	-0.243	0.547	-0.047	0.546
15	55	Solid	-0.275	0.602	-0.067	0.511
16	45	Solid	-0.289	0.488	-0.079	0.496
17	45	Solid	-0.266	0.518	-0.099	0.424
18	45	Solid	-0.259	0.453	-0.064	0.481
19	45	Solid	-0.277	0.471	-0.101	0.444
20	45	Solid	-0.284	0.451	-0.078	0.427
21	45	Solid	No Warning	No Warning	-0.085	0.498
22	45	Solid	No Warning	No Warning	-0.083	0.504
23	45	Solid	No Warning	No Warning	-0.126	0.553
24	45	Solid	No Warning	No Warning	-0.041	0.496
25	45	Solid	-0.341	0.642	-0.133	0.546
26	45	Solid	-0.295	0.617	-0.084	0.454
27	45	Solid	-0.334	0.623	-0.101	0.545
28	45	Solid	-0.307	0.599	-0.066	0.522
29	45	Solid	-0.289	0.455	-0.066	0.515
30	45	Solid	-0.201	0.258	-0.082	0.325
31	45	Solid	-0.243	0.380	-0.033	0.410
32	45	Solid	-0.232	0.280	-0.073	0.445
33	45	Solid	-0.256	0.342	-0.071	0.468
34	45	Solid	-0.264	0.360	-0.069	0.432

Table 4.16 Straight Dashed Lane, Left LDW Tests Summary

Test No.	Test Speed (mph)	Lane Type	Mobileye		Takata	
			Warning Range (m)	Range Rate (m/s)	Warning Range (m)	Range Rate (m/s)
1	35	Dashed	-0.231	0.487	No Warning	No Warning
2	35	Dashed	-0.200	0.324	No Warning	No Warning
3	35	Dashed	-0.256	0.549	No Warning	No Warning
4	35	Dashed	-0.185	0.410	No Warning	No Warning
5	35	Dashed	-0.227	0.507	No Warning	No Warning
6	45	Dashed	-0.220	0.644	-0.042	0.693
7	45	Dashed	-0.201	0.601	-0.128	0.586
8	45	Dashed	-0.180	0.625	0.006	0.499
9	45	Dashed	-0.196	0.536	0.026	0.527
10	45	Dashed	-0.225	0.561	-0.027	0.545
11	55	Dashed	-0.196	0.624	0.006	0.610
12	55	Dashed	-0.193	0.621	0.006	0.581
13	55	Dashed	-0.215	0.634	0.022	0.604
14	55	Dashed	-0.246	0.716	-0.002	0.619
15	55	Dashed	-0.240	0.702	No Warning	No Warning

Table 4.17 Straight Dashed Lane, Right LDW Tests Summary

Test No.	Test Speed (mph)	Lane Type	Mobileye		Takata	
			Warning Range (m)	Range Rate (m/s)	Warning Range (m)	Range Rate (m/s)
1	35	Dashed	-0.179	0.275	No Warning	No Warning
2	35	Dashed	-0.209	0.396	No Warning	No Warning
3	35	Dashed	-0.209	0.384	No Warning	No Warning
4	35	Dashed	-0.232	0.312	No Warning	No Warning
5	35	Dashed	-0.244	0.464	No Warning	No Warning
6	45	Dashed	-0.248	0.414	-0.184	0.441
7	45	Dashed	-0.301	0.558	-0.438	0.648
8	45	Dashed	-0.259	0.447	-0.580	0.477
9	45	Dashed	-0.242	0.412	-0.067	0.406
10	45	Dashed	-0.253	0.447	-0.258	0.448
11	55	Dashed	-0.278	0.421	0.010	0.431
12	55	Dashed	-0.198	0.376	-0.587	0.543
13	55	Dashed	-0.297	0.620	-0.185	0.596
14	55	Dashed	-0.259	0.650	-0.692	0.744
15	55	Dashed	-0.308	0.531	-0.042	0.550

4.2 Curved-Lane Test Results

The curved lane tests were conducted on the 764-ft (233 m) radius South Loop and 630-ft (192 m) radius North Loop of the VDA. The test matrix for the curved-lane tests is given in Table 3.3 and lists conditions for baseline tests, lane change tests, and warning prevention tests. Each test was repeated 5 times for the north and south loops of the VDA for both the solid and dashed lines. This gives a total 120 tests, of which 80 tests are false positive tests. The results for each test type are discussed in the sections below.

4.2.1 Baseline Tests

The baseline tests involved driving the vehicle within the lane to check for false positives from the LDW systems. The baseline test consisted of 5 runs at 45 mph for both lane marking types (solid and dashed), for both sides of the vehicle, and for both the loops of the VDA. Overall, 40 trials of the baseline test were conducted. No false positive warnings were observed from either the Mobileye or Takata system.

4.2.2 Lane Change Tests

The lane change tests were performed to check the proper functioning of the LDW systems on curved roads. Lane change tests were performed at 45 mph, with 5 repetitions for each line type and each side of the vehicle. The tests were repeated for both the North and South loops of the VDA.

4.2.2.1 South Loop Data

Twenty lane change maneuvers were performed on the South loop of the VDA. Scatter plot of the warning ranges from these tests for the left and right side tests are shown in Figure 4.7 and Figure 4.8 respectively. The x-axis denotes test number and the y-axis shows the distance to the lane marking or range when the warning occurs. Positive values for the vehicle range indicate that the vehicle is yet to cross the lane marking and negative numbers indicate that the vehicle has crossed over the center line of the lane marking when warning occurs.

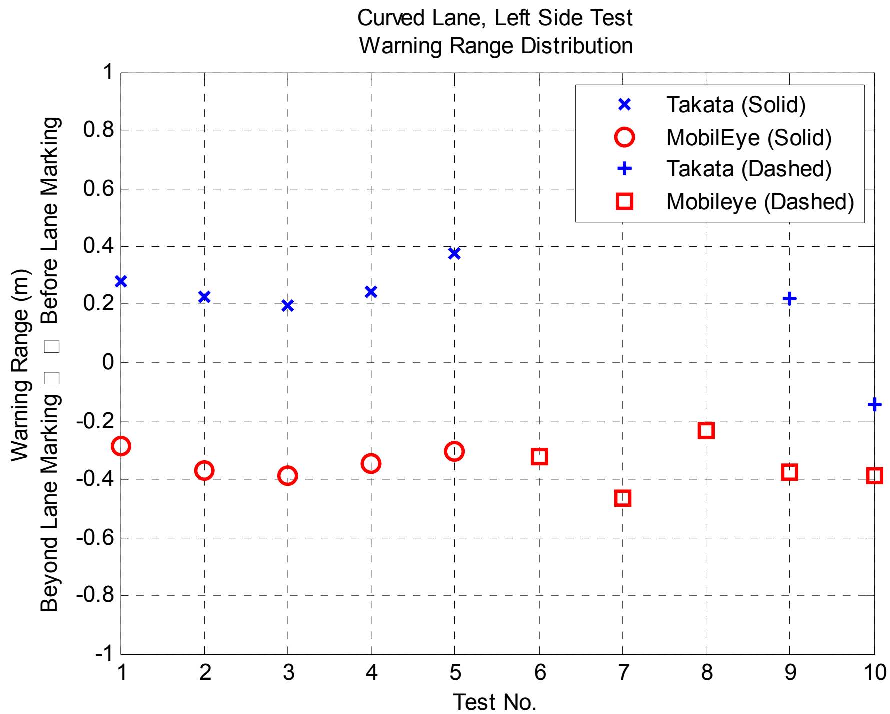

Figure 4.7 Curved Lane, Left Side Test - Warning Distribution

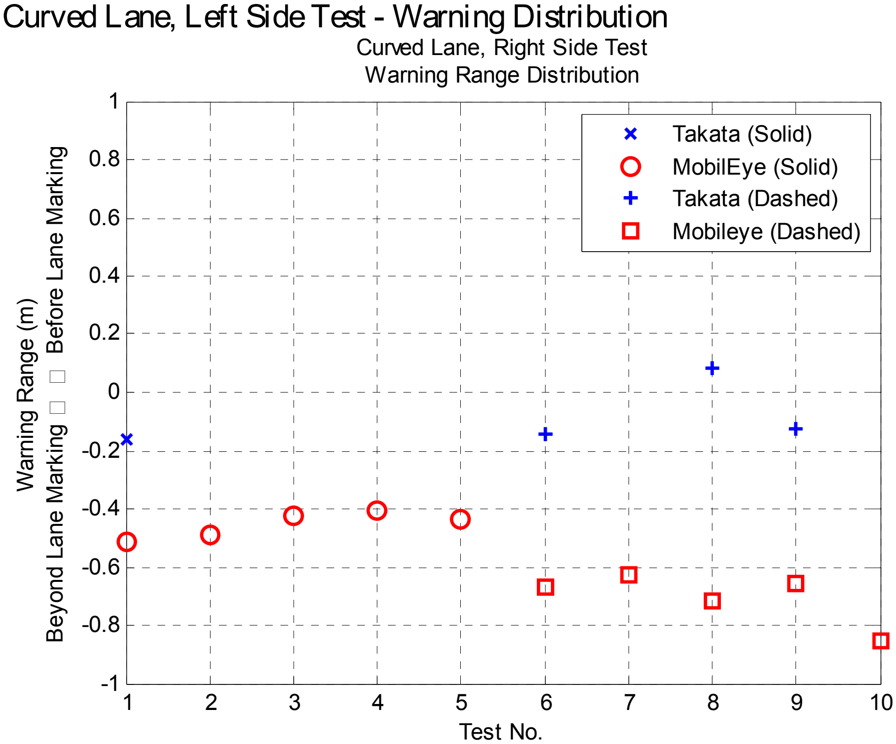

Figure 4.8 Curved Lane, Right Side Test – Warning Distribution

A few key statistics of warning range data for the left and right side trials are tabulated in Table 4.18 and Table 4.19 respectively. It is to be noted that there are very few data points for the

Takata warnings and hence the Takata statistical findings should be used with care. These statistics cannot be readily generalized as an indicator for the population.

Table 4.18 Curved Lane, Left Side, Warning Range Statistics

Statistic for Warning Range	Mobileye (m)	Takata (m)
Mean	-0.348*	0.200+
Median	-0.359*	0.228+
Range	0.234*	0.521+
Standard Deviation	0.065*	0.162+

* Statistics for only 10 data points + Statistics for only 7 data points

Table 4.19 Curved Lane, Right Side, Warning Range Statistics

Statistic for Warning Range	Mobileye (m)	Takata (m)
Mean	-0.579*	-0.087+
Median	-0.568*	-0.135+
Range	0.453*	0.246+
Standard Deviation	0.149*	0.114+

* Statistics for only 10 data points + Statistics for only 4 data points

The relation between warning range and the range rate (rate at which the vehicle is approaching the lane marking) are shown in Figure 4.9 and Figure 4.10 for the left and right side tests respectively. The scatter plots indicate that as the range rate increases, the warning occurs further into the lane change maneuver.

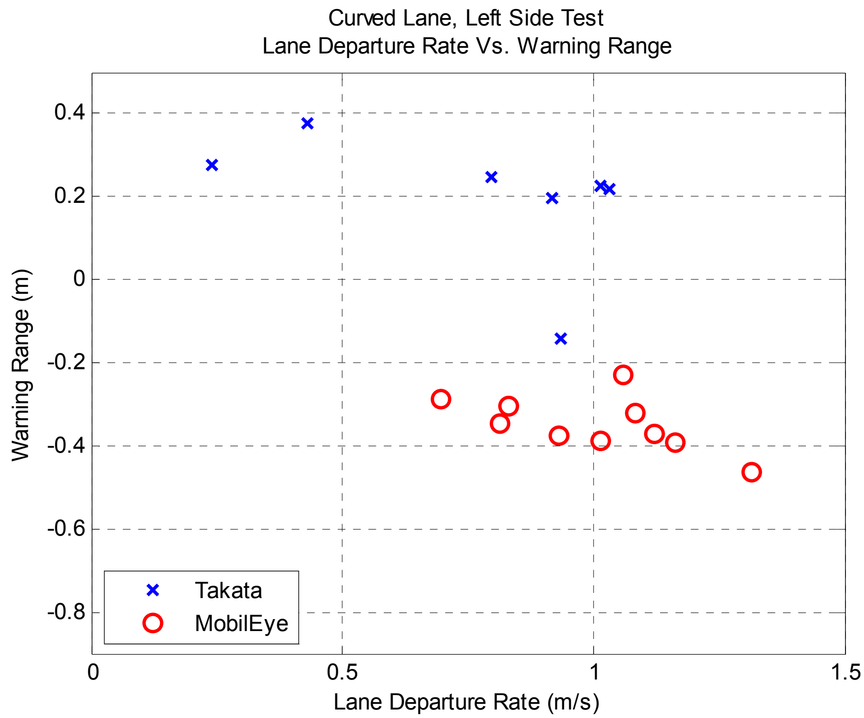

Figure 4.9 Curved Lane, Left Side Test – Range Versus Range Rate Plot

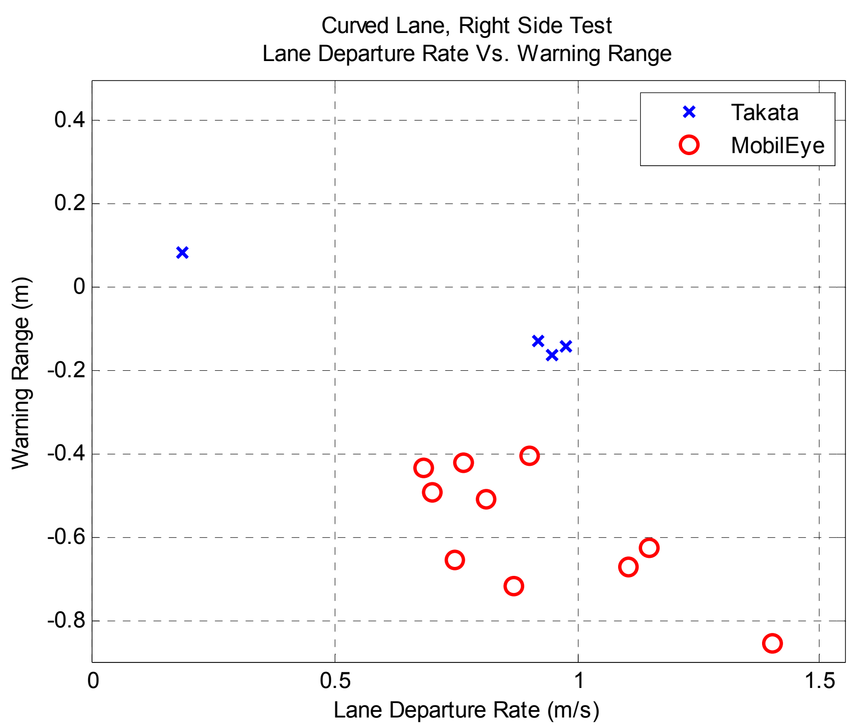

Figure 4.10 Curved Lane, Right Side Test – Range Versus Range Rate Plot

The statistics of the warning range vs. range rate data are tabulated in Table 4.20 and Table 4.21 for the left and right side respectively. The negative correlation values confirm that as the range rate increases, the warning occurs further into the lane change. For the left side tests, the correlation values indicate that there is moderate correlation between range rate and warning range. The high P value for the Takata indicates that the correlation is not statistically significant. For the Mobileye, the P value is 0.084, slightly higher than the 0.05 threshold for statistical significance. For the right side tests, the correlation values indicate a strong correlation and the P values are lower than the 0.05 threshold indicating statistical significance. However, it is to be noted that the data set is very small for the Takata warning rage data.

Table 4.20 Curved Lane, Left Side, Warning Range Versus Range Rate Statistics

Warning Range vs. Range Rate Statistics	Mobileye	Takata
Pearson's Correlation (R)	-0.5724*	-0.4836+
P value	0.0838*	0.2716+

* Statistics for only 10 data points + Statistics for only 4 data points

Table 4.21 Curved Lane, Right Side, Warning Range Versus Range Rate Statistics

Warning Range vs. Range Rate Statistics	Mobileye	Takata
Pearson's Correlation (R)	-0.7291*	-0.9935+
P value	0.0167*	0.0065+

* Statistics for only 10 data points + Statistics for only 4 data points

The curved lane data presented above are detailed below in Table 4.22 and Table 4.23.

Table 4.22 Curved Lane Left LDW Tests Summary

Test No.	Test Speed (mph)	Lane Type	Mobileye		Takata	
			Warning Range (m)	Range Rate (m/s)	Warning Range (m)	Range Rate (m/s)
1	45	Solid	-0.287	0.697	0.278	0.239
2	45	Solid	-0.373	1.120	0.228	1.014
3	45	Solid	-0.386	1.015	0.196	0.919
4	45	Solid	-0.346	0.813	0.247	0.796
5	45	Solid	-0.306	0.831	0.378	0.429
6	45	Dashed	-0.322	1.083	No Warning	No Warning
7	45	Dashed	-0.465	1.316	No Warning	No Warning
8	45	Dashed	-0.231	1.060	No Warning	No Warning
9	45	Dashed	-0.375	0.932	0.218	1.032
10	45	Dashed	-0.391	1.163	-0.143	0.934

Table 4.23 Curved Lane Right LDW Tests Summary

Test No.	Test Speed (mph)	Lane Type	Mobileye		Takata	
			Warning Range (m)	Range Rate (m/s)	Warning Range (m)	Range Rate (m/s)
1	45	Solid	-0.511	0.812	-0.163	0.949
2	45	Solid	-0.492	0.701	No Warning	No Warning
3	45	Solid	-0.422	0.765	No Warning	No Warning
4	45	Solid	-0.403	0.901	No Warning	No Warning
5	45	Solid	-0.436	0.682	No Warning	No Warning
6	45	Dashed	-0.671	1.107	-0.142	0.976
7	45	Dashed	-0.625	1.147	No Warning	No Warning
8	45	Dashed	-0.718	0.869	0.083	0.186
9	45	Dashed	-0.656	0.749	-0.128	0.919
10	45	Dashed	-0.856	1.400	No Warning	No Warning

4.2.2.2 North Loop data

The warning results for the North loop of the VDA are tabulated in Table 4.24. The results of the 20 tests performed on the North loop of the VDA are not plotted due to the unavailability of RT-Range lane distance data for the North loop.

Data and video footage indicate that the Takata LDWS did not produce any warnings for the solid lane marking for the right side tests and only produced one warning for the dashed line for the right side. For the left side tests, the Takata system performed well for the solid line (warnings for all 5 trials), but only produced warnings on 3 out of 5 trials for the dashed line. The Mobileye system produced warnings for all the 20 trials.

Table 4.24 North Loop Curves Test LDW Data

Test No.	Lane Type	Side	Warning (Yes/No)	
			Takata	Mobileye
1	Solid	Left	Yes	Yes
2	Solid	Left	Yes	Yes
3	Solid	Left	Yes	Yes
4	Solid	Left	Yes	Yes
5	Solid	Left	Yes	Yes
6	Solid	Right	No	Yes
7	Solid	Right	No	Yes
8	Solid	Right	No	Yes
9	Solid	Right	No	Yes
10	Solid	Right	No	Yes
11	Dashed	Left	Yes	Yes
12	Dashed	Left	No	Yes
13	Dashed	Left	Yes	Yes
14	Dashed	Left	No	Yes
15	Dashed	Left	Yes	Yes
16	Dashed	Right	No	Yes
17	Dashed	Right	No	Yes
18	Dashed	Right	Yes	Yes
19	Dashed	Right	No	Yes
20	Dashed	Right	No	Yes

4.2.3 Warning Prevention Tests

The warning prevention tests for the curved lanes are similar to the lane change tests, but are performed with the appropriate turn-signal turned on. This is a false positive test. The warning prevention tests were performed at 45 mph, with 5 repetitions for each lane type and each side of the vehicle. The tests were repeated for both the North and South loops of the VDA. Overall, 40 runs were conducted. No false positives were observed for either the Mobileye or Takata systems.

4.3 Summary

The data of the lane departure tests performed for both the straight and curved lanes were discussed in detail and statistical analysis of the warning data is presented. Some general observations are presented below;

- Overall, there were no false positive warnings observed during the trials in either the straight or the curved lane tests.
- The Takata system did not produce a warning at 35 mph tests, while the Mobileye system did.
- The Mobileye system, as installed on this SV, does not differentiate between left and right turn signals and does not produce a warning when the wrong turn signal is activated. The Takata system does differentiate between left and right turn signals and did properly warn of lane departure while the wrong turn signal was activated.
- The application of the turn signal interrupted the warning from the Mobileye system, but did not have any effect on the warning from the Takata system.
- Brake application did not interrupt warnings from either of the LDW systems tested.
- The general trend indicates that as the range rate increases, the lane departure warning occurs later, further into the lane change.
- For the curves tested, the Mobileye system performed more consistently compared to the Takata system.
- For the camera-based LDW systems, the warning threshold speeds ranged from 34 to 42 mph (55 to 68 km/h).

5 CONCLUSION

5.1 Test Procedure Evaluation for Heavy-Vehicle LDW Systems

Two LDW systems were tested on straight and curved lane lines and their effectiveness in producing warnings for unintended lane departures were studied. From the results outlined in Chapter 4, basic observations and an evaluation of the test procedure are detailed below.

Curved lane testing results, discussed in Section 4.2, has its limitations and should be used with caution. Since suitable curved road test facilities with appropriate radii and superelevation banking are not readily available, the turning loops on the VDA were repurposed to conduct these tests. This allowed for only two fixed radii to be tested, but further research is needed to completely characterize the system performance in curved lane scenarios.The straight line test adopted from the NCAP test for light vehicles, with changes to accommodate heavy vehicles, as discussed in Section 3.2.1 appears to be a suitable test procedure for heavy vehicles.

5.2 Test Execution Guidelines Followed

Test guidelines were established to facilitate consistent and repeatable testing for the purposes of this study. The tests were considered invalid if the data did not conform to any of these guidelines. These guidelines included test speed variability, lane departure rate, visibility etc. and are detailied below.

5.2.1 General Test Validity Metrics Used

A valid test should conform to the test procedure, with some allowances made for test variabilities. For a test to be considered valid, the SV should pass through the test gate without knocking over any of the cones. The driver must refrain from applying the turn signal, any sudden acceleration, or braking during the test. Tests were conducted during dry weather conditions with visibility of 1 mile at the least. This is so that both the driver and the LDWS could see the lane markings and the tests are repeatable. Vehicle test speed and lateral lane departure velocity requirements are discussed below.

5.2.2 Test Vehicle Speed

The LDW developmental tests were conducted at 35 mph (56.3 km/h), 45 mph (72.4 km/h), and 55 mph (88.5 km/h). A test was considered valid if the test speed remained within ± 2 km/h (± 1.2 mph) from the target speed. It was required for the speed to remain within this window from the "entry gate" to the "test end point," where the end of the test is determined as when the appropriate front axle tire has crossed the lane line being tested by 1 m (3.3 ft).

5.2.3 Test Vehicle Lane Departure Rate

The test procedure is set up so that the lane departure rate remains low during the test. For this test, it was ensured that the lane departure rate be within 0.1 and 1 m/s (0.3 and 3.3 ft/s). Pylons may be placed on the test surface (CONE#1 and CONE#2 in Figure 5.1) to assist the driver in being able to efficiently achieve the lane departure rate range.

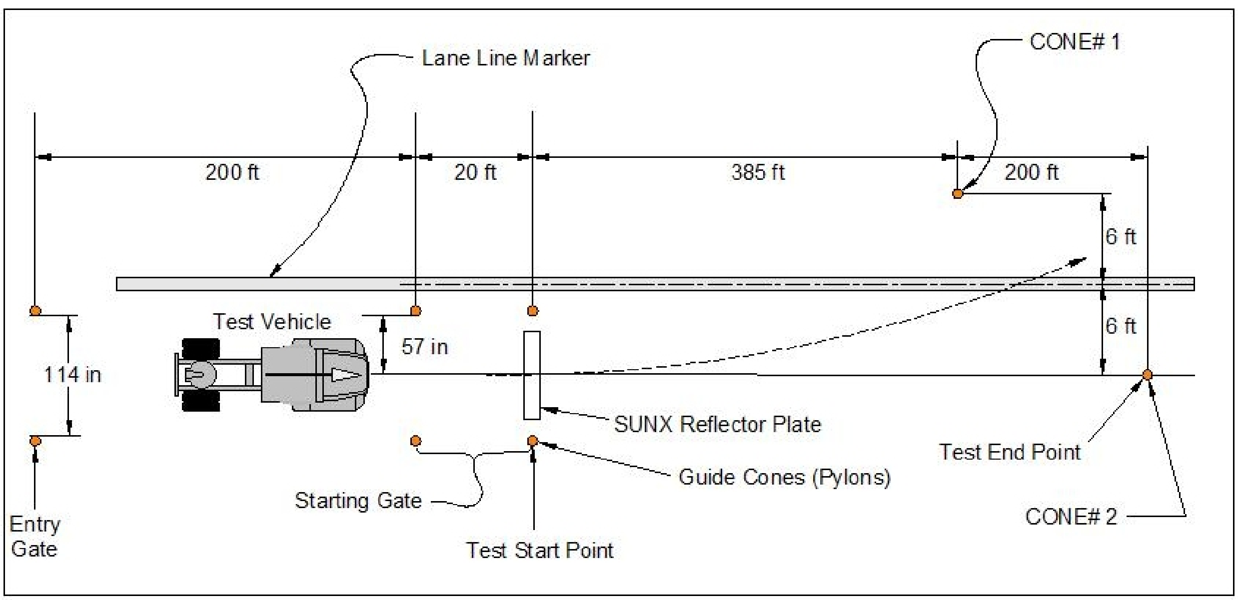

Figure 5.1 Recommended Pylon Spacing to Facilitate Valid Lateral Velocities
Note: For illustration only – not to scale.

5.3 Heavy-Vehicle LDW Test Evaluation

For this study, each valid test was judged depending on whether the LDWS produced an appropriate alert during the maneuver. In the context of this report, a lane departure is considered to occur when the appropriate front axle tire breaches the inboard lane line edge. The lateral distance from the front axle outside tire wall to the center line of the lane was measured when an alert was issued.

Test results indicate that alerts were generally issued within 0.5m after crossing the lane line. However, outliers were observed but never more than 1m. Alerts were more repeatable on straight segments compared to curved, and solid lines compared to dashed. A summary of the performance of the two systems (Mobileye and Takata) used in the test procedure evaluated is presented below. Table 5.1 lists the results for the straight line lane change tests, for two different speeds, and line types. The direction of test is also specified, followed by the performance which is indicated as "number of appropriate LDWs/number of tests conducted." Table 5.2 and Table 5.3 list the same results for the south-loop and north-loop curved-line lane change tests for the two systems.

Table 5.1 Heavy-Vehicle Straight Lane LDWS Evaluation

Velocity (mph)	Line Type	Departure Direction	Score	
			Mobileye	Takata
45	Solid	L	5/5	5/5
		R	5/5	5/5
	Dashed	L	5/5	5/5
		R	5/5	3/5
55	Solid	L	5/5	4/5
		R	5/5	5/5
	Dashed	L	5/5	4/5
		R	5/5	3/5
		Total	40/40	34/40
		Percentage	100%	85%

Table 5.1 indicates that the Takata LDWS performance was degraded on the dotted lines when compared to its performance on the solid line. The Takata system's performance also appears to be degraded during right side lane departures on the dashed line compared to left side lane departures. The Mobileye system performed very well on the straight line tests and correctly identified and warned on each unintended lane crossing. Overall, the Mobileye system had a perfect score in straight-line lane-change only tests, whereas the Takata system scored 85 percent.

Table 5.2 Heavy-Vehicle Curved Lane LDWS Evaluation – VDA South Loop

Velocity (mph)	Curved Line Type	Departure Direction	Score	
			Mobileye	Takata
45	Solid	L	5/5	5/5
		R	5/5	1/5
	Dashed	L	5/5	2/5
		R	5/5	3/5
		Total	20/20	11/20
		Percentage	100%	55%

Table 5.3 Heavy-Vehicle Curved Lane LDWS Evaluation – VDA North Loop

Velocity (mph)	Curved Line Type	Departure Direction	Score	
			Mobileye	Takata
45	Solid	L	5/5	5/5
		R	5/5	0/5
	Dashed	L	5/5	3/5
		R	5/5	1/5
		Total	20/20	9/20
		Percentage	100%	45%

Data shown in Table 5.2 and Table 5.3 indicates that the Mobileye system performed well for the curved lane tests as well (scoring a 100 percent), while the Takata system faired poorly (scoring only 55 and 45 percent for the south and north loop tests respectively). Here again, the Takata system performed worse on the dashed line when compared to the solid line.

5.4 Additional Comments

For optimal effectiveness of the system, the occurrences of false warnings and early warnings in systems should be discouraged. Repeated warnings may by a source of annoyance to the driver, which may lead to the system being disabled. On similar lines, the authors observed that it appears to be beneficial for the LDW systems to be capable of interrupting a warning, should the driver activate the appropriate turn signal while/prior to the lane departure event.

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APPENDIX A- RT AND RT RANGE

This section is based on a NHTSA report titled "A Test Track Protocol for Assessing Forward Collision Warning Driver-Vehicle Interface Effectiveness [32]. Although the text describes the configuration and operation of the RT ranging system as used for a dynamic braking test, the same installation was used for the dynamic lane tests in this report.

RT range monitoring systems were installed in the SV and POV. The following detail describes the installation of these systems as they were configured.

Oxford Technical Solutions' RT3002 and RT-Range provided inertial data and high accuracy GPS positions in real-time. The RT3002 is comprised of an inertial measuring unit and an RTK (real time kinematic) GPS engine. The IMU contains a 6-degree-of-freedom inertial sensing unit. The RTK makes use of L1/L2 band GPS, receiving differential correction from a local base station. The IMU measurements are then augmented with the differentially corrected RTK-GPS data at a 100Hz sample rate. Sixteen channels were recorded on a laptop computer using OTS software. The majority of channels come directly from the RT3002 via ethernet, while the remaining ones are calculated by the software. Below is a list of channels and accuracy specifications (Table B.1.).

Table B.1. RT3002 Channels and Accuracy Specifications

Channels	Range	Accuracy	Sensory Mode
X, Y, Z Accelerations	100 m/s^2	0.01 m/s^2	IMU
X,Y, Z Angular Rates	100 deg/s	0.01 deg/s	IMU
Pitch and Roll (calculated)	0-90 deg	0.03 deg	IMU
Vehicle Heading (calculated)	0-360 deg	0.1 deg	IMU / GPS
GPS Position (Lat, Long, Alt)	extensive[1]	2 cm	IMU / GPS
Velocities (North, East, Down)	0.05km/h and higher	0.05 km/h	IMU / GPS
Vehicle Speed (calculated)	practically unlimited[2]	0.05 km/h	IMU / GPS

The RT-Range is used in conjunction with the RT3002 inertial and GPS navigation system to measure the relative position, i.e., range, between the SV and a POV, which could be another

[1] Anywhere on or near the Earth with an unobstructed view of four or more GPS satellites.

[2] While the exact upper limit is not known, it exceeds the top speed of the test vehicle.

vehicle (SMLV scenario) or a fixed point on the ground (SLV scenario). Positional accuracy between two RT3002's using RT-Range is 3 cm. From the RT-Range User Manual:

> "The Range between two vehicles works by putting an RT3000 system in each vehicle. Measurements of distance are made from the SV to the POV. The measurements are in the reference frame of the SV, so a longitudinal, lateral and resultant range can be measured.
>
> The measurements in the POV are transmitted by radio back to the SV. The RT-Range computes the distances, velocities, accelerations and other parameters about the vehicles. The radio is a high speed Wireless LAN. Because of radio delays the RT-Range will predict the position of the POV so that the measurements can be output in real-time with a low latency. … Typically the radio delay is 10ms and there is no degradation in performance with this delay. Even when the radio delay is up to 50ms, the error in range is very small (less than 1cm)." [3]

The RT-Range and the RT3002 both have the ability to displace their measurements to a remote position. As used in this research, the RT3002's held a fixed location near the vehicle center of gravity without displaced measurements, while the two RT-Range units did use this displacement feature. The exact position and orientation of the IMU's were resolved to vehicle C.G. to improve the accuracy of the angular rates and accelerations.

The RT-Range SV unit was used for all tests and had its position displaced to the leading edge of the test vehicle's front bumper. The RT-Range POV unit was only used during the Slower Moving Lead Vehicle scenarios. It was located in the tow vehicle and had its position displaced to the rearmost edge of the towed plywood platform while the tow rope was placed under tension of 100 lbs.

Initial installation of the RT3002 into the test and tow vehicles required that measurements be made for the antenna and IMU's exact locations in and on the vehicles and then entered into a software configuration file (Figure B.1). The locations of the center of the front and rear bumpers

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[3] Any effect these delays and attendant estimations might have had on data accuracy would only occur in real time under highly dynamic situations. Post processing the core data from both RT3002's eliminated this form of error from the test results.

were also recorded. These measurements were obtained using a Faro Arm Fusion (12 ft) portable measuring arm, accurate to ±0.049 in (±0.124 mm). Subsequent power up cycles for a given test vehicle do not require reentry of setup measurements. The RT3002 provides traceability of the setup data for every power-on cycle.

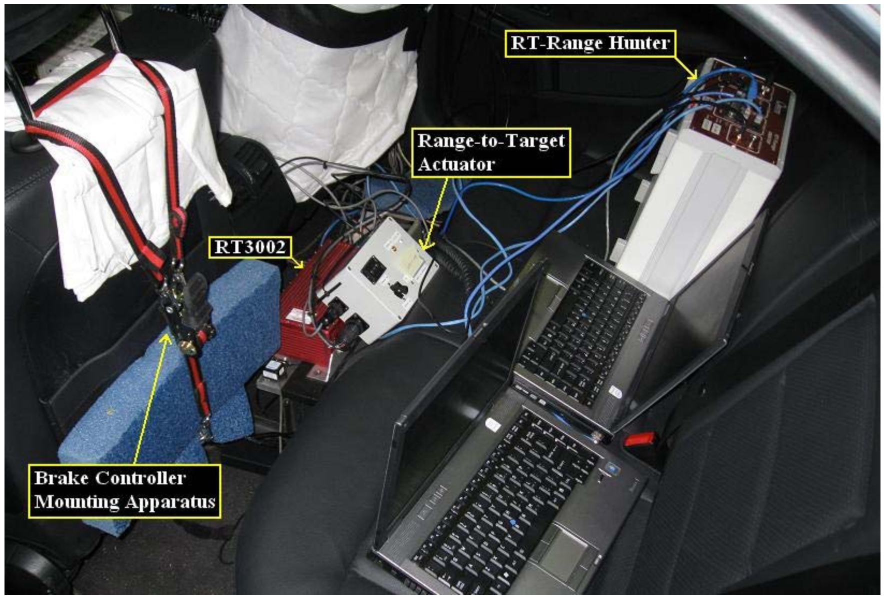

Figure B.1. RT Test Equipment in Rear Seat of Vehicle

The 16 channels mentioned above were recorded using a laptop on the rear seat. A separate data acquisition system on the front passenger seat recorded the analog channels from the test vehicle (Section 3.3). A digital link between the two systems provided a channel that was common to both systems. When data collection started during each test run, this link passed a 'trigger' input through the RT3002's J5 connector to each computer's respective test file. The trigger input allowed the two systems' respective analog and GPS data files to be accurately synchronized in post processing. During this data-merging process, the RT3002 data was interpolated from 100Hz to 200Hz to match the sample rate of the analog channel recorder running in the front seat.

APPENDIX B - Comparison of LDW Objective Test Procedures

Standards and proposed standards of evaluation for LDWS from around the world were reviewed as part of this study. Standards and proposals reviewed included NHTSA's "NCAP for Light Vehicles" [1]; ISO/DIS 17361, "LDWS Intelligent Transport Systems - Lane Departure Warning Systems - Performance Requirements and Test Procedures" (164 member countries including the United States) [33]; Commission Regulation (EU) No. 351/2012, "Type-Approval Requirements for the Installation of Lane departure Warning Systems in Motor Vehicles" (European Parliament and Council) [34]; and FMCSA's "Voluntary Requirements for Large Truck LDWS" [35]. A description of each document is presented below including an assessment of strengths and weaknesses.

B.1. NHTSA's NCAP Light Vehicle Lane Departure Warning System Confirmation Test [1]

The NCAP test is a NHTSA test procedure used to certify the performance of safety devices on new light vehicles (less than 10,000-lb GVWR) that are sold in the United States [1]. The LDWS test program component only requires one test site and no special ballast other than driver, full vehicle fluids, and a data collection system.

The NCAP LDWS test series [1] is performed on a long straight roadway (greater than 1,530 feet long) and a minimum width of 50 or 100 feet using 3 lane line marker types. The road surface must be dry (with no large chips, dips, or cracks) and provide a peak coefficient-of-friction (PCF) of 0.9. Testing should be performed with winds no greater than 22 mph (35 km/h), ambient temperatures between 32° F (0° C) and 100° F (38° C), no precipitation (such as rain, snow, hail, fog, smoke, or ash), visibility of more than 3 miles (5,000 meters), and sun angle greater than 15 degrees above the horizon.

Table C.1. LDW Test Matrix

Lane Geometry	Lateral Velocity	Line Type	Departure Direction	Number of Trials
Straight	Low	Solid	L	5
			R	5
		Dashed	L	5
			R	5
		Botts Dots	L	5
			R	5

The test series consists of evaluations on three lane-line marker types (solid, dashed, and Botts dots), tested in both left and right lane departure directions, and with 5 test repetitions for each marker type/lane direction combination giving a total of 30 tests. A trained test driver should be able to perform these tests without the need for a steering control machine.

The NCAP test procedure specifies using a test area that provides an acceleration zone plus a 1,000-foot test area (distance after the starting gate). An example test would cover the following distances: 330 ft to accelerate to 45 mph in 10 seconds, 200 feet constant speed soak before entering starting gate, 385 feet to first target cone, 200-foot longitudinal target-window length, and 415 feet to stop (allows for up to 2 seconds of driver and brake response time followed by vehicle deceleration of 7.7 feet/sec^2 {~0.24 G}), for a total distance of 1,530 feet (see Figure C.1. A shorter straight-away distance could be used if large turn-around loops or alternate acceleration and deceleration zones are available, and both driver response time and higher deceleration rates are acceptable for the test track conditions and vehicle.

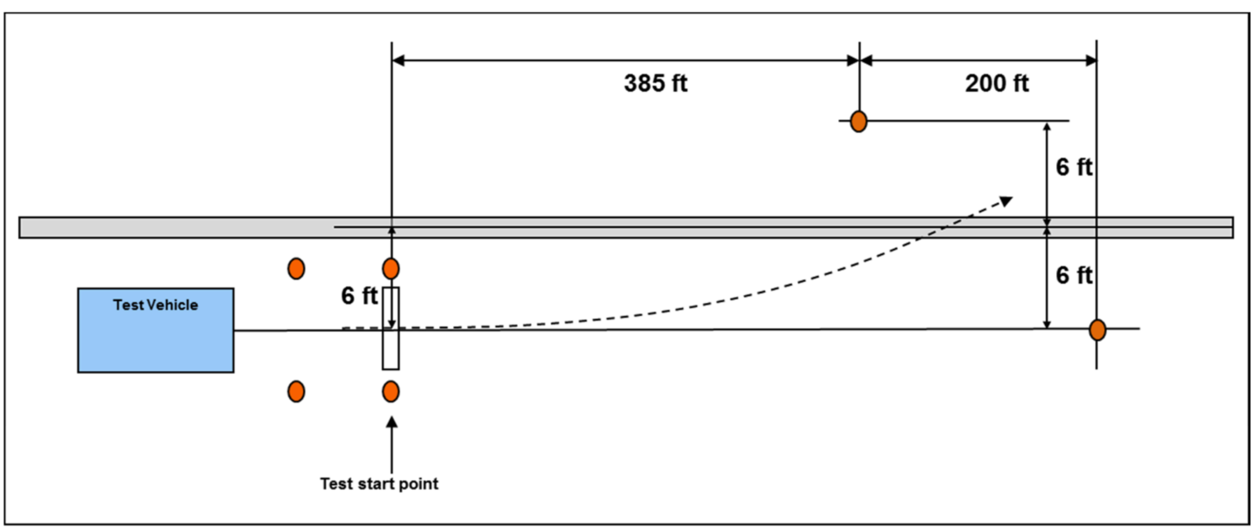

Figure C.1 NCAP Recommended Pylon Spacing to Facilitate Valid Lateral Velocities [1]
Note: For illustration only – not to scale.

To perform a test, the driver accelerates the vehicle to 45 mph (+/- 1.2 mph) while passing through an "extra gate" of spaced pylons placed 246 feet ahead of the test start point. At a distance of 200 feet ahead of the test start point, the vehicle should be at 45 mph (which is held constant until the vehicle completes the lane change maneuver). As the vehicle nears the test start point, it must pass between two pylons at the control gate (spaced 4 inches wider than each side of the vehicle polygon and 20 feet before the test start point). Next the vehicle passes through the test start point (two more pylons laterally spaced the same as the control gate) and over a non-contact retro-reflective "trigger" device to indicate time zero for the data acquisition system. The driver continues driving forward and gradually adds a gentle steering input to the left (or to the right) and aims the vehicle to depart the lane between the final two pylons that mark the target trajectory area, which is located downrange from the test start point. The target lateral velocity is 1.6 ft/s (0.5 m/s) with respect to the lane line. The nearest target pylon is positioned 6 feet out of lane (left of the inside edge of the lane-line marker) and 385 feet longitudinally from the center of the test start point. The second target pylon is centered on the original lane (6 feet to the right of the inside edge of the lane-line marker) at a distance of 585 ft from the test start point. The lane departure warning alert is expected to activate while the test vehicle is approaching the target zone, but before the vehicle polygon exceeds the inside edge of the lane line marker plane by a distance of 1.7 feet (0.5 m). The vehicle yaw rate must not exceed 1.0 deg/sec at any time during the performance of the LDW maneuver.

A valid group of tests must have achieved at least 3 of 5 (60%) alert activations. For LDWS acceptability, a success rate of 20 for the total of 30 tests (66%) is required.

Only one lane-line style is to be observed by the LDWS for each test; therefore, the line markers must either be swappable (remove one style marker set before applying the next when using a single 50-foot wide test area) or be made permanent by arranging the three style markers in parallel lines spaced 25 feet apart (for a 100-foot wide test area). Repairs to the roadway surface and any added guidance cones (pylons) must be made of materials whose color does not contrast with the nominal roadway surface color, so they are not misidentified as valid lane markings.

Valid marker styles include: continuous solid white, discontinuous dashed yellow, and discontinuous raised pavement (Botts dots) markers. The lane-line marker types must have a width of 4 to 6 inches (10 to 15 cm) according to the Manual on Uniform Traffic Control Devices (MUTCD) and must extend for the whole length of the soak and test lane[23].

Data to be collected include: vehicle speed, yaw rate, lateral acceleration, start event timing data flag, lateral position and lateral velocity (both with respect to road edge), lane departure warning event data flag, and vehicle physical dimensions that describe a 2-D polygon as orthogonally projected to the ground beneath the outer-sidewall lateral-centerlines of the vehicle tires. Data parameters may be measured using discrete hardware or GPS-based sensors, provided sampling rates are at least 100 Hertz per channel.

B.2. ISO 17361

A copy of the draft document ISO/DIS 17361 [33] was obtained through NHTSA from the ISO committee TC204/WG14. The working document number was N123.36, 36th edition, Sept 26, 2005, with updates added from the PPT presentation given at the GRRF-65-20, 1st meeting of GRRF informal group on AEBS and LDWS, Paris, June 25 and 26, 2009.

ISO 17361 indicates that “LDWS are based on fundamental traffic rules,” where the main focus is to help the driver keep the vehicle in the lane while on highways, but are not intended to issue warnings with respect to other vehicles or to control vehicle motions. ISO 17361 applies to passenger cars (Class I), and to heavy vehicles and buses (both Class II heavy duty vehicles). The LDWS may use optical, electromagnetic, GPS, or other sensor technologies to provide warnings consistent with the visible lane line markings.

The ISO 17361 LDW tests must be performed on a flat, dry surface (asphalt or concrete), with ambient temperatures from -20° to +40°C (-4° to +104°F), with visible lane markings that are in good condition, and when the horizontal visibility range is greater than 1 km (0.62 miles). ISO defines visibility as the distance at which the illuminance of a non-diffusive beam of white light with the colour temperature of 2,700K (toward the red end of the incandescent light spectrum) is decreased to 5 percent of its original light source illuminance.

Two different courses are required to test LDWS. A large constant radius curve is used for "warning generation" tests (see Figure C.2) and a long straightaway is used for "repeatability" and "false alarm" tests (see Figure C.3).

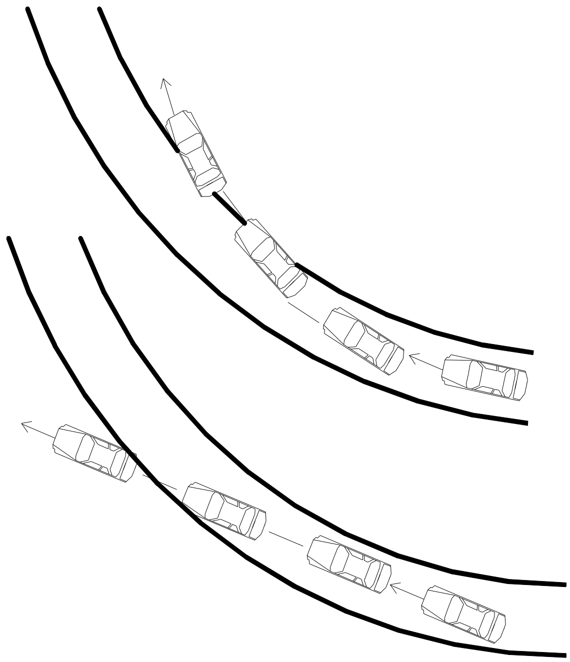

Figure C.2 Method of How To Carry Out Warning Generation Test [33]

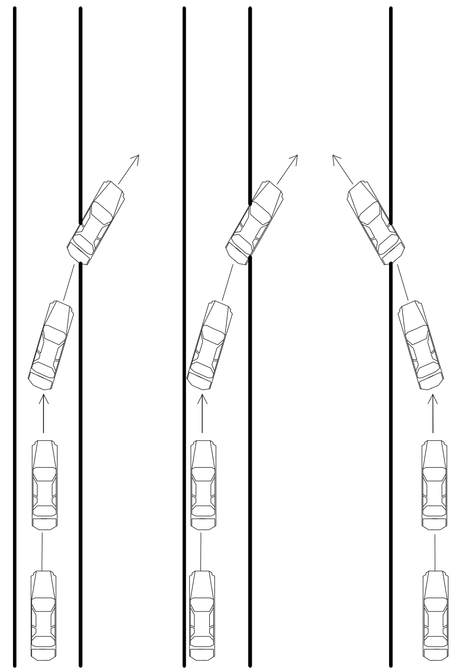

Figure C.3 Method of How to Carry Out Repeatability Test [33]

The first test provides a constant radius of curvature of at least 500 m (1,640 ft) for Class 1 vehicles and at least 250 m (820 ft) for Class 2 (see Table C.2.). The tolerance on the radius is +/- 10 percent. The arc length must be long enough to maintain vehicle speeds ranging from 20 to 22 m/s (44.7 to 49.2 mph) or 17 to 19 m/s (38.0 to 42.5 mph), respectively, to allow drifting out from the lane at a lateral departure rate above 0 m/s, but not greater than 0.8 m/s (2.6 f/s). The curve test requires one trial at each lateral "rate-of-departure" speed range 0.0 to 0.4 m/s (0 to 1.3 f/s) and 0.4 to 0.8 m/s (1.3 to 2.6 f/s). The test is repeated for a drift to the left side and to the right side, of the lane, for both a left-turning curve and a right-turning curve, for a total of 8 trials (see Table C.3.).

Table C.2. ISO 17361 – System Classification [33]

Class	I	II
R	500 m	250 m
Vx	20 m/s	17 m/s

- Notes: latest warning (beyond lane marking) revised to All Vehicles: 0.3 m

Table C.3. Warning Generation Test Matrix [33]

	Right Curve		Left Curve	
Rate of Departure	Left Departure	Right Departure	Left Departure	Right Departure
0.0 – 0.4 m/s	One Trial	One Trial	One Trial	One Trial
0.4 – 0.8 m/s	One Trial	One Trial	One Trial	One Trial

The second test course is a long straight roadway used for "repeatability" and "false alarm" tests (see Table C.4.). The test speeds are the same as for the previous warning generation tests. Lane boundary lines may be present on both sides of the travel lane. The vehicle can be driven either in the center of the lane or along the lane line opposite to the lane line to be driven across for the test. Sixteen total tests are performed, two groups departing the lane to the right and two to the left. For each respective direction, one group uses a lateral rate of departure between 0.1 and 0.3 m/s (0.328 and 0.984 f/s) with a tolerance of +/-0.05 m/s (X1+/-0.164 f/s); while the other group uses a range between 0.6 and 0.8 m/s (1.97 and 2.62 f/s) with a tolerance of +/-0.05 m/s (X2+/□ 0.164 f/s). The X1 and X2 values are to be selected by the manufacturer. Lane departure trials are to be conducted until four trials meet the required lateral departure rates for each group.

Table C.4. Repeatability Test Matrix [33]

Rate of Departure	Departure Direction	
	Left	Right
0.1 < X1□0.05 □0.3 m/s	Group 1 Four Trials	Group 2 Four Trials
0.6 < X2□0.05 □0.8 m/s	Group 3 Four Trials	Group 4 Four Trials

For “false alarm” tests, the system shall produce no warnings while driving within the no warning zone for a total distance of 1000 m (3,281 f). If only short test lanes are available, the false alarm test may be split over two 500 m (1,640 f) stretches.

B.2.1. The Basic Operational Requirements [33]

1. The LDWS must power-up upon turning ignition key to the “run” position and automatically activate when the vehicle exceeds 60 km/h (37.3 mph).
2. The LDWS must warn the driver (latest warning for all vehicles) no later than when the vehicle is 0.3 m outside of the lane boundary (laterally outside of the inner edge of the lane line). In 2009, this limit was reduced from 1 m for heavy vehicles);
3. The earliest warning is determined by one of three combinations of V and D:
    1. 0 < V <= 0.5 m/s at 0.75 m inside the lane boundary (see Figure C.4).
    2. 0.5 < V <= 1.0 m/s at a range of 1.5 s * V m/s inside the lane boundary.
    3. 1.0 m/s < V at 1.5 m inside the lane boundary;
4. The LDWS must generate valid and repeatable warnings, and limit false alarms; and
5. The system must be operable at 20 m/s or higher for Class I.

LDWS - ISO 17361 [33]
Intelligent Transport Systems -
Lane departure warning systems –
Performance requirements and
test procedures:
1 Lane Boundary
2 Lane Departure
3 Warning Threshold (reference only)
4 Earliest Warning Line
5 Latest Warning Line

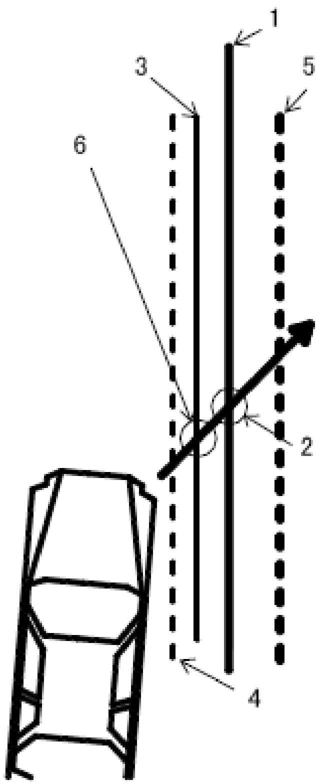

Figure C.4 ISO 17361 Lane Boundary Lines [33]

The driver may suppress a lane departure warning by applying the turn signal in the direction of an intended turn or lane change, or by turning off the LDWS. The LDWS must automatically turn back on at the next on-cycle of the ignition switch.

The minimum data collected must include: warning issue point, rate of departure, and vehicle speed. All warnings that occur during the tests must be recorded.

B.2.2. Pass Criteria:

1. Warning Generation Tests: the LDWS must provide repeatable warnings within a crossing zone of 30 cm (11.8 in) prior to crossing the latest warning line for each test case. This zone is called the Warning Threshold Placement Zone – or the region where the warning is likely to occur.
2. Repeatability Test: The LDWS must provide results of all four trials within a width of 30 cm (11.8 in) for each test group and no warnings outside of the warning threshold placement zone. If more than four tests are required per group to achieve the required speed tolerance band, only the first four trials within the band will be considered.
3. False Alarm Test: No warnings shall occur between the left earliest warning line and the right earliest warning line (the center portion of the driving lane).

B.3. EU No. 351/2012 Requirements for Installation of LDWS in Motor Vehicles

Commission Regulation (EU) No. 351/2012 "Type-Approval Requirements for the Installation of Lane Departure Warning Systems in Motor Vehicles" dated April 23, 2012, (of the European Parliament and of the Council) [34] implementing Regulation (EC) No 661/2009 requirements of general safety of motor vehicles, now regulates the type of vehicle in which the LDWS is installed, the LDWS, and basic safety obligations using the LDWS. This rule became effective on the 20th day following the listed publish date. EU No. 351 covers LDWS applications in most vehicle categories M2, M3, N2, and N3, which are heavy straight trucks, tractors, and large commercial buses. European-use vehicles made in and after November 2013 must meet this compliance specification.

This regulation requires that the LDWS should warn the driver if the vehicle crosses over a visible lane line on a roadway that may vary in curvature from a minimum radius of 250m to straight.

B.3.1. BASIC OPERATIONAL REQUIREMENTS

Similar to the NCAP LDWS test, only one test speed is required. EU No. 351 tests are performed at 40.4 mph +/- 1.9 mph (65 km/h +/- 3 km/h) for both straight and curved road tests. The LDWS must become active above 37.3 mph (60 km/h) and provide an out-of-lane warning before the vehicle's leading front tire (outside edge) reaches a point 0.3 m beyond the outside edge of the lane line being crossed. A warning may be suppressed when the driver applies the turn signal for an intended lane change. If LDWS is equipped with a user-adjustable warning threshold, the LDW test should be performed using the maximum lane departure setting. Out-of-lane drift tests are performed for both the left and right side of the vehicle at two different rates-of-departure between 0.33 and 2.6 f/s (0.1 and 0.8 m/s). If a manual warning suppression feature is activated by the driver, it must be automatically reset by the LDWS upon each ignition "power-on" cycle such that warnings will be reinstated during operation. Whenever the LDWS is manually deactivated, the system must display a constant status indicator to the driver.

The warning indicator should be noticeable to the driver by providing at least two types of sensory feedback (optical, acoustic, or haptic), or provide either a haptic or acoustic type of warning, with a spatial indication of the unintended drift direction. The optical warning signals need to be visible for both daytime and nighttime operation.

The vehicle can be tested at any weight or load condition with tires inflated to that recommended by the vehicle manufacturer. The test surface must be flat, dry, asphalt of concrete. Weather conditions include ambient temperatures between 32F and 113F (0C and 45C) and visibility conditions that allow for safe driving at the required 40.4 mph (65 km/h).

B.3.2. PASS CRITERIA:

1. Only 8 tests are required to pass: left and right side drift, two drift rates, performance on curve and a straight roadway.
2. Must identify lane markers listed in document Annex for numerous European localities.

3. Automatic reinstatement of warnings is required after each initiation of an ignition "key on" cycle.

B.4. HOUSER-FMCSA – VOLUNTARY REQUIREMENTS FOR LARGE TRUCK LDWS

The Houser report [35] presents concept of operations and voluntary requirements LDWS for large trucks greater than 10,000 pounds. Four applications studied were each vision-based systems: AssistWare Technology, Delphi Electronics and Safety, Iteris, and Mobileye NV.

B.4.1. Concept of Operations

LDWS warn the driver when traveling above a threshold speed and the vehicle's turn signal is not activated. The LDWS may also warn the driver of system malfunctions and when lane markings are not adequate for detection [36]. The LDWS measures the lane and projects a warning zone (see Figure C.5) where the system will alert the driver if the vehicle begins to depart from the lane.

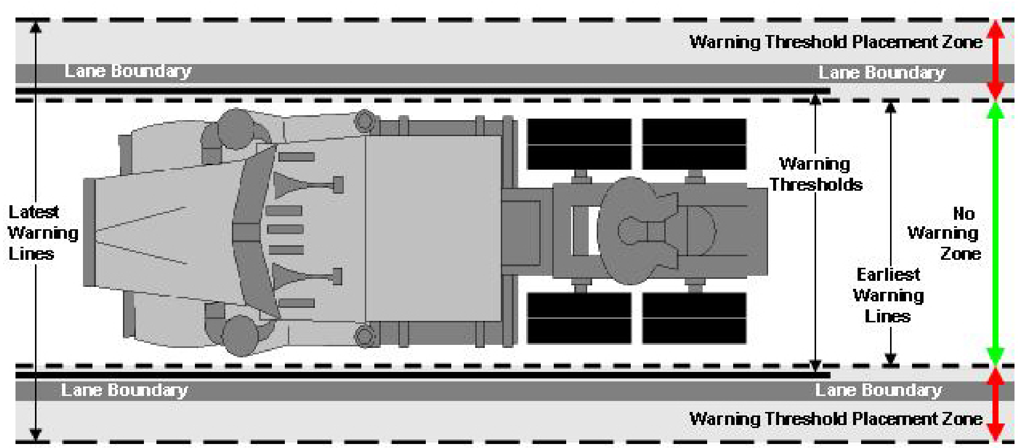

Figure C.5 LDWS Warning Thresholds and Warning Threshold Placement Zones [35]
Note: For illustration only – not to scale.

B.4.2. Voluntary Requirements

The Houser report includes five types of voluntary requirements that each LDWS should include functional, data, hardware and software, driver vehicle interface (DVI), and maintenance and support; and LDWS must comply with all existing FMCSA safety regulations.

B.4.3. Functional Requirements

LDWS specifications for Functional target requirements include:

- Perform power-on-self-test (POST), be operational within 30 seconds of starting the vehicle, and alert the driver if a fault exists;
- Be able to detect vehicle position relative to visible lane boundaries including: (1) painted lines that are solid or dashed, single or double, yellow or white; (2) raised pavement markers (Botts dots), and (3) lines with and without reflectors or reflective material;
- Capability to issue warnings at vehicle speeds exceeding 60 km/h (37 mph) and at any time of the day or night;
- Warn the driver when the vehicle departs - or is about to leave - the lane, and be optimized to the particular vehicle to provide sufficient time for the driver to respond, but without being over-sensitive such that it would produce nuisance warnings. Warning points should be within ±0.1 m (±4 in) from the warning thresholds when the vehicle's rate of lane departure is < 0.8 m/s (2.6 ft./s);
- LDWS should track lane boundary and be able to issue lane departure warnings 95 percent of the time on dry straight roads and when at least one of the roadway curvature test conditions listed in Table C.5. is encountered; and
- Warnings should be suppressed when the turn signal is applied, but function normally when

Table C.5. LDWS Warning Curved Roadway Test Conditions [35]

Condition	Road Curvature Radius	Operating Speed
1 (metric units)	≥ 250 m	< 72 km/h, ≥ 61 km/h
1 (English units)	820 feet	< 45 mph, ≥ 38 mph
2 (metric units)	≥ 500 m	≥ 72 km/h
2 (English units)	1640 feet	≥ 45 mph

Where Condition 1 = Passenger Cars; Condition 2 = Commercial Trucks and Buses

LDWS specification for Functional options may include:

- An audible warning may be presented, such as rumble strip sound in left or right speaker, or a tactile vibration may be added to the driver seat or steering wheel;
- The LDWS may move the lateral warning threshold outward to allow for "curve-cutting" to reduce nuisance warnings;
- The lane departure warning may issue a warning ahead of actual crossing of the lane line based on the analysis of time-to-lane crossing (TLC) rate;
- Differential warning based on solid or dashed line (may adjust volume or length of alert sound);
- Ability to identify an un-marked road edge as a lane boundary; and
- LDWS may report a system fault in construction zones or areas where conflicting lines appear; and may warn the driver if the turn signal has been left on longer than a pre-set duration, so as to not suppress future warnings.

B.4.3.1. Data Requirements

Data may be obtained through the OBD connector from one of the in-vehicle data networks, J1708 or J1939, whichever is installed on the truck.

B.4.3.2. Typical System Hardware

Typical LDWS primary physical components are: lane boundary sensor (LBS), electronic control unit (ECU), driver vehicle interface (DVI), turn signal status interface (TSI), vehicle power, driver warning (audible, visual, or tactile annunciators), visual status indication (VSI) to alert the driver of the system status, and optionally – the vehicle network (see Figure C.6).

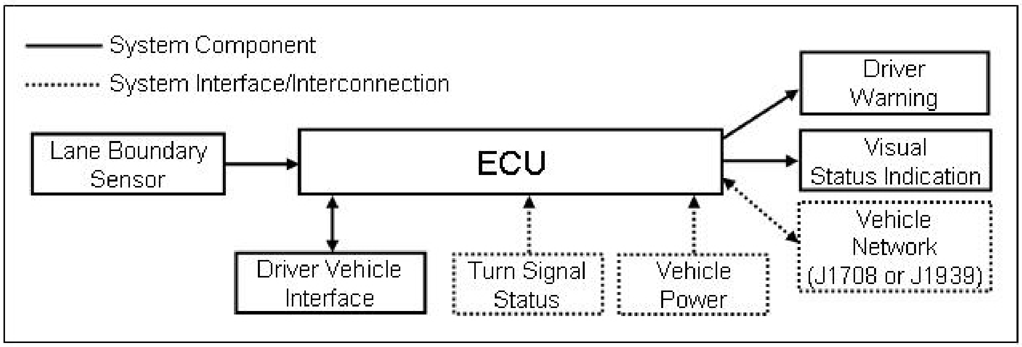

Figure C.6 LDWS Major Functional Components [35]

B.4.3.2.1. Environmental Requirements

FMCSA recommends using the SAE J1455 equipment environment standard to safeguard the LDWS against vapors and particulate debris, along with extremes in temperature, shock, and vibration.

B.4.3.2.2. Electrical Requirements

The truck will provide all electrical power to the LDWS. The LDWS must withstand a 100-volt transient from the alternator or discharge from static buildup (repetition and waveforms were not prescribed). Specifics include:

- LDWS should meet the electrical requirements stated in the most recent version of the following SAE standards: J1455, Joint SAE/TMC Recommended Environmental Practices for Electronic Equipment Design (Heavy-Duty Trucks); and J1113, Electromagnetic Compatibility Measurement Procedures and Limits for Vehicle Components (Except Aircraft) (60 Hz to 18 GHz). The following environmental aspects are covered by the standards: steady state electrical characteristics, transient electrical characteristics, electromagnetic susceptibility, and electromagnetic emission.

- LDWS data should not be destroyed or corrupted during a power surge.

B.4.3.2.3. Mounting and Installation Requirements

Mounting and installation requirements include all aspects related to the installation of LDWS hardware onto the vehicle. There are no specific requirements pertaining to system size or weight. If sensors are mounted in the windshield area, they must not block the driver's view of the road. LDWS sensors should be isolated from the chassis on a vibration-free mount. All LDWS cables, connectors, and components should be rated to SAE standards. Major LDWS components should be marked with the manufacturer's identification.

B.4.3.2.4. Software Requirements

Software refers to the programs embedded in the LDWS firmware, which controls all measurement and display functions. The microcontroller (CPU) must continuously run the system program when the ignition key is turned on. An optional program function may include: capability to download ASCII data files for user processing or upload periodic program updates through common networks, including J1587 or J1939 in-vehicle networks or external ports like RS-232 or USB.

B.4.3.3. Driver Vehicle Interface Requirements

Driver-Vehicle Interfaces include indicator lights and displays to present visual warnings or system status conditions, buzzers or computer generated sounds for audible awareness, and seat or steering wheel vibrations for tactile warnings. The warning devices can be either built-in to the LDWS device or connected to annunciators placed in the cab near the driver. NHTSA's FMVSS 101 [36] should be used as a guide for the LDWS indicators.

Proposed voluntary requirements include:

- The DVI should issue an audible or tactile warning when the vehicle crosses the warning threshold;
- The DVI display or dash light should show when the system is operational and ready for use as well as when the LDWS is not able to track the vehicle's position in the lane due to poor lane-line conditions, and either system malfunction or failure; and

- The DVI should be visible in direct sunlight and illuminated for night use.

DVI Options may include:

- Ability to render a screen image of the vehicle's position with respect to both lane boundaries, to emphasize the side where the vehicle appears to be leaving the lane, and to notify the driver if one side is not tracking;
- A provision for tactile warning (such as a rumble seat) to provide an indication of left or right lane departure;
- Variable volume control of the audible warnings (but not lower than a minimum sound level of 65 dB-A;
- A graphical indication of time-averaged lane centering;
- Operational or diagnostic codes or messages to alert the driver of specific faults, conditions, or concerns.

B.4.3.4. Maintenance and Support Requirements

Maintenance and support are functionality and feature items that should be provided with all LDWS to ensure that they will be operated correctly and maintained properly. Requirements include: maintaining a clean windshield so driver and camera can see the road, automatic LDWS calibrations to compensate for normal or expected vehicle changes in loading (such as fuel level, bobtail or with trailer, weight of cargo, and number of passengers), an in-vehicle operator's checklist, placard, or user manual (to include minimum vehicle speed at which the LDWS operates, the types of line markings LDWS can track, and the screen icons and system annunciators used for driver warnings and information if the LDWS is both functioning properly and tracking the lane), and training for LDWS users.

Optional Maintenance items include: multi-media training for fleet managers and drivers, and flexibility of the LDWS to be transferred and re-calibrated to a different vehicle during periods of prolonged vehicle maintenance or replacement.

DOT HS 812 078
November 2014

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10926-112114-v4