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Van Hool 2014 CX45 Motorcoach Lane Departure Warning System Evaluation

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16. Abstract

This report documents an evaluation of a 2014 Van Hool Motorcoach equipped with a lane departure warning system. The main objective of this work was to perform test track research on lateral crash warning systems applications for motorcoaches. This work supports the 2012 U.S. Department of Transportation's Motorcoach Safety Action Plans and Moving Ahead for Progress in the 21st Century Act (MAP-21) requirements. The system was evaluated 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. Test results indicate that alerts were issued within 0.2m after crossing the lane line for straight line tests. The system performance on the curved left-side tests was comparable to the straight line tests. However, in curved right-side tests the system did not produce warnings in 3 out of 20 tests and produced warnings further into the lane change.

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EXECUTIVE SUMMARY

The Lane Departure Warning (LDW) system is a driver aid that uses visual sensors to detect lane markers ahead of the vehicle. The LDW system 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 LDW system sounds an audible tone or beeps or provides haptic alarm to the driver and is often accompanied with a visual dash lamp or display icon to indicate which side of the vehicle is departing the lane.

This report documents an evaluation of a 2014 Van Hool CX45 56-passenger motorcoach equipped with a lane departure warning system (referred to as "Van Hool LDW system" in the report). The system was evaluated 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 in wet and dry pavement conditions as well as day and night lighting conditions.

The Van Hool LDW system presented haptic alerts to the driver, through vibrations in the seat 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 Heavy Vehicle LDW [1] test were adequate and only required minor changes such as adjusting lateral spacing to accommodate the larger size of the motorcoach.

Test results indicate that alerts were issued within 0.2m after crossing the lane line for straight line tests. The system performance on the curved left-side tests was comparable to the straight line tests. However, in curved right-side tests the system did not produce warnings in 3 out of 20 tests and produced warnings further into the lane change.

The results of the data analysis indicated that increasing only the base speed of the subject vehicle did not appear to change the performance of the LDW system. As designed, the LDW system did not present out-of-lane alarms at or below 42 mph.

1 INTRODUCTION

Motorcoach travel is a very safe mode of passenger transportation in the United States. Despite this, fatalities result each year among the pedestrians, drivers, and passengers of other vehicles involved in crashes with motorcoaches. Each of these fatalities is a tragedy that the National Highway Traffic Safety Administration (NHTSA) attempts to prevent. From 2007 to 2012 the U.S. Department of Transportation and its agencies, including NHTSA, developed approaches and Motorcoach Safety Action Plans [2] aimed at improving motorcoach safety. The plans were originally issued in 2009 [3] and were later updated in 2012. The most recent Motorcoach Safety Action Plan calls for research on recently available crash avoidance warning technologies for motorcoaches.

In July 2012, the Moving Ahead for Progress in the 21st Century Act (MAP-21) was signed into law. This act authorized funds for Federal aid highways, highway safety programs, transit programs, and for other purposes for fiscal years 2013 and 2014. Section 32705. (a),(3) of the act mandates the Secretary (of the Department of Transportation, DOT), to research and test, forward and lateral crash warning system applications for motorcoaches within 3 years. NHTSA interpreted the reference to forward and lateral crash warning systems as forward crash warning (FCW) and lane departure warning (LDW) systems.

To fulfill the department action plans and the MAP-21 requirement to test lateral crash warning systems, NHTSA initiated a research project in 2013 to evaluate the test track performance of a motorcoach equipped with a contemporary LDW system. This research project focused on characterization and performance of original equipment technology for motorcoaches. The test vehicle used in this research was a class 8, air braked 2014 Van Hool CX45 56-passenger motorcoach equipped with an LDW system. The results and observations from this test track research are presented in this report.

1.1 Background

NHTSA has conducted research in the area of lane departure warning and lane departure prevention (LDP) systems for a number of years. This research has included sensor development, test track characterization, over the road evaluation, and human performance testing. This work was important in the development of the "Lane Departure Warning System Confirmation Test" [4] as part of the agency's New Car Assessment Program (NCAP) for crash avoidance technologies. The Lane Departure Warning system Confirmation Test is currently only applicable to light vehicles (LVs). The LV LDW system test procedure was used to develop an initial draft test procedure for heavy vehicles (HVs), since there are no NCAP or Federal Motor Vehicle Safety Standards for LDW systems that are applicable to heavy vehicles with a Gross Vehicle Weight Rating (GVWR) greater than 10,000 pounds.

In a previous NHTSA test track research project, LDW technologies were integrated into a truck-tractor. Test track work was conducted to characterize the performance of LDW systems marketed for heavy vehicles. LDW NCAP procedures were adapted for heavy vehicles and were performed with the truck-tractor equipped with LDW systems from Mobileye and Takata. The test results are documented in the following report, "Heavy-Vehicle Lane Departure Warning Test Development" DOT HS 812 078, [5].

The two systems installed on the tractor were tested for various scenarios on both straight and curved lane lines which included both solid and dashed lane markings (Botts dots, one of several different styles of raised pavement markers supplementing painted lane lines, were not used in this study due to project time and cost constraints). In summary, the Mobileye system produced an appropriate warning in all 40 of the straight line tests performed, whereas the Takata system produced warnings in only 34 of the same tests. In the curved lane tests, the Mobileye system again produced warnings in all 40 tests, while the Takata system produced warnings in only 20 of the 40 tests. It was also noted during testing that the Mobileye LDW system was capable of interrupting a warning on application of a turn signal, while the Takata system did not. Another observation was that the Mobileye system did not differentiate between left or right turn signals, and as a consequence, suppressed warnings even when the wrong turn signal was activated. The Takata system however, did differentiate between the left and right turn signals.

The test results showed that the NCAP LDW test procedures that had been adapted for heavy vehicles were capable of differentiating levels of performance between lane departure warning applications for commercial vehicles. These heavy vehicle test procedures were used in this research to see if they could be applied to tests performed with a motorcoach.

1.2 Objectives

The objectives of this tests track research were to:

- Develop a basic LDW test plan for examination of Motorcoach LDW system;
- Prepare the test facility and surfaces for conducting the proposed LDW test plan;
- Conduct LDW testing according to the test plan;
- Summarize test results and provide observations about the motorcoach's LDW system and the test procedure.

2 TESTING METHODOLOGY

The protocol used to test the LDW system in the Van Hool motorcoach 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, LDW system, test site preparation, and instrumentation.

2.1 Test Procedures

After reviewing the results of previous studies and related test procedures, the straight-lane and curved lane tests from the “Heavy Truck Lane Departure Warning Test Development” report [5] were used to perform LDW test track performance research on the motorcoach. During conduct of the tests, modifications to the in-lane cone spacing was necessary to accommodate the motorcoach. The test procedures for the straight and curved lane tests along with the modifications are discussed below.

2.1.1 Straight Lane Departure Test Maneuver

Originally, 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 2.1. 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).

In previous research with heavy truck tractors [5], eight inches (20 cm) were allowed on each side of the vehicle for clearance of passage, which resulted in a net spacing of 114 inches (290 cm) between the “starting gate” cones. It was found however, that due to the long wheel base of the motor coach and a marginally wider body (100 in or 254 cm) this spacing proved difficult to pass through at the test speeds. As a result, the spacing was increased to 126 inches (320 cm) centered on the center of the lane, 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 stable lane “preview” time for the LDW system prior to beginning the actual lane departure maneuver. Two cones were positioned with their bases 126 inches (320 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.

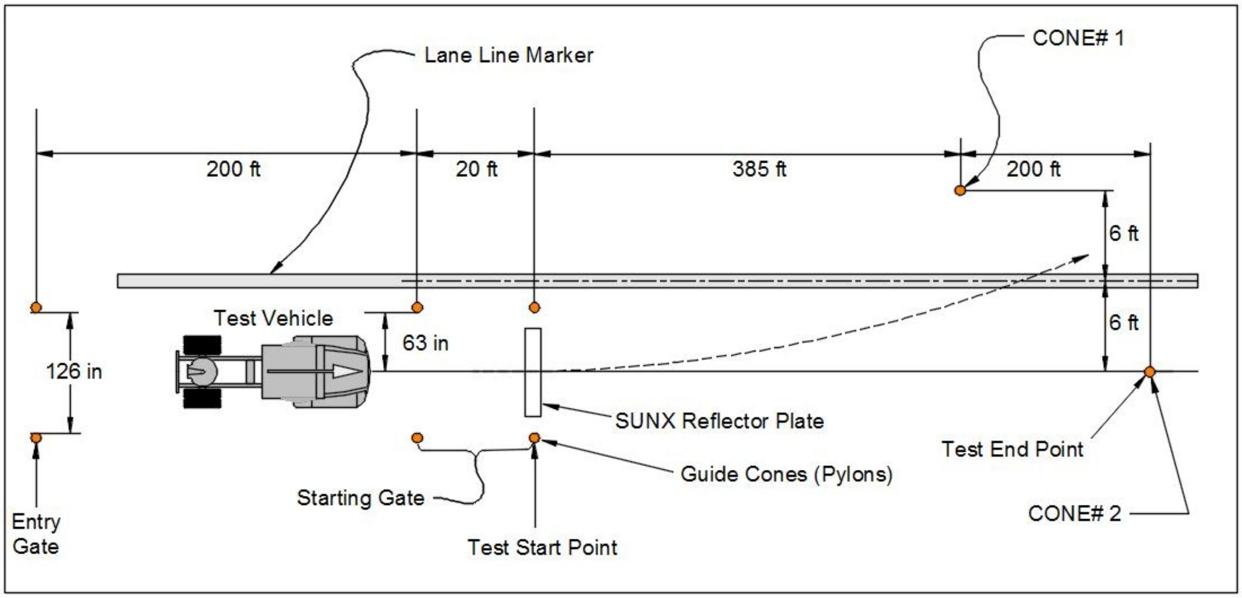

Figure 2.1 Heavy Vehicle LDW Left Lane-Change Test Procedure and Layout

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 in achieving proper and consistent 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.

During the LDW test the driver approaches the "Entry Gate" at a constant test speed, centering the vehicle between the pylons. The test starts once the vehicle passes the Test Start Point, 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 test course is shown in Figure 2.2, including the test lane line and the specified gate and guide cones.

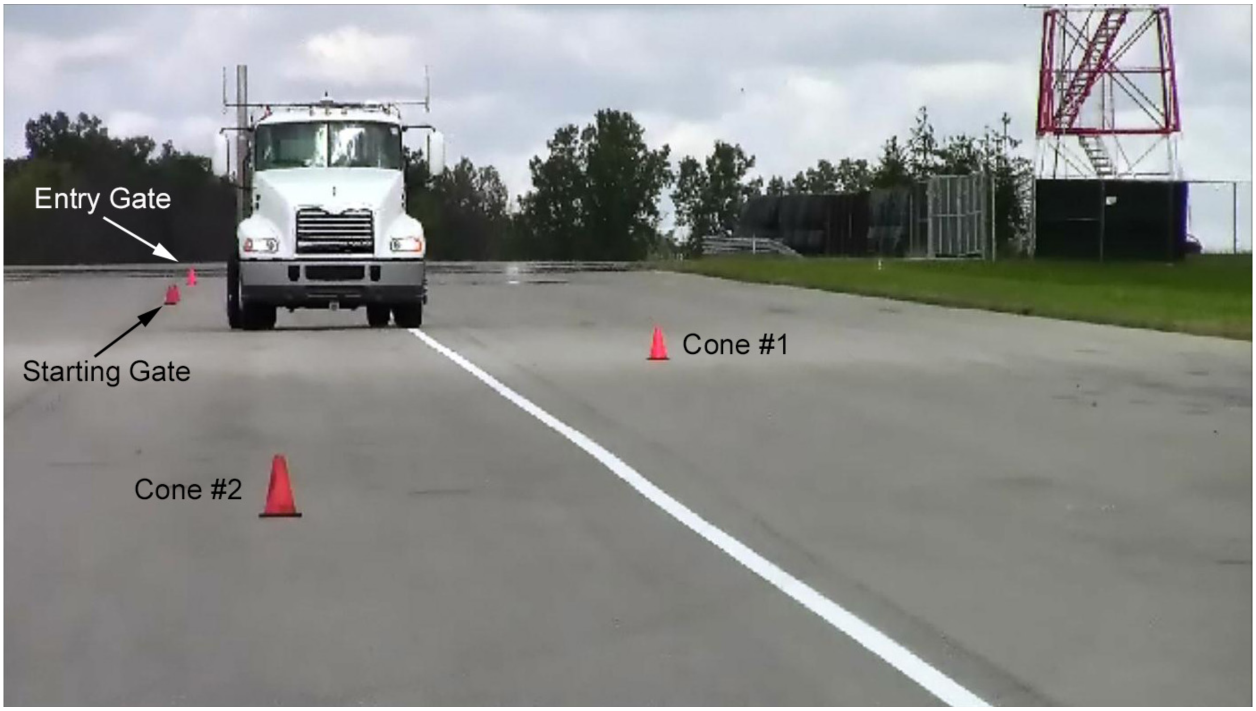

Figure 2.2 Straight-Lane Solid-Line – Lane Change to the Left

2.1.2 Curved Lane LDW Test – Course Layout

The NCAP procedure was adapted for curve testing on the TRC Vehicle Dynamics Area (VDA) 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. Here again, the lane width was increased to 126 in (320 cm) to accommodate the longer wheelbase and wider motorcoach. 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 13-1/3 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 15-2/3 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, steady-state (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 2.3. All tests on the curved roadway were performed in a clockwise direction only.

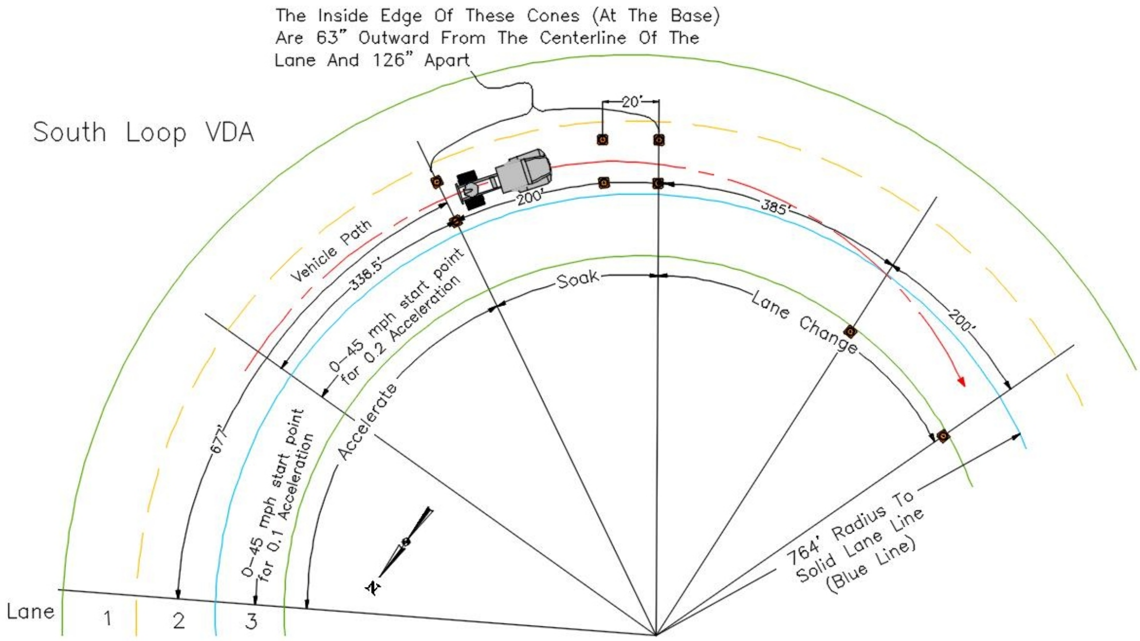

Figure 2.3 Curved Lane Test – Course Layout

Note: For illustration only – not to scale.

2.2 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.

2.2.1 Straight-Lane Test Procedures

The straight-lane test matrix was designed to include LDW system effectiveness, longitudinal speed sensitivity characterization, duration of warning characterization, warning interrupt or prevention modes with the use of turn signals, and LDW system's effectiveness in wet surface and low light conditions. The lane mode, speeds evaluated, turn signal application and general notes for each test procedures are listed in Table 2.1. The purpose of each test procedure is discussed below.

Table 2.1 Straight Lane Test Matrix (Tested On Left and Right Sides of the Motorcoach)

Test Procedure	Lane Mode	Lane Type	Speeds (mph)	Turn Signal Application	Description
Base Line Test	In Lane	Solid, Dashed	55	No	Check for false Positive
Lane Change Test	Change Lane	Solid, Dashed	45, 55	No	
Turn Signal Warning Prevention Capability	Change Lane	Solid, Dashed	45	Yes	Check capability of system to ignore intentional lane changes
Turn Signal Warning Interrupt Capability	Change Lane	Solid, Dashed	45	Yes	Capability of system to shut off warning on turn signal activation
Opposite Turn Signal Test	Change Lane	Solid, Dashed	45	Yes	Capability of system to warn on incorrect turn signal
Wet Road Lane Change Test	Change Lane	Dashed*	45, 55	No	
Night time Lane Change Test	Change Lane	Solid, Dashed	55	No	Check system capabilities in dark conditions
Hazard Light Lane Change Test	Change Lane	Solid	55	Hazards On	Check system capability to distinguish turn signal and hazard lights.

* Solid lane markings were omitted due to time constraints. The dashed lines were considered more challenging.

Baseline Test: A baseline test was performed to determine if the LDW system 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). The Van Hool LDW system was observed to enable at a threshold speed of 45 mph and stays enabled till the speed drops below 42 mph. The test driver ensured that the system was armed during each test. This was indicated by a light turning off on the dash board. A baseline test speed of 55 mph was selected to evaluate the LDW system because it was used previously in LDW research and was above the 45 mph needed to enable the system. Five test repetitions were performed for each lane type, 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 without application of the turn signals was performed where the vehicle remained centered in the lane until passing through the starting "gate" followed by the lane-change maneuver. The LDW system was expected to warn the driver when the vehicle moved out of lane. Following previously developed test procedures, this test was performed at 45 and 55 mph. Five tests were performed at both speeds, for each line type and lane change direction.

Warning Prevention Test: The turn signal "warning prevention" capability of the LDW system was evaluated by having the driver apply the appropriate turn signal prior to performing a lane change. The turn signal was applied as the vehicle entered the test course and stayed on until the lane change maneuver was complete. Here, the LDW system was evaluated as to whether it maintained functionality of the warning capability when the driver signaled prior to initiating an intentional lane change. 45 mph was chosen as the test speed and five repetitions performed for each lane type and lane change direction.

Warning Interrupt Test: A turn signal "warning interrupt" test was performed to see if applying the turn signal after the warning is initiated would cause the warning 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 LDW system 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 each lane type and 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 vice-versa. The LDW system 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 five repetitions for each line type and lane departure side.

Wet Lane Change Test: The "wet lane change test" was conducted to test the capability of the system to detect lanes when the road surface is wet. The test procedure was identical to the lane change tests, but was performed in the rain, when the test surface was fully soaked and there were patches of standing water. Five repetitions were performed at both test speeds and both lane change directions. This test was performed only on the dashed lane line due to limited duration of precipitation on the test track during the testing window.

Night Time Lane Change Test: Night testing was conducted to check the effectiveness of the system under dark conditions under the illumination of the head lights. The procedure was identical to the lane change tests and was performed well past sunset. Sunset and sunrise illumination threshold conditions for this testing were not considered. Light meter readings during the tests were approximately 0.002 lm/ft.

Hazard Light Lane Change Test: Lane change tests were conducted with the hazard lights turned on to check the capability of the system to distinguish normal turn signal application and hazard light application.

2.2.2 Curved-Lane Test Procedures

Two curved lane test procedures were evaluated: baseline and speed sensitivity tests. Lane changes to the left and to the right were performed for each lane line type in a counter-clockwise direction. The lane mode and speeds, for each curved roadway test procedure are listed in Table 2.2. The procedures were the same as those for straight roadways except for test location (VDA South Loop).

Table 2.2 Curved Roadway Test Matrix

Test Procedure	Lane Mode	Lane Type	Speeds (mph)	Turn Signal Application	Description
Base Line Test	In Lane	Solid, Dashed	55	No	Check for false Positive
Lane Change Test	Change Lane	Solid, Dashed	45, 55	No	

2.3 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 GPS survey of lane lines, and vehicle instrumentation. Details of these activities are discussed in this section.

2.3.1 Test Vehicle

The test vehicle used in this research was a class 8 2014 Van Hool CX45 56-passenger motorcoach, shown in Figure 2.4. The Motorcoach is equipped from the manufacturer with a air disc brake system, a 6S/6M Meritor WABCO ABS/ESC system, a Tire Pressure Monitoring System, and a Bendix Commercial Vehicle Systems AutoVue Lane Departure Warning System (referred to as "Van Hool LDW system"). Figure 2.5 shows the windshield mounted camera of the LDW system as well as the haptic feedback equipped driver's seat. The camera is mounted close to the center of the windshield. The seat is equipped with electric motors that vibrate the appropriate side to provide a silent warning to the driver. Table 2.3 presents some basic information about the motorcoach. Table 2.4 presents the test vehicles "as received" measured axle weights, and total vehicle weight. Table 2.5 presents the test vehicles Gross Axle Weight Ratings (GAWR) and Gross Vehicle Weight Ratings (GVWR).

Figure 2.4 Van Hool CX45 56-passenger Motorcoach

Figure 2.5 Left: Bendix AutoVue LDW System Video Camera Sensor
Right: Haptic Feedback Equipped Driver's Seat

Table 2.3 Vehicle Information, 2014 Van Hool Motor Coach

Model Year, Make, Model	2014 Van Hool CX
VIN	YE2XC22B5E3048282
Wheelbase Axle 1 to Axle 2	304.5 inches
Wheelbase Axle 2 to Axle 3	51 inches
Track - Steer Axle	80 inches
Track - Drive Axles	95 inches
Overall Length	45 feet
Overall Width	100 inches
Overall Height	138 inches
Steering Ratio	ZF Variable Ratio Steering

Table 2.4 Motorcoach As Received Measured Axle Weights

Vehicle	Steer Axle Load (lbf)	Drive Axle (lbf)	Tag Axle (lbf)	Total Test Weight (lbf)
2014 Van Hool CX	10,880	16,310	11,450	38,640

Table 2.5 Motorcoach GAWRs and GVWR Placard Specifications

Vehicle	GAWR Steer (lbf)	GAWR Drive Axle (lbf)	GAWR Tag Axle (lbf)	GVWR (lbf)
2014 Van Hool CX	17,640	27,575	17,640	54,000

2.3.2 Test Site Preparation

The 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 South Loop of the VDA (Figure 2.6). 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.

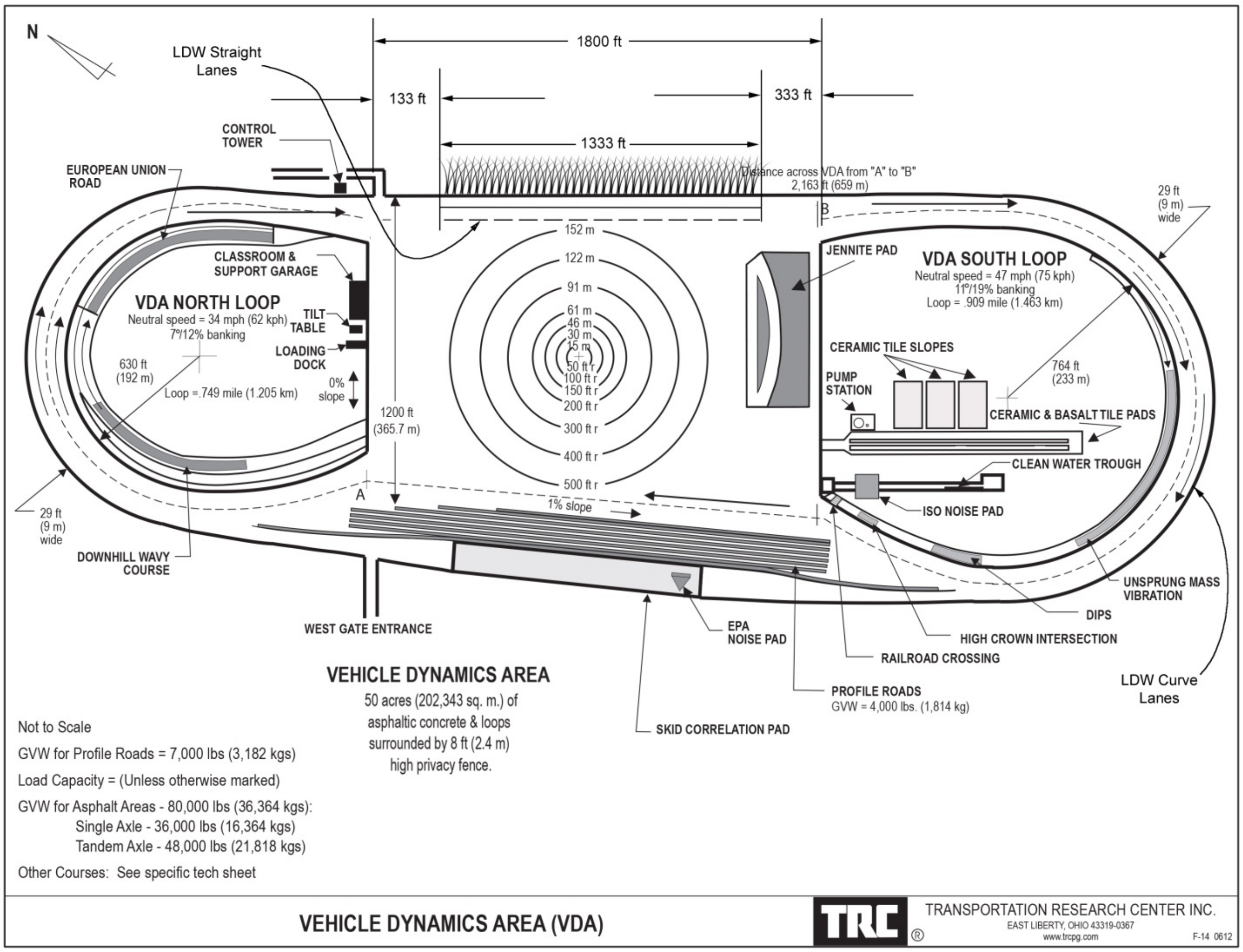

Figure 2.6 TRC VDA – LDW Straight Lanes and LDW Curve Lanes

Note: For illustration only – not to scale.

2.3.3 Test Instrumentation

In-vehicle instrumentation was implemented to collect information obtained during the lane change maneuvers. Off-board instrumentation included video, sunlight monitor, and lane survey equipment. The test vehicle was instrumented with several levels of data acquisition equipment, including controller area network (CAN), global positioning system (GPS), and digital and analog monitors.

A United Electronic Industries (UEI) “Cube” data acquisition system was installed to collect data from the numerous data sources [6]. The J1939 CAN was monitored to identify motorcoach health and activity signals. A second CAN interface was connected to the Oxford Technologies [7] RT Hunter differential GPS unit, while a third CAN interface merged the independent RT 3003 Inertial Measurement Unit (IMU) [7] data (see 0).

Analog data was collected with the Cube for numerous discrete sensors added to the test vehicle. A test lane starting point location was identified with a retro-reflective SUNX [8] sensor attached to the front bumper. The turn signal light circuits were monitored and the voltages to the LDW motors that produce the left and right-side haptic warnings were also independently recorded. Steering wheel input was measured with a potentiometric device added to the steering column. Data files were collected for a duration of 35 seconds when the driver pressed a “trigger” button. The files included five seconds of pre-trigger and 30-seconds of post trigger data logging.

2.3.4 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.

2.3.5 Illuminance Readings

Periodic illuminance readings were taken of the sunlight impinging upon the test pad. An International Light Model ILL1400 Radiometer/Photometer [9] was used to make the illuminance readings.

3 RESULTS

This chapter details the results of the LDW tests outlined in Chapter 2. The results of the straight lane tests are discussed first followed by the results for the curved lane.

3.1 Straight-Lane Test Results

The straight lane tests were conducted on the LDW test lanes on the East side of the VDA. The SV participated in 160 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.

3.1.1 Baseline Tests

The baseline tests involved driving the vehicle within the lane to check for false positive warnings from the LDW system. Tests were run at 55 mph, well above the LDW system's activation speed of 45 mph. Five repetitions were conducted for each lane marking type (solid and dashed) and for each side of the vehicle (left and right) giving a total of 20 tests. No false positive results were observed in any of the baseline tests.

3.1.2 Lane Change Tests

The lane change tests are true positive tests and were conducted to test the proper functioning of the LDW system. The test was conducted at two speeds; 45 and 55 mph with five repetitions at each speed, for each side of the vehicle, and for each lane marking type (solid and dashed). Overall, 40 lane change tests were conducted.

The data from these tests are shown in Table 3.1. The lateral distance from the outside wall of the corresponding front axle tire to the lane marking when the warning occurred and the lane departure rate are also tabulated. A negative "Lateral distance to the Lane " value indicates that the warning occurred after the vehicle had crossed over the center of the lane line. The warning trends are plotted and discussed in Section 3.1.7. It is to be noted that the system failed to warn on one occasion (denoted by NW – no warning), highlighted in yellow in the table.

Table 3.1 Straight Lane – Lane Change Test Data

Test No.	Lane Type	Side	Speed mph (km/hr)	At Lane Departure Warning	
				Lateral Distance to Lane Line (m)	Lane Departure Rate (m/s)
1	Dashed	Left	45 (72.4)	0.046	0.378
2	Dashed	Left	45	0.122	0.257
3	Dashed	Left	45	0.141	0.195
4	Dashed	Left	45	0.123	0.229
5	Dashed	Left	45	0.119	0.122
6	Dashed	Left	55 (88.5)	0.087	0.367
7	Dashed	Left	55	0.090	0.301
8	Dashed	Left	55	0.090	0.371
9	Dashed	Left	55	0.055	0.271
10	Dashed	Left	55	0.070	0.303
11	Solid	Left	45	0.182	0.146
12	Solid	Left	45	0.167	0.284
13	Solid	Left	45	0.182	0.175
14	Solid	Left	45	0.217	0.031
15	Solid	Left	45	0.115	0.324
16	Solid	Left	55	0.175	0.343
17	Solid	Left	55	0.165	0.464
18	Solid	Left	55	0.161	0.278
19	Solid	Left	55	0.125	0.363
20	Solid	Left	55	0.038	0.401
21	Dashed	Right	45	0.018	0.102
22	Dashed	Right	45	0.032	0.121
23	Dashed	Right	45	0.034	0.180
24	Dashed	Right	45	0.015	0.324
25	Dashed	Right	45	0.033	0.260
26	Dashed	Right	55	-0.017	0.396
27	Dashed	Right	55	0.022	0.225
28	Dashed	Right	55	0.014	0.258
29	Dashed	Right	55	0.029	0.333
30	Dashed	Right	55	0.005	0.344
31	Solid	Right	45	-0.027	0.262
32	Solid	Right	45	0.008	0.385
33	Solid	Right	45	-0.018	0.385
34	Solid	Right	45	-0.021	0.213
35	Solid	Right	45	NW	NW
36	Solid	Right	55	-0.091	0.357
37	Solid	Right	55	-0.084	0.335
38	Solid	Right	55	-0.055	0.413
39	Solid	Right	55	-0.046	0.254
40	Solid	Right	55	-0.153	0.169

3.1.3 Wet Condition Lane Change Tests

The wet lane change test was conducted to test the capability of the system to detect lanes when the road surface is wet. The test procedure was identical to the lane change tests, but was performed in the rain, when the test surface was fully soaked with patches of standing water.

Five repetitions were performed at both test speeds and both lane change directions. This test was performed only on the dashed lane line due to limited duration of precipitation on the test track during the testing window. A total of 20 tests were performed and the data is shown in Table 3.2.

Table 3.2 Wet Condition Lane Change Data

Test No.	Lane Type	Side	Speed mph (km/hr)	At Lane Departure Warning	
				Distance to Lane Line (m)	Lane Departure Rate (m/s)
1	Dashed	Right	45 (72.4)	-0.037	0.521
2	Dashed	Right	45	-0.135	0.209
3	Dashed	Right	45	-0.007	0.513
4	Dashed	Right	45	-0.059	0.369
5	Dashed	Right	45	-0.097	0.285
6	Dashed	Right	55 (88.5)	-0.042	0.344
7	Dashed	Right	55	-0.013	0.516
8	Dashed	Right	55	0.011	0.345
9	Dashed	Right	55	0.038	0.217
10	Dashed	Right	55	-0.063	0.610
11	Dashed	Left	45	0.110	0.223
12	Dashed	Left	45	0.157	0.234
13	Dashed	Left	45	0.163	0.230
14	Dashed	Left	45	0.199	0.234
15	Dashed	Left	45	0.108	0.230
16	Dashed	Left	55	0.143	0.274
17	Dashed	Left	55	0.161	0.172
18	Dashed	Left	55	0.068	0.499
19	Dashed	Left	55	0.116	0.190
20	Dashed	Left	55	0.159	0.241

3.1.4 Warning Prevention Tests

The warning prevention tests were conducted to check if the LDW system produced warnings when the driver changed lanes intentionally with proper signal use. No warning is expected with proper turn signal use. This test is a standard lane change maneuver, with the appropriate turn signal activated while changing lanes. The test was conducted at 45 mph with five repetitions for each side and lane type giving a total of 20 trials. The Van Hool LDW system did not produce any warnings in any of these trials.

3.1.5 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 once the lane departure warning occurs. This test was conducted at 45 mph with five repetitions for each side and each line type giving a total of 20 trials. The warning durations for these tests are compared to the average warning durations of the LDW system during the Lane Change tests (at both speeds) when no interrupt action was taken. The average normal warning durations with no interruptions are shown in Table 3.3.

Table 3.3 Average Normal Warning Duration

Side	Average LDW Duration (s)
Left	3.23
Right	3.26

Data detailing the results from the turn signal interrupt left and right-side tests are presented in Table 3.4 and Table 3.5. The time at which the LDW system produced a warning, the time at which the turn signal was activated, the duration of the warning, and finally the duration of the warning after interrupt action are listed in each table.

For the left-side trials, the warnings were shortened from a nominal duration of 3.23 s to around 1.10 s depending on when the turn signal was activated. The average duration of the warning after turn signal activation was 0.278 s.

It is to be noted that, for the right-side tests, though shorter warning durations were noticed for the solid lane line tests, only data for the dashed lines is presented since turn signal data was not collected during the solid line tests. The turn signal data channels were added after the solid line tests. For the right-side trials also, the warning duration was reduced to around 1 s from a nominal duration of 3.26 s, and the average duration of the warning post application of the turn signal is 0.248 s.

The shorter duration of the warnings and the consistently shorter warning-durations after turn signal activation for both left and right-side tests confirms that the LDW system is capable of interrupting the warning when the driver activates the turn signal.

Table 3.4 Left-Side Warning Interrupt Data

Test No.	Lane Type	Warning Time (s)		Warning Duration (s)	Turn Signal Activation Time (s)	Warning Duration after Interrupt Action (s)
		Start	End			
1	Dashed	17.185	18.270	1.085	17.930	0.340
2	Dashed	17.945	20.245	2.300	19.855	0.390
3	Dashed	13.995	15.085	1.090	14.955	0.130
4	Dashed	17.085	18.155	1.070	17.900	0.255
5	Dashed	17.725	18.815	1.090	18.605	0.210
6	Solid	13.100	14.070	0.970	13.670	0.400
7	Solid	17.310	18.315	1.005	18.115	0.200
8	Solid	14.035	15.100	1.065	14.905	0.195
9	Solid	12.905	13.830	0.925	13.470	0.360
10	Solid	11.770	12.870	1.100	12.565	0.305

Table 3.5 Right-Side Warning Interrupt Data

Test No.	Lane Type	Warning Time (s)		Warning Duration (s)	Turn Signal Activation Time (s)	Warning Duration after Interrupt Action (s)
		Start	End			
1	Dashed	16.695	17.645	0.950	17.360	0.285
2	Dashed	15.925	16.880	0.955	16.680	0.200
3	Dashed	16.035	17.035	1.000	16.775	0.260
4	Dashed	15.455	16.450	0.995	16.225	0.225
5	Dashed	14.020	15.305	1.285	15.035	0.270

3.1.6 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 with five repetitions for each side and each lane type for a total of 20 tests.

It was noted that the system did not warn for 19 of the 20 tests conducted with the opposite turn signal switched on. For one of the left-side lane departure tests conducted on the solid lane marking, the system turned on and the warning stayed on for more than a minute. The warning cleared only after the turn signal had been shut off and another lane departure was performed.

This was clearly an instance of the system malfunctioning and staying on. Another occurrence of such an instance was also noticed while driving the vehicle between runs and hence that data was not collected.

3.1.7 Night Time Lane Change Test

Night testing was conducted to check the effectiveness of the system under dark conditions under the illumination of the head lights. The procedure was identical to the lane change tests and was performed well past sunset. Light meter reading during the tests was 0.002 lm/ft^2. Five repetitions were conducted at 55 mph for each lane marking and each side for a total of 20 tests. The results are tabulated in Table 3.6.

Table 3.6 Night Time Lane Change Data

Test No.	Lane Type	Side	Speed mph (km/hr)	At Lane Departure Warning	
				Lateral Distance to Lane Line (m)	Lane Departure Rate (m/s)
1	Dashed	Left	55 (88.5)	0.093	0.433
2	Dashed	Left	55	0.152	0.342
3	Dashed	Left	55	0.140	0.171
4	Dashed	Left	55	0.103	0.346
5	Dashed	Left	55	0.150	0.264
6	Dashed	Right	55	0.033	0.335
7	Dashed	Right	55	-0.022	0.312
8	Dashed	Right	55	0.011	0.413
9	Dashed	Right	55	-0.036	0.370
10	Dashed	Right	55	0.006	0.231
11	Solid	Left	55	0.199	0.238
12	Solid	Left	55	0.158	0.376
13	Solid	Left	55	0.200	0.432
14	Solid	Left	55	0.171	0.261
15	Solid	Left	55	0.164	0.236
16	Solid	Right	55	-0.029	0.171
17	Solid	Right	55	0.026	0.220
18	Solid	Right	55	0.022	0.256
19	Solid	Right	55	0.018	0.114
20	Solid	Right	55	-0.022	0.443

3.1.8 Hazard Light Lane Change Test

This test is identical to the lane change tests, but was conducted with the hazard lights turned on. Only five tests were conducted on the solid line type for the right-side lane departure case. No warnings were produced in any of the runs.

3.1.9 Lateral Distance to the Lane Line and Lane Departure Rate Analysis

Combining all the tests, a total of 50 trials in each direction were true positive tests where the LDW system was expected to produce a warning. These tests included the Lane Change, Wet Lane Change, Warning Interrupt, and Night Lane Change tests conducted at either test speed. The two different longitudinal test speeds (45 and 55 mph) were used to produce a range of different lane departure rates (lateral speeds) for this analysis. Results from all of these tests were combined to examine the lateral distance to the lane line and lane departure rate at warning trends for the Van Hool LDW system.

The scatter plot of the warnings for the solid and dashed lane line tests are presented in Figure 3.1 and Figure 3.2 respectively. The y-axis denotes test number, with the tests of different speeds and conditions clearly demarcated with different markers on the plots. The x-axis shows the distance from the outside tire wall of the corresponding front axle tire to the center of the lane marking when the warning occurs. Positive values for lateral distance 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 the system produces a lane departure warning within a consistent range.

For a different perspective, APPENDIX C shows the lateral distance to the lane line plots for the left and right-side tests plotted separately. From these plots it is apparent that the warnings occur earlier in the maneuver for the left-side trials compared to the right-side trials.

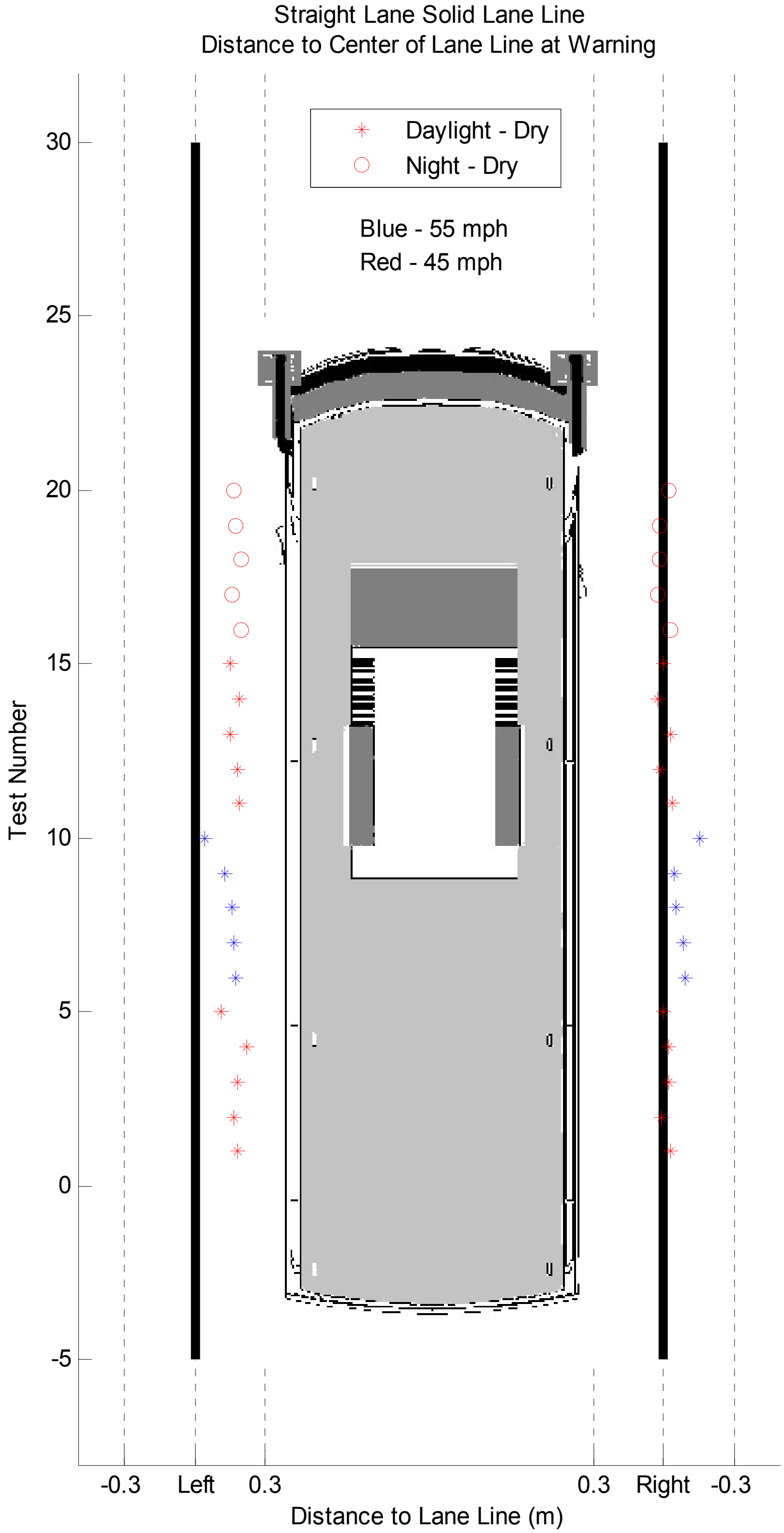

Figure 3.1 Straight Lane Solid Lane Line – Lateral Distance to Lane Line Distribution at LDW

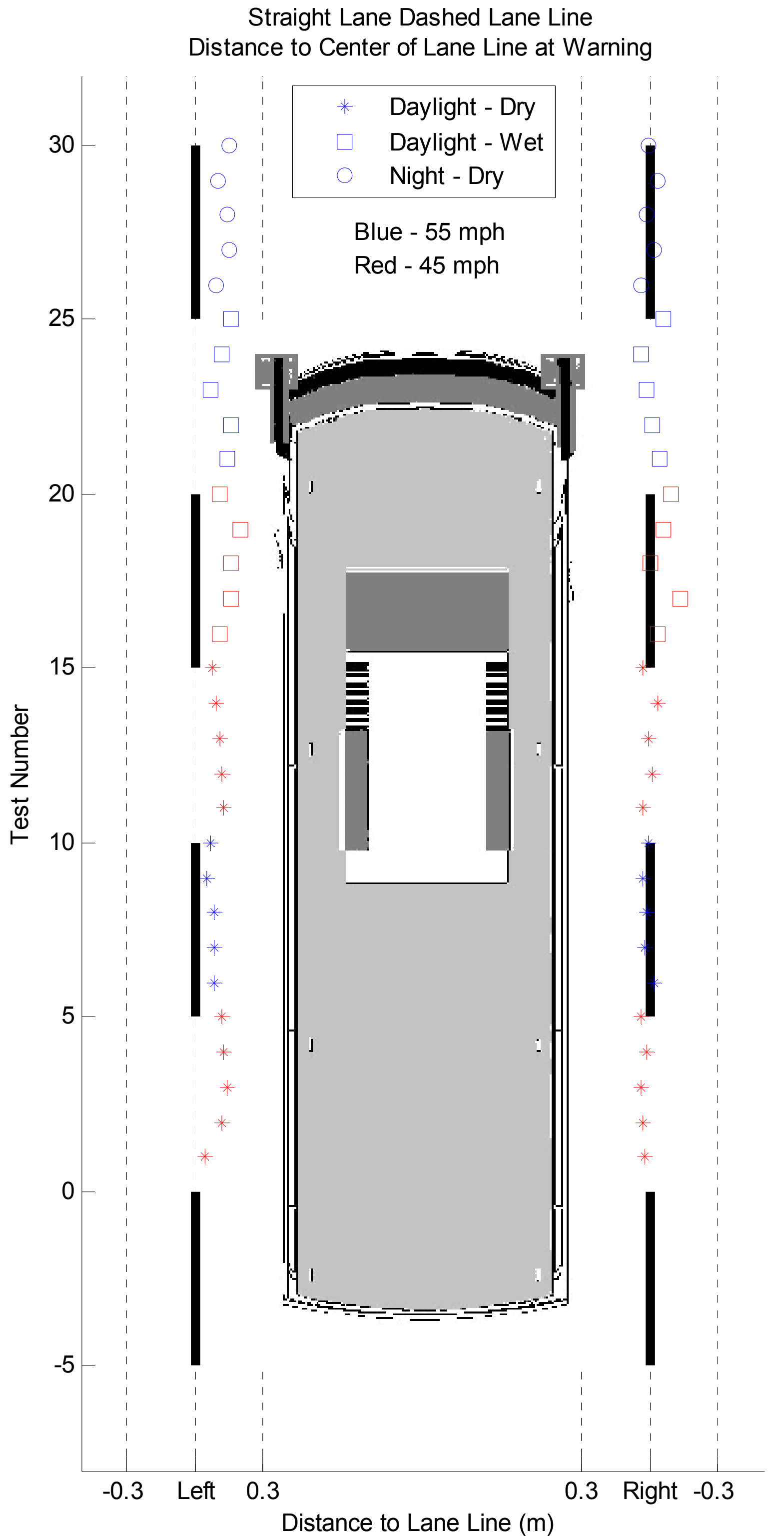

Figure 3.2 Straight Lane Dashed Lane Line – Lateral Distance to Lane Line Distribution at LDW

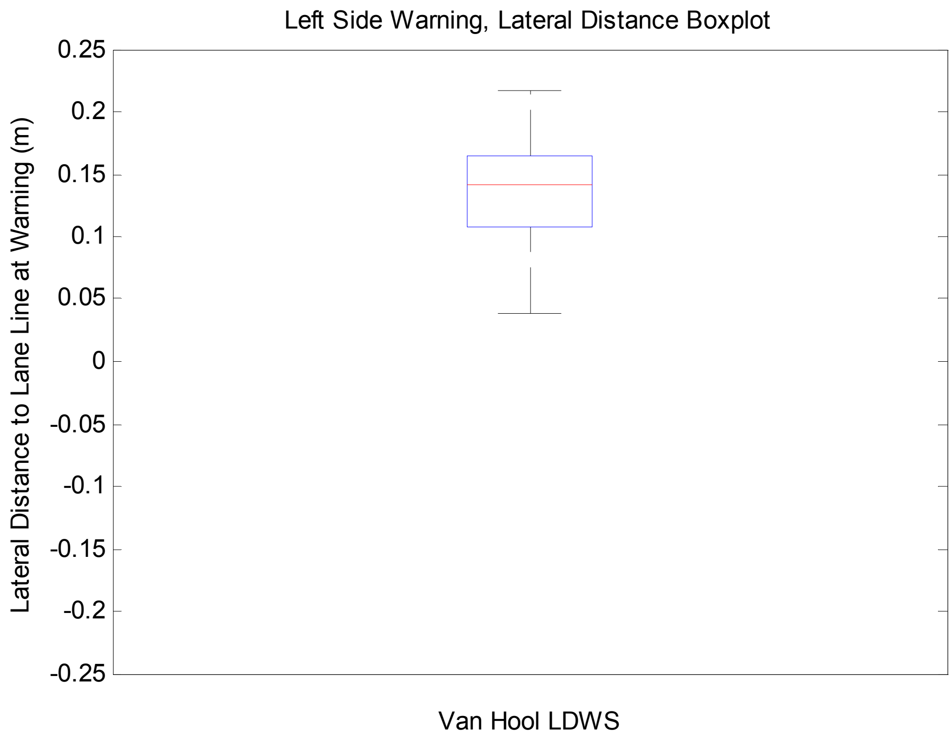

Figure 3.3 Straight Lane, Left-Side Test – Lateral Distance to Lane Line at Warning-Box Plot

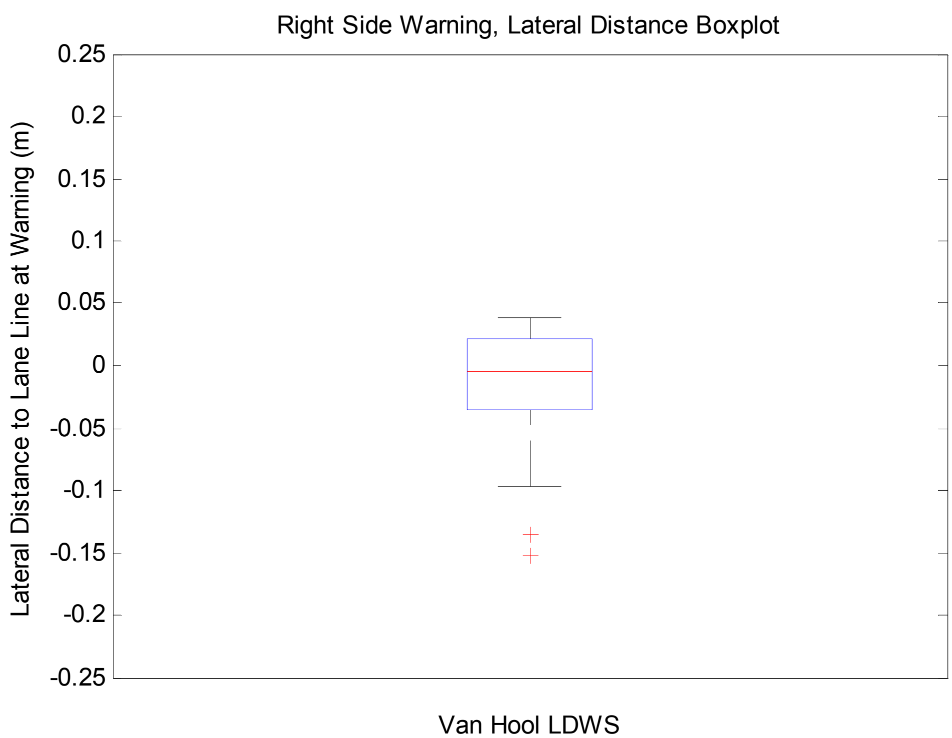

Figure 3.4 Straight Lane, Right-Side Test – Lateral Distance to Lane Line at Warning-Box Plot

Table 3.7 Straight Lane, Left-Side – Lateral Distance to Lane Line at Warning Statistics

Statistic for Lateral Distance to Lane Line at Warning	Van Hool LDW System (m)
Mean	0.136
Median	0.142
Range	0.179
Standard Deviation	0.044

Table 3.8 Straight Lane, Right-Side – Lateral Distance to Lane Line at Warning Statistics

Statistic for Lateral Distance to Lane Line at Warning	Van Hool LDW System (m)
Mean	-0.014
Median	-0.004
Range	0.191
Standard Deviation	0.044

Box plots of the lateral distance to lane line at warning data for the left and right-side tests are shown in Figure 3.3 and Figure 3.4 respectively. Outliers present in the right-side data are identified with red plus signs in the figure. Key statistics of the lateral distance to lane line at warning data are presented in Table 3.7 and Table 3.8 respectively for the left and right-side tests.

The relation between lateral distance to lane line at warning and the lane departure rate (rate at which the vehicle is approaching the lane marking) for the left-side tests are shown in Figure 3.5. One would expect that as the lane departure rate increases, the warning would occur later, further into the lane change. Such trends though are not immediately apparent, which indicates the capability of the LDW system to adjust to lane departure rate. However a conclusive claim either way cannot be made with the available evidence.

For the left-side trials, the negative Pearson's Correlation value (Table 3.9) confirms that, as the lane departure rate increases, the warning occurs later, further into the lane change maneuver. The correlation value indicates that there is moderate to low correlation between lane departure rate and lateral distance to lane line at warning. The P value of 0.0021 indicates moderate statistical significance.

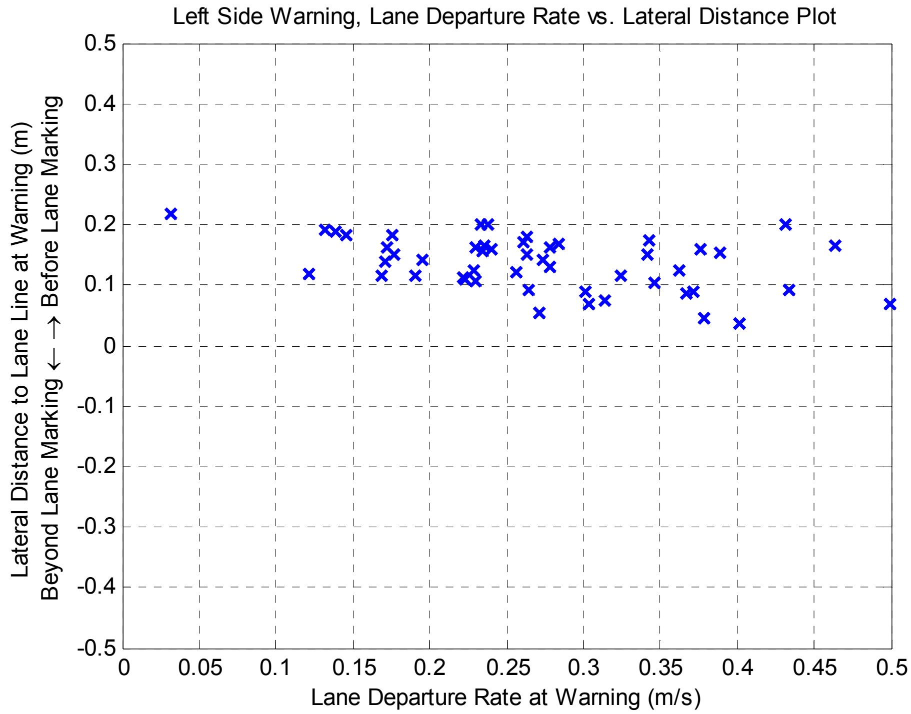

Figure 3.5 Left-Side Test – Lateral Distance to Lane Line at Warning Versus Lane Departure Rate Plot

Table 3.9 Left-Side – Lateral Distance to Lane Line at Warning Versus Lane Departure Rate Statistics

Lateral Distance to Lane Line at Warning vs. Lane Departure Rate Statistics	Van Hool LDW System (m)
Pearson's Correlation (R)	-0.4242
P value	0.0021

The lateral distance to lane line at warning vs. lane departure rate data for the right-side trials is shown in Figure 3.6. Data from the statistical analysis of the same is shown in Table 3.10. The negative Pearson's correlation value indicates that as the lane departure rate increases, the warning occurs later, further into the lane change maneuver. The correlation value (-0.1858) indicate that there is weak correlation between lane departure rate and lateral distance to the lane line. The P value of 0.1965 indicates that the null hypothesis cannot be rejected, i.e., the correlation between the lateral distance to the lane line and lane departure rate is statistically insignificant.

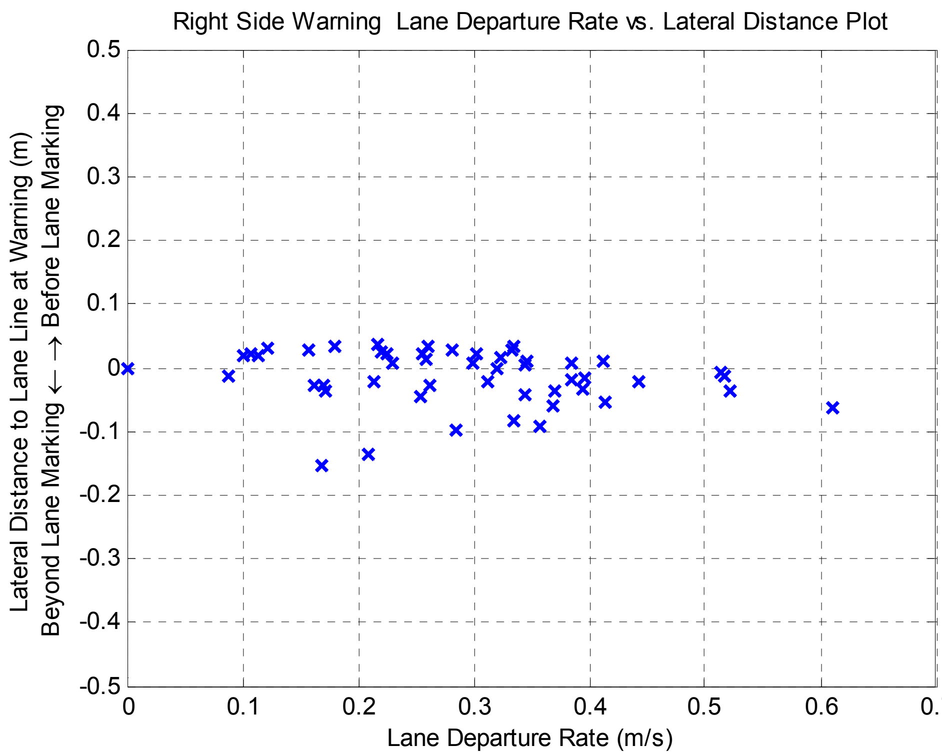

Figure 3.6 Right-Side Test – Lateral Distance to Lane Line at Warning Versus Lane Departure Rate Plot

Table 3.10 Right-Side – Lateral Distance to Lane Line at Warning Versus Lane Departure Rate Statistics

Lateral Distance to Lane Line at Warning Versus Lane Departure Rate Statistics	Van Hool LDW System (m)
Pearson's Correlation (R)	-0.1858
P value	0.1965

3.2 Curved Lane Test Results

The curved lane tests were conducted on the 764-ft (233 m) radius South Loop of the VDA. The test matrix for the curved-lane tests is given in Table 2.2 and lists conditions for baseline tests, and lane change tests. Each test was repeated five times for both the solid and dashed lines. This gives a total of 60 tests, of which 20 tests are false positive tests. The results for each test type are discussed in the sections below.

3.2.1 Baseline Tests

The baseline tests involved driving the vehicle within the lane to check for false positives from the LDW system. The baseline test consisted of five runs at 55 mph for both lane marking types (solid and dashed) and both sides of the vehicle. Overall, 20 trials of the baseline test were conducted. No false positive warnings were observed.

3.2.2 Lane Change Tests

The lane change tests were performed to check the proper functioning of the LDW system on curved roads. Lane change tests were performed at 45 mph and 55 mph, with five repetitions for each line type and each side of the vehicle adding up to 40 tests. Of the 40 tests, the LDW system failed to produce warnings on three occasions during right-side tests.

Scatter plots of the lateral distance to the lane line from these tests for the solid and dashed lane lines are shown in Figure 3.7 and Figure 3.8 respectively. The y-axis denotes test number and the x-axis shows the distance to the lane marking when the warning occurs. Positive values for the lateral distance 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.

The figures show that the right-side warnings occur much farther into the lane change maneuver than the left-side warnings. This is attributed to that fact that these curve tests were conducted while running clockwise through the curves. While running clockwise, the right-side lane lines go away from the field of view and this may limit the system’s ability to detect the lane line. This may be a contributing factor to the system failing to warn on three occasions during the right-side tests.

APPENDIX C shows the lateral distance to the lane line plots for the left and right-side tests plotted separately. These plots again reiterate the fact that the warnings for the right-side occur much later in the maneuver.

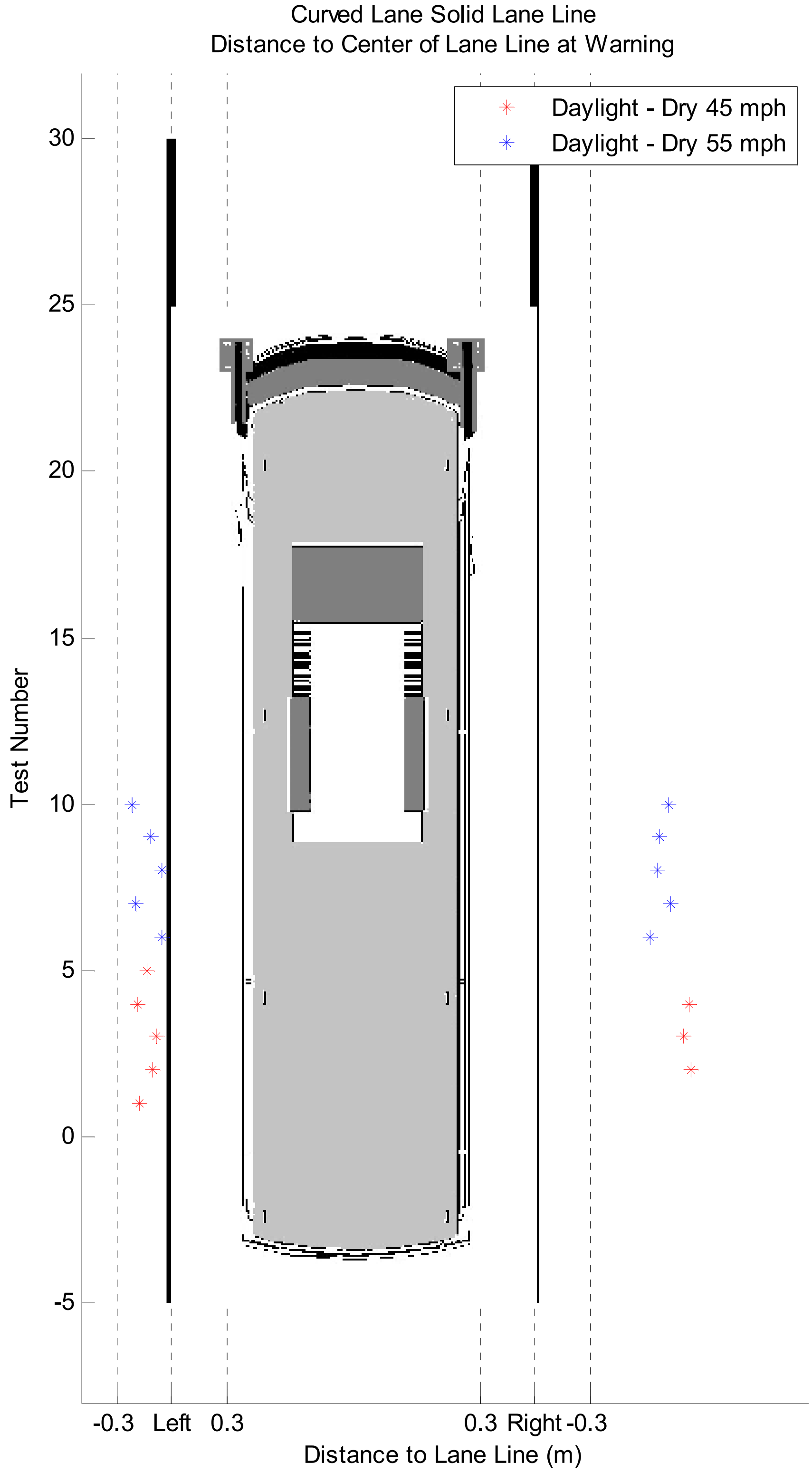

Figure 3.7 Curved Solid Lane – Warning Distribution

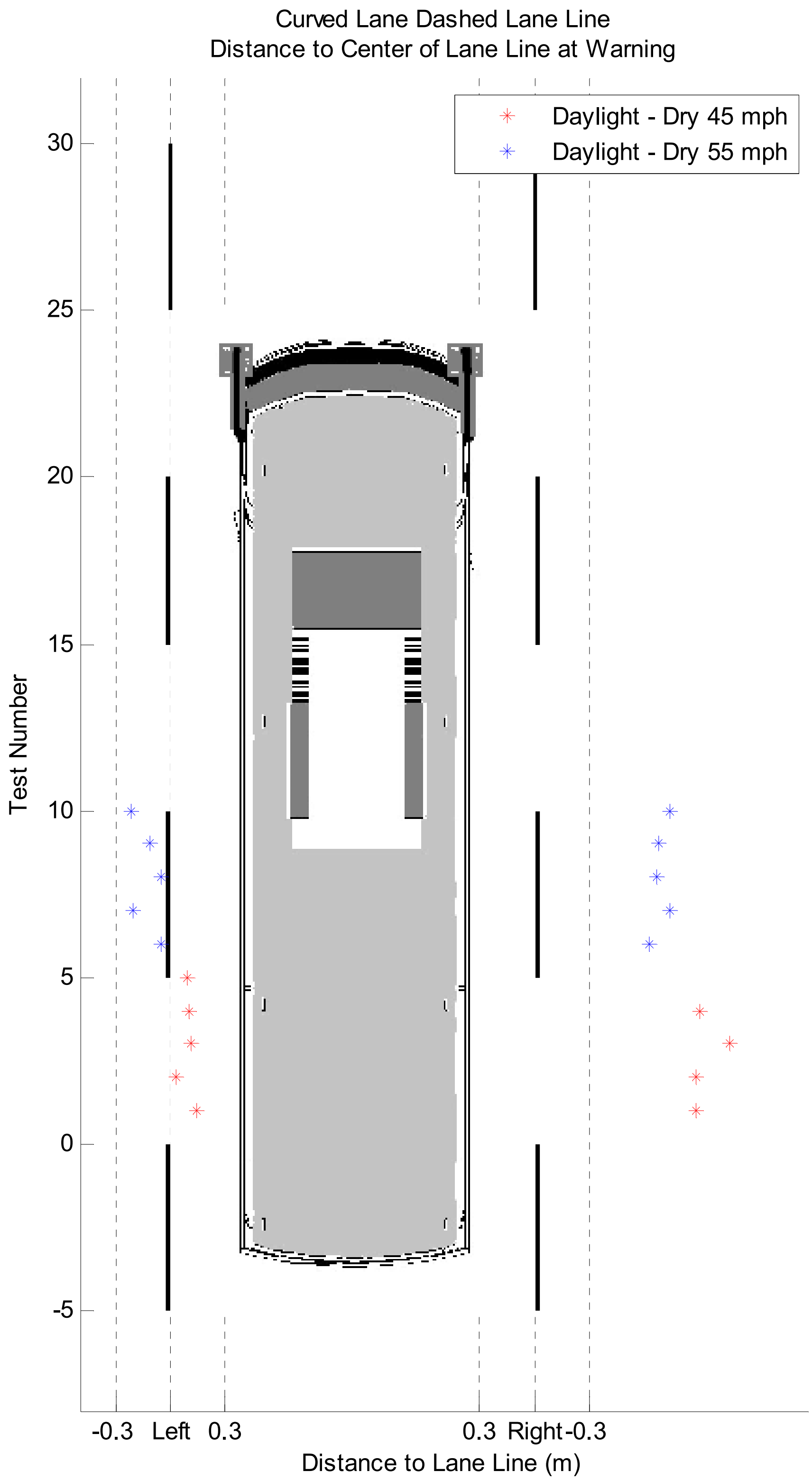

Figure 3.8 Curved Dashed Lane – Warning Distribution

A few key statistics of the lateral distance to the lane line data for the left and right-side trials are tabulated in Table 3.11 and Table 3.12 respectively.

Table 3.11 Curved Lane, Left-Side – Lateral Distance to the Lane Line at Warning Statistics

Statistic for Lateral Distance to the Lane Line at Warning	Van Hool LDW System (m)
Mean	-0.043
Median	-0.053
Range	0.442
Standard Deviation	0.125

Table 3.12 Curved Lane, Right-Side – Lateral Distance to the Lane Line at Warning Statistics

Statistic for Lateral Distance to the Lane Line at Warning	Van Hool LDW System (m)
Mean	-0.770
Median	-0.820
Range	0.442
Standard Deviation	0.218

The lateral distance to lane line at warning boxplots are shown in Figure 3.9 and Figure 3.10. The right-side warning boxplot shows an outlier marked by a red plus sign.

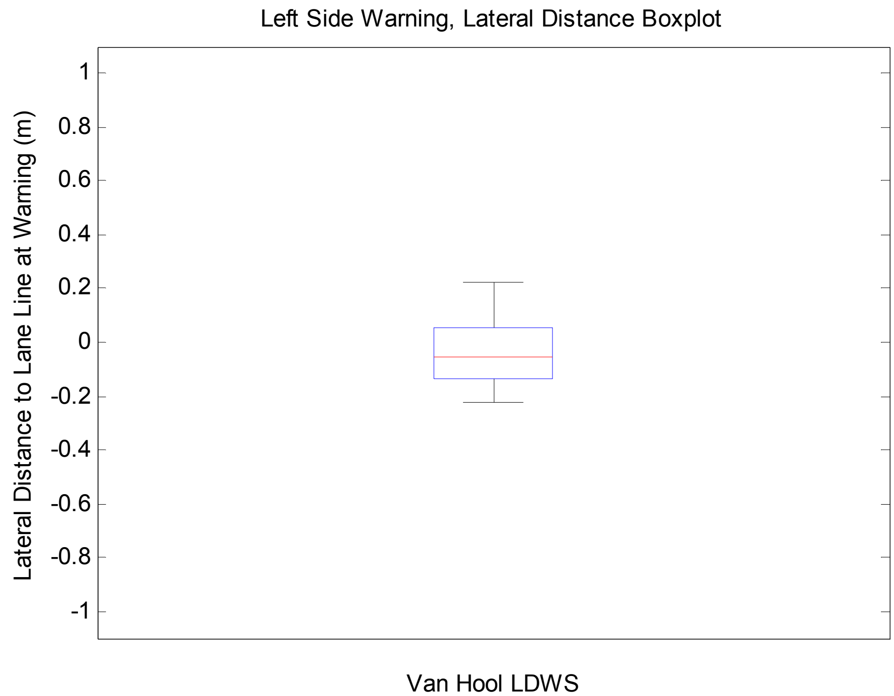

Figure 3.9 Curved Lane, Left-Side Test – Lateral Distance to the Lane Line at Warning Boxplot

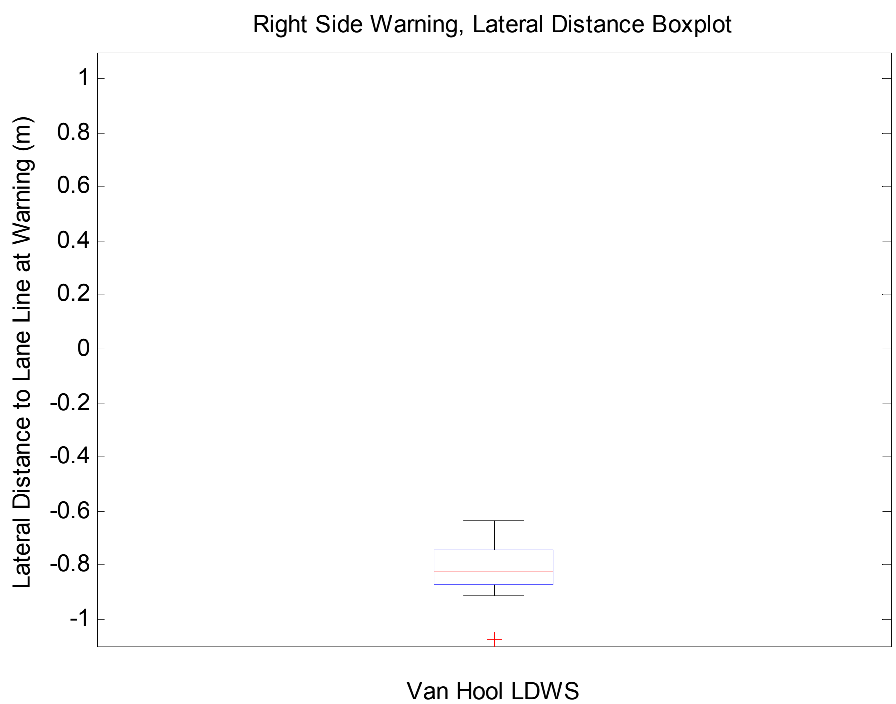

Figure 3.10 Curved Lane, Right-Side Test – Lateral Distance to the Lane Line at Warning Boxplot

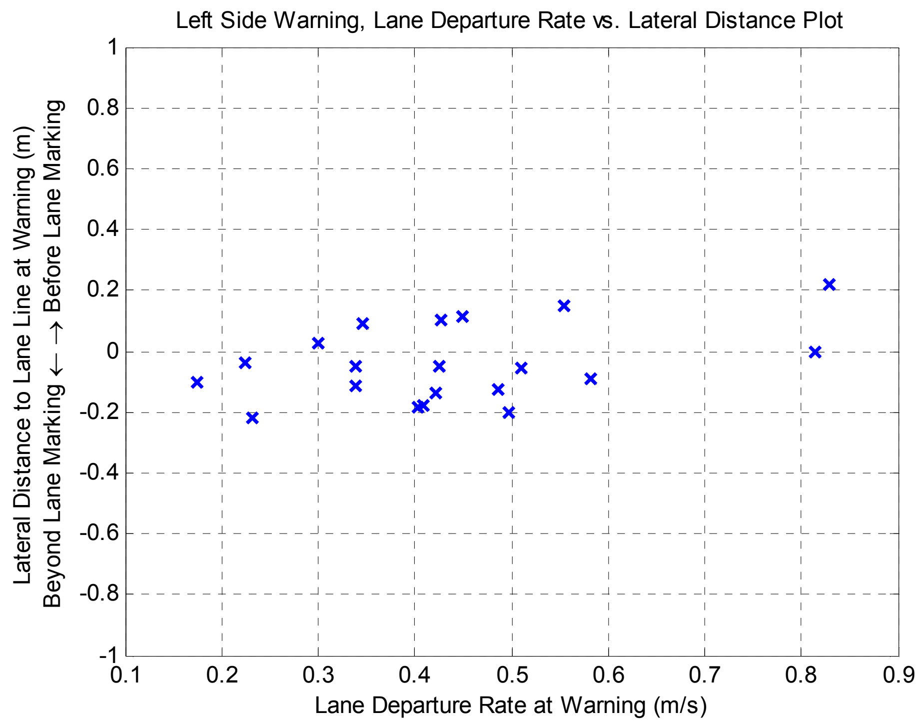

Figure 3.11 Curved Lane, Left-Side Test – Lateral Distance to Lane Line at Warning Versus Lane Departure Rate Plot

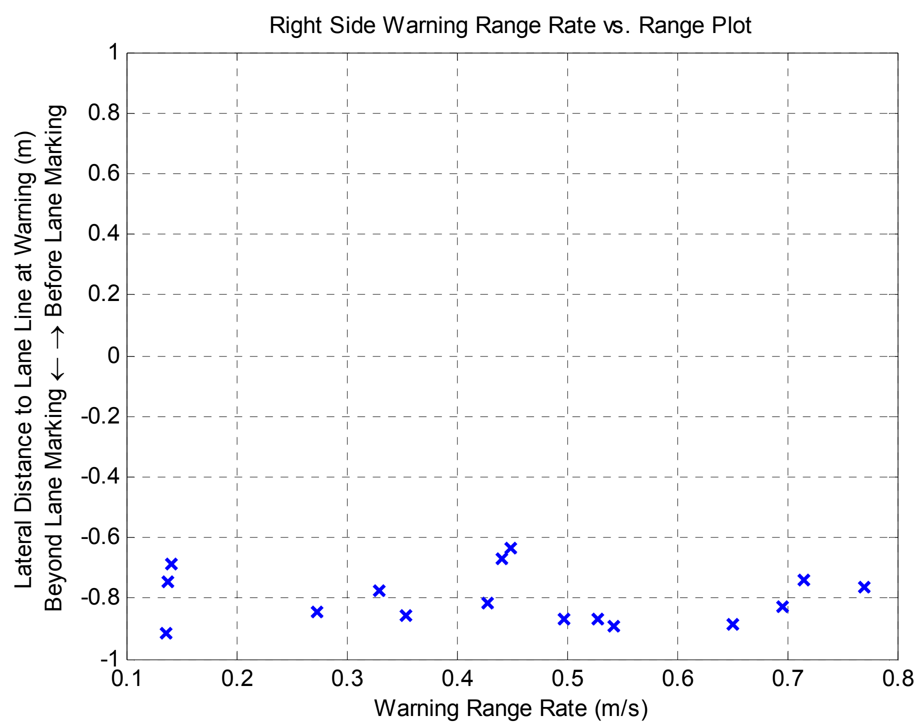

Figure 3.12 Curved Lane, Right-Side Test – Lateral Distance to Lane Line at Warning Versus Lane Departure Rate Plot

The relation between the lateral distance and the lane departure rate (rate at which the vehicle is approaching the lane marking) are shown in Figure 3.11 and Figure 3.12 for the left and right-side tests respectively. The scatter plot for the left side indicates that as the lane departure rate increases, the warning transitions from occurring slightly over the lane boundary to occurring slightly before crossing the lane boundary. The warnings occur as early as 0.26 s before lane departure and as late as 0.6 s after lane departure, with a mean warning start time of 0.1 s after lane departure. No trend is apparent for the right-side plot. Here the warnings occur much later, after the lane departure and the warning start times range from 0.9 s after lane departure to 4.1 s after lane departure, with a mean warning start time of 2.0 s after lane departure.

The statistics of the lateral distance to lane line at warning vs. lane departure rate data are tabulated in Table 3.13 and Table 3.14 for the left and right side respectively. The positive correlation value for the left side indicates that as the lane departure rate increases, the warning occurs earlier in the lane change. The correlation values indicate that there is moderate correlation between lane departure rate and lateral distance to the lane at warning. The high P value indicates that the correlation is not statistically significant. For the right-side tests, the correlation value indicates a very weak correlation and the high P value indicates that this correlation is statistically insignificant.

Table 3.13 Curved Lane, Left-Side – Lateral Distance to Lane Line at Warning Versus Lane Departure Rate Plot Rate Statistics

Lateral Distance to Lane Line Versus Lane Departure Rate Plot Statistics	Van Hool LDW System
Pearson's Correlation (R)	0.4129
P value	0.0704

Table 3.14 Curved Lane, Right-Side – Lateral Distance to Lane Line at Warning Versus Lane Departure Rate Plot Rate Statistics

Lateral Distance to Lane Line Versus Lane Departure Rate Plot Rate Statistics	Van Hool LDW System
Pearson's Correlation (R)	-0.1441
P value	0.5810

The curved lane data presented above are detailed below in Table 3.15 and Table 3.16. The runs that did not produce a warning (denoted by NW – no warning) are highlighted in yellow.

Table 3.15 Curved Lane Left LDW Tests Summary

Test No.	Test Speed mph (km/hr)	Lane Type	At LDW	
			Lateral Distance to Lane Line (m)	Lane Departure Rate (m/s)
1	45 (72.4)	Dashed	0.147	0.553
2	45	Dashed	0.026	0.300
3	45	Dashed	0.114	0.450
4	45	Dashed	0.104	0.428
5	45	Dashed	0.089	0.346
6	55 (88.5)	Dashed	-0.037	0.224
7	55	Dashed	-0.005	0.814
8	55	Dashed	-0.052	0.338
9	55	Dashed	-0.128	0.487
10	55	Dashed	0.221	0.828
11	45	Solid	-0.179	0.409
12	45	Solid	-0.103	0.175
13	45	Solid	-0.088	0.582
14	45	Solid	-0.185	0.403
15	45	Solid	-0.140	0.422
16	55	Solid	-0.052	0.426
17	55	Solid	-0.202	0.497
18	55	Solid	-0.054	0.510
19	55	Solid	-0.113	0.339
20	55	Solid	-0.221	0.231

Table 3.16 Curved Lane Right LDW Tests Summary

Test No.	Test Speed mph (km/hr)	Lane Type	At LDW	
			Lateral Distance to Lane Line (m)	Lane Departure Rate (m/s)
1	45 (72.4)	Solid	NW	NW
2	45	Solid	-0.859	0.353
3	45	Solid	-0.815	0.429
4	45	Solid	-0.844	0.273
5	45	Solid	NW	NW
6	55 (88.5)	Solid	-0.633	0.450
7	55	Solid	-0.746	0.137
8	55	Solid	-0.672	0.441
9	55	Solid	-0.687	0.141
10	55	Solid	-0.740	0.715
11	45	Dashed	-0.890	0.542
12	45	Dashed	-0.888	0.651
13	45	Dashed	-1.075	0.556
14	45	Dashed	-0.913	0.137
15	45	Dashed	NW	NW
16	55	Dashed	-0.765	0.771
17	55	Dashed	-0.777	0.331
18	55	Dashed	-0.825	0.696
19	55	Dashed	-0.868	0.528
20	55	Dashed	-0.866	0.498

3.3 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 system did not produce a warning when any turn signal was applied prior to the lane change. The system did not differentiate between left or right turn signal or the hazard lights and suppressed all warnings when any turn signal or hazard lights were turned on.

- The application of the turn signal interrupted the lane departure warning, reducing the warning duration to around 1 s from an average of around 3.2 s. The average duration of the warning after turn signal application was 0.27 seconds confirming the warning interrupt capability of the LDW system

- The warnings for the right side (average warning range of 0.02 m past the lane line) occurred slightly later compared to the left (average warning range or 0.14 m before the lane line) for the straight runs.

- Though lane change tests were conducted for different speeds, no general trends relating warning distance to vehicle speed were apparent in the statistical analysis. Increasing the vehicle speed did not necessarily translate to higher lane departure rates due to variations in driver inputs between tests.

- The system worked in wet conditions, and produced warnings during every run in a similar manner as observed in dry test conditions

- For the curved lane runs, the right-side warnings occurred much further into the lane change, at an average distance of 0.77 m into the next lane. This was attributed to the fact that the lane lines curve out of the field of view during the right-side tests.

- Nonetheless, when the vehicle is 0.77 m into the next lane, approximately 30 percent of the vehicle's width has already crossed over the lane line.

- Statistical analyses of the relationship between warning range and lane departure rate did not find consistent trends for either the left or right sides.

- The LDW system failed to warn on one occasion for the straight runs and on three occasions for the right-side curve runs.

- During the course of testing, on two occasions, the LDW system turned on and stayed on till another "unintended" lane departure was performed.

4 CONCLUSION

4.1 Introduction

The Van Hool LDW system was tested on straight and curved lane lines and its effectiveness in producing warnings for unintended lane departures was studied. From the results outlined in Chapter 3, basic observations and conclusions are detailed in this chapter.

4.2 Van Hool LDW Test Evaluation

For this study, each valid test was evaluated depending on where the LDW system produced an 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 tire to the center line of the lane line was measured when an alert was issued.

Test results indicate that alerts were on average issued at 0.06 m prior to crossing the lane line (all warnings were generally issued within 0.2m after crossing the lane line) for straight line tests. The system performance on the curved left-side tests was comparable to the straight line tests. However, in curved right-side tests the system did not produce warnings in 3 out of 20 tests and generally produced warnings further into the lane change. This is attributed to that fact that these curve tests were conducted while running clockwise through the curves.

While running clockwise, the right-side lane lines go away from the field of view of the camera and this may limit the system's ability to detect the lane line. This may be a contributing factor to the system failing to warn on 3 occasions during the right-side tests.

A summary of the performance of the LDW system evaluated is presented below. Table 4.1 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 LDSs/number of tests conducted." Table 4.2 lists the same results for the south-loop curved-line lane change tests. Table 4.1 indicates that the LDW system performed well on the straignt line tests and failed to produce a warning on only one occasion. Data shown in Table 4.2 indicates that LDW system performed well for the curved lane left-side tests (scoring 100 percent), and scored 85 percent in the right-side tests. It is also to be noted here that during the right-side curve tests, the warnings occurred on average at a distance of 0.77 m past the lane marking, i.e., 30 percent of the vehicle width was over the lane marking when the warning occurred.

Table 4.1 Van Hool Straight Lane LDW System Evaluation

Velocity (mph)	Line Type	Departure Direction	Score
45	Solid	L	5/5
		R	4/5
	Dashed	L	5/5
		R	5/5
55	Solid	L	5/5
		R	5/5
	Dashed	L	5/5
		R	5/5
45	Dashed Wet	L	5/5
		R	5/5
55	Dashed Wet	L	5/5
		R	5/5
Total (Percentage)		(98%)	59/60

Table 4.2 Van Hool Curved Lane LDW System Evaluation – VDA South Loop

Velocity (mph)	Curved Line Type	Departure Direction	Score
45	Solid	L	5/5
		R	3/5
	Dashed	L	5/5
		R	4/5
55	Solid	L	5/5
		R	5/5
	Dashed	L	5/5
		R	5/5
Total (Percentage)		(93%)	37/40

4.3 Additional Comments

The authors observed that the LDW system did not generate warnings during turn signal application tests, and suppressed warnings even when the opposite turn signal/hazard lights were activated. It is unknown if this attribute is important to the lane departure crash problem, additional research is needed to determine if this reduces the system efficacy.

During the course of testing, the authors believe the system malfunctioned a couple of times. The haptic seat vibratory warning stayed on for more than a minute and stopped when an "unintended" lane change was performed. The driver reported that this was an uncomfortable experience. It is unknown what caused the extended duration warnings. Though the driver's opinion is subjective, it may mean additional discussion is warranted with the manufacturer to determine the cause of the malfunction.

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APPENDIX B. RT AND RT RANGE

This section is based on a NHTSA report, *A Test Track Protocol for Assessing Forward Collision Warning Driver-Vehicle Interface Effectiveness,* written by Andrew Snyder, Mark Heitz, Richard L. Hoover, Bryan O'Harra, Scott Vasko, and Larry Smith, Transportation Research Center Inc. and Garrick Forkenbrock, NHTSA, in July 2011. [10] 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 position in real-time. The RT3002 is comprised of an IMU (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 Oxford Technical Solutions 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 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.

[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.

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 (C.G.) 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 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.

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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 RT3002s eliminated this form of error from the test results.

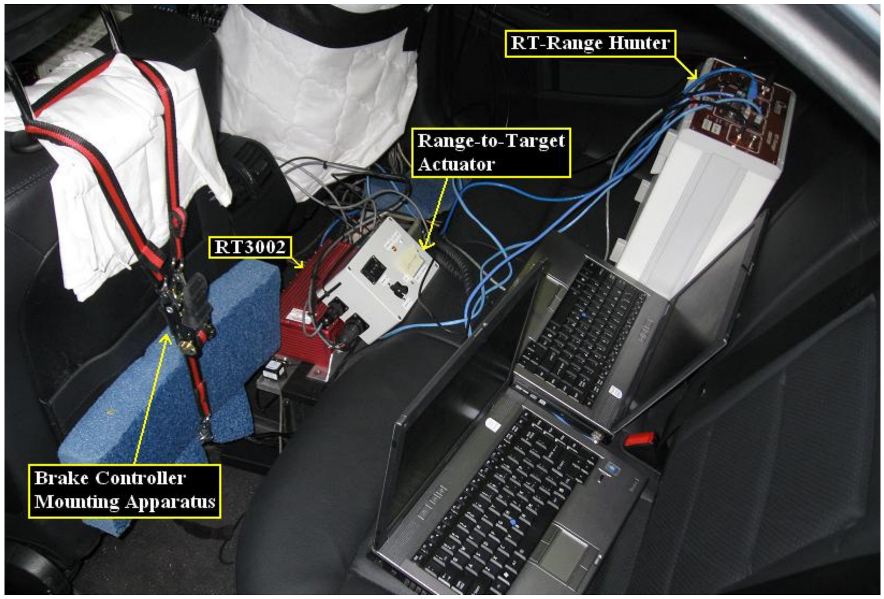

Figure B.1 RT Test Equipment in Rear Seat of Vehicle

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 C: DISTANCE TO THE LANE AT WARNING SCATTER PLOTS

Solid Lane Results:

The scatter plot of the warnings for the left and right-side tests is presented in Figure C.1 and Figure C.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 from the outside tire wall of the corresponding front axle tire to the center of the lane marking when the warning occurs. Positive values for lateral distance 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 the system produces a lane departure warning within a consistent range. For the left-side trials, the warnings occur earlier in the maneuver compared to the right-side trials.

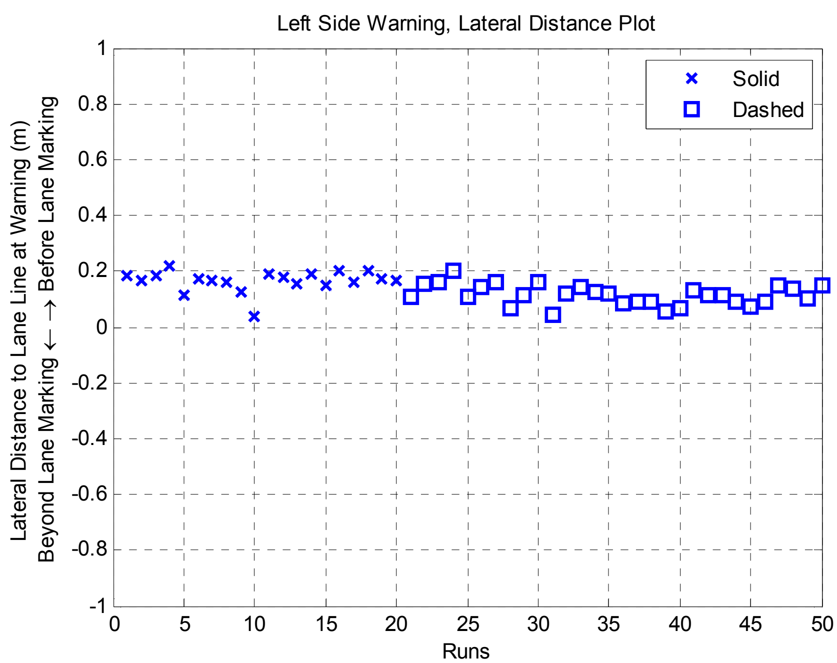

Figure C.1 Straight Lane, Left-Side Test - Lateral Distance to Lane Line at LDW Distribution

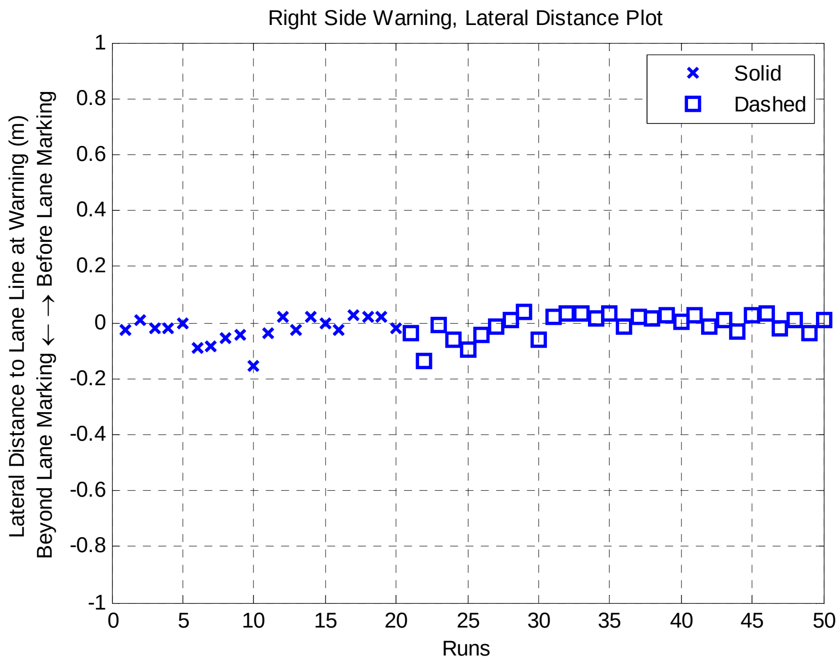

Figure C.2 Straight Lane, Right-Side Test - Lateral Distance to Lane Line at LDW Distribution

Curve Lane Results:

Scatter plots of the lateral distance to the lane line from these tests for the left and right sides are shown in Figure C.3 and Figure C.4 respectively. The x-axis denotes test number and the y-axis shows the distance to the lane marking when the warning occurs. Positive values for the lateral distance 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.

The figures show that the right-side warnings occur much farther into the lane change maneuver than the left-side warnings. This is attributed to that fact that these curve tests were conducted while running clockwise through the curves. While running clockwise, the right-side lane lines go away from the field of view and this may limit the system's ability to detect the lane line. This may be a contributing factor to the system failing to warn on 3 occasions during the right-side tests.

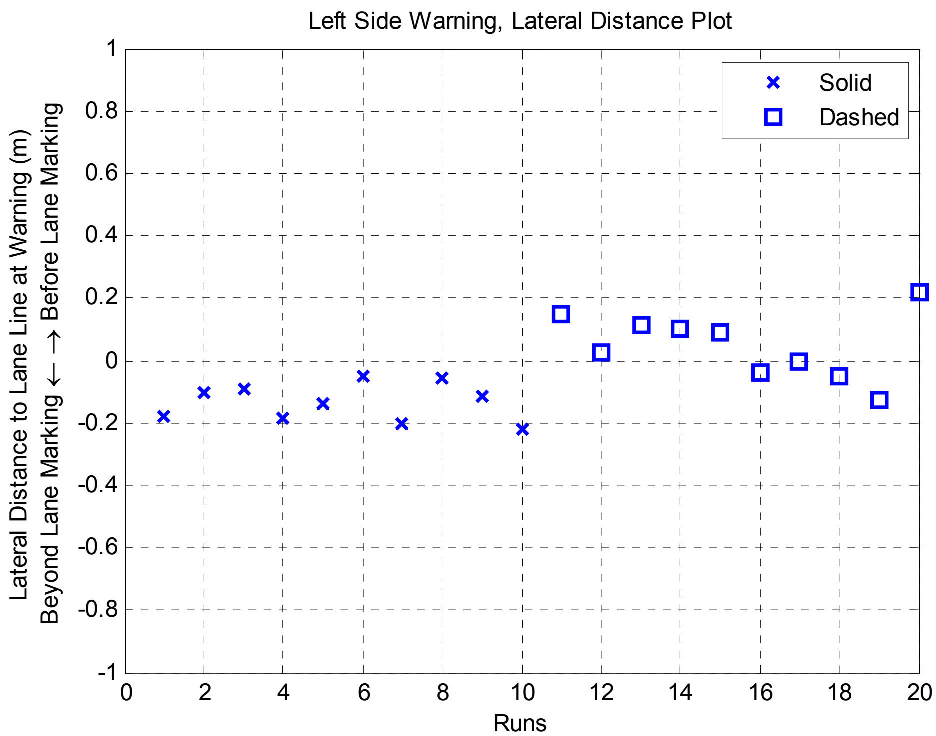

Figure C.3 **Curved Lane, Left-Side Test – Warning Distribution**

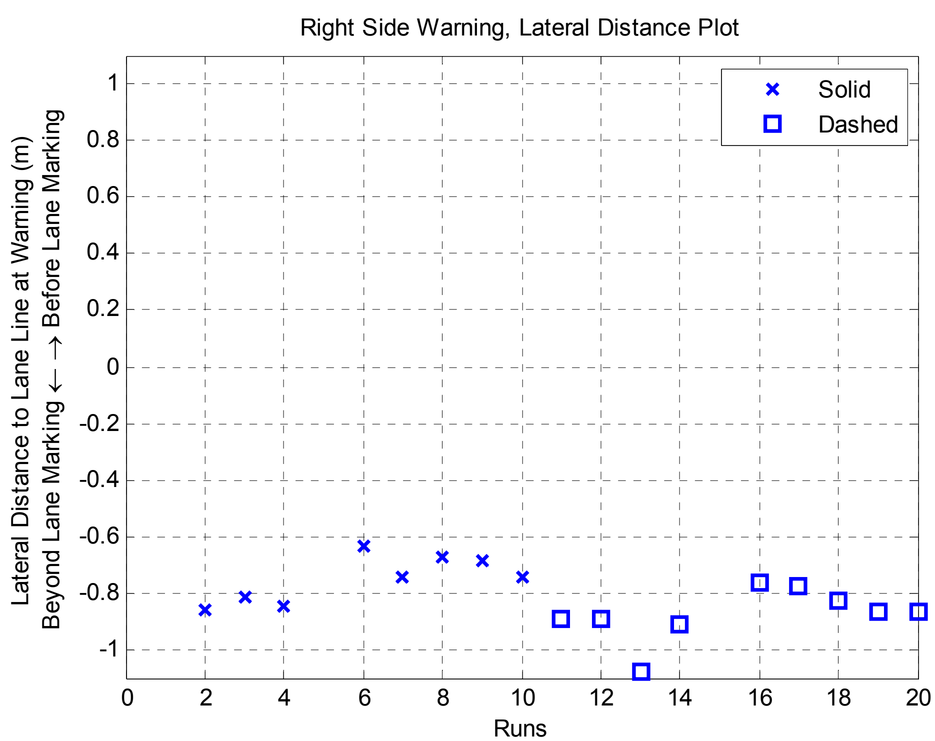

Figure C.4 **Curved Lane, Right-Side Test – Warning Distribution**

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