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Classification of Level 2 Driving Events Observed on Public Roads

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16. Abstract

This report summarizes data collected with three commercially available light vehicles equipped with SAE level 2 driving automation systems: a 2018 Cadillac CT6, a 2018 Nissan Leaf, and a 2018 Lexus LS500. SAE level 2 driving automation systems are referred to as partial driving automation systems and require the full and undivided attention of the driver at all times, and drivers are expected to assure the safety of the vehicles.

Up to three routes with a different mix of roadway types were used: (1) a highway route composed exclusively of divided, limited-access highways with exit and on ramps; (2) a rural route that consisted primarily of roads with a single lane per travel direction passing through signalized or signed intersections; and (3) a mixed route composed of highway, rural, and city driving.

The operation of each level 2 driving automation system was recorded. The responses of the systems to various real-life traffic scenarios were studied, and observed "events" were categorized into one of three categories: (1) events where the vehicle, during otherwise normal driving, suddenly terminated its level 2 driving automation system operation and transferred full control back to the driver (Type I); (2) driving situations where the system remained in operation but satisfied certain classification criteria (Type II); and (3) driving situations where either the driver performed a manual override to disengage the system, or an unintended lane departure had occurred (Type III). Details regarding the availability of the level 2 driving automation systems, the various events recorded, and the prevailing road and weather conditions are provided.

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GLOSSARY

ACC	adaptive cruise control
LKA	lane keeping assist (relates to the Lexus LS500)
LTA	lane tracing assist (relates to the Lexus LS500)
ODD	operational design domain
SC	Super Cruise (relates to the Cadillac CT6)
S.R.	State Route
TRAC	traction control (relates to the Lexus LS500)
TRC	Transportation Research Center, Inc.
VDC	vehicle dynamic control (relates to the Nissan Leaf)
VSC	Vehicle Stability Control (relates to the Lexus LS500)

EXECUTIVE SUMMARY

This report summarizes the data collected while operating three vehicles equipped with SAE level 2 driving automation systems, which are a form of advanced driver assistance systems, on three different routes. The three vehicles driven were a 2018 Cadillac CT6, a 2018 Nissan Leaf, and a 2018 Lexus LS500. The three routes used a different mix of roadway types: (1) a highway route composed exclusively of divided, limited-access highways with exit and on ramps; (2) a rural route that consisted primarily of roads with a single lane per travel direction passing through signalized and non-signalized intersections; and (3) a mixed route with a mix of highway, rural, and city roadways.

Two of the three vehicles were repeatedly driven on each route, and the operations of their respective level 2 driving automation systems were recorded. The Cadillac CT6 level 2 driving automation system, trademarked as "Super Cruise," is geofenced to work only on certain limited-access divided highways that have been mapped by General Motors, according to the manufacturer. For this reason, the Cadillac CT6 was only operated on the highway route. While operating the vehicles in level 2 driving automation, the drivers, who were professional experimenters and/or test drivers, held their hands just above or lightly touched the respective steering wheels.

Using instrumented cameras, driver-annotated video and GPS were used to document system availability and operation to various real-life traffic scenarios. Three classification types were developed to describe events that observed during the drives.

- Type I events occurred when the level 2 driving automation system, during otherwise normal driving operation, (1) suddenly terminated its level 2 driving automation operation; (2) issued a takeover notification to the driver; and (3) transferred full control back to the driver. This required the driver to immediately respond by resuming manual control of the vehicle.

- Type II events occurred when the level 2 driving automation system exhibited some form of subjectively noteworthy operation, but not to the point where the driver believed it was necessary to manually override the system to regain full control of the vehicle. At the time of the Type II event, the level 2 driving automation system was actively providing lateral and longitudinal control of the vehicle without issuing an alert or warning to the driver.

- Type III events occurred during driving situations where either the driver performed an override input to immediately disengage the system and resumed full manual control, or an unintended lane departure had occurred.

From the driver's perspective, the important distinction between Type II and III events was how they responded to the event. A driving situation where the vehicle maintained a lane position bias near the roadway center line separating the driver's vehicle from oncoming traffic is an example of a Type II event. Conversely, when a Type III event concluded with the driver applying a manual override, it was because they believed the vehicle was unable to continue automatically performing the driving task. A common Type III event example occurred when the vehicle

entered, and initially responded to, a curved section of road, but was unable to maintain lane position within the entire curve. In this case, the driver had to resume manual steering of the vehicle to prevent a lane departure.

For the Cadillac CT6, Super Cruise would sometimes disengage on roads within its operational design domain (ODD). Over the 1,620 miles of highway route driving, 95.8 percent of which were within the Super Cruise ODD, the system was unavailable for 24.1 percent of the miles. It is important to highlight that the Cadillac CT6 received a map update midway through the testing. After the map update, the Super Cruise unavailability averaged 18.0 percent of the highway route miles.

In summary, the Cadillac CT6 averaged:

- 22.7 Type I events per 100 miles on the highway route, often due to geofencing near entry/exit ramps;
- 2.4 Type II events per 100 miles on the highway route; and
- 0.7 Type III events every 100 miles on the highway route.

For the Nissan Leaf:

- Type I events per 100 miles averaged 10.5, 23.7, and 21.3, for the highway, rural, and mixed routes, respectively.
- Type II events per 100 miles averaged 4.1, 3.1, and 4.8, for the highway, rural, and mixed routes, respectively.
- Type III events per 100 miles averaged 13.0, 15.4, and 27.5, for the highway, rural, and mixed routes, respectively. All the rural and mixed route Type III events were lane departures. Overall, 480 of the 486 Type III events were lane departures for the Nissan Leaf.

The Lexus LS500 averaged:

- Type I events per 100 miles averaged 4.8, 10.3, and 38.7, for the highway, rural, and mixed routes, respectively.
- Type II events per 100 miles averaged 6.5, 11.3, and 32.6, for the highway, rural, and mixed routes, respectively.
- Type III events per 100 miles averaged 23.5, 178.0, and 124.6, for the highway, rural, and mixed routes, respectively. All Type III events were lane departures for the Lexus LS500.

While this study documents observed statistics for the identified categories of events associated with the tested SAE level 2 driving automation systems (SAE International, 2018), there are no documented or implied conclusions in this report over their correlation to driving safety, driver engagement, or consumer acceptance.

1 INTRODUCTION

There are many factors that can affect the performance of SAE driving level 2 driving automation systems (SAE International, 2018),[1] and not all systems have the same operational characteristics. As such, better understanding how vehicles equipped with these systems operate in the real world is of great interest to NHTSA.

1.1 Objective and Evaluation Overview

The work described in this report was performed to document the observations that were made while operating three passenger cars equipped with level 2 driving automation systems on public roads. Up to three test routes, and multiple drives per route, were used. Additionally, since a driver must instantly respond to a take-over request presented by a level 2 driving automation system, the state of the vehicle and the driving environment surrounding it at the time of the request was documented. The process used to perform this evaluation included the following steps.

- Identify and procure three vehicles equipped with a level 2 driving automation system.
- Select routes for highway driving, rural driving, and mixed driving.
- Instrument test vehicles.
- Perform test-drives on the selected test routes.
- Summarize the performance of the vehicles.

1.2 Test Vehicles

Among the pool of candidate vehicles equipped with level 2 driving automation systems at NHTSA's Vehicle Research and Test Center, the three most recent model year vehicles were selected.

1. 2018 Cadillac CT6
2. 2018 Nissan Leaf
3. 2018 Lexus LS500

A brief description of each vehicle is provided in the following subsections.

1.2.1 2018 Cadillac CT6

The level 2 driving automation system, available for the 2018 Cadillac CT6 (**Figure 1.1**), is named Super Cruise. Super Cruise can automatically steer to maintain lane position under certain

[1] SAE J3016 defines level 2 driving automation as "the sustained and ODD-specific execution by a driving automation system of both the lateral and longitudinal vehicle motion control subtasks of the DDT with the expectation that the driver completes the OEDR subtask and supervises the driving automation system," where the ODD is the operational design domain, DDT is the dynamic driving task, and OEDR is the object and event detection and response.

conditions on limited-access freeways that are separated from opposing traffic. The system works in conjunction with adaptive cruise control (ACC), which controls acceleration and braking while Super Cruise is enabled and in operation. At the time this report was written, Super Cruise was the only level 2 driving automation system available on the market, suggesting that drivers can use it hands-free. **Figure 1.2** illustrates the system's availability map around Columbus, Ohio, from the Cadillac website during this study (www.cadillac.com/world-of-cadillac/innovation/super-cruise).

Figure 1.1. 2018 Cadillac CT6.

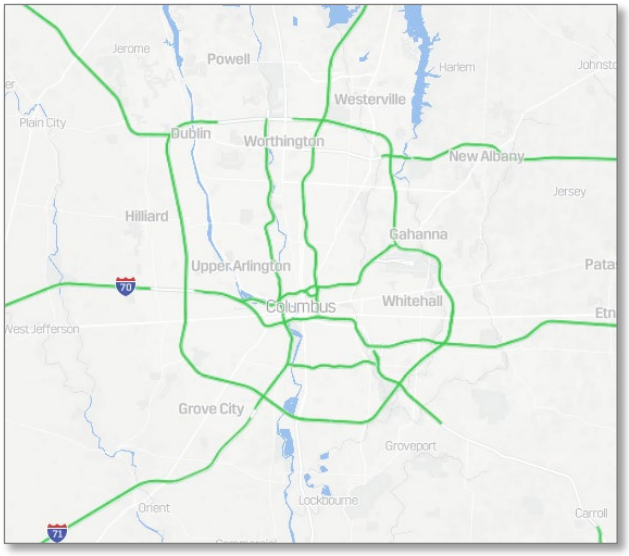


Figure 1.2. GM Super Cruise availability map.[2]

The Super Cruise driver indications and warnings are detailed in **Appendix A**. The following operating conditions, taken from the Cadillac CT6 owner's manual (General Motors LLC, 2018), is indicated to be satisfied for Super Cruise to be engaged:

1. ACC is turned on.
2. Forward automatic braking is set to "Alert and Brake" in the vehicle settings.

[2] The Super Cruise availability map on the Cadillac website has since been updated. This figure shows the availability map when the work described in this report was conducted.

3. The vehicle is located on a limited-access freeway where Super Cruise is available.
4. The Super Cruise camera and radar sensors are not obstructed or damaged.
5. Lane markings are clearly visible.
6. Driver attention is detected by driver facing camera.
7. Teen driver setting is not active.

1.2.2 2018 Nissan Leaf

The 2018 Nissan Leaf (**Figure 1.3**) is available with an optional level 2 driving automation system named ProPILOT Assist (subsequently referred to simply as ProPILOT). ProPILOT includes Nissan's intelligent cruise control (ICC) and steering assist (SA) systems. When both these features are activated, ProPILOT provides level 2 driving automation functionality. The Nissan Leaf owner's manual (Nissan North America, Inc., 2018) states that ProPILOT should only be engaged during highway driving, but since the driver can enable and operate ProPILOT off highway (i.e., it is not geofenced), the Nissan Leaf was tested on the mixed and rural routes in addition to the highway route.

Figure 1.3. 2018 Nissan Leaf.

The ProPILOT Assist driver indications and warnings are detailed in **Appendix B**. The Nissan Leaf owner's manual (Nissan North America, Inc., 2018) states that ProPILOT cannot be set when:

1. Vehicle speed is below 20 mph (32 km/h) and the vehicle ahead is not detected.
2. The shift lever is not in the D (drive) position.
3. Parking brake is applied.
4. Brakes are operated by the driver.
5. Vehicle dynamic control (VDC) is off.[3]
6. VDC system is operating.[4]

[3] Although it is not directly stated in the owner's manual, NHTSA interprets "VDC off" as being switched off by the driver or disabled due to a system fault. Nissan uses VDC to describe the Leaf's electronic stability control system.
[4] Although it is not directly stated in the owner's manual, NHTSA interprets "VDC system is operating" as a time during which electronic stability control is actively trying to stabilize the vehicle.

7. Wheel slip is occurring.
8. Any door is open.
9. Driver's seat belt is not fastened.

1.2.3 2018 Lexus LS500

The level 2 driving automation system available for the 2018 Lexus LS500 (**Figure 1.4**) is part of the Lexus Safety System +A option package. This package includes lane-tracing assist (LTA) and lane-keeping assist (LKA) which, when used in conjunction with ACC, to provide level 2 driving automation functionality. The Lexus LS500 owner's manual (Lexus, 2018) states that the LTA and LKA systems should only be engaged during highway driving. However, since the driver can enable and operate these systems off highway (i.e., the system operation is not geofenced), the vehicle was tested on the mixed and rural routes in addition to the highway route.

Figure 1.4. 2018 Lexus LS500.

The Lexus LS500 driver indications and warnings are detailed in Appendix C. The Lexus LS500 owner's manual (2018) states that the following conditions must be met for the vehicle's level 2 driving automation system to operate:

1. LKA is turned on.
2. Setting for "Steering Assist" and "Lane Center" in the multi-information display are set to "On."
3. System recognizes white or yellow lines.
4. Dynamic radar cruise control with full-speed range is in operation.
5. Width of traffic lane is approximately 8.2 to 13.5 ft (2.5 to 4.1 m).
6. Turn signal lever is not operated.
7. Vehicle is driven on a straight road or around a gentle curve with a radius of more than approximately 656 ft (200 m).
8. No system malfunctions are detected.
9. Vehicle does not accelerate or decelerate by a fixed amount or more.
10. Steering wheel is not operated with a steering force level suitable for changing lanes.
11. Hands off steering wheel alert is not displayed.

12. Vehicle Stability Control (VSC) and traction control (TRAC) are turned on.
13. VSC, TRAC, antilock brake system (ABS) and pre-collision system are not operating.
14. Steering assist function is not operating.

1.2.4 Level 2 Driving Automation System Implementation and Functionality

The implementation and functionality of level 2 driving automation systems can vary widely. Variations can include not just the features and/or capabilities of the system (e.g., an ability to perform automatic lane changes around slower-moving traffic) but also the enabling sensors. A description of these factors, for the vehicles used in this study, is presented in **Table 1.1**.

Table 1.1. Level 2 Driving Automation System Implementation and Functionality Summary

Description	**Cadillac CT6**	**Nissan Leaf**	**Lexus LS500**
Sensors	Front-facing short- and long-range radars, mono camera. lidar mapping and GPS data.	Front-facing radar and mono camera.	Front-facing short- and long-range radars, and stereo cameras.
Geographical operational design domain	Certain limited-access, divided highways mapped by General Motors.	Highway driving	Highway driving
Availability	Geofenced to certain divided highways mapped by General Motors.	System available on all public roads with lane lines at the discretion of driver; owner's manual suggests to only use on highways.	System available on all public roads with lane lines at the discretion of driver; owner's manual suggests to only use on highways.
Auto lane change capability	None	None	None
Driver attention monitoring	Monitors driver gaze and attention with driver-facing camera.	Driver engagement monitored only through a steering wheel torque sensor.	Driver engagement monitored only through capacitive touch sensor on steering wheel.
Hands free driving	Potentially unlimited duration of hands-off driving (within the ODD) for as long as camera-based attention monitoring system confirms engagement.	Limited duration (~10s) of hands-off driving before system issues warning to hold steering wheel.	Limited duration (~17s in straights, ~4s in curves) of hands-off driving before system issues warning to hold steering wheel.

1.3 Test Routes

Three separate test routes were designed to include a specific mix of road types and diverse operating conditions. Some of these routes were outside the intended geographical and/or environmental ODD of the test vehicles' level 2 driving automation systems. The routes are described in the following subsections.

1.3.1 Highway Route

The highway route (**Figure 1.5**) consisted exclusively of divided, controlled-access highways with exit ramps and on ramps. This route:

- Began on Ohio State Route (S.R.) 347 heading west at the entrance of Transportation Research Center Inc. (TRC);
- Turned southwest on U.S. 33;
- Went onto I-270 south counterclockwise around Columbus;
- Took I-71 north through Columbus;
- Merged onto I-270 west;
- Went onto U.S. 33 traveling northeast; and
- Ended on S.R. 347 at the TRC entrance.

The highway route was 108 miles long and under normal traffic conditions took approximately one hour and 40 minutes to complete.

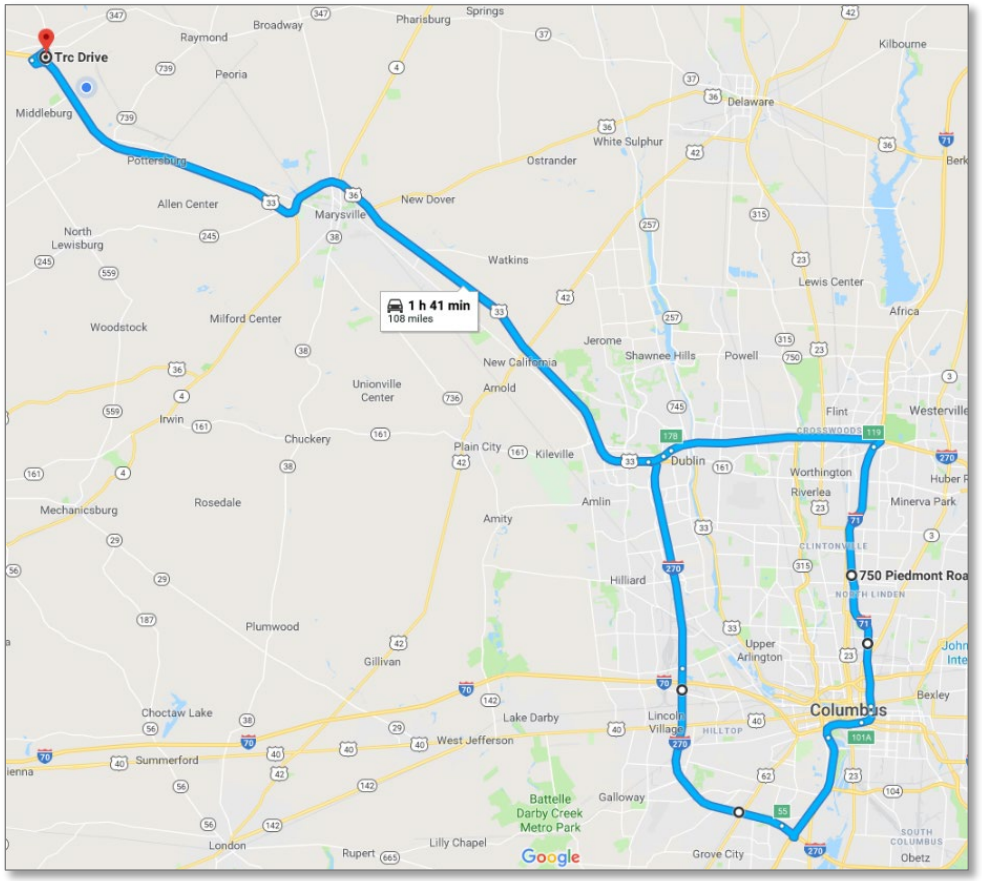


Figure 1.5. Highway route.

1.3.2 Rural Route

The rural route (**Figure 1.6**) was composed of single-lane-per-direction-of-travel roads, that had signed or signalized intersections. Unlike the highway route, some of the rural route roadways had undulations, hills, and sharp corners. This route:

- Started on S.R. 347 at the TRC entrance (heading east);
- Headed north on County Road 222;
- Continued to S.R. 31;
- Headed west on S.R. 47;
- Went south on S.R. 292; and
- Ended on S.R. 347 at the TRC entrance.

The rural route, 32.4 miles long and under normal traffic conditions, took approximately 45 minutes to complete.

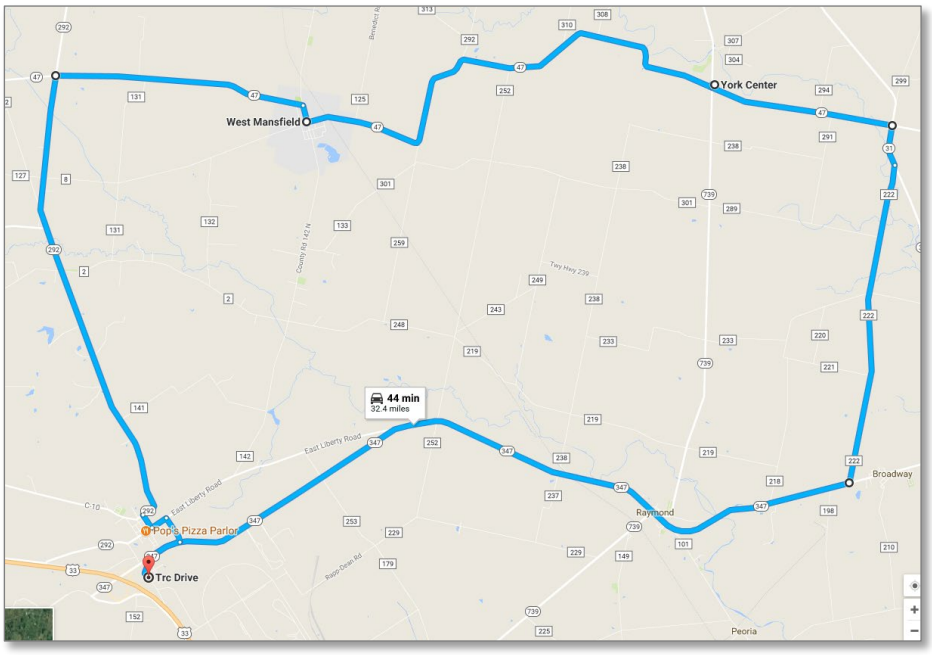


Figure 1.6. Rural route.

1.3.3 Mixed Route

The mixed route (**Figure 1.7**) consisted of highway, rural, and residential roads. This route:

- Began heading west on S.R. 347 from the TRC entrance;
- Turned south on US 33;
- Exited left onto US 36 toward the city of Delaware, Ohio;

- Went west on S.R. 37;
- Continued onto S.R. 347; and
- Ended on S.R. 347 at the TRC entrance.

The different roadway types on the mixed route and their corresponding distances are listed in **Table 1.2**. The mixed route, 63.1 miles long and under normal traffic conditions, took approximately one hour and 17 minutes to complete.

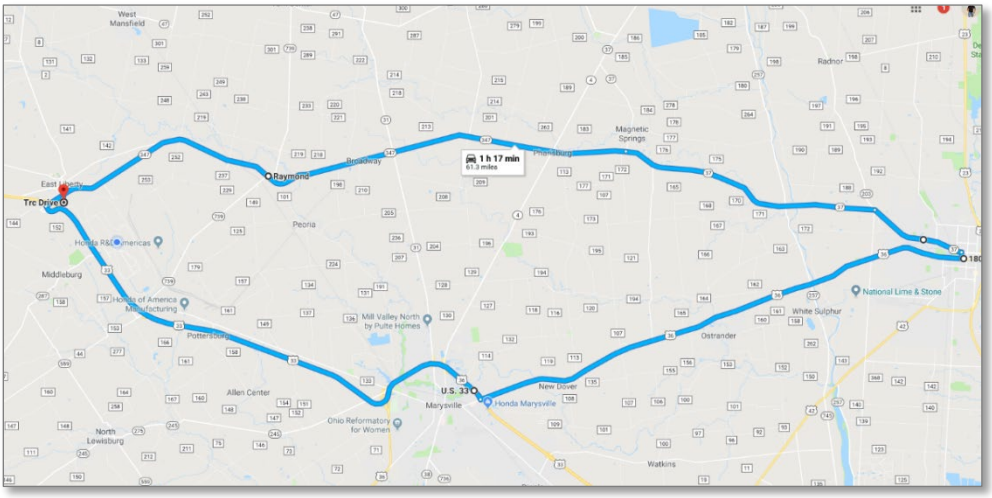


Figure 1.7. Mixed route.

Table 1.2. Mixed Route Roadway Types and Distances

Environment	**Distance (miles)**
Freeway	16.1
Rural	41.1
Residential	5.9
Total	63.1

1.4 Vehicle Drives Matrix

It was initially intended to drive each vehicle 15 times on each route. However, the number of times the vehicles were actually driven on a given route (**Table 1.3**) was often less.

Table 1.3. Vehicle Drives Matrix

Vehicle	**Highway Route**		**Rural Route**		**Mixed Route**	
	No.	**Miles**	**No.**	**Miles**	**No.**	**Miles**
Cadillac CT6	15	1,620	-	-	-	-
Nissan Leaf	15	1,620	3	97.2	15	946.5
Lexus LS500	5	540	3	97.2	5	315.5

- The Cadillac CT6 was only tested on the highway route since Super Cruise was not available (i.e., not able to be enabled or put into operation) on the rural route and for most of the mixed route.

- For two reasons, testing on the rural route was limited to three exploratory drives with the Nissan Leaf and the Lexus LS500. First, the time where the respective level 2 driving automation system could be enabled and put into operation was limited (recall that the roads associated with this route were outside of the vehicles' stated ODDs). Second, when level 2 driving automation systems were in operation, a relatively high number of the events described in Chapter 2 were observed. Completing 15 rural route drives per vehicle would therefore have imposed an unnecessarily high data processing burden.

- The Lexus LS500 was limited to five drives on the highway and mixed routes to reduce the high data processing burden imposed by the relatively high number of the events described in Chapter 2.

1.5 Instrumentation

Two Waylens Horizon cameras were used to capture video, inertial, and GPS data during testing. The cameras were equipped with a 3-axis accelerometer, a 3-axis magnetometer, and a 3-axis solid state gyroscope. The cameras record GPS data at 10 Hz and video with a resolution of 1080p at 60 frames per second. One camera was mounted over the driver's shoulder to record their driving actions, and the second camera was mounted on the wind shield to record a front-facing view outside of the vehicle.

2 EVENT OCCURANCE AND PREVAILING ENVIRONMENTAL AND ROAD CONDITIONS

This chapter defines and describes the driving events that occurred while attentive professional drivers were operating each vehicle in level 2 driving automation. The environmental conditions at the time the events were also observed, were recorded, reviewed, and classified.

Note: The events observed, and the prevailing environmental and road conditions, are reported as they were encountered. Testing was not designed or intended to normalize for exposure to the various environmental and road conditions. As an example, no attempt was made to have a similar number of drives in wet and dry conditions; it was only noted if the roadway was wet or dry when an event occurred.

2.1 Event Classification

While operating the vehicles in level 2 driving automation, the drivers, who were professional experimenters and/or test drivers, held their hands just above or lightly touched the respective steering wheels until a noteworthy "event" occurred, at which time they would typically place their hands back on the steering wheel, push a steering wheel-mounted button to flag the event in the drive video, and briefly annotate the driving situation. Later, during post-processing at VRTC, the drivers reviewed their respective videos and subjectively[5] classified their flagged events into one of three categories, Type I, Type II, or Type III.

Type I events occurred when the system, during otherwise normal driving, (1) suddenly terminated its level 2 driving automation system operation; (2) issued a takeover notification to the driver; and (3) transferred full control back to the driver. This required the driver to immediately respond by resuming manual control of the vehicle. The takeover prompts may be composed of any combination of auditory, visual, and/or haptic modality. To be classified as a Type I takeover event, it was required that the vehicle was being driven in level 2 driving automation, and that the system was performing the driving task in a manner free from anomalous behavior until the transfer of control occurred.

Type II events occurred when the level 2 driving automation system exhibited some form of subjectively noteworthy operation, but not to the point where the driver believed it was necessary to manually override the system to regain full control of the vehicle. At the time of the Type II event, the level 2 driving automation system was actively providing lateral and longitudinal control of the vehicle without issuing an alert or warning to the driver.

A driving situation where the level 2 driving automation system biased the vehicle's lane position very near the roadway center line separating the driver's vehicle from oncoming traffic is an example of a Type II event referred to as "lane hugging." Another example occurred when the level 2 driving automation system repeatedly steered the vehicle to the left and right of the lane center while being driven in a curve, which can cause the vehicle to wander back and forth about the center of the lane. In this report, this phenomenon is referred to as "dithering in lane."

[5] To remove as much ambiguity from this process as possible, the drivers each received a common set of Type I, II, and III event definitions and examples of how sample driving events should be classified before post-processing began.

Type III events were broken down into two sub-categories: "driver intervention events" and "lane departure with automatic centering events."

- **Type III driver intervention events** occurred during driving situations where the driver, believing the vehicle was unable to automatically perform the driving task any further, performed an override input to immediately disengage the system and resume full manual control. Transfer of control from the vehicle back to the driver always occurred after the override input during a Type III driver intervention event. The driver override inputs used during a Type III driver intervention event could be any combination of steering or braking, which are described as lateral and longitudinal interventions, respectively.

- **Type III lane departure with automatic centering events** occurred when the vehicle, while operating in level 2 driving automation without traffic in an adjacently lane, breached a lane boundary but then automatically (i.e., without any intervention from the driver) returned back toward the center of the original travel lane.

The key difference between the initial conditions of the two Type III event sub-categories had to do with whether other vehicles were present or approaching the test vehicle. If so, the driver was instructed to prevent the vehicle from entering the adjacent lane, and the event was classified as a Type III driver intervention event. If not, and if the driver believed if the unintended lane change into an adjacent lane would not affect other traffic present on the roadway, the driver used the opportunity to let the event "play out" to assess if or how their vehicle was able to recover from the unintentional (i.e., vehicle-induced) lane departure, and classified the event as a Type III lane departure with automatic centering event.

The events, along with the prevailing road and environmental conditions when they occurred, were catalogued for each vehicle. The events were then statistically analyzed, and then summarized.

2.2 Environment Classification

The environmental conditions prevailing during each event were recorded and classified into three broad categories: roadway type, roadway condition, and lane line condition.

Roadway type:

Two special roadway types were classified (entry/exit ramp and merge lane), while all other roadways were considered "normal."

> Entry/Exit Ramp: Highway entry and exit ramps can have sharp curves, high banking, and steep grades. These conditions pose challenges to the vehicles operating in level 2 driving automation.[6] If the event occurred on an entry/exit ramp, it was classified as such).

[6] Although they were outside of the stated ODD for the vehicles described in this report, at times it was possible to engage the Lexus LS500 and Nissan Leaf level 2 driving automation system while driving on entrance and exit ramps.

Merge Lane: When two lanes merge or split, the lane lines on the merge side disappear for a short distance, and the effective lane width increases as a result. It was observed that such a situation can pose problems for vehicles operating in level 2 driving automation, and hence the category is of interest.

Roadway condition:

Roadway conditions were classified subjectively by reviewing the video of the event.

Wet/Dry: It is noted whether the event occurred on wet or dry road.

Straight/Curved: It is noted whether the event occurred on straight or curved road segment.

Flat/Not Flat: It is noted whether the event occurred on a flat or sloped road segment.

Lane line condition:

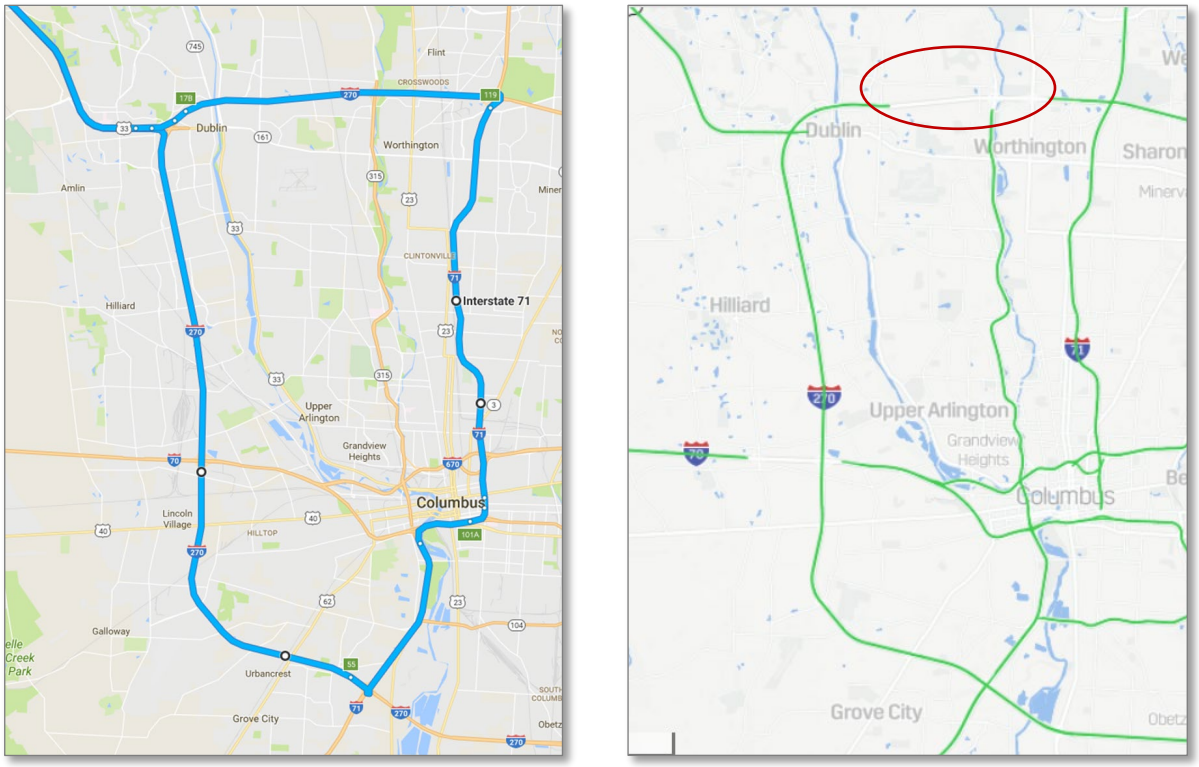
Lane line condition was classified by subjective review of the test video. Since the level 2 driving automation systems described in this report depend heavily on lane lines to provide the information needed for them to help keep the vehicle centered within the lane, it is noted whether the lane lines are good, degraded, or missing when an event occurs.

2.3 Cadillac CT6 Performance

The Cadillac CT6 was only tested on the highway route since the Super Cruise was not available on some or all of the roads included within the rural and mixed routes. This section describes the performance of the Cadillac on the highway route.

2.3.1 Cadillac CT6 Super Cruise Availability Analysis

A side-by-side comparison of most of the highway route and the corresponding Super Cruise availability map (at the time of testing) is shown in **Figure 2.1**. It is evident from this comparison that Super Cruise was not available for a portion of the designed route. During testing, it was noticed that the system was not available to be engaged during other portions of the drive as well. This section discusses the statistics pertaining to Super Cruise availability over the 15 drives performed on the highway route.



a) Highway route section b) Super Cruise availability map

Figure 2.1. Comparison of highway route and Super Cruise availability map.

From the availability map, the distance for which Super Cruise was not expected to be available on the highway route (circled in red in **Figure 2.1b**) was calculated to be 4.25 miles. The number of miles and percentage of the drive for which Super Cruise was actually unavailable for each test drive was calculated using **Equation 1**. Since the Cadillac CT6 was out of its ODD for 4.25 miles during the test route, this was subtracted to calculate the net miles unavailable, and percentage net miles unavailable using **Equation 2**.

$$\%\, Total\ Miles\ Unavailable = \frac{Total\ Miles\ Unavailable}{Total\ Drive\ Distance\ (108\ miles)} \times 100 \qquad \ldots. (1)$$

$$\%\, Net\ Miles\ Unavailable = \frac{Total\ Miles\ Unavailable - 4.25}{Total\ Drive\ Distance - 4.25} \times 100 \qquad \ldots. \quad (2)$$

The Super Cruise unavailability statistics for each of the 15 drives is shown in **Table 2.1**. The plot of the net miles unavailable is shown in **Figure 2.2**. During testing, a map update was pushed to the Cadillac CT6 after drive number 9. **Table 2.1** illustrates that the net Super Cruise unavailability was consistently below 20 percent for the drives after the map update.

Table 2.1. Super Cruise Unavailability Statistics for Each Drive

Drive No.	Total Miles Unavailable	Total % Miles Unavailable	Net Miles Unavailable	% Net Miles Unavailable
1	27.5	25.5%	23.3	22.4%
2	28.6	26.5%	24.3	23.5%
3	35.9	33.2%	31.7	30.5%
4	35.1	32.5%	30.8	29.7%
5	34.2	31.7%	29.9	28.9%
6	38.7	35.8%	34.4	33.2%
7	30.9	28.6%	26.6	25.7%
8	29.5	27.3%	25.2	24.3%
9	47.9	44.3%	43.6	42.0%
10	23.3	21.6%	19.1	18.4%
11	21.2	19.7%	17.0	16.4%
12	22.4	20.7%	18.2	17.5%
13	23.3	21.6%	19.1	18.4%
14	20.7	19.2%	16.5	15.9%
15	20.3	18.8%	16.0	15.5%
Total	**439.5**	**27.1%**	**375.7**	**24.1%**

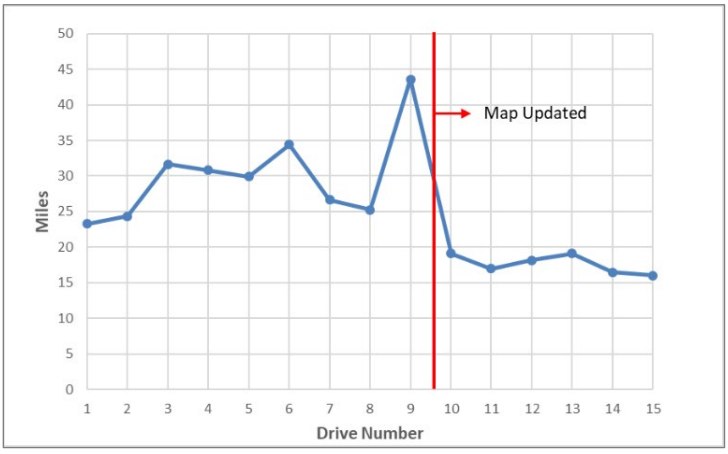


Figure 2.2. Net miles of Super Cruise unavailability

Of the 1,620 total nominal miles driven on the highway route, Super Cruise was available and active for a total of 1,180.5 miles. Of the 1,620 miles, the system was geofenced out for 63.75 miles, and the overall percentage of the net miles unavailable was 24.1 percent. It is important to highlight that, for the 6 drives after the map update, net Super Cruise unavailability averaged 18.0 percent, which was an improvement of 6.1 percent over the overall average.

2.3.2 Cadillac CT6 – Highway Route Performance

Super Cruise was operational for 1,180.5 of the 1,620 total miles driven with the Cadillac CT6, during which time a total of 304 events were recorded. These events included 268 Type I events, 28 Type II events, and 8 Type III events (**Table 2.2**).

Table 2.2. Cadillac CT6 Highway Route Event Categories Breakdown

Event Category	Number
Type I	268
Type II	28
Type III	8
Total	**304**

The Type I event distribution over the various environmental conditions for the Cadillac CT6 highway drives is presented in **Table 2.3**. The percentage of the total number of Type I events is also presented. As noted previously, the drives were not designed to normalize for exposure to the various environmental and road conditions.

Table 2.3. Cadillac CT6 Highway Drive Type I Event Results

Total Type I Events		268	
Roadway Type	Exit Ramp	28	10.4%
	Merge Lane	33	12.3%
	Normal	207	77.2%
Road Condition	Dry	264	98.5%
	Wet	4	1.5%
	Straight	205	76.5%
	Curved	63	23.5%
	Flat	249	92.9%
	Not Flat	18	6.7%
Lane Line Condition	Good	247	92.2%
	Degraded	14	5.2%
	Missing	4	1.5%

During the 15 drives, the Cadillac CT6 presented a total of 268 Type I events. There were 10.4 percent of these events that occurred on exit ramps[7] while another 12.3 percent occurred on merge lanes. The remaining occurred on normal highway roads. There were 98.5 percent of the Type I events that happened in dry conditions, while the remaining 1.5 percent occurred in wet conditions. There were 76.5 percent of the Type I events that occurred on straight road segments and the remaining 23.5 percent occurred on curved road segments. 92.9 percent of the Type I events occurred on flat roads. There were 92.2 percent of all the Type I events that occurred when clear lane lines were present, 5.2 percent of the events occurred while the lane lines were degraded, and only 1.5 percent of the events occurred when one or both lane lines were missing.

[7] Although exit and on ramps are outside the ODD of Super Cruse, the system stayed active long enough on certain exit ramps where these events occurred.

The Type II event distribution over the various environmental conditions for the Cadillac CT6 highway drives is presented in **Table 2.4**. During the 15 highway drives, the Cadillac CT6 had 28 total Type II events. Dithering in lane accounted for 64.3 percent of all the Type II events, 1 occurrence (3.6 percent) of lane hugging was recorded, while the remaining 32.1 percent were miscellaneous Type II events that included, but were not limited to, Super Cruise not recognizing the posted speed limit, being available but driver unable to engage it, and/or having issues with glare on the driver attention monitoring camera and the driver wearing sunglasses.

Table 2.4. Cadillac CT6 Highway Drive Type II Event Results

Total Type II Events		28	
Event Description	Dithering in Lane	18	64.3%
	Lane Hugging	1	3.6%
	Other	9	32.1%
Roadway Type	Exit Ramp	1	3.6%
	Merge Lane	9	32.1%
	Normal	18	64.3%
Road Condition	Dry	28	100.0%
	Wet	0	0.0%
	Straight	12	42.9%
	Curved	16	57.1%
	Flat	23	82.1%
	Not Flat	5	17.9%
Lane Line Condition	Good	24	85.7%
	Degraded	3	10.7%
	Missing	1	3.6%

Of the 28 total Type II events, 32.1 percent occurred in a merge lane, while 1 (3.6 percent) event occurred on an exit ramp. All the Type II events were recorded in dry road conditions. There were 42.9 percent of the Type II events that occurred on straight road segments and the remaining 57.1 percent occurred on curved road segments. There were 82.1 percent of the Type II events that occurred on flat roads and the remaining 17.9 percent of the events occurred on roads that are not flat. There were 85.7 percent of the Type II events that occurred while clear lane lines were present, 10.7 percent of the events occurred while the lane lines were degraded, and 3.6 percent of the events occurred when one or both lane lines were missing.

The Type III event distribution over the various environmental conditions for the Cadillac CT6 highway drives is presented in **Table 2.5**. Due to the small sample size of events, the percentages are only displayed to maintain consistency throughout this document but are not discussed.

Table 2.5. Cadillac CT6 Highway Drive Type III Event Results

Total Type III Events		8	
Event Description	Lane Departure w/ Auto Centering	1	12.5%
	Lateral Intervention	6	75.0%
	Longitudinal Intervention	1	12.5%
Roadway Type	Exit Ramp	2	25.0%
	Merge Lane	1	12.5%
	Normal	5	62.5%
Road Condition	Dry	8	100.0%
	Wet	0	0.0%
	Straight	5	62.5%
	Curved	3	37.5%
	Flat	7	87.5%
	Not Flat	1	12.5%
Lane Line Condition	Good	4	50.0%
	Degraded	2	25.0%
	Missing	2	25.0%

In the 15 drives on the highway route, the Cadillac CT6 had 8 Type III events, which included 1 lane departure where the system re-centered the vehicle, 6 incidents where the driver had to intervene using the steering wheel (lateral intervention) and 1 instance where the driver had to apply the brakes (longitudinal intervention). Of the 8 Type III events, 2 occurred on highway exit/on ramps, while 1 event occurred on a merge lane. All 8 Type III events occurred in dry conditions. Five of the 8 Type III events occurred on straight sections of road. Seven of the 8 Type III events occurred on flat roads. Four Type III events occurred on good lane line conditions while 2 occurred when lane lines were degraded, and a further 2 occurred when lane lines were missing on one or both sides.

2.4 Nissan Leaf Performance

The Nissan Leaf was tested on all three routes: highway, rural, and mixed. Results for each route are described in the following sections.

2.4.1 Nissan Leaf – Highway Route Performance

The Nissan Leaf was driven 15 times on the highway route for a nominal total of 1,620 miles. A total of 448 events were recorded. These events included 211 Type III events, 171 Type I events, and 66 Type II events (**Table 2.6**).

Table 2.6. Nissan Leaf Highway Route Event Types Breakdown

Event Category	Number
Type I	171
Type II	66
Type III	211
Total	**448**

The Type I event distribution over the various environmental conditions for the Nissan Leaf highway drives is presented in **Table 2.7**.

Table 2.7. Nissan Leaf Highway Route Type I Event Results

Total Type I Events		171	
Roadway Type	Exit Ramp	70	40.9%
	Merge Lane	101	59.1%
	Normal	0	0.0%
Road Condition	Dry	148	86.5%
	Wet	23	13.5%
	Straight	92	53.8%
	Curved	79	46.2%
	Flat	110	64.3%
	Not Flat	61	35.7%
Lane Line Condition	Good	155	90.6%
	Degraded	10	5.8%
	Missing	6	3.5%

Of the 171 Type I events, 40.9 percent occurred on exit ramps while another 59.1 percent occurred on merge lanes, with none occurring on normal highway roads. There were 865 percent of the Type I events that happened in dry conditions, while the remaining 13.5 percent occurred in wet conditions. 53.8 percent of the Type I events occurred on straight road segments and the remaining 46.2 percent occurred on curved road segments. There were 64.3 percent of the Type I events that occurred on flat roads (35.7 percent on not flat roads). There were 90.6 percent of all the Type I events that occurred when clear lane lines were present, 5.8 percent of the events occurred while the lane lines were degraded, and only 3.5 percent of the events occurred when one or both lane lines were missing.

The Type II event distribution over the various environmental conditions is presented in **Table 2.8** for the Nissan Leaf highway route drives. Of the 66 total Type II events, dithering in lane accounted for 47.0 percent. There were 53.0 percent were miscellaneous Type II events that included, but were not limited to, false lane departure warnings, ProPILOT not disengaging despite large input from driver, driver attention warning disappearing before driver touched the steering, etc. No lane line hugging events were recorded.

Table 2.8. Nissan Leaf Highway Route Type II Event Results

Total Type II Events		66	
Event Sub-type	Dithering in Lane	31	47.0%
	Lane Hugging	0	0.0%
	Other	35	53.0%
Roadway Type	Exit Ramp	21	31.8%
	Merge Lane	37	56.1%
	Normal	8	12.1%
Road Condition	Dry	62	93.9%
	Wet	4	6.1%
	Straight	42	63.6%
	Curved	24	36.4%
	Flat	44	66.7%
	Not Flat	22	33.3%
Lane Line Condition	Good	60	90.9%
	Degraded	5	7.6%
	Missing	1	1.5%

There were 31.8 percent of the Type II events that occurred on an exit ramp, while 56.1 percent occurred on a merge lane. There were 93.9 percent of the Type II events that occurred in dry road conditions. There were 63.6 percent of the Type II events that occurred on straight road segments and the remaining 36.4 percent occurred on curved road segments. There were 66.7 percent of the Type II events that occurred on flat roads and the remaining 33.3 percent of the events occurred on roads that were not flat. There were 90.9 percent of the Type II events that occurred while clear lane lines were present, 7.6 percent of the events occurred while the lane lines were degraded, and 1.5 percent of the events occurred when one or both lane lines were missing.

The Type III event distribution over the various environmental conditions for the Nissan Leaf highway route drives is presented in **Table 2.9**. Of the 211 Type III events recorded on the Nissan Leaf, 68.2 percent of the events were lane departure where the system re-centered the vehicle, 28.9 percent of the incidents involved driver lateral intervention, and the remaining 2.8 percent of the incidents involved a driver longitudinal intervention.

There were 31.3 percent of the Type III events that occurred on exit ramps while another 34.1 percent occurred on merge lanes. The remaining 34.6 percent occurred on normal highway roads. There were 81.5 percent of the Type III events that occurred in dry conditions, while the remaining 18.5 percent occurred in wet conditions. There were 51.2 percent of the Type III events that occurred on straight road segments and the remaining 48.8 percent occurred on curved road segments. There were 67.8 percent of the Type III events that occurred on flat roads

(32.2 percent on not flat roads). There were 84.8 percent of all the Type III events that occurred when clear lane lines were present, 12.3 percent of the events occurred while the lane lines were degraded, and 2.8 percent of the events occurred when one or both lane lines were missing.

Table 2.9. Nissan Leaf Highway Route Type III Event Results

Total Type III Events		211	
Event Sub-type	Lane Departure w/ Auto Centering	144	68.2%
	Lateral Intervention	61	28.9%
	Longitudinal Intervention	6	2.8%
Roadway Type	Exit Ramp	66	31.3%
	Merge Lane	72	34.1%
	Normal	73	34.6%
Road Condition	Dry	172	81.5%
	Wet	39	18.5%
	Straight	108	51.2%
	Curved	103	48.8%
	Flat	143	67.8%
	Not Flat	68	32.2%
Lane Line Condition	Good	179	84.8%
	Degraded	26	12.3%
	Missing	6	2.8%

2.4.2 Nissan Leaf – Rural Route Performance

The rural route was outside of the Nissan Leaf ODD (according to the user manual), so there were only three exploratory drives of this route for a total of 97 miles. A total of 41 events (**Table 2.10**) were recorded which included 15 Type III events, 23 Type I events, and 3 Type II events. The three categories of events are further categorized, and the results presented in this section.

Table 2.10. Nissan Leaf Rural Route Event Categories Breakdown

Event Category	**Number**
Type I	23
Type II	3
Type III	15
Total	**41**

The Nissan Leaf rural route Type I events are presented in **Table 2.11**. A total of 23 Type I events were recorded, all of which were recorded on dry roads. There were 87.0 percent of the events that occurred on straight road segments, and the remaining 13.0 percent occurred on curved roads. There were 82.6 percent of the events that occurred on flat road segments, and the remaining 17.4 percent occurred on road segments that were not flat. There were 69.6 percent of the Type I events that occurred while clear lane lines were present, 17.4 percent of the events occurred while the lane lines were degraded, and 13.0 percent of the events occurred when one or both lane lines were missing.

Table 2.11. Nissan Leaf Rural Route Type I Event Results

Total Type I Events		23	
Roadway Type	Exit Ramp	0	0.0%
	Merge Lane	0	0.0%
	Normal	23	100.0%
Road Condition	Dry	23	100.0%
	Wet	0	0.0%
	Straight	20	87.0%
	Curved	3	13.0%
	Flat	19	82.6%
	Not Flat	4	17.4%
Lane Line Condition	Good	16	69.6%
	Degraded	4	17.4%
	Missing	3	13.0%

The Nissan Leaf rural route Type II event distribution over the various environmental conditions is presented in **Table 2.12**. Due to the small sample size, the percentages are displayed in the table only to maintain consistency but are not discussed. During the three rural route drives, the Nissan Leaf had 3 Type II events. Dithering in lane accounted for 2 of the Type II events, and 1 miscellaneous Type II event was recorded. No lane hugging events were recorded.

All 3 Type II events occurred on dry road conditions. Two occurred on straight road segments, and the remaining event occurred on a curved road segment. Two of the Type II events occurred on flat roads, while 1 occurred on a road that was not flat. All 3 Type II events occurred while clear lane lines were present.

Table 2.12. Nissan Leaf Rural Route Type II Event Results

Total Type II Events		3	
Event Sub-type	Dithering in Lane	2	66.7%
	Lane Hugging	0	0.0%
	Other	1	33.3%
Roadway Type	Exit Ramp	0	0.0%
	Merge Lane	0	0.0%
	Normal	3	100.0%
Road Condition	Dry	3	100.0%
	Wet	0	0.0%
	Straight	2	66.7%
	Curved	1	33.3%
	Flat	2	66.7%
	Not Flat	1	33.3%
Lane Line Condition	Good	3	100.0%
	Degraded	0	0.0%
	Missing	0	0.0%

The Nissan Leaf rural route Type III event distribution over the various environmental conditions is presented in **Table 2.13**. Due to the small sample size, the percentages are displayed in the table only to maintain consistency but are not discussed. Lane departure followed by the vehicle re-centering itself in the original travel lane accounted for all 15 of the Type III events recorded. All the events occurred in dry driving conditions. Nine of the 15 events occurred on straight road segments while the remaining 6 occurred on curved roads. Thirteen of the 15 events occurred on flat road segments while the remaining 2 occurred on road segments that were not flat. All 15 events occurred when the lane lines were present and in good condition.

Table 2.13. Nissan Leaf Rural Route Type III Event Results

Total Type III Events		15	
Event Sub-type	Lane Departure w/ Auto Centering	15	100.0%
	Lateral Intervention	0	0.0%
	Longitudinal Intervention	0	0.0%
Roadway Type	Exit Ramp	0	0.0%
	Merge Lane	0	0.0%
	Normal	15	100.0%
Road Condition	Dry	15	100.0%
	Wet	0	0.0%
	Straight	9	60.0%
	Curved	6	40.0%
	Flat	13	86.7%
	Not Flat	2	13.3%
Lane Line Condition	Good	15	100.0%
	Degraded	0	0.0%
	Missing	0	0.0%

2.4.3 Nissan Leaf – Mixed Route Performance

The Nissan Leaf was driven 15 times on the mixed route for a total of 947 miles. A total of 507 events (**Table 2.14**) were recorded, which included 260 Type III events, 202 Type I events, and 45 Type II events. The three categories of events are further categorized, and the results presented in this section.

Table 2.14. Nissan Leaf Mixed Route Event Categories Breakdown

Event Category	**Number**
Type I	202
Type II	45
Type III	260
Total	**507**

The Nissan Leaf, mixed route Type I event distribution over the various environmental conditions is presented in **Table 2.15**. In the 15 drives, the Nissan Leaf had a total of 202 Type I events. One percent of the events occurred on exit ramps while another 6.9 percent occurred on merge lanes. The remaining occurred on normal roads. There were 91.1 percent of the Type I events that occurred on dry road conditions, while the remaining 8.9 percent occurred in wet conditions. There were 80.7 percent of the Type I events that occurred on straight road segments,

and the remaining 19.3 percent occurred on curved road segments. There were 86.6 percent of the Type I events that occurred on flat roads, and the remaining 13.4 percent of the events occurred on roads that were not flat. There were 69.3 percent of all the Type I events that occurred when clear lane lines were present, 4.5 percent of the events occurred while the lane lines were degraded and 26.2 percent of the events occurred when one or both lane lines were missing.

Table 2.15. Nissan Leaf Mixed Route Type I Event Results

Total Type I Events		202	
Roadway Type	Exit Ramp	2	1.0%
	Merge Lane	14	6.9%
	Normal	186	92.1%
Road Condition	Dry	184	91.1%
	Wet	18	8.9%
	Straight	163	80.7%
	Curved	39	19.3%
	Flat	175	86.6%
	Not Flat	27	13.4%
Lane Line Condition	Good	140	69.3%
	Degraded	9	4.5%
	Missing	53	26.2%

The Nissan Leaf Type II event distribution over the various environmental conditions for the mixed route is presented in **Table 2.16**. During the 15 mixed route drives, 45 Type II events were recorded. Dithering in lane accounted for 20.0 percent of all the Type II events, 73.3 percent were lane hugging events, while the remaining 6.7 percent were miscellaneous other Type II events. The miscellaneous Type II events comprised false lane departure and forward crash warnings.

Of the 45 total Type II events, 2.2 percent occurred on exit ramps, while 8.9 percent occurred on merge lanes. There were 93.3 percent of the Type II events that occurred on dry road conditions, and the remaining 6.7 percent occurred in wet conditions. There were 66.7 percent of the Type II events that occurred on straight road segments, and the remaining 33.3 percent occurred on curved road segments. There were 86.7 percent of the Type II events that occurred on flat roads and the remaining 13.3 percent of the events occurred on roads that were not flat. There were 88.9 percent of the Type II events that occurred while clear lane lines were present, 4.4 percent of the events occurred while the lane lines were degraded, and the remaining 6.7 percent of the events occurred when one or both lane lines were missing.

Table 2.16. Nissan Leaf Mixed Route Type II Event Results

Total Type II Events		45	
Event Sub-type	Dithering in Lane	9	20.0%
	Lane Hugging	33	73.3%
	Other	3	6.7%
Roadway Type	Exit Ramp	1	2.2%
	Merge Lane	4	8.9%
	Normal	40	88.9%
Road Condition	Dry	42	93.3%
	Wet	3	6.7%
	Straight	30	66.7%
	Curved	15	33.3%
	Flat	39	86.7%
	Not Flat	6	13.3%
Lane Line Condition	Good	40	88.9%
	Degraded	2	4.4%
	Missing	3	6.7%

The Nissan Leaf Type III event distribution over the various environmental conditions for the mixed route is presented in **Table 2.17**. In the 15 drives on the mixed route, 260 Type III events were recorded on the Nissan Leaf. There were 78.1 percent of the events were lane departures where the system re-centered the vehicle, and the remaining 21.9 percent of the incidents involved driver lateral interventions. No driver longitudinal intervention events occurred.

Of the 260 events, 2.3 percent occurred on merge lanes while the remaining occurred on normal roads. There were 87.3 percent of the events that occurred in dry conditions, while the remaining 12.7 percent occurred in wet conditions. There were 48.1 percent of the Type III events that occurred on straight road segments, and the remaining 51.9 percent occurred on curved road segments. There were 61.2 percent of the Type III events that occurred on flat roads, and the remaining 38.8 percent occurred on roads that were not flat. There were 93.5 percent of all the Type III events that occurred when clear lane lines were present, 0.8 percent of the events occurred while the lane lines were degraded, and 5.8 percent of the events occurred when one or both lane lines were missing.

Table 2.17. Nissan Leaf Mixed Route Type III Event Results

Total Type III Events		260	
Event Sub-type	Lane Departure w/ Auto Centering	203	78.1%
	Lateral Intervention	57	21.9%
	Longitudinal Intervention	0	0.0%
Roadway Type	Exit Ramp	0	0.0%
	Merge Lane	6	2.3%
	Normal	254	97.7%
Road Condition	Dry	227	87.3%
	Wet	33	12.7%
	Straight	125	48.1%
	Curved	135	51.9%
	Flat	159	61.2%
	Not Flat	101	38.8%
Lane Line Condition	Good	243	93.5%
	Degraded	2	0.8%
	Missing	15	5.8%

2.5 Lexus LS500 Results

The Lexus LS500 was tested on all three routes: highway, rural, and mixed. Results for each route are described in the sections below.

2.5.1 Lexus LS500 – Highway Route Performance

The Lexus LS500 was driven five times on the highway route for a total of 540 miles. Although this route was within the ODD of the Lexus LS500, evaluation of the vehicle was limited (i.e., data from a full 15 drives was not collected) to reduce the subsequent data analysis burden imposed by the relatively high number of events observed. A total of 169 events were recorded which included 127 Type III events, 26 Type I events, and 35 Type II events (**Table 2.18**). The three categories of events are further classified, and the results presented in this section.

Table 2.18. Lexus LS500 Highway Route Event Types Breakdown

Event Category	**Number**
Type I	26
Type II	35
Type III	127
Total	**168**

The Lexus LS500 Type I event distribution over the various environmental conditions for the highway route is presented in **Table 2.19**. In the five drives, the Lexus LS500 had a total of 26 Type I events. There were 15.4 percent of the events that occurred on exit ramps while another 15.4 percent occurred on merge lanes. The remaining 69.2 percent occurred on normal highway roads. There were 65.4 percent of the Type I events that happened on dry road conditions, while the remaining 13.5 percent occurred in wet conditions. There were 46.2 percent of the Type I events that occurred on straight road segments and the remaining 53.8 percent occurred on curved road segments. There were 53.8 percent of the Type I events that occurred on flat roads, and the remaining 46.2 percent occurred on roads that were not flat. There were 65.4 percent of all the Type I events that occurred when clear lane lines were present, 30.8 percent of the events occurred while the lane lines were degraded, and 3.8 percent of the events occurred when one or both lane lines were missing.

Table 2.19. Lexus LS500 Highway Route Type I Event Results

Total Type I Events		26	
Roadway Type	Exit Ramp	4	15.4%
	Merge Lane	4	15.4%
	Normal	18	69.2%
Road Condition	Dry	17	65.4%
	Wet	9	34.6%
	Straight	12	46.2%
	Curved	14	53.8%
	Flat	14	53.8%
	Not Flat	12	46.2%
Lane Line Condition	Good	17	65.4%
	Degraded	8	30.8%
	Missing	1	3.8%

The Lexus LS500 highway route Type II event distribution over the various environmental conditions is presented in **Table 2.20**. During the five highway drives, the Lexus LS500 had 35 total Type II events. Dithering in lane accounted for 45.7 percent of all the Type II events, 14.3 percent were lane hugging events, while the remaining 40.0 percent were miscellaneous other Type II events that included, but were not limited to, false warnings, and repeated quick enabling and disabling of the system. There were 2.9 percent of the events (one event) that occurred on exit ramps, while 17.1 percent occurred on a merge lane. The remaining 80.0 percent of events occurred on normal highway roads. There were 71.4 percent of the Type II events that occurred on dry road conditions, and the remaining 28.6 percent of events occurred in wet conditions. There were 62.9 percent of the Type II events that occurred on straight road segments and the remaining 37.1 percent occurred on curved road segments. There were 88.6 percent of the Type II events that occurred on flat roads, and the remaining 11.4 percent of the events occurred on

roads that were not flat. There were 74.3 percent of the Type II events that occurred while clear lane lines were present, 14.3 percent of the events occurred while the lane lines were degraded, and 11.4 percent of the events occurred when one or both lane lines were missing.

Table 2.20. Lexus LS500 Highway Route Type II Event Results

Total Type II Events		35	
Event Sub-type	Dithering in Lane	16	45.7%
	Lane Hugging	5	14.3%
	Other	14	40.0%
Roadway Type	Exit Ramp	1	2.9%
	Merge Lane	6	17.1%
	Normal	28	80.0%
Road Condition	Dry	25	71.4%
	Wet	10	28.6%
	Straight	22	62.9%
	Curved	13	37.1%
	Flat	31	88.6%
	Not Flat	4	11.4%
Lane Line Condition	Good	26	74.3%
	Degraded	5	14.3%
	Missing	4	11.4%

The Lexus LS500 highway route Type III event distribution over the various environmental conditions is presented in **Table 2.21**. During the five highway route drives performed with the Lexus LS500, 127 Type III events were recorded. There were 11.8 percent of the events that were lane departures where the system re-centered the vehicle, and 88.2 percent of the incidents involved driver lateral interventions. No driver longitudinal intervention events occurred.

Of the 127 Type III events, 16.5 percent of the events occurred on exit ramps while another 28.3 percent occurred on merge lanes. The remaining occurred on normal highway roads. There were 83.5 percent of the events that occurred in dry conditions, while the remaining 16.5 percent occurred in wet conditions. There were 45.7 percent of the Type III events that occurred on straight road segments and the remaining 54.3 percent occurred on curved road segments. There were 74.0 percent of the Type III events that occurred on flat roads, and the remaining 26.0 percent occurred on roads that were not flat. There were 62.2 percent of all the Type III events that occurred when clear lane lines were present, 19.7 percent of the events occurred while the lane lines were degraded, and 18.1 percent of the events occurred when one or both lane lines were missing.

Table 2.21. Lexus LS500 Highway Route Type III Event Results

Total Type III Events		127	
Event Sub-type	Lane Departure w/ Auto Centering	15	11.8%
	Lateral Intervention	112	88.2%
	Longitudinal Intervention	0	0.0%
Roadway Type	Exit Ramp	21	16.5%
	Merge Lane	36	28.3%
	Normal	70	55.1%
Road Condition	Dry	106	83.5%
	Wet	21	16.5%
	Straight	58	45.7%
	Curved	69	54.3%
	Flat	94	74.0%
	Not Flat	33	26.0%
Lane Line Condition	Good	79	62.2%
	Degraded	25	19.7%
	Missing	23	18.1%

2.5.2 Lexus LS500 – Rural Route Performance

Since the rural route was outside the Lexus LS500's ODD (according to the user manual), only three exploratory drives of this route were performed for a total of 97 miles. A total of 194 events were recorded which included 173 Type III events, 10 Type I events, and 11 Type II events (**Table 2.22**). The three categories of events are further categorized, and the results presented in this section.

Table 2.22. Lexus LS500 Rural Route Event Categories Breakdown

Event Category	**Number**
Type I	10
Type II	11
Type III	173
Total	**194**

The Lexus LS500 Type I event distribution over the various environmental conditions for the rural route is presented in **Table 2.23**. Due to the small sample size, the percentages are displayed in the table only to maintain consistency but are not discussed. Ten Type I events were recorded on the Lexus LS500 on the rural route, all of which were recorded on dry road conditions. Six of the events occurred on straight road segments, and the remaining 4 occurred

on curved roads. All 10 of the events occurred on flat road segments. Eight of the Type I events occurred while clear lane lines were present, and the remaining 2 events occurred when one or both lane lines were missing.

Table 2.23. Lexus LS500 Rural Route Type I Event Results

Total Type I Events		10	
Roadway Type	Exit Ramp	0	0.0%
	Merge Lane	0	0.0%
	Normal	10	100.0%
Road Conditions	Dry	10	100.0%
	Wet	0	0.0%
	Straight	6	60.0%
	Curved	4	40.0%
	Flat	10	100.0%
	Not Flat	0	0.0%
Lane Line Condition	Good	8	80.0%
	Degraded	0	0.0%
	Missing	2	20.0%

The Lexus LS500 Type II event distribution over the various environmental conditions for the rural route is presented in **Table 2.24**. Due to the small sample size, the percentages are displayed in the table only to maintain consistency but are not discussed. During the three rural route drives, the Lexus LS500 had 11 total Type II events. Dithering in lane accounted for 4 of the Type II events, and 7 lane hugging events were recorded. No miscellaneous Type II events were recorded.

All 11 Type II events occurred on dry road conditions. Six of these events occurred on straight road segments, while 5 occurred on curved road segments. Ten of these events occurred on flat roads, and 1 occurred on a road that was not flat. Nine Type II events occurred while clear lane lines were present, and 2 events occurred when one or both lane lines were absent.

Table 2.24. Lexus LS500 Rural Route Type II Event Results

Total Type II Events		11	
Event Sub-type	Dithering in Lane	4	36.4%
	Lane Hugging	7	63.6%
	Other	0	0.0%
Roadway Type	Exit Ramp	0	0.0%
	Merge Lane	0	0.0%
	Normal	11	100.0%
Road Condition	Dry	11	100.0%
	Wet	0	0.0%
	Straight	6	54.5%
	Curved	5	45.5%
	Flat	10	90.9%
	Not Flat	1	9.1%
Lane Line Condition	Good	9	81.8%
	Degraded	0	0.0%
	Missing	2	18.2%

The Lexus LS500 Type III event distribution over the various environmental conditions for the rural route is presented in **Table 2.25**. In the three drives performed on the rural route, 173 Type III events were recorded on the Lexus LS500. There were 24.9 percent of the events that were lane departures where the system re-centered the vehicle, and the remaining 75.1 percent of the events involved driver lateral interventions. No driver longitudinal intervention events occurred.

Of the 173 events, 2.3 percent occurred on merge lanes while the remaining occurred on rural roads. All the events occurred on dry road conditions. There were 64.2 percent of the Type III events that occurred on straight road segments, and the remaining 35.8 percent occurred on curved road segments. There were 79.2 percent of the Type III events occurred on flat roads, and the remaining 20.8 percent occurred on roads that were not flat. There were 69.9 percent of all the Type III events that occurred when clear lane lines were present. There were 2.3 percent of the events that occurred while the lane lines were degraded, and 27.7 percent of the events occurred when one or both lane lines were missing.

Table 2.25. Lexus LS500 Rural Route Type III Event Results

Total Type III Events		173	
Event Sub-type	Lane Departure w/ Auto Centering	43	24.9%
	Lateral Intervention	130	75.1%
	Longitudinal Intervention	0	0.0%
Roadway Type	Exit Ramp	0	0.0%
	Merge Lane	4	2.3%
	Normal	169	97.7%
Road Conditions	Dry	173	100.0%
	Wet	0	0.0%
	Straight	111	64.2%
	Curved	62	35.8%
	Flat	137	79.2%
	Not Flat	36	20.8%
Lane Line Condition	Good	121	69.9%
	Degraded	4	2.3%
	Missing	48	27.7%

2.5.3 Lexus LS500 – Mixed Route Performance

The Lexus LS500 was driven five times on the mixed route for a total of 316 miles. As previously mentioned in Section 1.4, testing of the Lexus LS500 was limited to five route mixed route drives due to the relatively high number of events observed, and a need to constrain the data analysis burden from what would have been imposed by performing a full set of 15 drives. A total of 618 events (**Table 2.26**) were recorded, which included 393 Type III events, 122 Type I events, and 103 Type II events.

Table 2.26. Lexus LS500 Mixed Route Event Categories Breakdown

Event Category	**Number**
Type I	122
Type II	103
Type III	393
Total	**618**

The Lexus LS500 Type I event distribution over the various environmental conditions for the mixed route is presented in **Table 2.27**. During the 5 mixed route drives, the Lexus LS500 had a total of 122 Type I events. There were 1.6 percent of the events that occurred on merge lanes, while the remaining occurred on normal roads. There were 83.6 percent of the Type I events that

occurred on dry road conditions, while the remaining 16.4 percent occurred in wet conditions. There were 69.7 percent of the Type I events that occurred on straight road segments, and the remaining 30.3 percent occurred on curved road segments. There were 86.9 percent of the Type I events that occurred on flat roads, and the remaining 13.1 percent of the events occurred on roads that were not flat. There were 47.5 percent of all the Type I events that occurred when clear lane lines were present. There were 1.6 percent of the events that occurred while the lane lines were degraded, and 50.0 percent of the events occurred when one or both lane lines were missing.

Table 2.27. Lexus LS500 Mixed Route Type I Event Results

Total Type I Events		122	
Roadway Type	Exit Ramp	0	0.0%
	Merge Lane	2	1.6%
	Normal	120	98.4%
Road Condition	Dry	102	83.6%
	Wet	20	16.4%
	Straight	85	69.7%
	Curved	37	30.3%
	Flat	106	86.9%
	Not Flat	16	13.1%
Lane Line Condition	Good	58	47.5%
	Degraded	2	1.6%
	Missing	61	50.0%

The Lexus LS500 Type II event distribution over the various environmental conditions for the mixed route is presented in **Table 2.28**. During the five mixed route drives, 103 total Type II events were recorded. Dithering in lane accounted for 73.8 percent of all the Type II events, 8.7 percent were lane hugging events, and the remaining 17.5 percent were miscellaneous other Type II events that included, but were not limited to, the vehicle's level 2 driving automation system repeatedly and quickly enabling and disabling and false lane departure warnings.

Of the 103 total Type II events, 96.1 percent occurred on normal roadways, while 3.9 percent of the events occurred on a merge lane. There were 79.6 percent of the Type II events that occurred on dry road conditions, and the remaining 20.4 percent occurred in wet conditions. There were 72.8 percent of the Type II events that occurred on straight road segments, and the remaining 27.2 percent occurred on curved road segments. There were 89.3 percent of the Type II events that occurred on flat roads and the remaining 13.3 percent of the events occurred on roads that were not flat. There were 78.6 percent of the Type II events that occurred while clear lane lines were present, 12.6 percent of the events occurred while the lane lines were degraded, and the remaining 9.7 percent of the events occurred when one or both lane lines were missing.

Table 2.28. Lexus LS500 Mixed Route Type II Event Results

Total Type II Events		103	
Event Sub-type	Dithering in Lane	76	73.8%
	Lane Hugging	9	8.7%
	Other	18	17.5%
Roadway Type	Exit Ramp	0	0.0%
	Merge Lane	4	3.9%
	Normal	99	96.1%
Road Condition	Dry	82	79.6%
	Wet	21	20.4%
	Straight	75	72.8%
	Curved	28	27.2%
	Flat	92	89.3%
	Not Flat	11	10.7%
Lane Line Condition	Good	81	78.6%
	Degraded	13	12.6%
	Missing	10	9.7%

The Lexus LS500 Type III event distribution over the various environmental conditions for the mixed route is presented in **Table 2.29**. In the 5 drives on the mixed route, 393 Type III events were recorded. There were 45.3 percent of these events that were lane departures where the system re-centered the vehicle, and the remaining 54.7 percent of the events involved driver lateral interventions. No driver longitudinal intervention events occurred.

Of the 393 events, 96.4 percent occurred on normal roads and 3.6 percent occurred on merge lanes. There were 79.6 percent of the events that occurred on dry road conditions, while the remaining 20.4 percent occurred in wet conditions. There were 63.9 percent of the Type III events that occurred on straight road segments, and the remaining 36.1 percent occurred on curved road segments. There were 81.4 percent of the Type III events that occurred on flat roads, and the remaining 18.6 percent occurred on roads that were not flat. There were 88.8 percent of all the Type III events that occurred when clear lane lines were present, 2.3 percent occurred while the lane lines were degraded, and 8.9 percent occurred when one or both lane lines were missing.

Table 2.29. Lexus LS500 Mixed Route Type III Event Results

Total Type III Events		393	
Event Sub-type	Lane Departure w/ Auto Centering	178	45.3%
	Lateral Intervention	215	54.7%
	Longitudinal Intervention	0	0.0%
Roadway Type	Exit Ramp	0	0.0%
	Merge Lane	14	3.6%
	Normal	379	96.4%
Road Condition	Dry	313	79.6%
	Wet	80	20.4%
	Straight	251	63.9%
	Curved	142	36.1%
	Flat	320	81.4%
	Not Flat	73	18.6%
Lane Line Condition	Good	349	88.8%
	Degraded	9	2.3%
	Missing	35	8.9%

3 SUMMARY OF AVERAGE NUMBER OF EVENTS PER CATEGORY

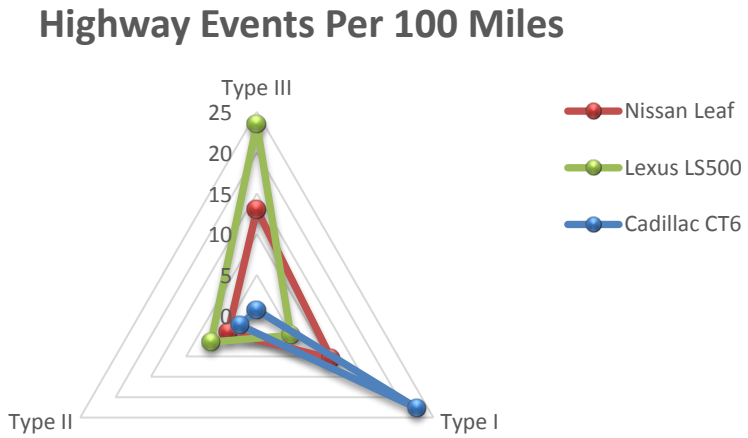
This section presents the overall performance of the three vehicles tested for the three routes used in this study. The number of events per 100 miles of driving is calculated for each event category, route, and vehicle, and are presented on radar plots.

3.1 Overall Highway Route Performance

All three vehicles were driven on the highway route, since this route was mostly within the intended ODD of each vehicle's level 2 driving automation system. The "events per 100 miles" statistic for each event category is shown in **Figure 3.1**.

NOTE: For the Cadillac CT6, only the miles where Super Cruise was active were considered for this analysis, so as to not artificially reduce the number of events per 100 miles.

The Cadillac CT6, Nissan Leaf, and Lexus LS500 had averages of 0.7, 13.0, and 23.5 Type III events per 100 miles of level 2 driving automation, respectively. For the Type II events, the Cadillac CT6, Nissan Leaf, and the Lexus LS500 averaged 2.4, 4.1, and 6.5 events per 100 miles, respectively. The Cadillac CT6, Nissan Leaf, and Lexus LS500, on average, had 22.7, 10.5, and 4.8 Type I events per 100 miles, respectively.



3.2 Overall Rural Route Performance

Only the Nissan Leaf and the Lexus LS500 were tested on the rural route, and only three exploratory drives were performed per vehicle. This is because these drives were primarily performed for research purposes. This provides data for NHTSA to better understand how level 2 driving automation systems may behave when used on roads outside of their stated ODD. The events per 100 miles radar plot is shown in **Figure 3.2**.

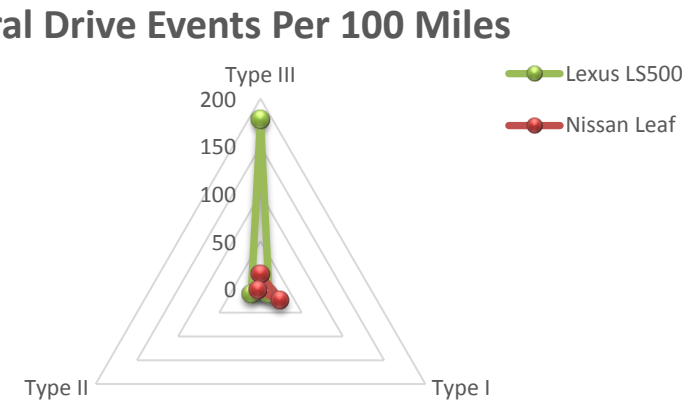


Figure 3.2. Rural route – events per 100 miles comparison by event category.

The Lexus LS500 and Nissan Leaf averaged 10.3 and 23.7 Type I requests per 100 miles for the Lexus LS500 and Nissan Leaf, respectively. Type II events averaged 11.3 per 100 miles for the Lexus LS500, and 3.1 per 100 miles for the Nissan Leaf. The Lexus LS500 averaged 178.0 Type III events per 100 miles. The Nissan Leaf averaged 15.4 Type III events per 100 miles.

The Lexus LS500 averaged one Type III event every 0.6 miles compared to the Nissan Leaf's 6.5 miles. All the Type III events, for both the Lexus LS500 and the Nissan Leaf operated on the rural route, were lane departure events that either needed driver intervention or the level 2 driving automation system eventually re-centered the vehicle in its original travel lane.

3.3 Overall Mixed Route Performance

Only the Lexus LS500 and Nissan Leaf were operated on the mixed route, and the number of repeated drives per vehicle were 5 and 15, respectively. The events per 100 miles radar plot is shown in **Figure 3.3**.

The Lexus LS500 averaged 38.7 Type I events per 100 miles, while the Nissan Leaf averaged 21.3. The Lexus LS500 averaged 32.6 Type II events per 100 miles while the Nissan Leaf averaged 4.8. The Lexus LS500 averaged 124.5 Type III events for 100 miles, while the Nissan Leaf averaged 27.5.

The Lexus LS500 averaged one Type III event every 0.8 miles compared to the Nissan Leaf's 3.6 miles. All the Type III events, for both the Lexus LS500 and the Nissan Leaf operated on the mixed route, were lane departure events that either needed driver intervention or the level 2 driving automation system eventually re-centered the vehicle in its original travel lane.

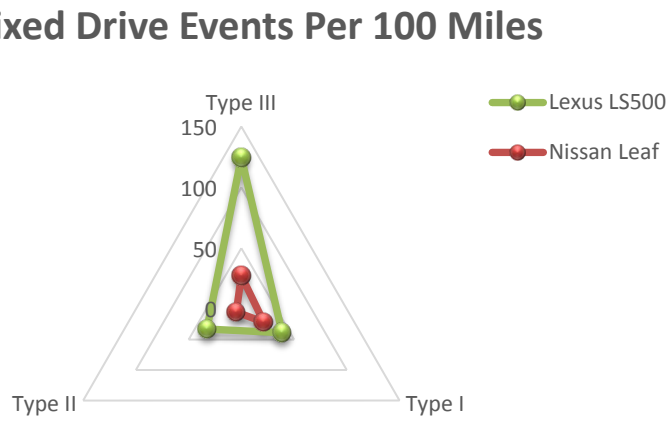


Figure 3.3. Mixed route – events per 100 miles comparison by event category.

3.4 Miscellaneous Comments

Cadillac CT6 Super Cruise:

- Super Cruise relies on camera-based attention confirmation. It does not require the driver to physically touch the steering wheel while the system is engaged and in operation for as long as there is positive confirmation of driver engagement through the camera-based driver attention monitoring system.

- The takeover request and transition of control back to the driver occurs in multiple steps (see **Appendix A**), where the system warns the driver to resume the driving task before relinquishing control of the steering wheel. The other systems tested stopped steering when the warning to take control was issued.

- The camera-based driver attention monitoring system used by Super Cruise was observed to be susceptible to sun glare. Several instances of the system turning off due to glare on the related camera, but working fine when the visor was moved to shield it, were recorded.

Nissan Leaf ProPILOT:

- The Nissan Leaf requires the driver to touch the steering wheel for the system to remain active. The maximum hands-free driving duration with ProPILOT prior to issuance of a system warning was measured to be approximately 10 seconds.

Lexus LS500 Level 2 Driving Automation System:

- The Lexus LS500's level 2 driving automation system requires the driver to touch the steering wheel for the system to remain active. For this system, maximum hands-free driving duration prior to issuance of a system warning was measured to be approximately 4 seconds on curves and approximately 17 seconds on straight roadways.

4 CONCLUSIONS

Three light vehicles equipped with level 2 driving automation driver assistance systems were operated on up to three real-world test routes. Since Super Cruise is geofenced to work only on certain limited-access divided highways that have been mapped by General Motors, Cadillac CT6 was only operated on the highway route. Some vehicle/drive combinations were limited for the Lexus LS500 and Nissan Leaf. Although their respective level 2 driving automation systems could be enabled and put into operation while operating on rural roads (provided the lane lines were perceived), these roads were outside the stated ODD for these vehicles. As such, only three exploratory drives were performed. For the Lexus LS500, only 5 drives were performed on the highway and mixed routes to reduce the high data processing burden imposed by the relatively high number of events observed.

Events observed during the drives were recorded and categorized. Some observations and key finding include:

1. During the 15 highway route drives, the Cadillac CT6 Super Cruise system was unavailable for 24.1 percent of the miles driven when the system was used within its stated ODD. A system availability update pushed to the vehicle before the last six drives reduced unavailability to less than 18.0 percent for the subsequent drives.

2. The Cadillac CT6, the Nissan Leaf, and the Lexus LS500 averaged 22.7, 10.5, and 4.8 Type I events per 100 miles of highway driving, respectively.

3. The Cadillac CT6 averaged 2.4 Type II events per 100 miles of highway driving. The Nissan Leaf and the Lexus LS500 averaged 4.1 and 6.5, respectively.

4. The Cadillac CT6 averaged approximately 0.7 Type III events per 100 miles of highway driving. The Nissan Leaf and the Lexus LS500 averaged 4.8 and 23.5, respectively.

5. The Nissan Leaf and Lexus LS500 averaged 23.7 and 10.3 Type I events per 100 miles of rural route driving, respectively.

6. The Nissan Leaf and Lexus LS500 averaged 3.1 and 11.3 Type II events per 100 miles of rural route driving, respectively.

7. The Nissan Leaf and Lexus LS500 averaged 15.4 and 178.0 Type III events per 100 miles of rural route driving, respectively.

8. The Nissan Leaf and Lexus LS500 averaged 21.3 and 38.7 Type I events per 100 miles of mixed route driving, respectively.

9. The Nissan Leaf and Lexus LS500 averaged 4.8 and 32.7 Type II events per 100 miles of mixed route driving, respectively.

10. The Nissan Leaf and Lexus LS500 averaged 27.5 and 124.5 Type III events per 100 miles of mixed route driving, respectively.

11. All Type III events observed during drives performed with the Lexus LS500 were lane departure events, either requiring driver intervention, or the system re-centered the vehicle.

12. Overall, 480 of the 486 Type III events observed during drives performed with the Nissan Leaf were lane departure events, either requiring driver intervention, or the system re-centered the vehicle.

While this study documents observed statistics for the identified categories of events associated with the tested SAE level 2 driving automation systems, there are no documented or implied conclusions in this report over their correlation to driving safety, driver engagement, or consumer acceptance.

5 REFERENCES

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Nissan North America, Inc. (2018, April). *2018 Leaf Owner's Manual* (Publication No. OM18EA 0ZE1U1). Author.

SAE International. (2018). *SAE J3016_201806: Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles*. Author.

APPENDIX A: Cadillac CT6 Super Cruise Driver Display

The instrument cluster of the Cadillac CT6 and the steering light bar is shown in **Figure 5.1**. The Super Cruise system status is displayed prominently on the steering wheel in the form of a light bar. It is also displayed on the instrument cluster in the form of the Super Cruise status icon. Both the light bar and status icon change color to indicate the state/warning to the driver. The different states and warnings and their corresponding light bar and icon colors are detailed in **Table 5.1**.

Figure 5.1. Cadillac CT6 instrument cluster.

Table 5.1. Super Cruise Status Indications

Driver Display	Status	
Steering light bar: solid green Super Cruise status icon: green	Super Cruise is engaged and actively steering the vehicle	
Steering light bar: flashing green Super Cruise status icon: green	Super Cruise is engaged but system detects driver is not attentive to the driving task	
Steering light bar: flashing blue Super Cruise status icon: blue	Super Cruise is active, but system detects manual steering override. Super Cruise will resume control once vehicle is centered in the lane and steering is held steady.	
Steering light bar: flashing red Super Cruise status icon: red Seat pulses and audible beep	The driver needs to assume control immediately. The vehicle will begin to coast until driver takes control. Super Cruise must be re-engaged.	

APPENDIX B: Nissan Leaf ProPilot Assist Driver Display

The Nissan Leaf ProPILOT Assist instrument cluster-based driver display is shown in **Figure 5.2**. When the system is disengaged, the lane line icon as well as the steering wheel icon appear grey (**Figure 5.2a**). When the system is engaged, the steering wheel icon and the lane line icons turn to green (**Figure 5.2b**). ProPILOT Assist engagement and disengagement is accompanied by an audible beep.

a. ProPILOT Assist disengaged b. ProPILOT Assist engaged

Figure 5.2. Nissan Leaf ProPILOT Assist instrument cluster display.

The Nissan Leaf monitors driver attention through touch sensors on the steering wheel. When the system senses that the driver has not touched the steering wheel for an extended period, it displays a warning to the driver to hold the steering wheel (**Figure 5.3**). Ignoring the warning leads to the system disengaging.

Figure 5.3. Nissan Leaf ProPILOT Assist driver engagement warning.

APPENDIX C: Lexus LS500 Driver Display

The Lexus LS500 instrument cluster icons used to display the status of the level 2 driving automation system are shown in **Figure 5.4**. The various icons and their functions are explained below.

A - Lane tracing assist status icon:

- Illuminated in white: Lane tracing assist is turned on but inactive.
- Illuminated in green: Steering wheel assist or lane centering function is operating.
- Flashing in orange: Lane departure alert is operating.

B - Operation display of steering wheel operation support:

- This is displayed on the outer side of both lane displays (**C**).
- Displayed solid: It indicates that the steering wheel assist of the lane centering function is operating.
- Displayed flashing: Alerts the driver that their input is necessary to stay in the center of the lane.

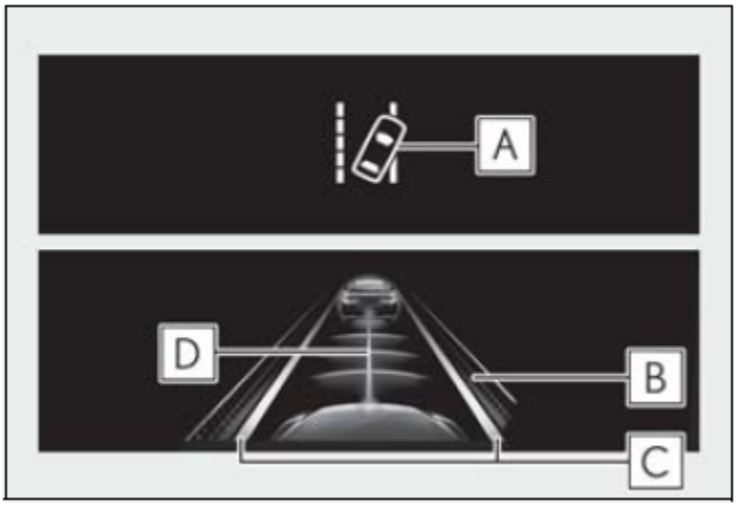

Figure 5.4. Lexus LS 500 instrument cluster display.

C - **Lane departure alert function display:**

- Solid white lines displayed (**Figure 5.5a**): Indicates that the system recognizes white/yellow lane lines.
- Flashing orange on one side: Indicates lane line departure on the side the orange lines is flashing.

- Hollow white lines displayed (**Figure 5.5b**): Indicates that the system does not recognize white/yellow lane lines, or the system is temporarily canceled.

a. Lane lines recognized ***b. No lane lines recognized***

Figure 5.5. Lexus LS500 lane departure alert function display.

D - Follow-up cruising display:

This icon indicates that the steering assist of the lane centering function is operating by monitoring the position of a lead vehicle.

Warning Display:

When the lane centering function is operating, and the system determines that the vehicle may depart from its lane due to a sharp curve, etc., a warning display (**Figure 5.6**) urging the driver to operate the steering wheel is displayed.

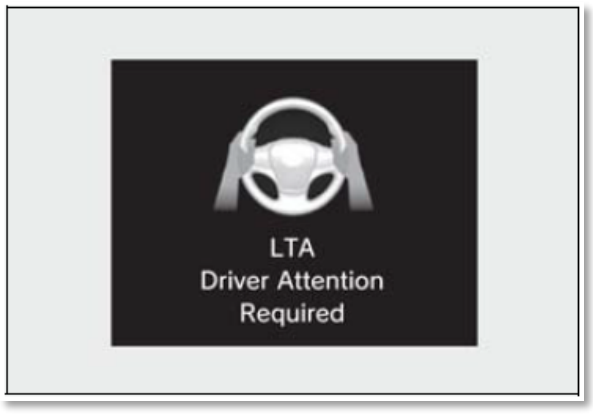

Figure 5.6. Driver attention warning.

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