Automated Vehicle and Pavement Marking Evaluation in Connecticut

Final Report

Prepared by:
Mohammad Razaur R Shaon, Ph.D., PE, PTOE, RSP1
Elena Orlova, M.Sc.
Eric Jackson, Ph.D.

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David C. Elder
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16. Abstract
The condition, visibility, and contrast of longitudinal pavement markings are critical to roadway safety and have been used for decades by infrastructure owner operators (IOOs) as a frame of reference to communicate to drivers how to navigate roadways. Over the last decade, vehicle manufacturers have also begun incorporating new intelligent, advanced driver assistance systems (ADAS) and sensors in their vehicles to further improve vehicle safety, performance and interactions between the driver and other roadway users. Is it wise to rely on the existing roadway markings to guide the new cars of today as well as the cars of the future? What are the minimum longitudinal marking requirements for driver assistance technologies to be successful in improving roadway performance and safety? This study explored the effect of longitudinal pavement marking quality using a variety of pavement marking performance levels on the detectability of pavement markings by machine vision systems. To evaluate the effect that various pavement marking characteristics have on machine vision detection, this study collected roadway lane marking characteristics and ADAS lane marking detection information on selected public roadways in Connecticut under various lighting conditions. All data using retroreflectometer and vehicles equipped with ADAS features and camera assembly were collected in three phases: pre-construction, during construction, and post-construction of lane marking improvements to evaluate the differences in ADAS machine vision lane marking detection in different lane marking width, color, contrast, and retroreflectivity. A data visualization tool was developed to visualize the lane marking characteristics. Outcomes from this study will be used to help the CTDOT and other IOOs determine the type, width, materials, and maintenance intervals of lane marking improvements to meet the demands of automated vehicles in the future.

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METRIC CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
ºF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	ºC
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

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EXECUTIVE SUMMARY

Over the last decade, auto manufacturers have incorporated more Advanced Driver Assistance Systems (ADAS) in new vehicles sold each year across the light duty fleet (SAE International, 2024). These new ADAS include a combination of hardware sensors (camera, radar, etc.) and software that enable a broad range of features, including features that provide warnings to the driver and/or momentary interventions as well as some convenience features that enhance driver support. Examples of ADAS features include lane departure warnings, blind spot detection, adaptive cruise control, lane keeping assistance, automatic emergency braking, etc.[1] These ADAS features are designed or intended to improve vehicle safety, performance, and convenience to the driver. ADAS are also designed or intended to enhance vehicle perception of and interactions with the driver, other roadway users, and the roadway infrastructure itself.

Longitudinal pavement markings are one of the primary roadway assets that ADAS sensors currently look for reference to assist drivers in providing safe navigation on the roadway. This report documents a study completed by the University of Connecticut (UConn) to explore the effect of longitudinal pavement marking quality on the detectability of longitudinal pavement markings by ADAS machine vision systems. This report is funded by the Federal Highway Administration (FHWA) and the Connecticut Department of Transportation (CTDOT) and was completed in partnership with data and other resources provided by The Eastern Transportation Coalition (TETC) and Consumer Reports (CR).

The study documented in this report set out to address questions like what are the minimum longitudinal pavement marking requirements for certain ADAS features to be successful in improving vehicle performance and safety on public roadways and what do infrastructure owner operators (IOOs) need to know about how their longitudinal pavement marking design, construction, and maintenance practices that may need to adapt or not adapt to sync up with current ADAS capabilities as well as future ADAS capabilities. Understanding these impacts is especially key as ADAS hardware and software improves and as more ADAS features are rapidly deployed at scale across the light duty fleet.

The UConn researchers compiled and analyzed various data to evaluate the effect that in-service longitudinal pavement marking characteristics such as width, color, contrast, and retroreflectivity have on ADAS machine vision detection. The data primarily included (1) roadway asset and condition information supplied by CTDOT; (2) data collected using a vehicle-mounted mobile retroreflectometer that UConn researchers collected by driving on public roadways in the study area; and (3) ground truth ADAS longitudinal pavement marking detection data supplied by TETC

[1] Clearing the Confusion: Common Naming for Advanced Driver Assistance Systems. Accessed from https://newsroom.aaa.com/wp-content/uploads/2023/02/Clearing-the-Confusion-One-Pager-New-Version-7-25-22.pdf

and Consumer Reports from driving selected vehicles equipped with ADAS features on public roadways in the study area. Data items were collected over a few hundred miles of selected public roadways throughout the study area in Eastern Connecticut. ADAS ground truth data was collected under various lighting conditions (daytime and nighttime). Both ADAS and retroreflectometer data were also collected before and after various roadway improvements were made to some of the selected public roadways throughout the study area as applicable. This before and after data was collected to assess potential differences in longitudinal pavement marking detection attributable to various improvements made to those roadways, including but not limited to different types of paint and roadway surface improvements. The Consumer Reports fleet included a cross section of light duty production vehicles each equipped with their own ADAS longitudinal pavement marking detection feature(s). Each vehicle and their ADAS feature were evaluated based on whether or not, where, and under what conditions the longitudinal pavement markings were detected and visualized within the vehicle instrument cluster.

While most related ADAS-related research studies in this domain have used data collected using only one ADAS-equipped vehicle (many of which operating on closed facilities), this study used data collected on open public roadways from multiple ADAS-equipped vehicles for evaluation purposes. Consumer Reports was responsible for the on-road ADAS data collection using a total of eight production vehicles from different makes, models, and manufacturers. Each of the vehicles driven by Consumer Reports were equipped with ADAS machine vision features using an assembly of multiple video cameras. The UConn research team collected longitudinal pavement marking characteristics data using a vehicle-mounted mobile retroreflectometer adhered to a separate vehicle the UConn research team drove throughout the study area. This device was paid for using research funds provided to the project from FHWA and CTDOT and made available to UConn to use for the study.

Using the roadway in-service longitudinal pavement marking characteristics data collected by the UConn team, a longitudinal pavement marking characteristics data visualization tool was developed by the UConn team to visualize and interact with this data. The UConn team was also responsible for data processing and analysis of the raw video data collected by Consumer Reports, which included extracting and reviewing the pavement marking detection information displayed on the driver instrument cluster within each of the ADAS-equipped vehicles.

As the study progressed, there were notable limitations and challenges due to real-world data collection efforts that impacted the availability and quality of the data used in this study. Some of these real-world limitations and challenges experienced stemmed from changes in roadway construction contractors and roadway construction schedule changes that were out of the control of the research team. Other real-world challenges experienced were the result of various data issues such as low resolution of recorded videos, lack of detailed descriptions of the indicators on the instrument cluster, GPS errors, temporal and spatial inconsistencies, etc.

Ultimately, these real-world data collection and processing challenges affected the total number of vehicles fully assessed for cross comparison longitudinal pavement marking detection capabilities. That said, data collected from multiple (five out of the eight) ADAS-equipped vehicles utilized as part of this project were still assessed for cross comparison longitudinal pavement marking detection capabilities. In addition, other useful information was still gathered and realized from all ADAS-equipped vehicles. A summary of the valuable lessons from this research is included below.

Research results summary:

- No apparent relationship was found between the roadway longitudinal pavement marking characteristics for retroreflectivity, width, color, or contrast and the longitudinal pavement marking detection capabilities of the ADAS-equipped vehicles used in this study.
  - Retroreflectivity - Vehicle ADAS tends to detect longitudinal pavement markings with retroreflectivity values between 50 and 100 mcd/m2/lux. Please note that the latest MUTCD released in 2024 requires minimum pavement marking retroreflectivity of 50 mcd/m2 /lx under dry conditions on roadways with speed limits of 35 mph or greater. As this study was conducted before the publication of the latest MUTCD, 50-100 mcd/m2/lux was used as a lower range for pavement marking retroreflectivity in this study.
  - Width - Vehicle ADAS was able to reliably detect longitudinal pavement markings as narrow as 3 inches, which is below the latest MUTCD standard width of 4” – 6” for most public roadways.
  - Color – Vehicle ADAS tends to detect both yellow and white longitudinal pavement markings.
  - Contrast - No apparent relationship was found between the contrast value of longitudinal pavement markings and ADAS detection capabilities.

- When the vehicle’s ADAS failed to detect the longitudinal pavement markings, these events were not found to be associated with any of the vehicle speeds adhered to as part of this research.
  - For each route driven the Consumer Reports team adhered to a constant traveling speed of 5mph over the posted speed limit.
  - These speeds adhered to as part of this research project ranged from 40 mph (38 mph is the ADAS activation speed across all vehicles driven as part of this research) to over 50 mph depending on the posted speed limit for each route driven.
  - Both “detection” and “non detection” events were found at the same speed over the longitudinal profile of the selected sites.

- A few special scenarios were identified where the onboard ADAS failed to detect the longitudinal pavement markings due to changes in lane marking type and color (e.g., change in pavement marking from yellow to while, from solid marking to dashed marking), wide lane, object on the road, etc. A scenario was also identified where the onboard ADAS detected pavement joint and curb as lane marking.

- The longitudinal pavement marking detection systems across all vehicles assessed, while offering valuable assistance to drivers, do have certain limitations that should be considered in future studies. These limitations can impact the system's effectiveness in certain scenarios.

    - The performance of the ADAS may be influenced by the quality and condition of the pavement markings themselves, especially if they are faded, damaged, or poorly maintained.
    - Furthermore, driving conditions such as sharp turns, complex intersections, or construction zones may pose challenges for the system to accurately interpret the intended path.
    - Driver education regarding the use of ADAS is paramount in effectively using these systems. Being aware of limitations can help drivers use the longitudinal pavement marking system as a valuable aid while also exercising caution and attentiveness in various driving situations.

In summary, vehicle manufacturers have incorporated more ADAS features and sensors in their vehicles today to further improve vehicle safety, performance, and convenience to the driver. This study is timely and provides insights on the detection capabilities of ADAS features in real-world driving situations. While this study experienced some issues with data collection and processing, a series of valuable lessons about ADAS perception of real-world longitudinal pavement markings, can still be applied by IOOs today as well as be incorporated into future study designs.

Recommendations to improve data quality for future studies would be to:

1) Utilize high definition (HD) cameras to improve clarity of video feeds for data processing and analysis,
2) Automate data collection and file storage procedures using best practices and standards,
3) Generate detailed manuals on gage cluster symbology, alerts and interpretations,
4) Utilize real time kinematic (RTK) GPS receivers to improve quality and consistency of location data,
5) Plan and collect preconstruction data the year prior to construction. Then, collect post construction data collection at least 6 months post completion. During construction data collection should be limited, if collected at all, due to the challenges of collecting multiple vehicles during a small window.

CHAPTER 1 INTRODUCTION AND BACKGROUND

1.1 Background

The condition, visibility, and contrast of longitudinal pavement markings are critical to roadway safety and have been used for decades by infrastructure owner operators (IOOs) as a frame of reference to communicate to drivers how to navigate roadways. Over the last decade, vehicle manufacturers have also begun incorporating new, intelligent, Advanced Driver Assistance Systems (ADAS) in their vehicles to further improve vehicle safety, performance and interactions between the driver, other roadway users and the roadway infrastructure itself, including longitudinal markings. The ADAS include a combination of hardware sensors (camera, radar, etc.) and software that enable a broad range of features, including those that provide warnings to the driver and/or momentary interventions as well as some convenience features that enhance driver support. Applications of ADAS such as lane departure warnings, blind spot detection, adaptive cruise control, lane keeping assistance, automatic emergency braking, etc. are becoming more common in new model year vehicles across the light-duty vehicle fleet. These technologies have the potential to improve vehicle performance and reduce the number of roadway crashes that are driver behavior related.

Today, longitudinal pavement markings are the primary roadway asset that ADAS sensors look to for reference to assist drivers in providing safe navigation on the roadway. However, is it appropriate to rely on the existing roadway markings to guide modern cars, as well as the cars of the future? What are the minimum longitudinal marking requirements for driver assistance technologies to be successful in improving roadway performance and safety? Additionally, should machine vision and other ADAS sensors be explored to safely assist the driver in operating the vehicle? As more automated driving tools are being deployed rapidly to help support vehicle safety and performance, it is important for IOOs to understand how their infrastructure will need to adapt, if at all, to allow for the maximum benefit from such technological advances.

Although ADAS is becoming more common in cars today, more research is needed before ADAS is perfected and standardized across the light-duty fleet and across other fleets as well. ADAS is designed to support human drivers while driving, not replace them. However, over the coming decades, as new vehicle technologies emerge, the progression will be towards more reliance on ADAS to perform the real-time operational and tactical functions in on-road traffic (steering, accelerating, braking, etc.).

As new ADAS are deployed across the vehicle fleet, the IOOs need to better understand how the design and condition of the roadway infrastructure plays a role at helping achieve better safety and performance of ADAS-equipped vehicle operations on the roadway. Adequate pavement line stripping is identified as one of the major factors for the optimal operation of several ADAS technologies. Lane detection is important for any ADAS (Ambrosius, 2018; Mosböck et al., 2018; Nitsche et al., 2014; Steyvers & Waard, 2000) and is dependent on the visibility and consistency of lane markings (Donnell et al., 2009; Horberry et al., 2006).

Identification of lanes via longitudinal road markings is usually done with cameras, in either monocular or stereo vision (Ambrosius, 2018; Carlson et al.; 2013; Mosböck et al., 2018). Lane detection systems need to overcome several challenges, including knowing which lane a vehicle is in on a multilane road, separating road markings from other longitudinal lines such as asphalt surface cracks and guardrails, and accurately detecting worn markings, especially worn markings on light colored roadway surfaces (e.g., concrete roads) in both challenging light and weather conditions (Nitsche et al., 2014). Worn markings pose a similar safety concern for human drivers (Avelar & Carlson, 2014; Lyon et al., 2015). If changes are required to the design or maintenance of road markings to continually support and improve safety and performance of ADAS, then IOOs need to start planning to meet the future demands placed on the system.

Roadway design standards and practices for pavement marking design and maintenance have been developed in the past with the consideration of a human vision system of the driver. The most common feedback regarding highway infrastructure for the effective operation of ADAS applications such as lane departure warnings (LDW) or lane keeping assistance (LKA) is that the pavement markings need to be maintained in a state of good repair. One of the most important pieces of literature available on this topic is Project No. 20-102 (06), a study sponsored by the National Cooperative Highway Research Program (NCHRP). This study worked to understand and define how pavement markings could be designed and maintained to provide reliable machine vision detection (Bektaş et al., 2016). This study explored the effect of longitudinal pavement marking quality using a variety of pavement marking performance levels on the detectability of pavement markings by machine vision systems. Pavement marking performance levels were varied using white and yellow pavement markings along with retroreflectivity to represent a range of in-service markings. The field testing occurred under eight scenarios representing various lighting and roadway moisture conditions using two aftermarket Mobileye ADAS devices installed on separate vehicles. The detection confidence ratings that the LDW algorithm assigned to the pavement markings were recorded and used as the key measure of effectiveness. Overall, the results of this study suggest that to achieve consistently high machine vision detection confidence ratings, the contrast ratio of the pavement markings relative to the adjacent pavement needs to be of an adequate level to facilitate detection.

Following the same study design, the NCHRP 20-102 (06) research team conducted additional field testing sponsored by American Traffic Safety Services Association to investigate the performance of machine vision technology relative to 4-inch and 6-inch-wide pavement marking (Diamandouros & Gatscha, 2016). The testing results show that the 6-inch-wide longitudinal preformed tape markings consistently improved machine vision detection performance under wet daytime conditions. This is critical since wet daytime conditions provide a significant challenge for the machine vision technologies tested. Results also indicated that 6-inch-wide lane line markings can also be expected to improve machine vision detection performance as vehicle speed increases. According to the findings in the NCHRP 20-102 (06) research project, other conditions where 6-inch-wide longitudinal pavement markings may potentially improve machine vision detection performance as compared to 4-inch-wide markings are the following areas where potentially conflicting signals may confuse machine vision systems from detecting and tracking the markings: areas with remnants of previously removed markings, pavement scarring due to removal activities, blackout markings, crack seal, longitudinal seams in the pavement, varying road surfaces, cracking, rutting, shadows, or areas where glare is common and impacts marking visibility.

Based on the findings from existing literature, it can be noted that pavement lane line marking characteristics such as retroreflectivity, color, contrast, condition, material, type, and design need to be controlled to evaluate the effectiveness of ADAS machine vision detection.

1.2 Manual on Uniform Traffic Control Devices (MUTCD)

The Federal Highway Administration (FHWA) publishes the Manual on Uniform Traffic Control Devices (MUTCD), which contains all national design, application, placement, standards, guidance, options, and support provisions for traffic control devices (FHWA 2024). The purpose of the MUTCD is to provide uniformity of these devices, which include signs, signals, and pavement markings, to promote highway safety and efficiency on the Nation's streets and highways.

In Connecticut, the Connecticut Department of Transportation (CTDOT) has adopted the MUTCD as the State’s standard for such designs. The latest, 11th edition of the MUTCD was recently published in the Federal Register and became effective on January 18, 2024. However, as this study data collection and analysis was conducted before the publication of the latest version of the MUTCD, the requirement proposed in the 11th edition of MUTCD was not considered in this study. On December 14, 2020, the FHWA proposed wide-ranging revisions to the MUTCD. This was the first comprehensive draft update in more than 10 years to advance traffic operations and safety in states and cities nationwide. One of the key additions of the draft MUTCD update is a new chapter on automated vehicles.

The purpose of this chapter is to provide agencies with general considerations for vehicle automation as they assess their infrastructure needs, prepare their roadways for automated vehicle (AV) technologies, and to support the safe deployment of automated vehicle technologies. One of the key components of this AV chapter is new requirements and considerations for lane markings, some of which are also included in another chapter of the MUTCD dedicated specifically to lane markings.

Some of the proposed updates include:

- Normal-width longitudinal lines of at least 6 inches wide on freeways, expressways, and ramps and on all other roadways with speed limits greater than 40 mph.
- Edge lines of at least 6 inches in width on all conventional roadways.
- Dotted edge line extensions along all entrance and exit ramps, auxiliary lanes, and tapers where a deceleration or auxiliary lane is added.
- Chevron markings in the neutral areas of exit gores to distinguish them from travel lanes.
- Continuous markings at the beginning of work zones and in all lane transitions.
- Raised pavement markers only as a supplement to, rather than as a substitute for, markings.
- Uniform contrast markings on light-colored pavements to create greater contrast.
- Broken lines of at least 10 ft in length with a maximum gap of 30 ft.
- Avoidance of decorative elements in crosswalks.

Although FHWA proposed recommendations for changing lane markings for improved visibility of machine vision, several of the new proposed requirements and recommendations were based on findings from only a handful of studies. At present, it is still relatively unknown what factors in pavement markings are important to automated driving machine vision-equipped vehicles. Research findings indicate that more testing needs to be conducted to develop an acceptable relationship between pavement marking characteristics and machine vision quality score (Stacy, 2019).

1.3 Problem Statement

Historically, CTDOT and other IOOs have adopted traffic control device design, construction and maintenance policies and practices geared exclusively towards the needs of the human vehicle operator and the roadway infrastructure. With the proliferation of ADAS commercially available in many light duty vehicles sold today and the on-going advancements of ADAS technologies, CTDOT is committed to exploring the needs and potential impacts for adopting new traffic control device policies and practices that also consider the needs of new vehicle technologies, including ADAS, both present and future.

Like most IOOs, CTDOT is resource constrained. As a result, CTDOT is exploring and approaching the potential need for updating traffic control device policies and practices from an asset management, performance management, and resource optimization perspective. CTDOT and other IOOs certainly would not welcome the needs of ADAS and other related emerging technologies to become overly dependent on the IOO's ability to maintain pristine roads for these technologies to work properly. There needs to be a balance struck between technological effectiveness and the ability for IOOs to support improvements. It is also very important that any updates moving forward should be mutually beneficial for vehicle automation purposes and human drivers.

In addition, CTDOT and other IOOs believe that any FHWA-recommended or -required maintenance or design changes as part of the MUTCD update (described above) and future updates should be established on well documented and mature research demonstrating the benefits and challenges of such recommendations or requirements. Although some ADAS roadway infrastructure research has been published to date and documented in the MUTCD update, additional research is needed to further challenge and validate findings and address gaps. As a result, CTDOT initially requested this study to assess, validate, and challenge the need for and the implications of several of the new pavement marking provisions included in the draft MUTCD update that FHWA published in 2020. A summary of those draft provisions are included in Section 1.2.

As part of this research, CTDOT would also like to determine how the color, contrast, retroreflectivity, materials, design, configuration, condition, age, and other aspects of longitudinal pavement markings may impact the ability of ADAS-equipped vehicles to "see" and maintain safe operations on public roadways under automated driving modes. Furthermore, multi-state collaboration and learning through the Eastern Transportation Coalition (TETC) supports CTDOT's and other state and local IOO's desire for knowledge in this area. While this study was Connecticut-centric, the findings will apply widely throughout TETC membership states up and down the east coast from Maine to Florida and with other states around the nation. The findings of this research will help inform other research and other relevant future standards.

1.4 Project Partners

This research project was funded by CTDOT using their federal State Planning and Research (SP&R) funds and was executed by the University of Connecticut (UConn). CTDOT was responsible for overseeing UConn's work on the project including study area design, coordination, roadway base data collection, data storage, data analysis and reporting. The findings of this research project are based on the work performed by UConn, including UConn's analysis of consumer ADAS-equipped vehicle data made available to UConn from a separately funded, parallel project between The Eastern Transportation Coalition (TETC) and Consumer Reports (CR). CTDOT is a member state of TETC. Both CTDOT and UConn worked very closely with TETC and CR on the execution of the TETC funded project. The data and findings coming out of the TETC project were shared by CR and TETC with CTDOT and UConn for further analysis as part of this project. Figure 1-1 is a schematic that shows the interrelationships between the two projects, each of the project partners and the products and deliverables produced.

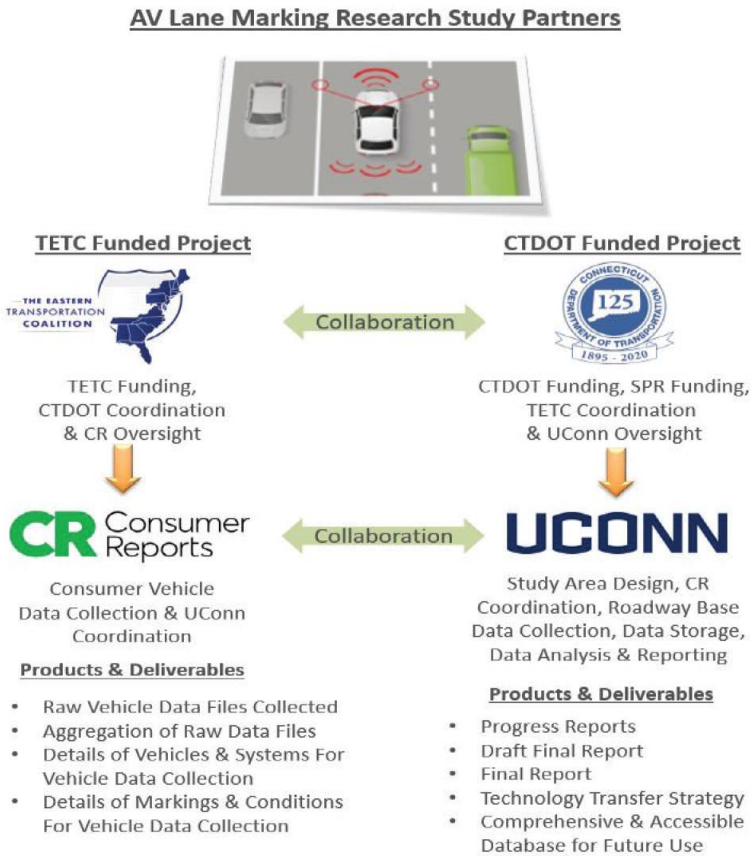


Figure 1-1: AV Lane Marking Evaluation Research Study Partners.

1.5 Objectives

The objectives of this study are to determine areas or instances where ADAS have success as well as difficulties maintaining a "visual" on road markings. Furthermore, to identify if there are differences across makes, models, and technologies used to identify lane markings while an ADAS-equipped vehicle is operating with their machine vision sensors engaged.

The main objectives of this study can be summarized as below:

- Evaluate the effect that various pavement marking characteristics, such as color, condition, contrast, retroreflectivity, design, materials, have on machine vision detection through an evaluation of vehicle performance operating on public roadway under various conditions as well as a pre- and post-improvement lane marking study design.
- Explore the machine vision lane marking detection accuracy under various daytime and nighttime lighting conditions.
- Explore the machine vision lane marking detection accuracy under mostly dry weather conditions, and potentially some wet weather conditions.
- Explore the differences, if any, across different makes, models, and machine vision

technologies used to detect lane marking and maintain safe operation with ADAS-equipped vehicles.

The Connecticut Transportation Safety Research Institute (CTSRC) at UConn worked with Consumer Reports (CR) to conduct field testing of machine vision detection of lane marking using multiple vehicles from varying makes and models equipped with an ADAS unit such as LDW and LKA. The consumer vehicle field testing was funded by TETC and conducted under different lighting (night vs day) and weather (mostly dry but potentially some wet weather) conditions. Furthermore, field data collection on defined routes was conducted under existing conditions and then new lane markings were added to existing routes.

The study was designed to track varying lane marking characteristics, such as width, color, materials, design, condition, contrast, and retroreflectivity, to represent a wide range of in-service lane markings on real-world roadways. Information on the machine vision lane marking detection was collected through field testing to understand and evaluate the relationship between lane marking characteristics and machine vision detection accuracy. Outcomes from this study can be used to help CTDOT and other IOOs determine the type, width, materials, and maintenance intervals of lane marking improvements to meet the demands of ADAS-equipped vehicles today and in the future.

CHAPTER 2 LITERATURE REVIEW

Lane-keeping systems are a form of advanced driver assistance technology that helps the driver maintain their vehicle in the correct lane and avoid unintentional lane departure. This system is particularly useful for highway driving, where drivers may experience fatigue or distractions and unintentionally drift from their lane. Lane detection technology is at the core of lane keep systems and it relies on pavement markings to determine the position of the vehicle on the road. To effectively utilize the lane keeping system, it is essential to have clear and consistent pavement markings that are easily visible to the driver (Ambrosius, 2018; EuroNCAP, 2011, EuroNCAP 2014; Mosböck et al., 2018; Nitsche et al., 2014). Therefore, it is essential to evaluate pavement markings to ensure their effectiveness in supporting the technology.

2.1 Lane Detection Technologies

Lane detection technology is a system designed to detect and monitor the lane markings on the road surface and provide feedback to drivers if they deviate from their lane. This technology plays an important role in preventing crashes caused by unintentional lane departure. Several lane detection technologies have been developed over the years, including machine-vision, radar, and LiDAR (Light Detection and Ranging) based systems.

Machine-vision-based systems are the most used type of lane detection technology by vehicle manufacturers and can be seen in many light duty vehicles currently available on the market. A vision-based lane detection system uses cameras mounted on the vehicle to capture images of the road ahead. The images are then processed using computer algorithms that analyze the lane markings and determine the vehicle's position within the lane. This type of system is easy to install and does not require any modifications to the road infrastructure. However, it may be affected by adverse weather conditions such as rain, snow, and fog.

2.2 Longitudinal Pavement Markings

Longitudinal pavement markings are critical for road safety and play an essential role in maintaining order and organization on the road. They provide visual cues to drivers indicating the location and boundaries of their lane, as well as provide warnings and guidance on speed limits, stop signs, and other traffic regulations. Pavement markings provide a reference for the vehicle's cameras or sensors to aid the lane keep system, which allow the system to determine the vehicle's position in the lane and alert the driver when they drift.

A study by Steyvers and Waard (2000) showed that providing pavement markings brings safety benefits compared to no pavement marking conditions. Multiple studies have focused on evaluating the effectiveness of enhanced pavement marking retroreflectivity on improving driver performance and reducing the number of certain types of crashes (e.g., run-off-road, lane encroachment, or wet road surface related). Generally, higher pavement marking retroreflectivity was found to be associated with higher levels of driver comfort and lower numbers of targeted crashes (Avelar & Carlson, 2014; Babić et al., 2020; Bektaş et al., 2016; Carlson et al., 2013; Diamandouros & Gatscha, 2016; Donnell et al., 2009; Horberry et al., 2006; Lyon et al., 2015; FHWA, 2009).

To ensure that pavement markings are effective, a set of standards has been established by various regulatory bodies. In the United States, the Federal Highway Administration (FHWA) has established standards for pavement markings under the Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2024). The MUTCD defines the acceptable pavement markings, their dimensions, color, placement, and the materials that should be used to create them. The MUTCD also provides guidance on the maintenance of pavement markings to ensure that they remain visible and effective. The MUTCD specifies that lane markings should be at least four inches wide, with a minimum gap of ten feet between the lines. The markings should be of a uniform color, with yellow indicating a two-way road, and white indicating a one-way road. The MUTCD also specifies that the markings should be reflective and visible in all weather conditions, including rain and fog. It should be noted that these new MUTCD standards were released post data collection and analysis for this project. However, draft versions of the new MUTCD and the potential release of new standards were a primary motivating factor for this research effort.

There are several methods of evaluating pavement markings, which include visual inspection, retroreflectivity measurement, and digital image analysis (American Society for Testing and Materials, 2005; Babić et al., 2015; Babić et at., 2016; Babić et al., 2019; Bowman & Abboud, 2001; Burghardt & Pashkevich, 2020; Burghardt et al., 2021; Donnell et al., 2009; Fares et al., 2012; Hummer et al., 2011; Choi et al, 2014; Mahlberg et al., 2021; Mohamed et al., 2020; Sitzabee et al., 2009; Stacy, 2019; Zhang & Ge, 2012; Zehr et al., 2019).

Visual inspection is the most common method used, where markings are assessed for their visibility, wear, and fading. Retroreflectivity measurement involves the use of a device, called a retroreflectometer, that measures the amount of light that is reflected back to the source. This method is used to evaluate the markings' brightness and is essential for ensuring that they are visible at night.

Digital image analysis involves the use of software to analyze images of pavement markings. The software can detect the presence and quality of the markings and can also provide information on their position and alignment. Visual inspection is a quick and easy method of pavement marking evaluation. However, it is subjective and relies on the inspector's experience and judgment, which can lead to inconsistencies in the results. Retroreflectivity measurement provides more objective results, but it requires specialized equipment and can be time-consuming. Digital image analysis is the most objective method of evaluation, as it eliminates human subjectivity. However, it requires specialized software and equipment and can be expensive.

2.3 Evaluation Of Pavement Markings using Vehicle Lane Detection Technology

As pavement markings are crucial for vehicle lane detection technology, it is essential to evaluate how pavement marking conditions affect the performance of the technology. The goal is to support the development of a new set of standards for pavement marking that ensures transportation safety through good cooperation between highway infrastructure and vehicle automation technology. For example, based on research done in Texas, the American Traffic Safety Services Association (ATSSA) published a Policy on Road Markings for Machine Vision Systems, in which the organization showed support to a proposal on pavement markings to accommodate driving automation technologies (ATSSA, 2019; Barrette & Pike, 2021).

ATSSA suggested that the next edition of MUTCD should include policy changes regarding pavement marking as follows.

- Inclusion of a rule on minimum pavement marking retroreflectivity levels.
- Longitudinal markings (edge lines, center lines, and lane lines) shall be six-inch wide on roads with a posted speed ≥ 40 mph.
- Lane line markings shall be 15-feet in length with a gap of 25 feet.
- Dotted edge line extensions shall be marked along exit and entrance ramps on roads with a posted speed ≥ 40 mph.
- Crosshatch (i.e., Chevron) markings shall be included in gore areas on roads with a posted speed ≥ 40 mph.
- Non-reflective Botts Dots should be eliminated or only used when supplementing pavement markings.
- Contrast striping should be required on PCC concrete roadways with a posted speed ≥ 40 mph.

Prior studies have used retroreflectivity measurement in evaluation of pavement markings for vehicle lane detection technology and have shown that it is an efficient method (Barrette & Pike, 2021; Babić et al., 2021; Burghardt et al, 2018; Burghardt, et al., 2021; Davies, 2016; Hadi & Sinha, 2011; Mahlberg et al., 2021a; Mahlberg, et al., 2021b; Marr, et al., 2020; Matowicki et al., 2016; Nayak et al., 2021; Pike et al., 2019; Stacy, 2019; Storsæter et al., 2021). It is an important attribute showing if pavement markings are visible and bright enough to be detected by lane detection systems' cameras or sensors.

In the real world, the retroreflectivity of pavement markings changes as the materials age and deteriorate over time due to impacts of vehicle tires, snow plowing, temperature changes, sunlight, and precipitation (Babić et al., 2019; Bowman & Abboud, 2001; Fares et al., 2012; Hummer et al., 2011; Kopf, 2004; MacEacheron, 2014; Sitzabee et al., 2009). Typically for a newly painted pavement marking, the retroreflectivity increases and reaches its maximum within the first 100 days and starts to degrade toward zero (Kopf, 2004; MacEacheron, 2014).

The lifespan of pavement markings is related to factors such as paint and bead materials, road surface, weather, etc. Prior studies have found that a higher retroreflectivity helps machine-vision-based lane detection during both daytime and nighttime, as well as under rain and low-light conditions (Barrette & Pike, 2021; Burghardt, et al., 2021; Hadi & Sinha, 2011; Marr, et al., 2020; Nayak et al., 2021; Pike et al., 2019).

Apart from retroreflectivity, other attributes such as contrast ratio, dimensions (e.g., stripe type, gap, and width), and color have been considered in prior evaluations of pavement markings for accommodation of vehicle lane detection systems (Barrette & Pike, 2021; Babić et al., 2021; Burghardt et al., 2021; Marr, et al., 2020; Nayak et al., 2021; Pike et al., 2019; Storsæter et al., 2021).

Based on prior studies, to achieve a better machine-vision-based lane detection performance, the pavement markings should have attributes meeting the following criteria as shown in Table 2-1. In addition to pavement marking attributes, other environmental and technological factors also affect the performance of machine-vision-based lane detection systems. Some examples are given in Table 2-2.

Table 2-1: Pavement Marking Criteria for a Better Machine-Vision-Based Lane Detection Performance.

Attribute	Criteria	Source
Retroreflectivity	Higher is better: daytime >= 85 mcd/m2/lx, nighttime >= 70, 100, or 150 mcd/m^2/lx, nighttime wet >= 20, 35 mcd/m^2/lx	Marr, et al., 2020
Contrast Ratio	Higher is better: marking:pavement >= 3:1 (general), 5:1(nighttime)	Barrette & Pike, 2021 Marr, et al., 2020
Dimensions: Gap Continuous vs. Dashed	Smaller gap is better: 30 ft better than 40 ft Continuous is better than dashed	Barrette & Pike, 2021 Marr, et al., 2020 Nayak et al., 2021
Width	Depends: six-inch for edge, four-inch for center	Marr, et al., 2020
Color	Yellow is better in snow than white	Storsæter et al., 2021

Table 2-2: Other Criteria for a Better Machine-Vision-Based Lane Detection Performance.

Factor	Criteria	Source
Daytime vs. Nighttime	Nighttime is better	Babić et al., 2021 Nayak et al., 2021
Glare	No glare is better	Barrette & Pike, 2021
Nighttime Lighting	Lower lighting is better	Barrette & Pike, 2021
Weather	Clear and dry is better	Burghardt et al., 2021
Speed	Lower is better, but difference not significant in nighttime	Barrette & Pike, 2021
Camera Field of View (FOV)	Near FOV (30 ft or less) is better than far FOV (beyond 30 ft)	Nayak et al., 2021

Various methods have been developed to evaluate the performance of vehicle lane detection systems in detecting pavement markings. One common method is the use of video data and image processing techniques to detect the location and boundaries of pavement markings accurately (Davies, 2016; Nayak et al., 2021; Storsæter et al., 2021). Researchers use different image processing algorithms to extract the pavement marking information from the video data. These algorithms may include edge detection, Hough transform, or machine learning algorithms, which use convolutional neural networks to detect pavement markings in real-time.

Another evaluation technique involves the use of LiDAR technology (Hadi & Sinha, 2011; Mahlberg et al., 2021). LiDAR sensors emit laser beams that bounce back to the sensor, creating a 3D map of the surrounding environment. LiDAR can accurately detect and measure the height, width, and position of pavement markings, making it a useful tool for evaluating their effectiveness. Researchers have also evaluated pavement markings' effectiveness by conducting experiments with test vehicles equipped with lane detection systems (Barrette & Pike, 2021; Babić et al., 2021; Mahlberg, Sakhare, et al., 2021; Marr, et al., 2020; Matowicki et al., 2016; Pike et al., 2019). In these experiments, the test vehicle drives along a test track or public roads with different types of pavement markings, and the system's performance is evaluated by measuring the accuracy of the lane detection and vehicle positioning.

CHAPTER 3 PAVEMENT MARKING DATA COLLECTION AND VISUALIZATION

3.1 Study Design Overview

The team developed a data collection plan to achieve the objectives of this study as outlined in Figure 3-1. Two types of data were mainly collected in this study: pavement marking characteristics (retroreflectivity, width, color, contrast) and on-road ground truth data of ADAS pavement lane marking detection. Consumer reports was responsible for on-road data collection using a variety of vehicles that were representative of the most commonly commercially available, Society of Automotive Engineer (SAE) Level 1 and 2 vehicles on the market with lane detection capabilities. UConn was tasked with the collection of pavement lane marking characteristics data using a retroreflectometer for the proposed study collection route pre, during, and post updating of lane markings. The UConn team was responsible for data processing and analysis of the video data collected by CR. More details regarding video data processing and analysis are presented in Chapter 4 and 5.

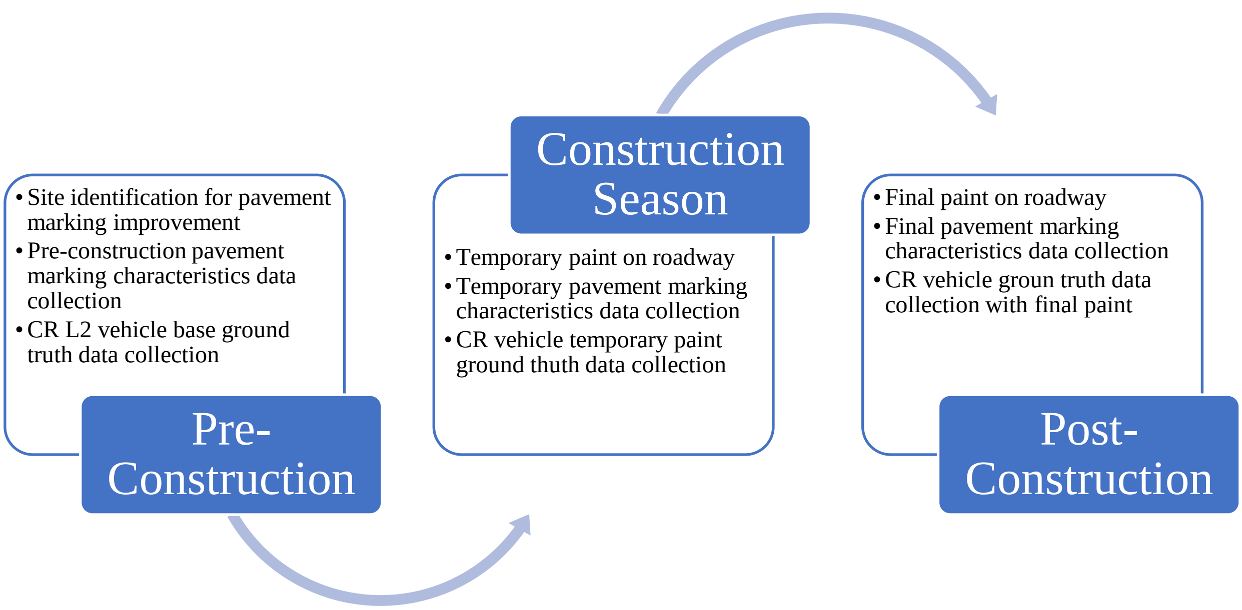


Figure 3-1: Data Collection Plan.

As illustrated in Figure 3-1, both pavement marking characteristics and on-road ground truth data were collected simultaneously to achieve the objectives of this study. Both types of data were collected in pre-construction, construction, and post-construction phases to compare and contrast the effects of pavement lane striping characteristics on the detectability of lane marking by on-board ADAS. While the CR team was responsible for collecting ground truth data using selected SAE Level 1 and 2 vehicles, the UConn team collected the pavement lane line marking characteristics data for this proposed study. The rest of this chapter presents details on the equipment used to collect pavement marking characteristics, extent of data collection, data processing, and development of data visualization tool that can allow users to interact with the data collected by the UConn team.

3.2 Pavement Lane Line Marking Data Collection

On behalf of CTDOT, UConn purchased a vehicle-mounted retroreflectometer to collect pavement lane line marking characteristics. UConn purchased a single unit of Laserlux G7 (LLG7) from RoadVista. An overview of the equipment used to collect pavement lane line marking characteristics is provided in the following sections.

3.2.1 Overview of LLG7

LLG7 is a mobile marking retroreflectometer unit (MRU) designed to be mounted on vehicles to measure pavement markings. The pavement marking geometry for lane line characteristics data collection using LLG7 is provided in Figure 3-2 (Austin & Schultz, 2020).

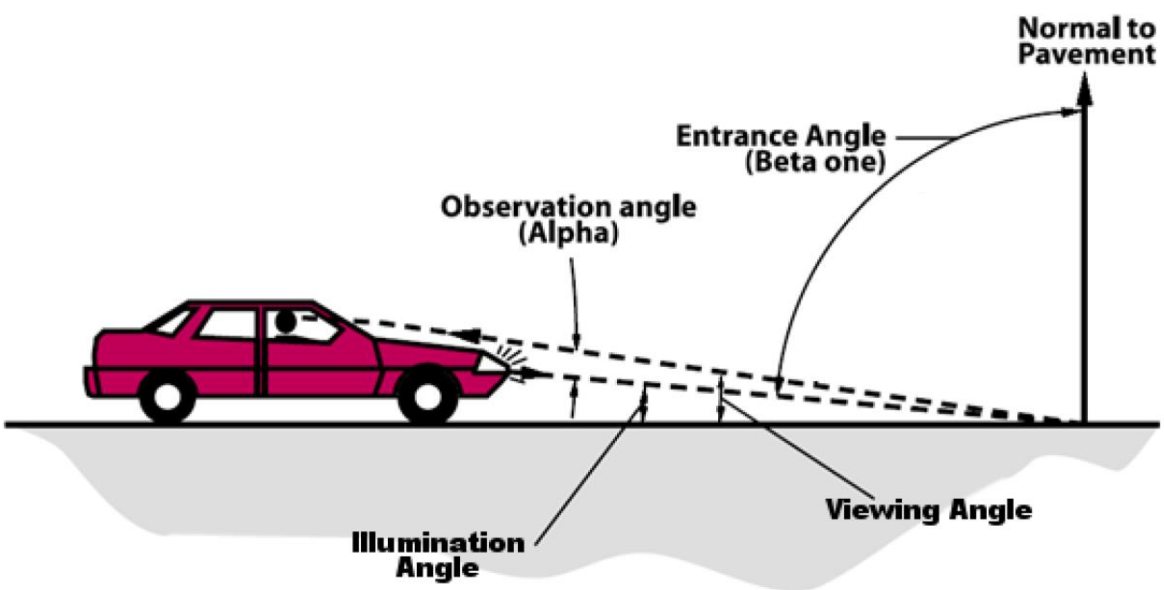


Figure 3-2: Pavement Marking Geometry for LLG7 (Austin & Schultz, 2020).

The current accepted working standard for machine-based retroreflective measurement described in ASTM E 1710 uses a "30-meter geometry" which was initially set by the European Committee for Normalization (CEN) (Burghardt et al., 2018). The standard was created to simulate the nighttime visibility for an average driver in a passenger car. This takes the form of a 1.2-meter eye

height and a 0.65-meter illumination height 30 meters away from a ground-based target. The standard also calls for a 1.05-degree angle between the emission source and the sensor.
In LLG7, the pavement marking is sampled at 1/5th scale of the CEN 30-Meter Geometry. The measurement distance of the LLG7 is 6 meters (19.685 feet) in front of the instrument. As defined by ASTM E1710, the Entrance Angle of the LLG7 is 88.76°, with corresponding Co-Entrance angle of 1.24°. Its Observation Angle is 1.05° as measured from the light source. As defined by EN 1436, the Illumination Angle of the LLG7 is 1.24° and its Viewing Angle is 2.29° as measured from the pavement (Figure 3-1). Additionally, a 15-meter geometry version is available for use in regions that are using 15-meter geometry standards. In that geometry version, the Entrance Angle is 86.50°, with corresponding Co-Entrance angle of 3.50°. Its Observation Angle is 1.50° as measured from the light source.

The LLG7 measures the Coefficient of Retroreflected Luminance (RL) of the pavement markings. In addition, it records the presence and relative retroreflective performance of RPM's (Raised Retroreflective Pavement Markers and Road Studs) with Global Positioning System (GPS) coordinates (Longitude and Latitude) of each one, perceived night-time line width, and contrast between the pavement and the markings. An optional add-in feature of the LLG7 is the ability to measure the nighttime chromaticity coordinates (color) of the pavement marking.

3.2.2 Vehicle Mounting System

The LLG7 quickly and easily attaches to almost all vehicles with the Squid Mount™ Vacuum Cup mounting system. When deployed properly, each one of the supplied 6" (15cm) vacuum cups are rated to hold 70 lbs. (31.8 kg) and the 10" (25cm) vacuum cups are rated to hold 175 lbs. (79.5kg). The 10" (25cm) cups also come with audible alarms to warn of vacuum leaks. An illustration of LLG7 mounted to a vehicle using the provided vacuum cup is provided in Figure 3-3.

Figure 3-3: LLG7 Mounted to a Vehicle using the Squid Mount™ (Austin & Schultz, 2020).

The vacuum cup's pump features a plunger with a red line, which serves as a vacuum indicator. Introduced by Wood's Powr-Grip (Wood’s Powr-Grip, 2023) in the 1960's, this safety device is still recognized as one of the most reliable warning systems available. A few strokes of the plunger evacuate the vacuum pad, causing it to seal securely to the attaching surface.

3.2.3 Data Items

The LLG7 utilizes its own internal Central Processing Unit (CPU) and network server to record and store all the collected data to plug-in, removable, flash memory. The instrument is operated wirelessly from any device that has Wi-Fi capability and a web-browser. Wi-Fi is a family of wireless network protocols based on the IEEE 802.11 family of standards, which are commonly used for local area networking of devices and Internet access, allowing nearby digital devices to exchange data by radio waves. Though it does not happen under normal operating conditions, should the operating device lose Wi-Fi connectivity with the instrument for any reason, the LLG7 will continue to operate and collect data from the last command received until Wi-Fi connectivity is restored. This ensures that you will never lose any data due to a loss of the Wi-Fi connection.

The LLG7 collects and stores retroreflectivity, contrast, and RPM data with corresponding date, time, and GPS coordinates, vehicle speed, and ambient conditions.
In addition, the following information is recorded:

- File Name.
- Record Description (Road Name and Direction, Job Number, Operator, etc.).

- Starting Point (Mile Post Marker or Origin).
- Quality of GPS Position Fix.
- Ambient Conditions (Temperature, Humidity).
- Retroreflective Width of Marking.
- Contrast Ratio Between the Pavement and the Marking.
- Night-Time Color Chromaticity Coordinates (With Optional Color Measurement Upgrade).
- Infrared Retroreflectivity for CAV Sensor Technology (With Optional IR Vision Measurement Upgrade).
- Vehicle Speed.
- Stripe Type.
- Road Condition Flag (User-Entered Comments).

The user-interface on the Wi-Fi-enabled device provides the operator with a visual representation of the retroreflectivity measurement, as well as all the necessary controls for calibration and operation of the LLG7.

3.3 Project-Specific Data Collection

Pavement marking data were collected by the UConn team in four runs, starting from April 2022 to January 2023. These runs were conducted in April 2022, June 2022, August 2022, and January 2023. Pavement marking data from both centerline and edgeline for the rightmost lane was collected using LLG7 based on recommendations from CTDOT, TETC, and CR. As the project team had only one unit of LLG7, pavement marking characteristics for centerline and edgeline were collected separately by mounting the LLG7 unit on the left and right side of the vehicle, respectively. In total, the project team collected 1,245 miles of centerline and 1,174 miles of edge line pavement marking characteristics. The spatial coverage of the pavement marking data collected under this project is provided in Figure 3-4.

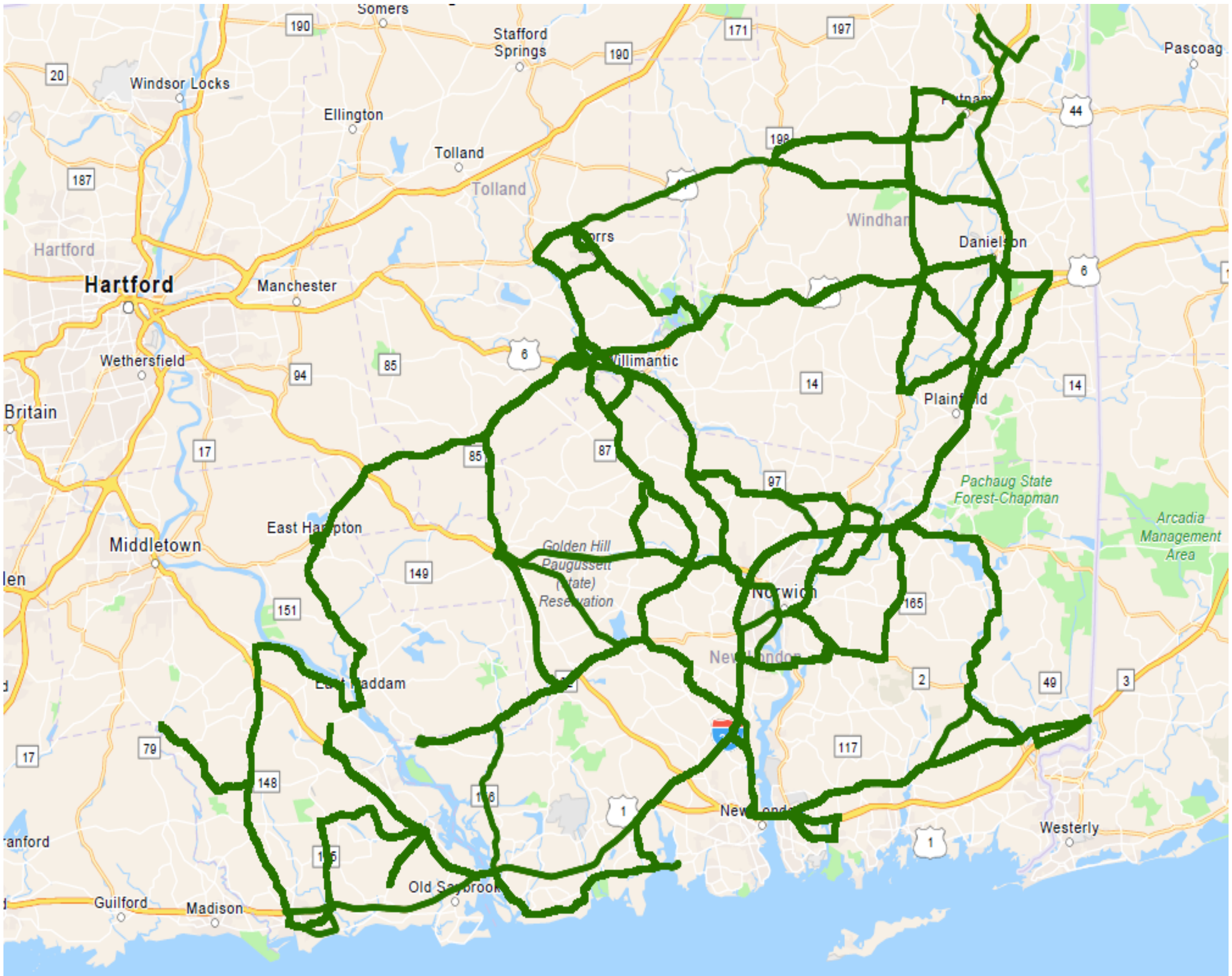


Figure 3-4: Spatial Coverage of Pavement Marking Data Collection.

3.4 Retroreflectivity Visualization Tool

A retroreflectivity data visualization tool[2] was developed using the pavement marking characteristics data collected in this project. The goal of this tool is to visualize and interact with the pavement marking characteristics data collected by the UConn project team. The functionalities of the data visualization tool are provided in the following sections.

User Interface

A screen capture of the retroreflectivity visualization tool user interface is presented in Figure 3-5. As mentioned earlier, two separate dashboard user interfaces were developed in this tool to separately visualize centerline and edgeline pavement marking characteristics data. Users can select either "Centerlines Dashboard" or "Edgelines Dashboard" from the top of the user interface

2 https://gis.cti.uconn.edu/portal/apps/experiencebuilder/experience/?id=a81a718919da4dff99096e3309ecba1e

to visualize pavement marking characteristics for the corresponding lane line marking. Specific functionalities of each dashboard are described below.

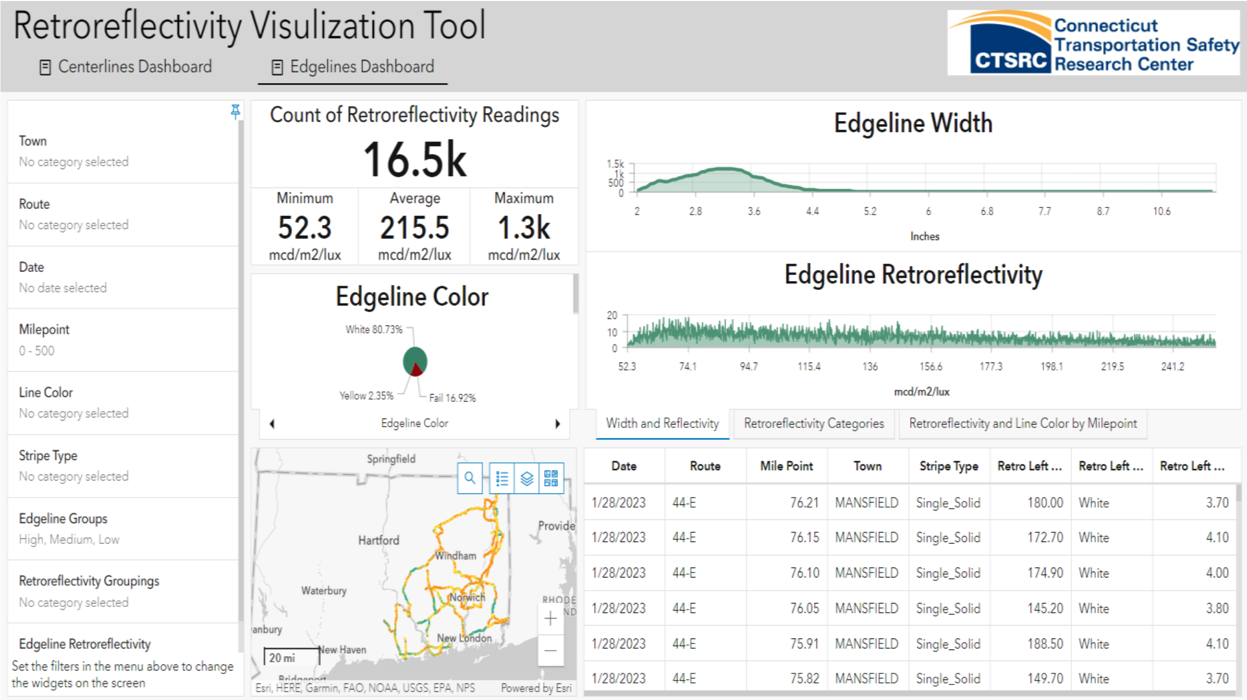


Figure 3-5: Retroreflectivity Visualization Tool User Interface.

Highlight Section

Both centerline and edgeline dashboard contains a highlight section that presents the count of pavement marking readings, minimum, maximum, and average value of pavement marking retroreflectivity in mcd/m2/lux unit.

Map View

The map view in the dashboard presents the spatial locations of the retroreflectivity data. Each point on the map represents a pavement lane line marking characteristic recorded using LLG7 equipment. The points on the map are color-coded based on the retroreflectivity readings. Users have the capability to zoom in and out and show legends on the map.

Widgets

Each dashboard contains multiple widgets. The widgets contain multiple graphs and data tables. The widget below the highlighted section includes three graphs: distribution of pavement lane line color, distribution of retroreflectivity readings, distribution of retroreflectivity groups, visualized using pie charts. The widget on the right of the highlighted section also includes three graphs, each combining two plots: distribution of lane marking width and retroreflectivity, distribution of retroreflectivity by color, and retroreflectivity and line color by milepost. The bottom right widget provides the tabulated data used to generate visualization in the tool.

Filter Menu

On the left side of the dashboard, there is a button that exposes a filter menu. This allows the user to filter specific attributes of pavement marking characteristics.

The items included in the filter are as follows:

- **Town:** User can filter data by town.
- **Route:** User can filter data by Route ID.
- **Date:** User can define range of date of data collecting using "From" and "Until". This option also allows the user to select a date using a calendar view.
- **Milepoint:** User can filter data by defining start and end mile points of interest.
- **Line Color:** User can select a specific line color detected by LLG7.
- **Stripe Type:** User can filter retroreflectivity data by stripe type identified during data collection. The types of stripe type available for selection are: ***Double_Solid, Single_Skip, Single_Solid, Skip_Left, and Skip_Right***.
- **Retroreflectivity Group:** The collected retroreflectivity readings were grouped into three groups: Low (less than 150 mcd/m2/lux), Medium (value between 150 and 400 mcd/m2/lux), and High (above 400 mcd/m2/lux). Users can also filter data for visualization using retroreflectivity groups.
- **Retroreflectivity Value:** User can filter retroreflectivity data by defining the minimum and maximum value of retroreflectivity in mcd/m2/lux.
- **Edgeline Width:** User can filter data by defining the minimum and maximum width of lane line markings.

The widgets and map within the dashboard will update with new metrics based on what is selected within the filter screen. A screen capture of the filter menu is presented in Figure 3-6.

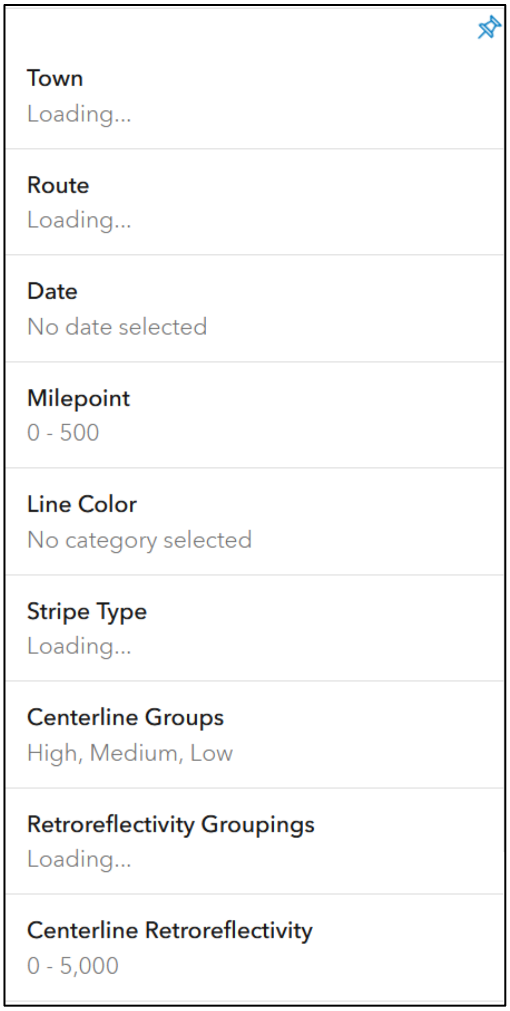


Figure 3-6: Screen Capture of the Filter Menu.

Other functionalities of the data visualization tool are as follows:

- Each widget within the dashboard can be expanded to a full screen view. In addition to expanding the widgets, the user can also interact with the legend to turn off categories.
- The filter menu can be docked on the left side of the tool by clicking on the pin in the top right-hand corner of the filter menu.
- Dashboards look best when viewed in web browsers on desktops and tablet devices. For best performance, use the latest version of a browser listed below:
    - Google Chrome.
    - Mozilla Firefox.
    - Safari.
    - Microsoft Edge.

CHAPTER 4 GROUND TRUTH DATA COLLECTION AND PROCESSING

4.1 Ground Truth Data Collection

Consumer Reports collected ground truth data on the performance of machine vision in detecting pavement lane line marking. CR selected eight light duty ADAS-equipped production vehicles from different makes and models from their available vehicle fleet. The selected vehicles have varying ground clearance which may result in different installation heights for the marking detection devices. An overview of the vehicles used in ground truth data collection is provided in Table 4-1. Please note that the make and model of vehicles is not disclosed as this is not an evaluation of how well individual vehicle function, but an evaluation of lane marking characteristics impacts on machine vision. Also, note that Tesla and any vehicle with Super Cruise were not considered in this study as these vehicles were equipped with proprietary roadway geolocation data that may bias data collected using other vehicles. These vehicles were not included in the list of test vehicles to be used for data collection based on inputs from CR, CTDOT, Consumer Reports, and TETC.

Table 4-1: Overview of Vehicles used by Consumer Reports for Data Collection.

Designation	Model Year	Description	Drivetrain	ADAS Lane Line Detection Feature
Vehicle 1	2022	Sedan	FWD	Lane Keeping Assist System (LKAS)
Vehicle 2	2021	SUV	AWD	Lane Keep Assist (LKA)
Vehicle 3	2020	SUV	4WD	Lane Keep Assist (LKA)
Vehicle 4	2022	SUV	4x4	Active Lane Management System (ALMS)
Vehicle 5	2022	Crew Cab, Truck	4x4	Lane Tracing Assist (LTA)
Vehicle 6	2022	Crew Cab, Truck	AWD	Lane Keeping System (LKS)
Vehicle 7	2022	SUV	AWD	Lane Keeping Assist

Vehicle 8	2022	Minivan	FWD	Lane Keeping Assist & Lane following Assist.

4.1.1 Overview of the ADAS Features

The study focused on evaluating the capabilities of ADAS features that assist vehicles in detecting a variety of lane line marking characteristics that were upgraded and altered over the course of the research project. The primary function of the lane keeping and lane assist ADAS feature is to assist the driver in keeping the vehicle within its designated lane. Various sensors, cameras, and algorithms are used in building this feature to detect pavement lane line markings.

When the system detects the vehicle deviating from its lane without activating the turn signal, it provides a warning to the driver, often termed as lane departure warning. This warning can be in the form of visual, auditory, or haptic cues, such as visual alerts on the instrument cluster, audible beeps, or steering wheel vibrations. In response to the detected lane deviation, the systems can initiate corrective actions to guide the vehicle back into the lane. This typically involves applying gentle steering inputs or making small adjustments to the vehicle's trajectory. When the vehicle nears a white or yellow line, the steering force will become stronger. The principle of operation of the lane marking detection system is provided in Figure 4-1 and Figure 4-2 (Honda, 2022).

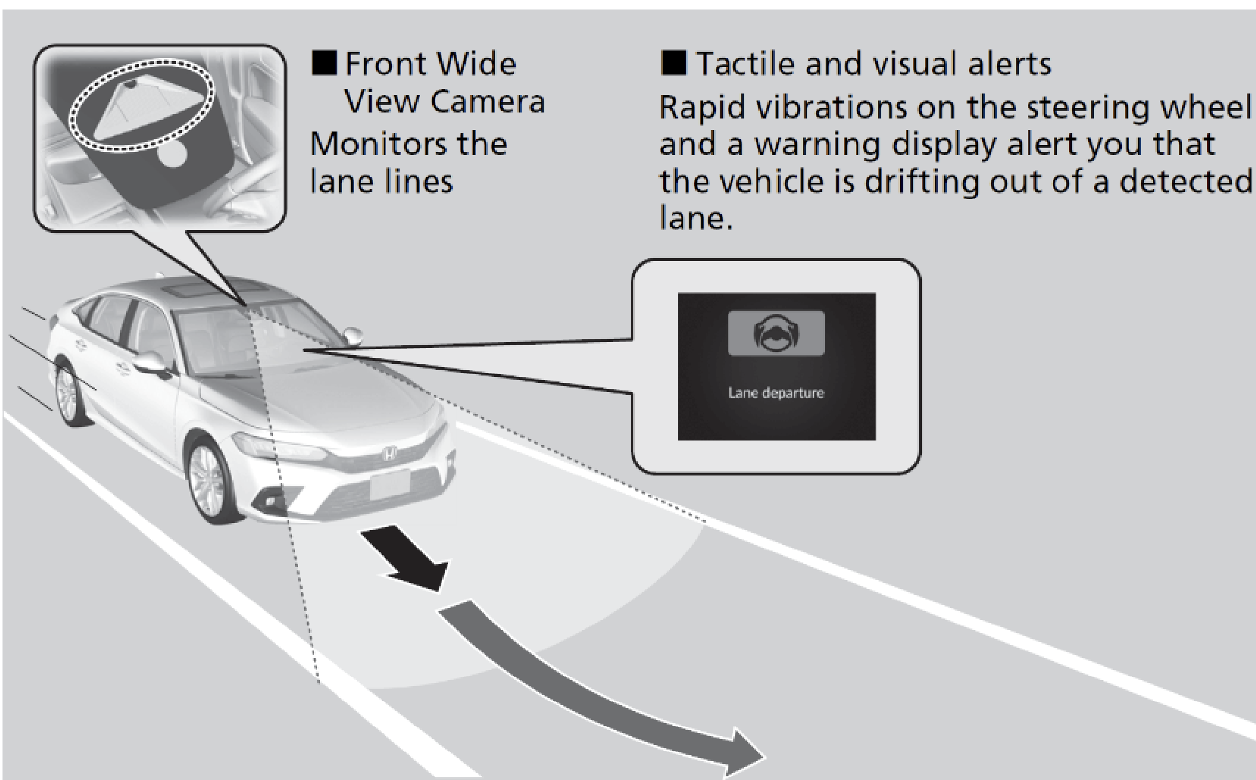


Figure 4-1: The Principle of Operation of the Lane Marking Detection System (Honda, 2022).

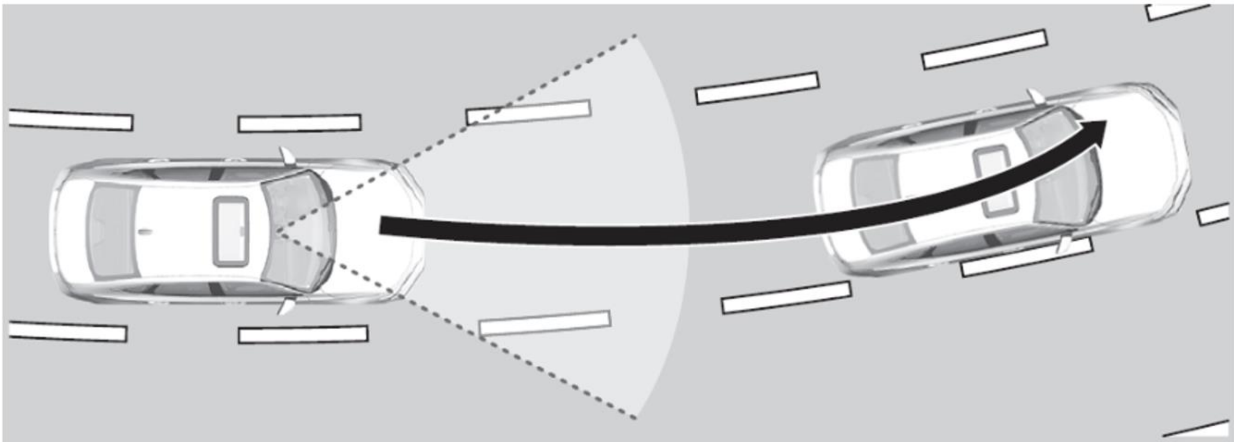


Figure 4-2: Demonstration of Corrective Actions (Honda, 2022).

As indicated in Table 4-1, each vehicle selected for data collection is manufactured by different vehicle manufacturers. The ADAS installed in each vehicle uses proprietary algorithms to detect pavement lane line markings and warn drivers in case of lane departure. Each vehicle manufacturer uses their own terminology and branding for their line marking detection systems.

For example, the lane marking detection system in *Vehicle 1* is called "Lane Keeping Assist System (LKAS)", while the ADAS feature used to detect lane line marking is called "Lane Keeping System" in *Vehicle 7*. Although all the systems rely on sensors and cameras to detect lane markings, the specific technologies used may vary. Different vehicles may employ different types of sensors, such as vision-based cameras or radar sensors, or a combination of multiple sensor technologies. A brief description of the system equipment and operation of the lane marking detection feature is provided in Table 4-2.

Table 4-2: ADAS Equipment and Operations.

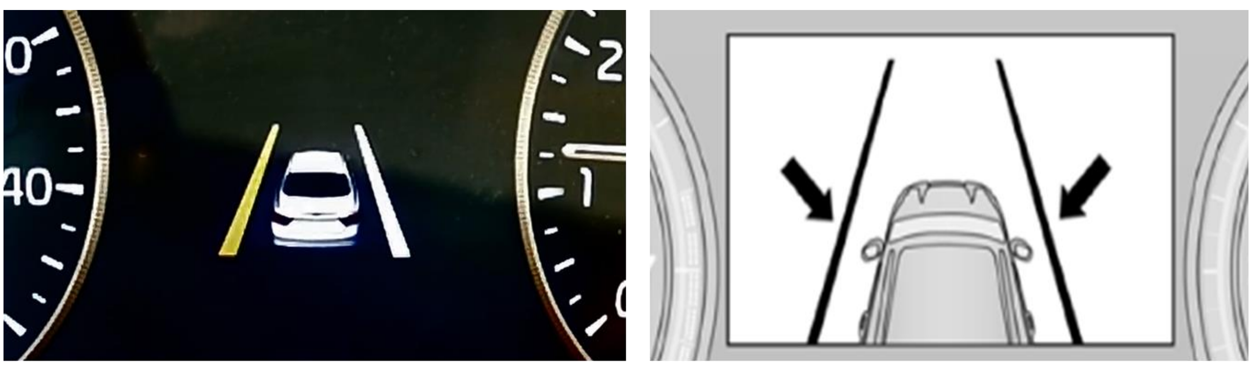
Vehicle ID	Equipment	Operation
Vehicle 1	Forward-facing camera mounted on the windshield	Operates based on the principle of computer vision and sensor technology. The system analyzes the captured images and identifies the position of the lane markings relative to the vehicle. It then compares the vehicle's position with the detected lane markings and provides steering assistance to keep the vehicle centered within the lane.
Vehicle 2	Advanced camera technology installed	Uses the concept of computer vision combined with sensor technology. This system examines the recorded visuals and

	on the windshield ahead of the rearview mirror	discerns the lane markings' location in relation to the car. When the system detects that the vehicle is unintentionally drifting out of its lane, it provides small adjustments to the steering wheel to assist the driver in staying within the lane boundaries.
Vehicle 3	Forward-facing camera mounted near the rearview mirror	The camera captures images of the road ahead, detecting lane markings such as solid lines, dashed lines, and other road features. The captured images are processed by onboard computer systems. The system analyzes the lane markings' positions relative to the vehicle's current location. If the system detects that the vehicle is drifting out of the lane unintentionally, it provides visual and audible warnings to alert the driver of the lane departure.
Vehicle 4	Cameras and sensors	The sensors continuously monitor the vehicle's position and analyze the data to determine if the vehicle is drifting or departing from its lane unintentionally. Corrective measures include gentle steering inputs that help guide the vehicle back into the center of the lane. The system can also provide visual and audible alerts to notify the driver of the lane departure and prompt corrective action.
Vehicle 5	Forward-facing camera and radar	While the dynamic radar cruise control with full-speed range is operating, this system will operate the steering wheel to maintain the vehicle’s lane position. The LTA system recognizes white (yellow) lane lines using the front camera. Additionally, it detects preceding vehicles using the front camera and radar.
Vehicle 6	Forward-facing camera	When the camera detects a drift out of the lane of travel, the lane keeping system alerts the driver by vibrating the steering wheel or aids the driver by providing a small steering input to move the vehicle back into the lane of travel.
Vehicle 7	Forward-facing camera mounted on the windshield	It operates based on a combination of camera and sensor technologies. The images are then processed by the system's software algorithms, which analyze the lane markings and vehicle's position relative to them. The Lane Keeping System continuously monitors the vehicle's position within the lane and detects any unintended drift or departure from the lane. If the system detects that the vehicle is veering off the intended path without the use of turn signals, it provides corrective action.

Vehicle 8	Forward-facing camera	If the system detects that the vehicle is drifting out of the lane without using the turn signal, it provides visual and audible warnings to alert the driver. In some cases, if the driver does not respond to the warnings and continues to drift out of the lane, Lane Keep Assist can automatically apply gentle steering input to guide the vehicle back into the center of the lane providing steering correction.

4.1.2 Dashboard Indication

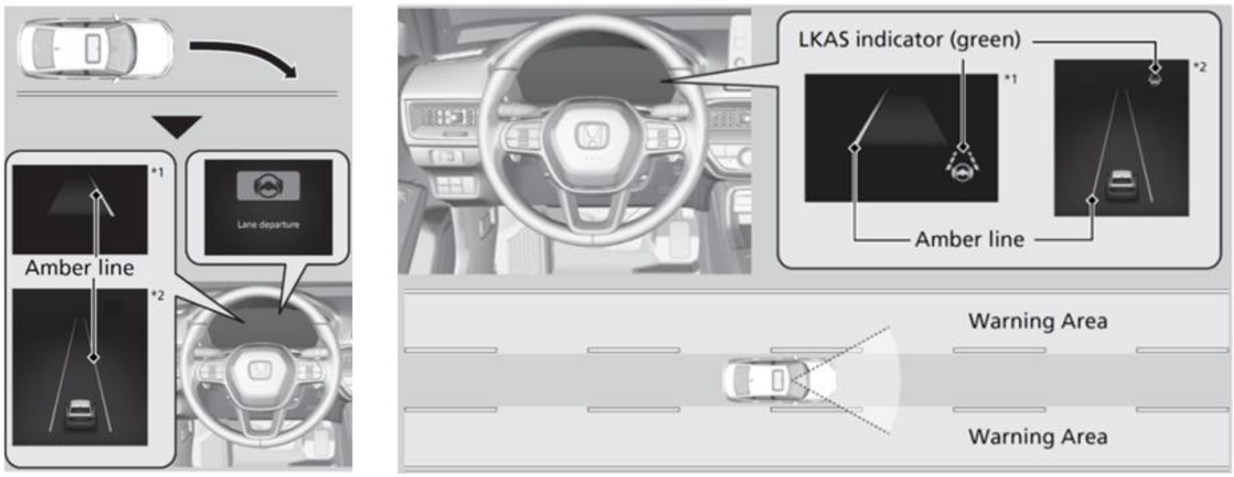
The ADAS feature that detects pavement lane line marking displays basic safety messages on the instrument cluster in front of the driver. The basic safety messages are often displayed as visual cues to provide feedback to the driver about the detected lane markings and the vehicle's position within the lane. A qualitative layout of the lane marking detection-related visual cue used in vehicles is presented in Figure 4-3 (Jeep Grand Cherokee, 2022).



(a) (b)

Figure 4-3: A Qualitative Layout of Lane Marking Detection-Related Visual Cue; (a) Only Left Lane Detected, (b) Both Lanes Detected (Jeep Grand Cherokee, 2022).

A color scheme is typically used in vehicles to present visual cues regarding lane marking detection. Lines filled with green color typically indicate that the lane lines are detected. They serve as a visual confirmation that the system detects the lane markings and considers the vehicle to be within the desired lane boundaries. When one or both lane lines are not detected, the system provides a visual warning and/or haptic feedback to warn the driver about the vehicle’s current position. In some vehicles, colored lines other than green are used to indicate different situations or warnings. For example, yellow or orange lines indicate a warning that the vehicle is approaching or crossing the lane markings without signaling. These colored lines act as a visual alert to prompt the driver to take corrective action. For example, when Vehicle 1 enters the warning area, the LKAS alerts the driver with slight steering wheel vibration as well as an amber line on the dashboard. In addition to the amber line, Vehicle 1 also displays a lane departure warning icon on the instrument cluster to warn the driver. Figure 4-4 is an example of what the layout of a lane departure warning indicator might look like (Honda, 2022).



(a) (b)

Figure 4-4: Layout of Lane Departure Warning Indicators; (a) Amber Line as Lane Departure Indicator, (b) Additional Lane Departure Indication (Honda, 2022).

A brief description of dashboard indications used to inform and warn drivers regarding lane marking detection used in the selected vehicles is provided below:

Vehicle 1: Vehicle 1 displays filled white lines on the dashboard as soon as the system recognizes the road markings. The LKAS indicator changes from white lines to green lines once the system starts operating after detecting the left and right lane markings. When lane markings are not defined, there are no lines on the dashboard. Lane departure (lane entry) indication is displayed with an amber line. Refer to Figure 4-5.

Figure 4-5: Lane Line Marking (a) Not Detected (with Exterior View), (b) Not Detected (Dashboard Only), (c) Detected (Dashboard Only) in Vehicle 1.

Vehicle 2: Vehicle 2 displays white lines on the dashboard as a layout for presenting lane marking detection and lane departure warning information. Once the lane line detection system is activated and the vehicle reaches activation speed, the lines on the dashboard turn green to present the lane line is detected. The lane departure warning is also indicated with an orange indicator. Refer to Figure 4-6.

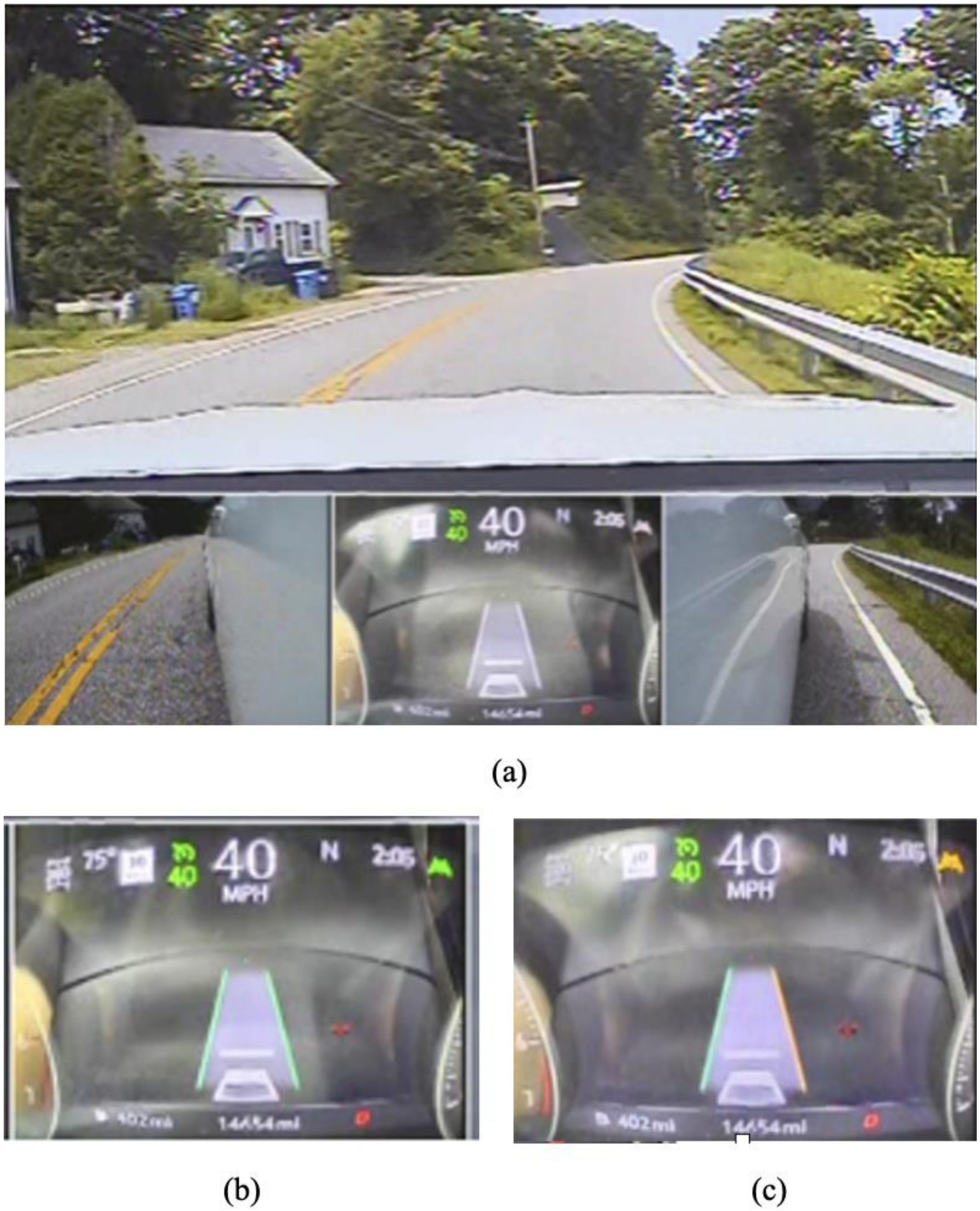


Figure 4-6: Lane Line Marking (a) Not Detected (with Exterior View), (b) Detected (Dashboard Only), (c) Lane Departure Warning (Dashboard Only) for Vehicle 2.

Vehicle 3: Vehicle 3 displays white lines on the dashboard as a layout for presenting lane marking detection. Once the line detection system engages and the car reaches activation speed to identify the markings, the lines on the dashboard change to green. Additionally, lane departure (lane entry) indication is displayed with a red line. Refer to Figure 4-7.

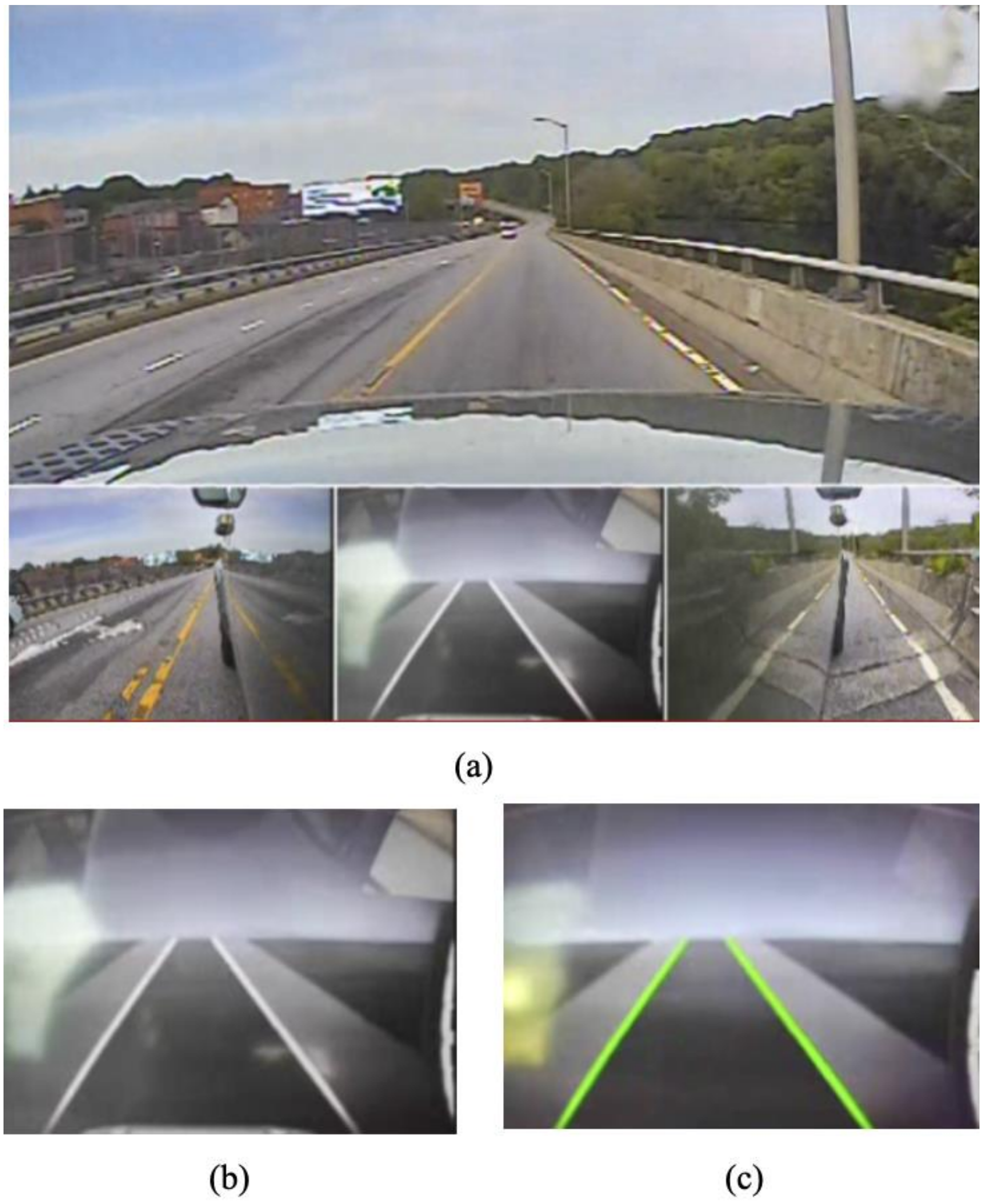


Figure 4-7: Pavement Marking (a) Not Detected (with Exterior View), (b) Not Detected (Dashboard Only), (c) Detected (Dashboard Only) for Vehicle 3.

Vehicle 4: Vehicle 4 displays white lines on the dashboard as a layout for presenting lane marking detection. As the line detection system activates and the vehicle accelerates to its activation speed, the lines on the dashboard change color to green. The indication of the lane departure system is implemented using animated lane movement on the monitor. Additionally, on the side where the marking is carried out, the line on the dashboard acquires a yellow color. Refer to Figure 4-8.

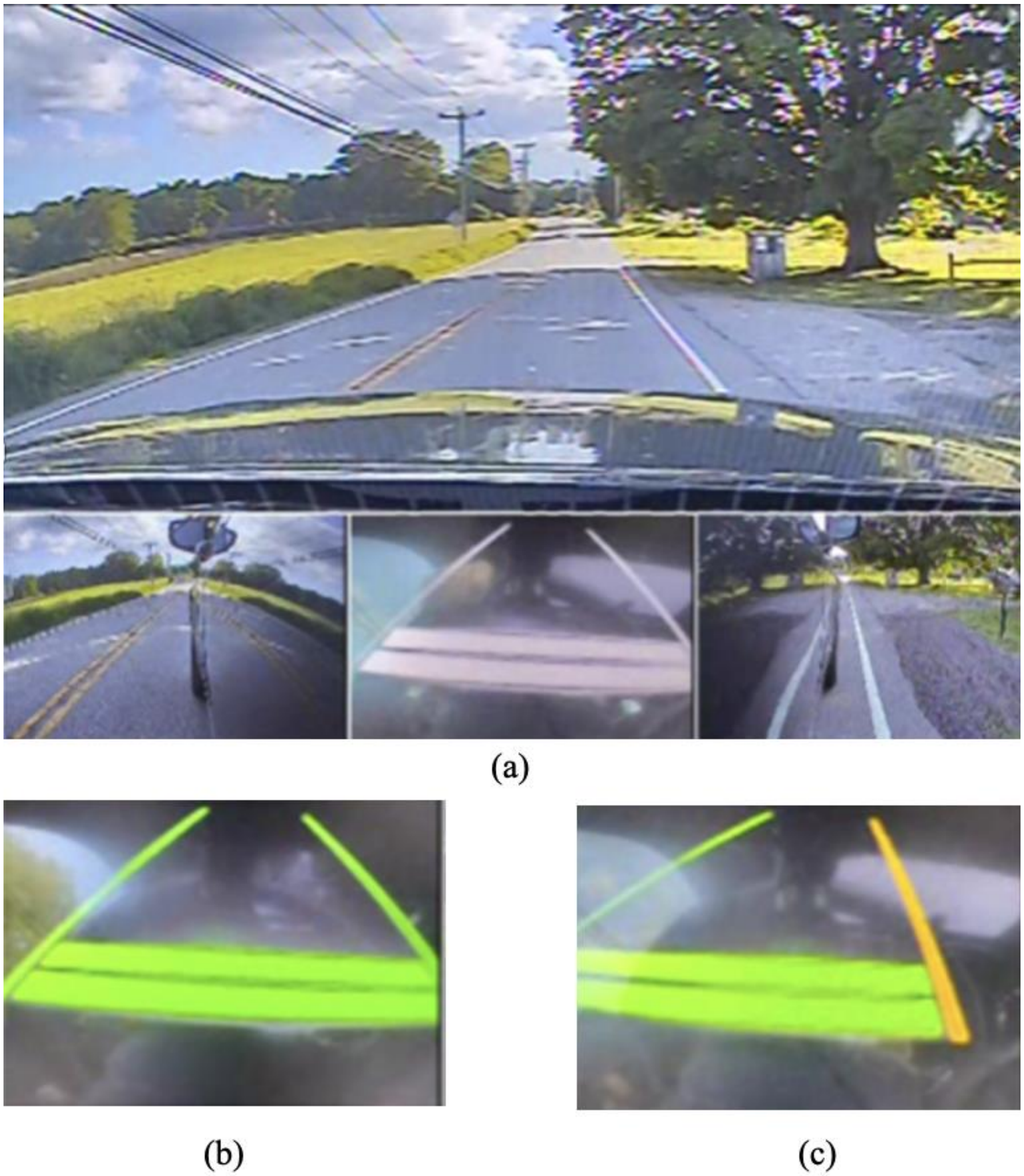
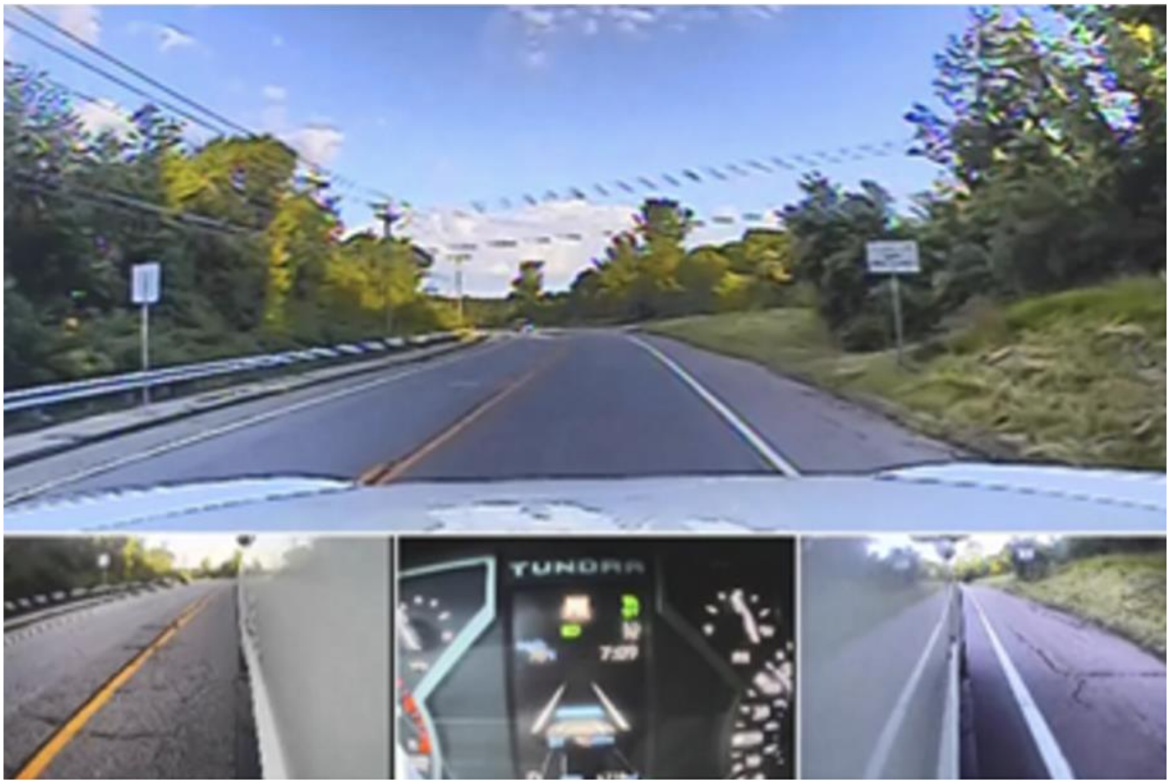
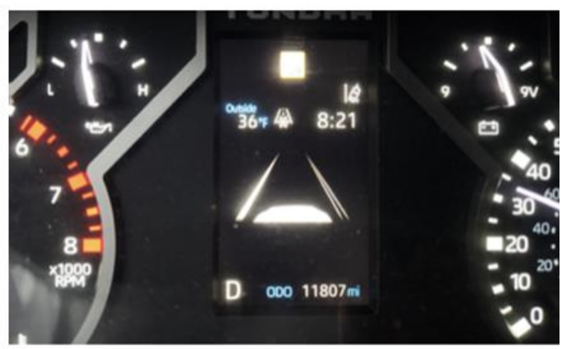


Figure 4-8: Pavement Marking (a) Not Detected (with Exterior View), (b) Detected (Dashboard Only), (c) Lane Departure Warning (Dashboard Only) for Vehicle 4.

Vehicle 5: The display of Vehicle 5 shows solid white lines when the road markings are defined. When the markup definition is lost, the line on the dashboard disappears. If the vehicle leaves the lane, the white lines on the dashboard flash with orange color), which lasts three seconds. Refer to Figure 4-9.



(a)



(b) (c)

Figure 4-9: Pavement Marking (a) Detected (with Exterior View), (b) Detected (Dashboard Only) (c) Not Detected (Dashboard Only) for Vehicle 5.

Vehicle 6: The system uses different colors for lane markings to indicate its status: gray (thin lines) shows a temporary inability to warn or intervene, white (thick lines) means the system is available or ready to intervene, yellow signifies lane-keeping aid intervention, and red indicates a lane-keeping alert warning. Refer to Figure 4-10.

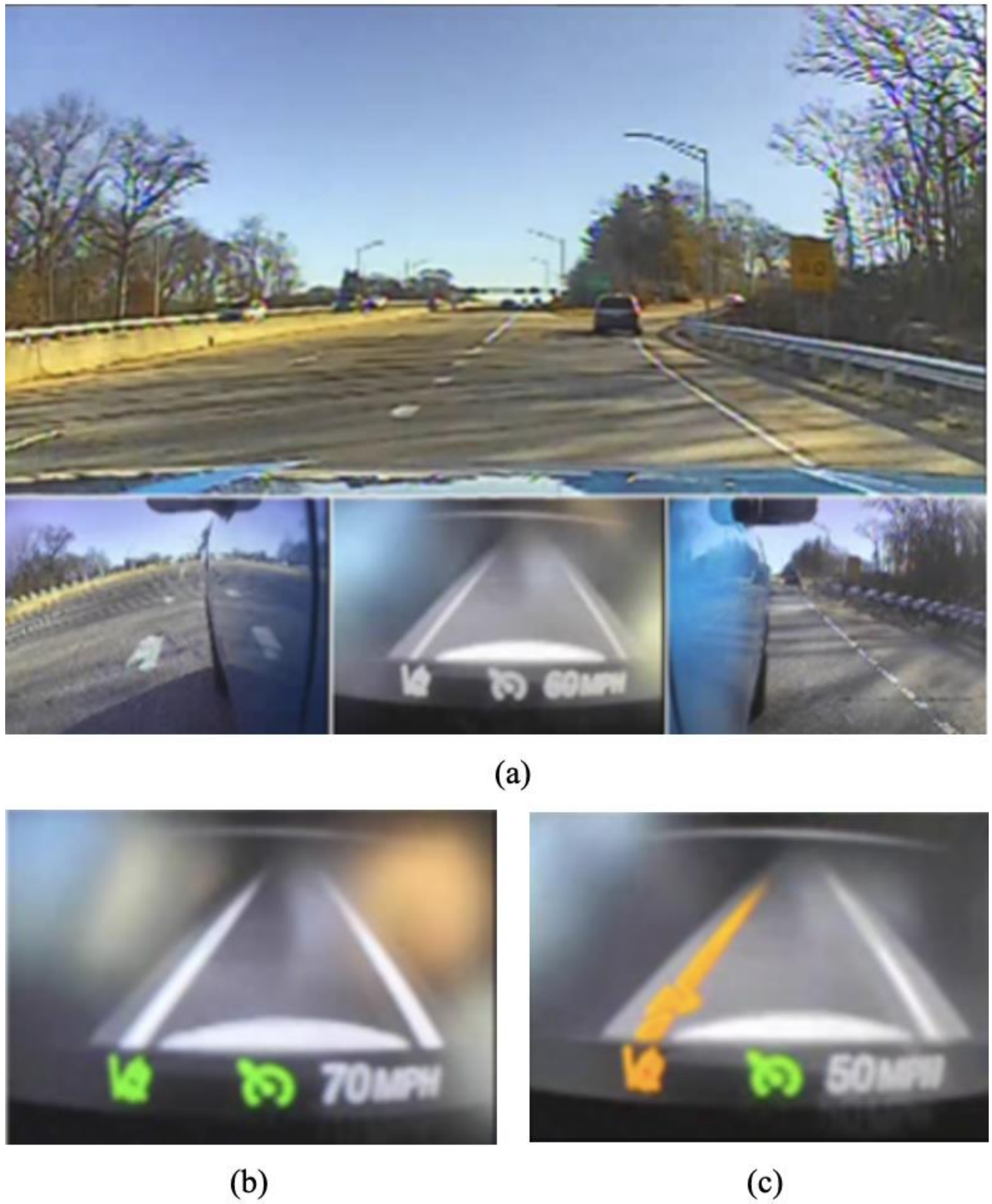
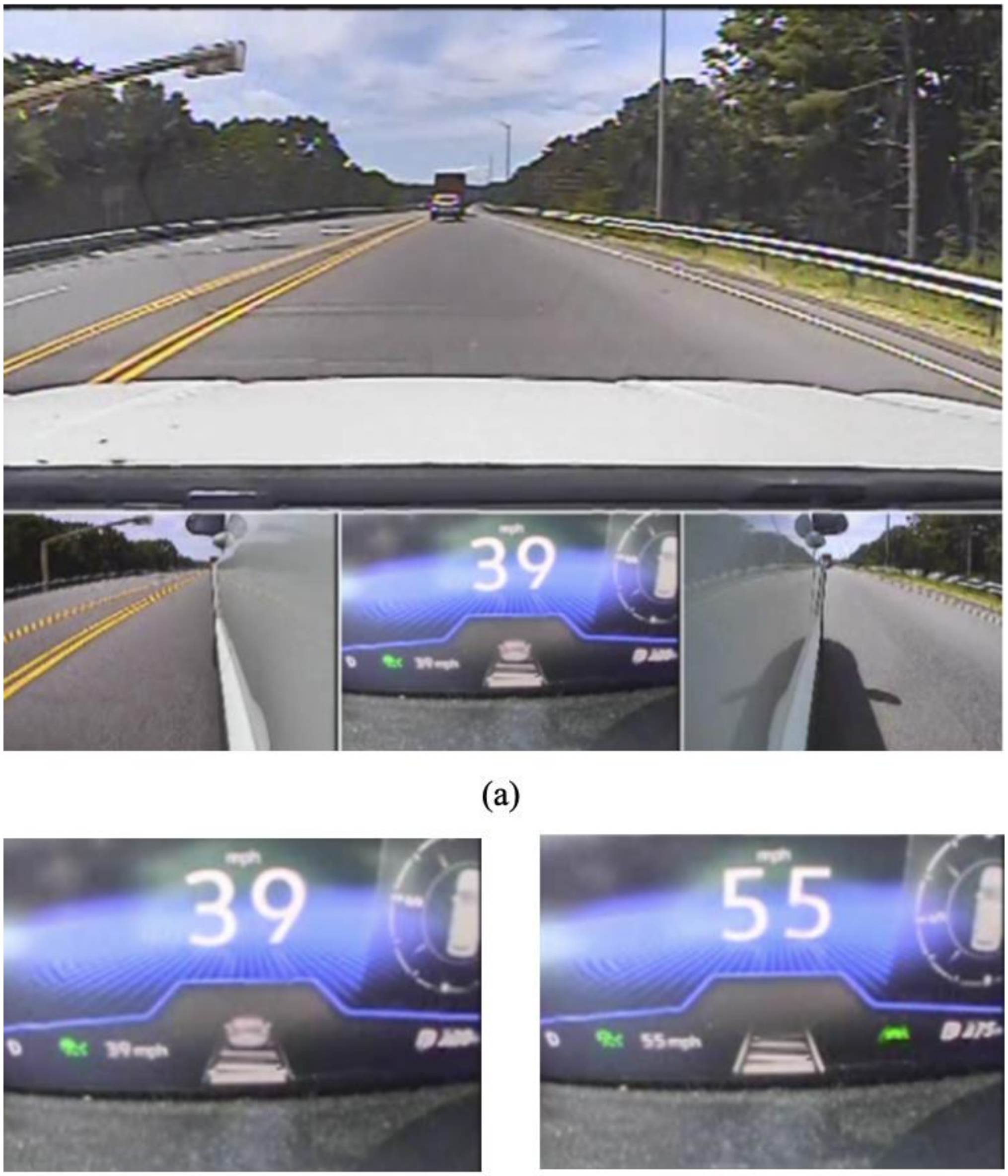


Figure 4-10: Pavement Marking (a) Not Detected (with Exterior View), (b) Detected (Dashboard Only), (c) Lane Departure Warning (Dashboard Only) for Vehicle 6.

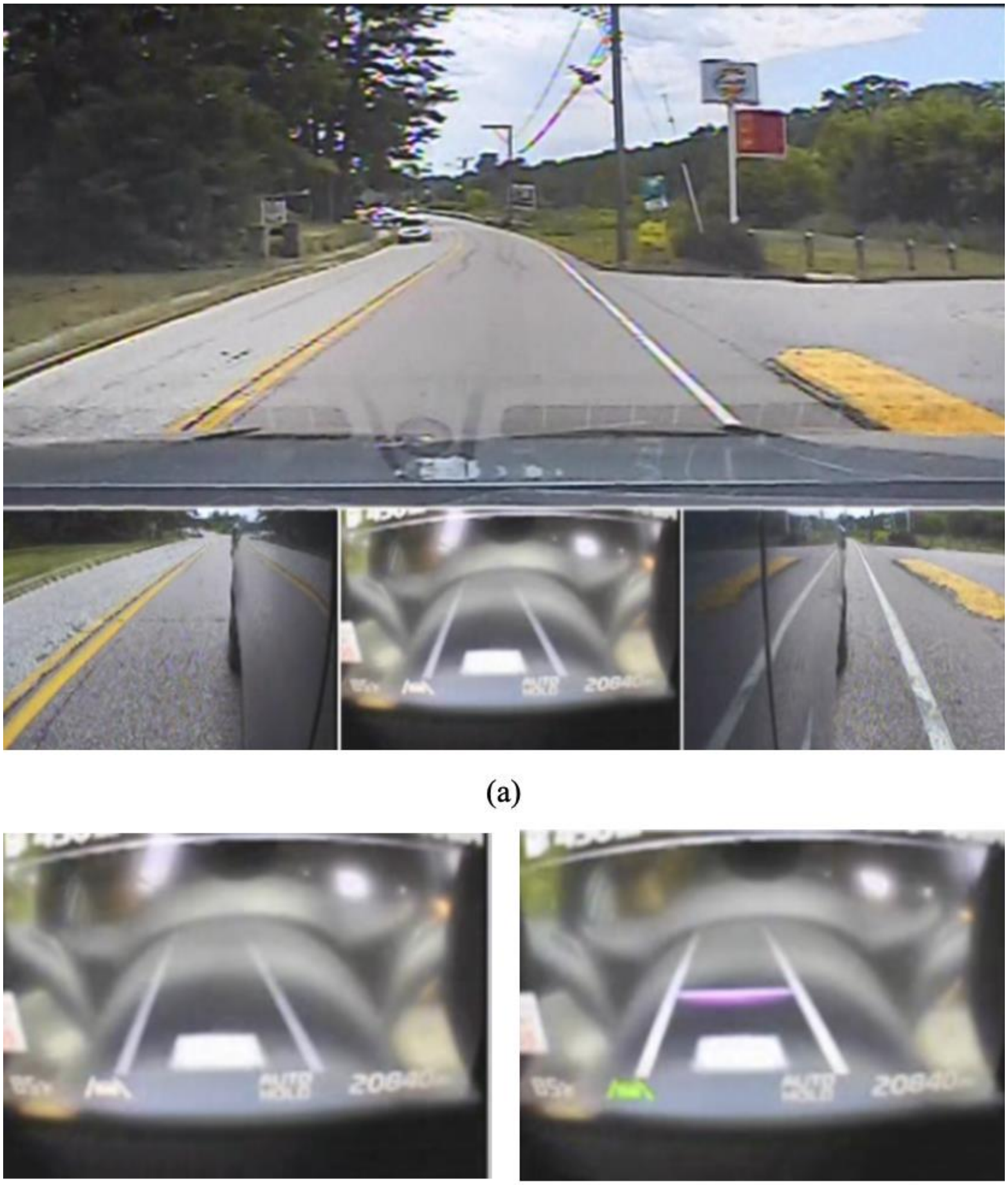
Vehicle 7: Car 6 shows thin gray lines before LKAS is activated and before any markings are detected. The indicator will turn white as soon as the system starts working after detecting the left and right lane markings. Lane departure (or lane entry) is indicated by a separate yellow indicator (depicting a car entering a road). Refer to Figure 4-11.



(a) (b) (c)

Figure 4-11: Pavement Marking (a) Not Detected (with Exterior View), (b) Not Detected (Dashboard Only), (c) Detected (Dashboard Only) for Vehicle 7.

Vehicle 8: Detecting no road markings, the system displays faint, thin white lines on the screen. However, the user manual describes them as gray, while they appear white in the video. Once road markings are detected, the system slightly lengthens and thickens the lines. Lane departure (lane entry) indication is displayed with an orange line. Refer to Figure 4-12.



(a) (b) (c)

Figure 4-12: Pavement Marking (a) Not Detected (with Exterior View), (b) Not Detected (Dashboard Only), (c) Detected (Dashboard Only) for Vehicle 8.

As the vehicles selected for data collection come from different manufacturers, the driver instrument cluster as well as the design, layout, and types of basic safety messages provided across selected vehicles are significantly different. The specific colors, line styles, and thicknesses used in presenting basic safety messages regarding lane line marking detection also vary between different vehicle models and manufacturers. A comparison of the visual warnings used in the vehicles selected for data collection is presented in Table 4-3.

Table 4-3: Types of Visual Cues for Lane Marking Detection used in Selected Vehicles.

Vehicle ID	Lane Line Detected	Lane Line Not Detected	Lane Departure Warning
Vehicle 1	Green lines	No lines	Amber line
Vehicle 2	Green lines	White lines	Orange line
Vehicle 3	Green lines	White lines	Red line
Vehicle 4	Green lines	White lines	Amber line + moving animation (lines move to the side)
Vehicle 5	Filled white	Hollow white lanes	Flashing animation
Vehicle 6	Gray thin lines	White thick lines	Orange or red lines
Vehicle 7	Gray lines	White lines	The activated system icon turns orange
Vehicle 8	Thin white lines	Thick white lines	Orange line

4.1.3 System Limitations

The longitudinal pavement marking detection systems in modern cars, while offering valuable assistance to drivers, do have certain limitations that should be considered. These limitations can impact the system's effectiveness in certain scenarios. Factors such as varying weather conditions, including heavy rain, fog, or snow, can affect the visibility of the road markings and pose challenges for accurate detection.

Additionally, the performance of the system may be influenced by the quality and condition of the pavement markings themselves, especially if they are faded, damaged, or poorly maintained. It's important to note that the system's reliability can also be influenced by the vehicle's speed, as higher speeds may require more precise and rapid detection and response. Furthermore, driving conditions such as sharp turns, complex intersections, or construction zones may pose challenges for the system to accurately interpret the intended path. Being aware of these limitations can help drivers use the line marking system as a valuable aid while also exercising caution and attentiveness in various driving situations.

The list of limitations in the operation of the longitudinal pavement marking detection system, as provided in the manual, may exhibit slight variations from one vehicle to another. However, it is important to note that most of these restrictions are applicable to all eight vehicles that have been used in the study. This ensures a consistent understanding of the limitations and challenges associated with the pavement lane line marking detection system across the vehicles under evaluation. By acknowledging these shared restrictions, it becomes easier to assess the overall capabilities and potential limitations of the line detection systems in the context of the study.

A common list of limitations of pavement marking detection system is provided below:

Contextual Factors

- Driving in bad weather (rain, fog, snow, etc.);
- Driving on a snowy or wet roadway;
- Driving into low sunlight (e.g., at dawn or dusk);
- Shadows of adjacent objects (trees, buildings, guard rails, vehicles, etc.) are parallel to white (or yellow) lines;
- Sudden changes between light and dark, such as the entrance or exit of a tunnel or the shadows of trees, buildings, etc.;
- Driving at night or in a dark place such as a tunnel (due to low-light conditions, lane lines or the road surface may not be illuminated);
- The distance between your vehicle and the vehicle ahead of you is too short, and lane lines and the road surface are not visible; and/or,
- Strong light is reflected onto the roadway.

Road Conditions

- There is little contrast between lane lines and the roadway surface;
- Driving on a road with temporary lane markings;
- Faint, multiple, or varied lane markings are visible on the roadway due to road repairs or old lane markings (Refer to Figure 4-13 and Figure 4-14);

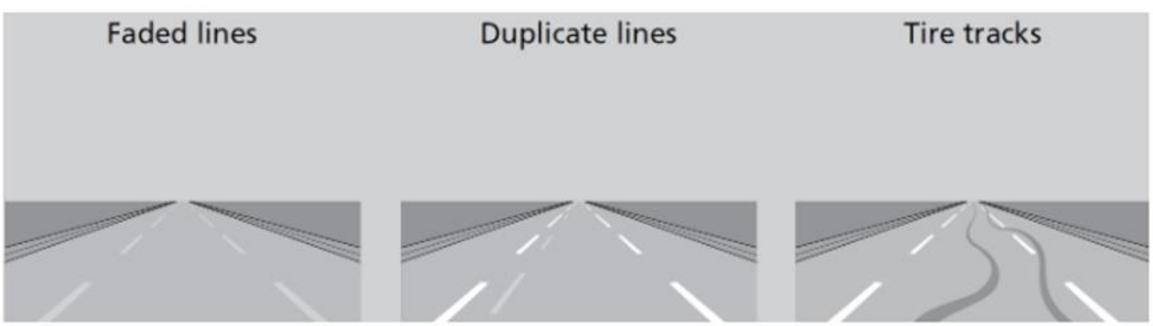


Figure 4-13: Confusing Pavement Marking on the Road (Honda, 2022).

Figure 4-14: Elements of Pavement Repair that are Perceived as Markings by ADAS.

- The roadway has merging, split, or crossing lines, such as at an intersection or crosswalk;
- The lane markings are extremely narrow, wide, or changing (Refer to Figure 4-15);

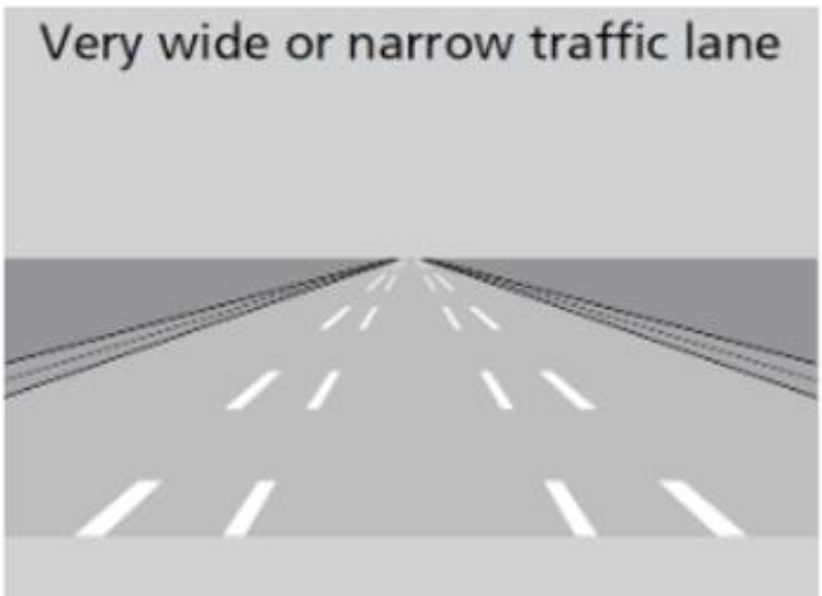


Figure 4-15: Detection Issue with Very Narrow or Wide Lane Markings (Honda, 2022).

- Part of the lane markings are hidden by an object, such as a vehicle;
- The road is hilly, or the vehicle is approaching the crest of a hill;
- Your vehicle is strongly shaken on uneven road surfaces;
- When objects on the road (curb, guard rail, pylons, etc.) are recognized as white (or yellow) lines;
- Driving on rough or unpaved roads, or over bumpy surfaces;
- Driving on roads with double lane lines;
- Passing through an exit or interchange (Refer to Figure 4-16);

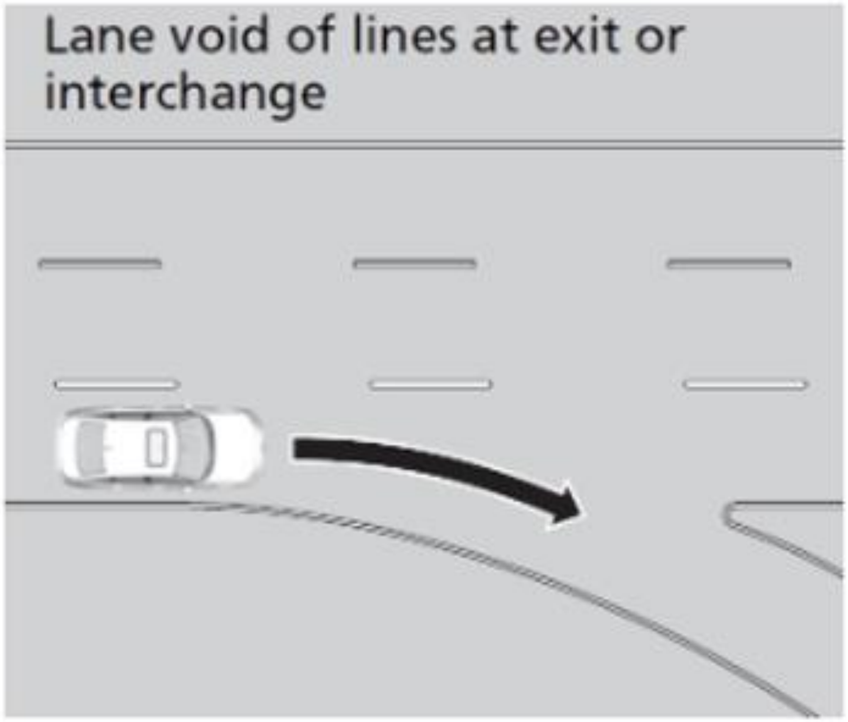


Figure 4-16: Pavement Marking Void at Exit or Interchanges (Honda, 2022).

- There is a boundary structure in the roadway, such as a tollgate, sidewalk, curb, etc.; and/or,
- The distance to the front vehicle is extremely short or the vehicle in front is covering the lane marking (or road edge).

Operating Limitations

- Reverse (**R**) or Park (**P**) is selected;
- The brake pedal is pressed;
- A turn signal is being used;
- The road lanes are not available or in poor condition;
- The road lane markings are not detected;
- The vehicle's speed is approximately below 40 mph (64 km/h) or above 112 mph (180 km/h);
- Driving in lanes narrower than approximately 10 ft (3 m) or wider than approximately 13 ft (4 m);
- Turning in tight road bends;
- Dynamic Stability Control (DSC) is active;
- An Anti-lock Braking System (ABS) event has occurred;
- A fault occurs in the system; and/or,
- The driver has applied excessive steering force.

4.1.4 Data Collection Setup

While the ADAS-equipped vehicles selected for data collection are equipped with SAE Level 1 or Level 2 ADAS features that can detect pavement markings, the CR team was restricted to tap into these ADAS equipment to collect data directly from the vehicles. Vehicles with SAE Level 1 or Level 2 ADAS features from different manufacturers use proprietary systems that convey basic safety messages to the driver. To overcome this limitation, the CR team equipped each vehicle with a VBOX system to collect data. The VBOX system has been proven to be a reliable and consistent source of information while collecting ground truth measurements for autonomous vehicles (VBOX Automotive, 2022).

VBOX system provides highly accurate positioning, navigation, and timing capabilities using a combination of multi-frequency Global Navigation Satellite System (GNSS), inertial data, and odometer input (utilizing wheel speed from the vehicle's controller network). The accuracy of VBOX solutions ensures positioning accuracy down to the centimeter level.

Key aspects of the VBOX system include:

- Position: The VBOX system uses multi-frequency GNSS technology with real-time kinematic correction to provide centimeter-accurate vehicle positioning.
- Navigation: Accurate speed and direction data are obtained, allowing a comprehensive view of the movement and direction of the vehicle during testing and verification.
- Timing: The system is equipped with GPS/UTC time and precise pulses per second functions. This ensures that all recorded data is synchronized, allowing for accurate analysis and correlation of events during testing.

By using VBOX systems, engineers evaluate the performance of the ADAS-equipped vehicles with a high degree of accuracy and reliability. The system's ability to provide precise ground measurements plays a vital role in evaluating and improving ADAS driving capabilities to effectively address real-world challenges.

The Racelogic Video VBOX Pro (20 Hz) RLVD20P was used by CR team to collect ground truth data. The Video VBOX Pro (20 Hz) RLVD20P is a product developed by Racelogic, a company specializing in data logging and video recording solutions for motorsports and automotive testing. The Video VBOX Pro RLVD20P is a versatile data logging system designed to capture high-quality video and data from various sensors to analyze and improve driver performance, vehicle dynamics, and vehicle testing. The Video VBOX Pro is an advanced system that combines a high-quality multi-camera video recorder with a powerful GPS data logger and real-time graphics engine. A four-camera setup is used to collect data from the surrounding of the vehicle in the VBOX setup as indicated in Figure 4-17 (VBOX Automotive, 2022).

Figure 4-17: Video VBOX Pro (20 Hz) RLVD20P (VBOX Automotive, 2022).

The Video VBOX Pro utilizes a 20 Hz GNSS engine, which provides precise information like circuit position, lap timing, speed (accurate to ±0.1 km/h), and acceleration. For enhanced data collection, there is an optional 32-channel CAN interface that can retrieve vital vehicle data such as throttle angle, RPM, and brake pressure. The recorded video files are saved in AVI format and synchronized with VBO data. All this data is stored on an SD card for easy access and management. The Video VBOX Pro introduces data logging capabilities, making it a highly versatile and valuable tool.

Key features of the Video VBOX Pro (20 Hz) RLVD20P include:

- Built in 20 Hz GNSS data logger;
- Up to four camera inputs with configurable picture in picture;
- Powerful yet intuitive graphics customization and analysis software;
- 8 CAN channels (upgrade for 32 channels available);
- USB / SD Card logging and USB 2.0 interface;
- Stereo Audio recording;
- Customizable real-time graphics, including gauges, bar graphs, circuit plots, lap times, and text;
- Preview over USB for camera and graphics set-up;
- Robust, light aluminum enclosure with internal battery keeps logging even when power lost for up to 10 seconds; and,
- Compatible with RACELOGIC input modules to log RPM and analogue inputs even in vehicles without Controller Area Network.

The four-camera setup in the VBOX was used to record video from the surrounding of a test vehicle while collecting ground-truth data. A camera setup layout used for data collection is presented in Figure 4-18. As the ground-truth on the machine vision pavement lane line markings detection by vehicles with SAE Level 1 and Level 2 ADAS features are only available from the vehicle dashboard instrument cluster, a camera was installed to record the basic safety messages (lane line markings detected, lane line markings not detected, lane departure warnings) presented while conducting the test runs on real-world roadways. To validate the information from the vehicle dashboard instrument cluster on the pavement lane line detection, two (2) cameras were installed on bothsides of the vehicle to record the presence of pavement lane line markings. The 4th camera was used to record the driver's point-of-view of the front of the vehicle.

Figure 4-18: VBOX Camera Setup Layout for Data Collection (MotorTrend, 2023).

4.1.5 Data Structure

Each run of data collection conducted by the CR team resulted in a list of files that were later used in data processing and analysis steps.

The list of files generated from VBOX setup are as follows:

1. A file with ".VBO" extension. This is a native file generated from VBOX data logger which

combined video streams captured using the four-camera setup as well as the main vehicle dynamics data for each run. The following variables are usually collected in the VBOX data logger:

  - Time: This is UTC time since midnight in the form HH:MM:SS.SS.
  - Latitude: Latitude in minutes MMMMM.MMMMM +ve = North, e.g., 03119.09973M = 51D, 59M, 5.9838S.
  - Longitude: Longitude in minutes MMMMM.MMM +ve = West, e.g., 00058.49277M = 00D, 58M, 29.562S.
  - Velocity: Velocity in km/h.
  - Heading: Heading in degrees with respect to North.
  - Height: Height above sea level in meters based on the WGS84 model of the earth used by VBOX GPS engines.
  - Vert-velocity: Vertical velocity in km/h. +ve velocity uphill, -ve velocity downhill.
  - Input Channels: Any channels from input modules are logged in an exponential form, e.g., +1.23456E+02 = 123.456.

2. An MP4 file recorded by a camera mounted inside the vehicle cabin. This video footage records driver actions while driving the target vehicle for data collection.
3. A comma delimited file exported from the .VBO file. This file contains the main data items collected by VBOX data logger as described above.

The files were organized in a folder system and labeled using the name of vehicle and the date of data collection. Within each folder, each ".VBO" file was labeled using the location information where the data was collected. All data collected by CR was then delivered to the UConn team for further data processing and analysis.

4.2 Data Processing Overview

As noted above, the CR team delivered all raw ground truth data to the UConn research team for further data processing and analysis. The data was organized and labeled in most cases. However, overall duration, temporal and spatial extents of the collected data were missing. To understand the magnitude of the data and appropriate handling during data processing, a ground truth data index document was created to systematically manage and track the progress of data processing.

The following key columns were included in the data index:

- vehicle name;
- data collection date;
- route;
- video duration;
- day or night test drive;

- time taken (in minutes) to process each files;
- additional service columns (agent name, processing date, current status); and,
- comments.

The date index was consistently updated by the UConn research assistants responsible for data processing throughout the video data processing. The assistants maintained the status of the files, promptly updating it once the video file was processed. Notes were attached to files that required comments in case there were challenges with processing or issues regarding file quality.

4.2.3. Data Processing Steps

The raw data included the recorded video footage from the four-camera setup used in the VBOX setup. The main data file from the VBOX output contained vehicle dynamics. However, the ground truth information on the lane marking detection during test drive was not included in the main data file. The ground truth on pavement marking detection by the onboard ADAS was however available in the recorded video from one of the four cameras that was mounted to record the instrument cluster in front of the driver. As a result, the UConn research team processed the collected video data to assign whether the pavement marking was detected or not by the onboard ADAS and linked the detection information to the geocoded VBOX data file using longitude, latitude, and data collection timestamp. The tools and processes used to process collected video data are provided in the following sections.

VBOX Circuit Tools

The data recorded by VBOX data logger can only be opened using VBOX Circuit Tools. The VBOX Circuit Tools is developed by Racelogic to assist in visualizing and comparing data collected using VBOX data logger from different test runs. A VBOX Circuit Tools user interface is provided in Figure 4-19.

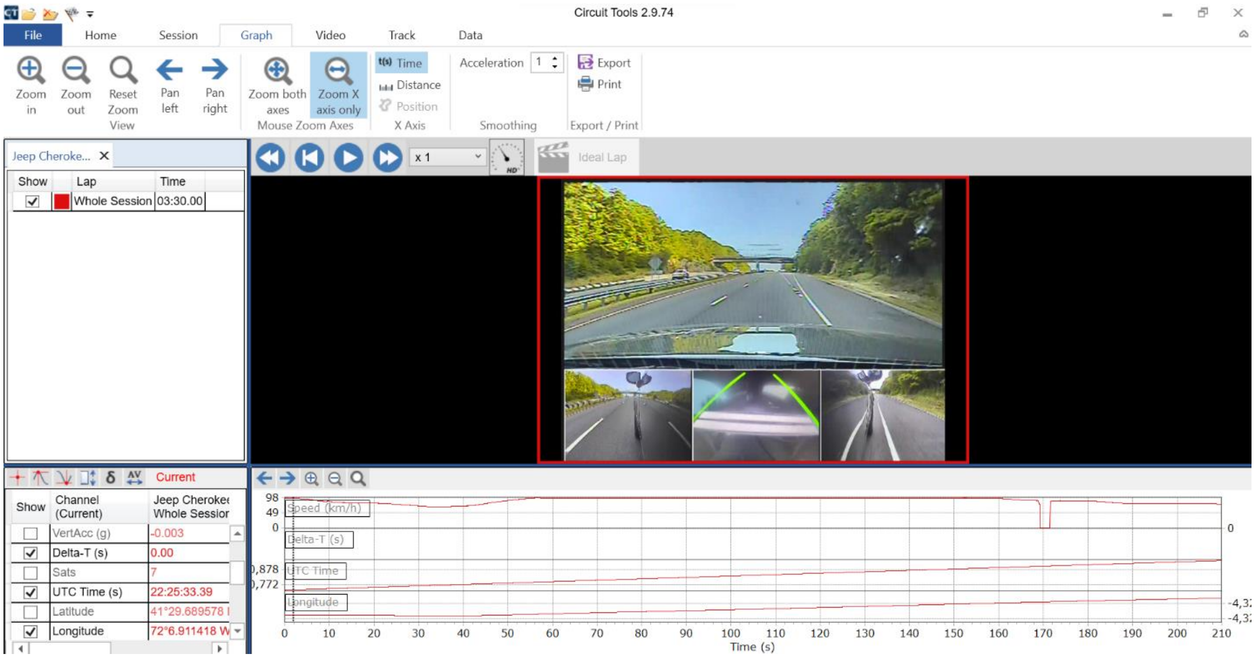
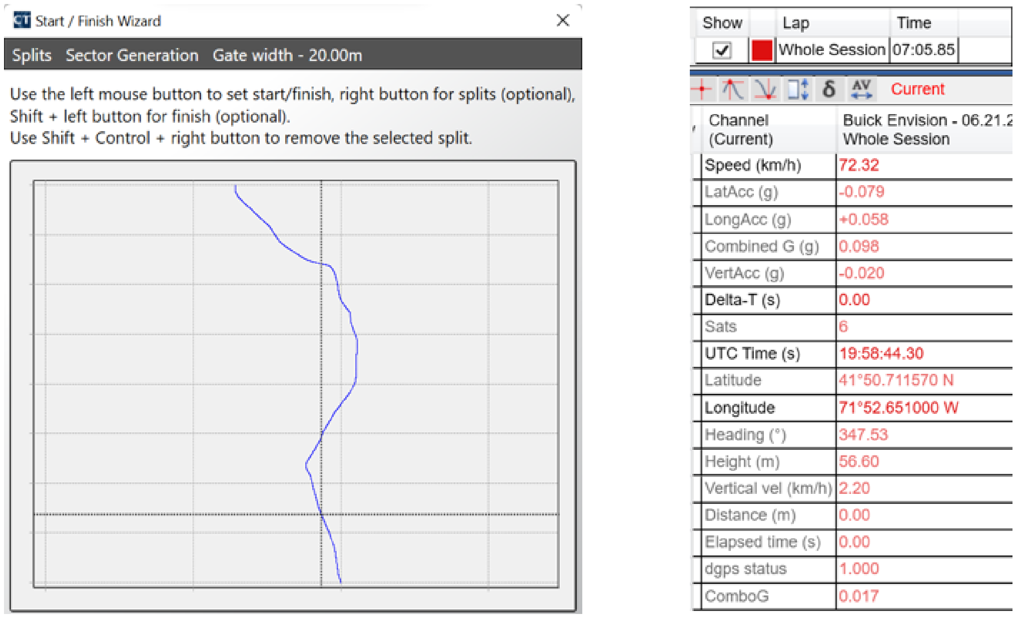


Figure 4-19: Circuit Tools Interface.

When a ".VBO" file is opened in Circuit Tools, a qualitative display of the lap is shown in a pop-up window which confirms the integrity of the video file and the presence of geolocation data. This assurance enables the processing of the video and its inclusion in the study. The bottom left corner of Circuit Tools provides the "Channel" widget that contains the key data items recorded using the VBOX data logger. Once the play button is pressed, the values of the key attributes including but not limited to UTC Time stamp, longitude, latitude, etc. are shown in this panel. A screen capture of the lap visualization and Channel widget is presented in Figure 4-20.



(a) (b)

Figure 4-20: Circuit Tools Interface; (a) Image for Visualizing Lap, (b) Information Contained in the VBO File.

The recorded video feeds from the four-camera setup are presented together in a grid layout in the VBOX Circuit Tools. On the top of the video screen, there is a control panel that can be used to control the video playback speed and provides the ability to rewind and forward the video as needed. A screen capture of video playback widget and the control panel to control playback speed is provided in Figure 4-21.

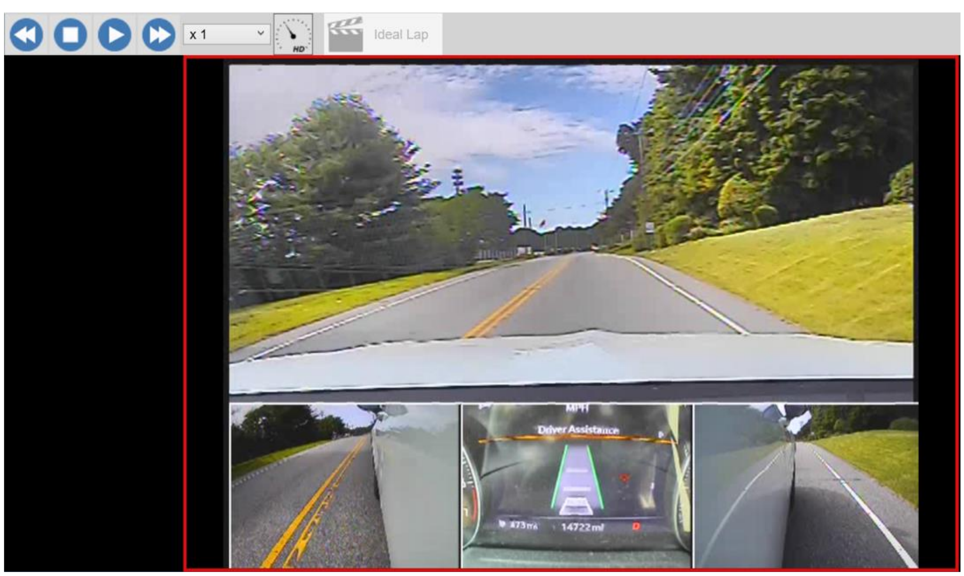
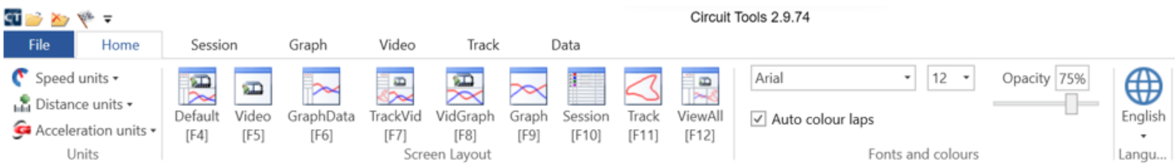
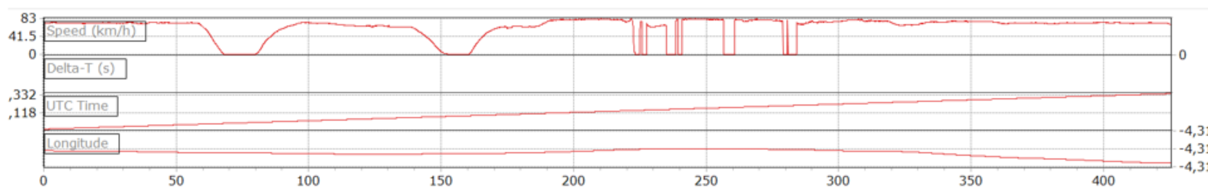


Figure 4-21: Video Playback Widget and Playback Speed Control Panel in the Circuit Tool.

Beneath the video playback widget, there is a data visualization widget. The variable to be used to visualize can be selected from the Channel widget. This visualization serves to expedite the video processing by allowing the omission of segments with zero speed. By selecting a specific portion on the graph, users can seamlessly transition to a frame-by-frame view (refer to Figure 4-22).



(a)



(b)

Figure 4-22: Circuit Tools Interface: (a) Session Homepage, (b) Speed Graph.

Data Processing Guide

The Circuit Tools software offers extensive capabilities for analyzing data obtained during vehicle trips. In this study, the speed of the vehicle and the timecode were the primary focus during the initial processing of the video data. The timecode played a vital role in synchronizing the video footage with the corresponding data in the CSV document. This synchronization ensures accurate alignment and facilitates seamless analysis of the video and associated data.

The UConn research team utilized students and staff researchers to process the raw ground truth data collected by the CR team. Each ".VBO" file contains recorded video footage and main data logged by VBOX on vehicle dynamics that were reviewed by human eyes and triggers/flags were manually added to the main data when the onboard ADAS failed to detect the pavement markings.

The following steps were performed to process the raw data collected from the CR team:

1. Download the latest version of VBOX Circuit Tools from Racelogic website (follow the installation instructions provided by Racelogic).
2. Import ".VBO" files into the Circuit Tools using the file import feature within the software.
3. Cancel the Start/Finish window that appears.
4. From the "Channels" section in the bottom left corner, select the following items:
    - Select: **Speed**, **UTC Time**, **Longitude** (See Figure 4-23 for reference).
    - All 3 channels should now appear in the graph window at the bottom.

Current

Show	Channel (Current)	Toyota Tundra - 06.20.2022 Night Whole Session
☑	Speed (km/h)	32.96
☐	LatAcc (g)	-0.251
☐	LongAcc (g)	-0.116
☐	Combined G (g)	0.276
☐	VertAcc (g)	-0.033
☐	Delta-T (s)	0.00
☐	Sats	8
☑	UTC Time (s)	01:25:15.40
☐	Latitude	41°29.190350 N
☑	Longitude	72°3.960320 W
☐	Heading (°)	51.83
☐	Height (m)	-7.69
☐	Vertical vel (km/h)	-0.94
☐	Distance (m)	0.00
☐	Elapsed time (s)	0.00
☐	dgps status	1.000
☐	ComboG	0.241

Figure 4-23: Channel Parameters used for Data Processing in Circuit Tools.

5. Extend the video panel to enlarge the video.
    - Slide the vertical split window panel to the left so the video is larger.
    - Slide the horizontal split window panel down, so the video is larger but leaves room for the graph needed in the following steps.
6. Using the mouse scroll function, 'zoom' in on the graph for finer video scrubbing control.
7. Use the space bar to start/stop the video.
8. Investigate the video:
    - Focus on the video feed from the camera installed to record vehicle instrument cluster (See Figure 4-24 for reference).

Figure 4-24 Screen Capture of the In-Vehicle Instrument Cluster.

- Note when the lane lines are not detected by the ADAS system.
- When one or both lane lines are not detected, ***pause*** the video, and ***determine the following***:
  - *Are the line(s) actually present*? This can be seen on the video panels on both sides of the instrument cluster video panel.
  - Is the vehicle above minimum ADAS activation speed, ~**38 MPH (61.16 km per hour).**
- Identify the first frame in the video when the event occurred.
- In the graph or channel section, note the UTC time stamp.
- In the CSV file, search for the UTC time stamp.
- When found, place the appropriate tag in the 'BrakeTrigger_Name' and 'Comments' columns.

The terminology "BrakeTrigger" is used in the VBOX application suite to analyze brake stops during a test run. This data item can be filled using a physical trigger while conducting test run with VBOX setup. For the purpose of this study, it would have been ideal if the driver could continuously monitor the instrument cluster and use the handheld trigger to record when the vehicle failed to detect lane markings. However, this approach is highly unsafe as the driver needs to carefully observe the road for traffic and abide by all traffic rules. Thus, the "BrakeTrigger" was not filled out by the CR team while collecting data. The UConn researchers who processed the raw data added tags in the BrakeTrigger column by manually reviewing the videos. A series of tags were developed to identify events. Table 4-4 provides a comprehensive overview of the utilized tags along with their corresponding descriptions on the events when the onboard ADAS failed to detect pavement markings. More details can be found on the tags utilized in this study in Appendix.

Table 4-4: Description of Tags used in Data Processing.

Tag	Description
LM	The system fails to detect left lane marking
RM	The system fails to detect right lane marking
LRM	The system fails to detect both left and right lane marking
SL	System limitations that indicate detection system was disengaged due to roadway circumstances (e.g., lane change, stopped vehicle, etc.)
NM	No left, right or both lane markings present on the road
99	The fragment cannot be processed for various reasons (video quality, sun and headlight glare, frequent changes in the dashboard indications)

4.3 Raw Data Processing Observations

Before discussing the issues associated with the raw ground truth data, it is important to note that the information provided in this section is factual based on the ground truth data collected in this study. In terms of the ground data collection scope, ground truth data from target sites were collected as identified at the beginning of this project. As this project attempted to collect data on real-world roadways, the data collection was affected by several contextual and traffic related factors. However, the real-world ground truth data collection issues identified in this study presents a series of lesson learned regarding data collection steps, equipment used to collect data, as well as collected data management which can be used to design future studies.

After carefully reviewing all ground truth ADAS data files, the following inconsistencies in data organization were noticed:

- **Missing VBO Files**: The ".VBO" file was missing in some folders. This file contains the vehicle dynamics data along with the GPS locations which rendered the materials in these folders inaccessible for processing. For example, Vehicle #2 trips on September 8 and October 6, 2022, had to be excluded from the study due to missing .VBO files.
- **Inconsistent VBO File Naming Convention**: VBO files were not renamed consistently and according to the corresponding route. This lack of consistent naming hindered the seamless integration of the data. Exporting data from the VBO files to a comma delimited file was relatively straightforward, but without proper renaming, linking the .CSV files to their respective routes became problematic. Consequently, additional effort and time were required to compare geographic coordinates and determine the routes of the trips.
- **Camera Failure:** Due to camera hardware failures and supply chain issues relating to the replacement of a broken camera, the CR team had to utilize a three-camera setup instead of four in some test runs for ground truth data collection. There was a lack of video footage of the driver's point of view of the roadway in these cases (refer to Figure 4-25). This absence complicated the interpretation of the traffic situation and hindered the ability to

identify the presence of markings during the video data processing. The displayed screen content only included the image from the side cameras and the dashboard view, omitting the overall road layout (Figure 4-25).

- **Damaged Video Files**: When processing the received video, it was discovered that a significant number of files were corrupted. Some of them could not be opened. For instance, none of the Vehicle #3 night files from January 27, 2023, could be viewed or processed. In certain cases, critical information/video was missing, such as marking lines on the dashboard.

(a) (b)

Figure 4-25: Screen Capture of Video Data (a) With and (b) Without Roadway View.

In future studies, determining a way to reduce data processing issues would be beneficial. These identified issues significantly impeded the video processing and necessitated additional steps and considerations to overcome these challenges effectively. Additionally, for various reasons discussed below, not all the data collected was able to be included in the final analysis. The selection of vehicles for analysis was influenced by factors such as the number of incomplete or corrupt files, the clarity of the video and ability to accurately view the line marking detection system on the gage cluster, the completeness of the file set provided by Consumer Reports. As a result, only five out of the eight cars that were used for data collection were included in the study analysis.

The time needed for data processing in manual processing of video data using the human eye depends on the consistency of the video data. As noted earlier, eight vehicles were used for ADAS ground truth data collection. As noted in Section 4.1.2, while all selected study vehicles were equipped with onboard ADAS, the indications used to provide pavement marking detection information in different test vehicles were significantly different from one another. The analysis of the data index reveals that the processing time for a single video file ranged from 3 to 200 minutes. There is no apparent correlation between the duration of the video file and the time required for processing. For instance, the average processing time for a five-minute file across all vehicles was found to be 22 minutes. There are several factors that significantly affect the speed of viewing and processing video as discussed below:

1. Video playback stops with a frozen frame. Refer to Figure 4-26.

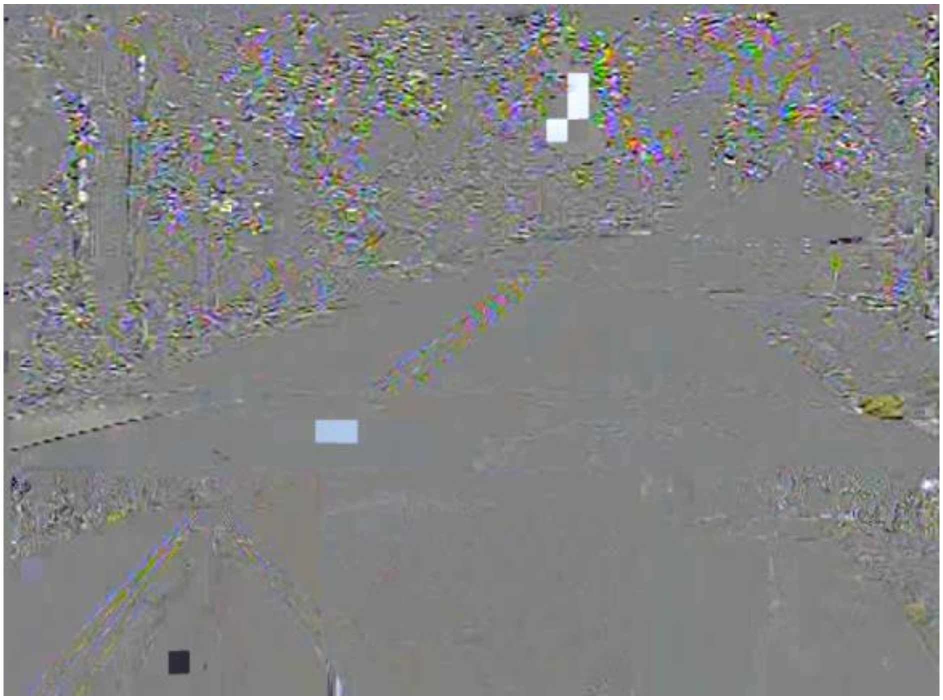


Figure 4-26: An Example of a Frozen Video in the Circuit Tools.

2. Video file size: Clips up to five minutes often play without freezing, while longer video files freeze more frequently.
3. The speed of processing video material depends on the completeness of the file set. Exporting .CSV files requires additional time. The absence of a front view of the vehicle necessitates more frequent rewinding of the video as the traffic situation is not transparent.
4. Viewing video material in a small window requires significant human resources as this task puts a strain on eyesight. Watching videos for more than six hours a day causes discomfort in the eyes.
5. The video image, captured on sunny days on roads with trees on both sides, is highly contrasted. Bright sunlight filtered through the foliage causes constant flashing in the video. Firstly, this significantly strains the viewer's eyes. Secondly, the high contrast "situation" complicates the system's ability to determine lane markings (Figure 4-27). This was especially noticeable when processing data from Vehicle #5. The higher the image contrast, the more interruptions occur in indicating lines, flags, and the processing time of the file.
6. There were a few VBOX files that lacked dashboard indications required to determine the

lane marking detection by on-board ADAS features (Figure 4-28).

7. The largest percentage of damage pertains to the loss of GPS connection during driving. At this point, the detection of vehicle speed and geographic coordinates is lost. Consequently, such fragments are unsuitable for analysis. The problem of GPS loss occurs, to varying degrees, in all files. However, in some cases, satellite communications were not established at all. This implies that the entire trip lacks geolocation (GPS data) and speed information (Figure 4-29, Table 4-5).

Figure 4-27: Screen Capture of ADAS Operating with Interruptions.

Figure 4-28: Lack of Necessary Information on the Dashboard.

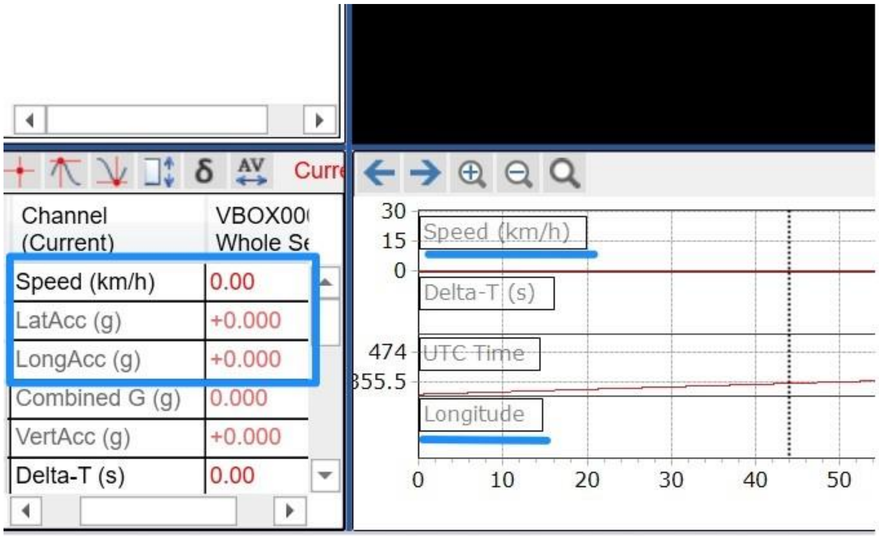


Figure 4-29: An Example of a VBO File Recorded without GPS Connection.

Table 4-5: An Example of a CSV File Recorded without GPS Connection.

VBOX0003					
[Information]					
[Unit]					
num	state	hh:mm:ss.ss	ddd°mmm.mmmmm'	ddd°mmm.mmmmm'	km/h
[Column name]					
Satellites	BrakeTrigger	Time	Latitude	Longitude	Velocity
0	0	15:23.5	0°0000.00000000 N	0°0000.00000000 E	0
0	0	15:23.6	0°0000.00000000 N	0°0000.00000000 E	0
0	0	15:23.7	0°0000.00000000 N	0°0000.00000000 E	0
0	0	15:23.7	0°0000.00000000 N	0°0000.00000000 E	0
0	0	15:23.8	0°0000.00000000 N	0°0000.00000000 E	0
0	0	15:23.8	0°0000.00000000 N	0°0000.00000000 E	0
0	0	15:23.9	0°0000.00000000 N	0°0000.00000000 E	0
0	0	15:23.9	0°0000.00000000 N	0°0000.00000000 E	0
0	0	15:24.0	0°0000.00000000 N	0°0000.00000000 E	0
0	0	15:24.0	0°0000.00000000 N	0°0000.00000000 E	0
0	0	15:24.0	0°0000.00000000 N	0°0000.00000000 E	0
0	0	15:24.1	0°0000.00000000 N	0°0000.00000000 E	0
0	0	15:24.1	0°0000.00000000 N	0°0000.00000000 E	0
0	0	15:24.2	0°0000.00000000 N	0°0000.00000000 E	0

A total of 11011 minutes of video footage was provided by CR to the UConn team for further processing and analysis, equivalent to over 183.52 hours. The size of the received files was 5.5 TB. Following the initial sorting and indexing of the files, valid records were identified and subsequently included in the study. Table 4-6 displays both the quantity of valid video minutes and the corresponding number of processed minutes encompassed within the study.

Table 4-6: Amount of Received and Processed Video Footage

Designation	Number of VBO Files	Number of Valid VBO Files	Amount of received video material (GB)	Total Duration of Valid Files (Minutes)	Total duration of Processed Files (Minutes)
Vehicle 1	234	234	944	1373.63	1373.63
Vehicle 2	144	141	711	823.95	823.95
Vehicle 3	89	59	487	365,92	365.92
Vehicle 4	85	85	271	533.53	533.53
Vehicle 5	243	243	1094	1494.27	1494.27
Vehicle 6	110	34	426	199.15	0
Vehicle 7	131	90	655	541.92	0
Vehicle 8	291	290	1107	1683.33	0

CHAPTER 5 DATA ANALYSIS

5.1 Processed Data Overview

CR conducted test runs using selected vehicles to collect ground-truth data on machine vision detection capabilities of pavement lane line markings in multiple phases from June 2022 to January 2023. The ground truth data from the ADAS-equipped vehicles was collected in phases to ensure sufficient data availability in different lane marking conditions: existing lane markings, during construction and post-construction of lane line markings. Data was also collected during day and night to compare and contrast between lane marking detection capabilities in different lighting conditions. Table 5-1 presents the total minutes of video recording for each vehicle by month. The color-coded cells indicate the intensity of duration and, consequently, the volume of data collected.

Table 5-1: Number of Minutes of Ground Truth Data for Each Vehicle by Month.

Vehicle ID	Day/Night	2022						2023
		June	July	Aug	Sep	Oct	Dec	Jan
Vehicle 1	Day	157.95	0	0	350.07	0	228.3	0
	Night	57.32	0	0	282	0	298	0
Vehicle 2	Day	76.3	0	142.67	0	1000.63*	123.85	0
	Night	56.9	0	134.13	0	146.3	0	0
Vehicle 3	Day	93.2	0	0	0	0	0	0
	Night	46.33	0	0	0	1715.33*	0	109.92
Vehicle 4	Day	135.33	0	0	0	0	0	0
	Night	138.25	0	0	0	279.95	0	0
Vehicle 5	Day	52.13	0	165.88	319.22	0	0	210.58
	Night	63.25	0	144.93	311.53	0	0	226.73
Vehicle 6	Day	0	0	0	159.08	0	0	1095.68*
	Night	0	0	0	0	0	0	224.2
Vehicle 7	Day	81.35	0	0	0	276.43	0	0
	Night	0	57.98	0	0	129.27	0	0
Vehicle 8	Day	0	246.5	141.22	150.4	138.42	0	217.93
	Night	0	156.72	131.85	148.65	121.3	0	235.3

Legend: 0 | 51-100 | 101-150 | 151-200 | 201-250 | 251-300 | >301

Note: Values with “*” exclude files that could not be processed in the Circuit Tools

As indicated in Table 5-1, the total amount of video footage (in minutes) is not the same for each vehicle. Additionally, the recorded video duration also does not match across day and night. The temporal distribution (amount of data collected by month) of data collected across different vehicles also varies significantly. Notably, values with an asterisk (*) denote the presence of data files with extremely long duration which cannot be processed in the Circuit Tools. Future studies should consider establishing parameters to limit video file duration appropriate for processing using data processing tools. These data limitations in temporal distribution indicated that ground truth data may not be available from all vehicles for the comparison between before, during, and after the permanent pavement marking were installed on the roadway. The temporal distribution also indicated that the comparison in pavement marking detection between day and night may not be possible for all sites. To identify sites with appropriate data for evaluation, all data was linked with study sites as discussed in the section below.

5.2 Data Preparation for Analysis

Once the raw data was manually processed by adding lane marking detection tags, the manually processed data was further processed to prepare the data for analysis. As indicated in the data processing steps, the activation of the pavement marking detection ADAS feature depends on the vehicle speed. Although all selected vehicles may have different threshold values for the activation of the onboard ADAS pavement marking detection feature, a common threshold value was selected that can be applied to all vehicles. Based on inputs from CR, a speed of 38 MPH was used as the pavement marking detection activation speed for all vehicles used to collect data in this study. A layout of the workflow to prepare the final dataset for analysis is provided in Figure 5-1.

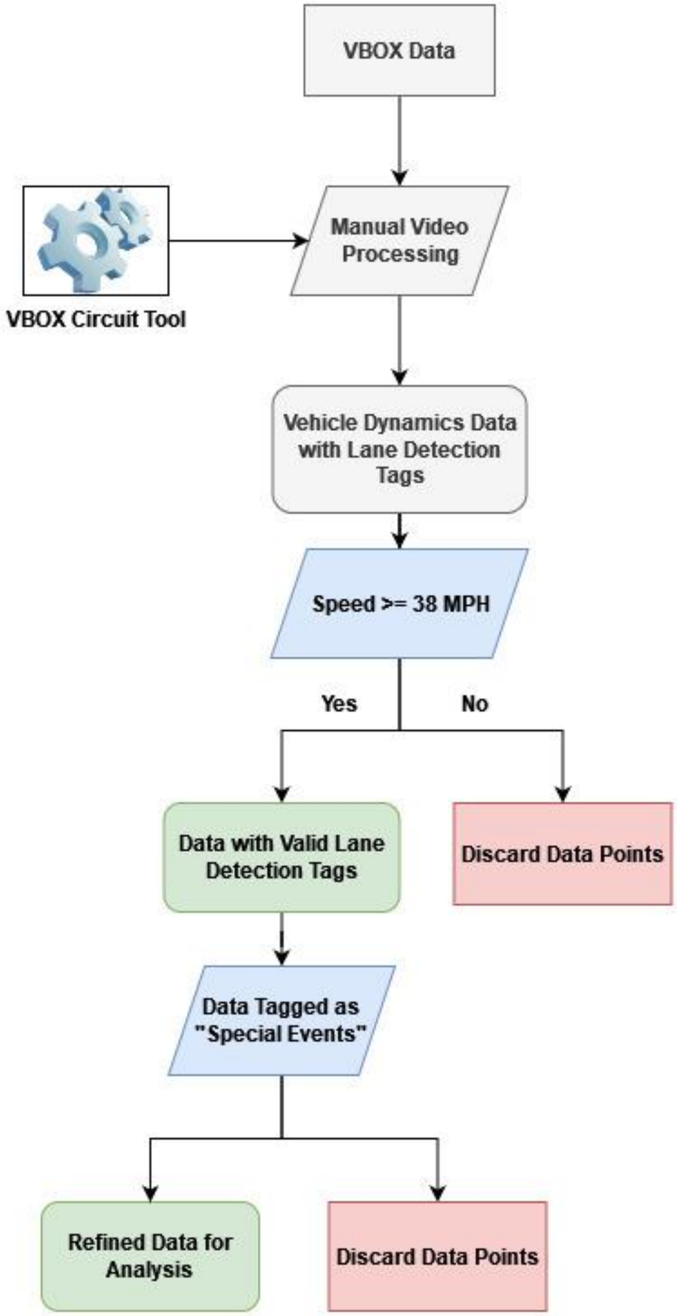


Figure 5-1: Workflow for Final Data Preparation for Analysis.

As indicated in Figure 5-1, data points with more than 38 MPH (61.16 KmPH) should have valid lane marking detection tags as all ADAS used for data collection should be activated at this speed. Any data points with vehicle speed below the threshold speed were discarded for final analysis. However, the ground truth ADAS data also included "Special Events" such as driving on locations without any physical pavement markings, lane change, pull over, etc. There were also a few instances when the person responsible for data processing could not definitively determine the lane marking detection status such as sun glare, headlight glare, low video quality, etc. Issues experienced while processing raw data were discussed in detail in Section 4.3. A refined database was prepared by discarding the data points with "Special Events" tag.

A brief description of "Special Events" that were discarded from the final analysis database are described below:

- Wide lane: A merging or diverging lane where the pavement markings exist but are significantly wider than average lane width.
- Lane Change: The ADAS feature is disengaged while changing lane with indication. As the UConn team does not have access to lane change indicator information, all visible lane changes were tagged while processing raw data.
- Passing an obstacle: Events where the vehicle had to drift away from the regular lane marking to pass an obstacle on the road.
- Data processing issues: Any event where a lane marking detection flag cannot be determined due to a data issue (please see Section 4.3 for more details).

After compiling data for analysis, a statistics summary was generated to investigate the percentage of data discarded. As indicated in Table 5-2, around 32% to 38% of the data was discarded based on the speed threshold and special events. While the test vehicles may have stopped or slowed down during data collection runs at intersections and due to traffic, a significant amount of data was tagged as GPS error due to losing GPS connection. As the GPS data was collected using the VBOX setup as mentioned in Section 4.3, the VBOX setup lost GPS connection which resulted in GPS error issue in the collected data. These statistics indicate that the data collection strategy should be designed with caution. A set of validated equipment should be used to collect data to minimize lost GPS connections. Moreover, sample data should be collected at each study site to verify the accuracy and availability of required data items before collecting bulk data. As the ADAS activation depends on a threshold vehicle speed (38 MPH), contextual factors such as availability of intersections within study site, traffic conditions (peak hour traffic), can also influence the speed of the test vehicle equipped for data collection. Caution should be used in identifying study sites and scheduling data collection time to minimize the effect of contextual factors.

Table 5-2: Percent of Data Discarded.

Vehicle ID	Percent of Observations Discarded
Vehicle 1	32%
Vehicle 2	38%
Vehicle 3	36%
Vehicle 4	35%
Vehicle 5	33%

5.3 Final Paint Schedule

A significant challenge for both roadway pavement markings and the ground truth data collection effort were determining the paint schedule, and which roads would have their lane markings updated. In 2021, the CTDOT awarded a lane marking contract for District 2 to a contractor that was not able to complete the required work. This delayed this project and added uncertainty to the data collection effort. The research team was not able to accurately determine when and where new paint would be placed, therefore ground truth data collection could not commence.

In 2022, a new paving contractor was under contract and communication improved. Additionally, paint became available again for lane marking updates. The planning process to outline data collection routes was an arduous task that was constantly changing based on a construction schedule that was dynamic and outside the control of anyone involved in this research effort. After months of meetings and a series of edits to possible data collection route the CTDOT and research team were able to define the study routes. However, the delay in identifying study routes with an evolving data collection timeline may not have aligned with dedicated CR staff used for data collection, creating staffing issues for CR.

The spatial locations of all sites selected for data collection and the travel route for CR data collection is presented in Figure 5-2 and Figure 5-3, respectively. The travel routes for CR data collection runs were developed to cover all selected sites as well as the roadways between these sites. The final pavement marking dates on the selected sites is presented in Table 5-3.

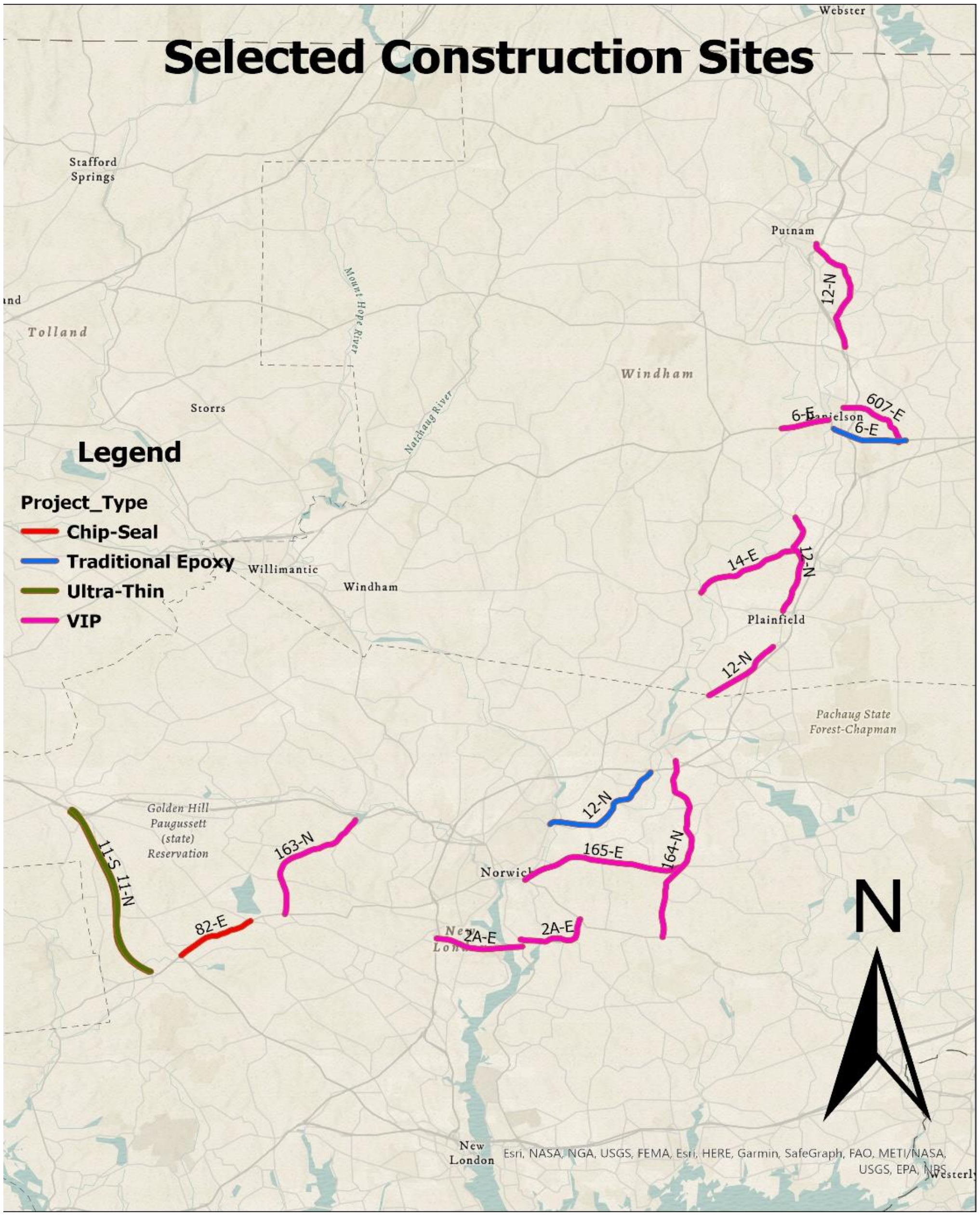


Figure 5-2: Selected Construction Sites for Ground Truth Data Collection.

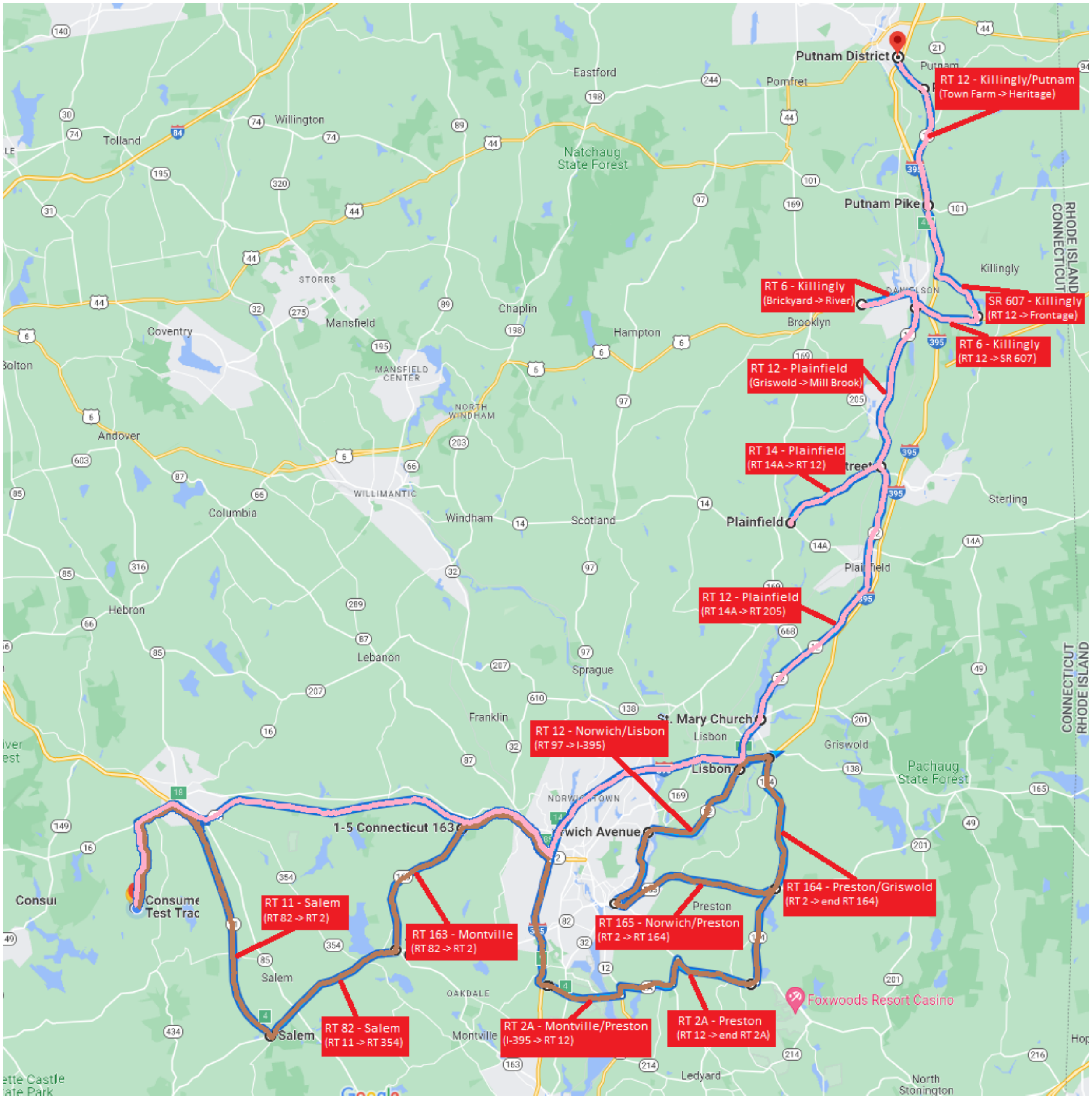


Figure 5-3: Final Data Collection Travel Routes.

Table 5-3: Final Paint Schedule for the Selected Sites at the Start of Data Collection.

Route Id	Town(s)	Project Type	BGN LOG MILES	END LOG MILES	LOG LENGTH	Termini	Date of Last Permanent Marking
6-E	Brooklyn/ Killingly	VIP	109.43	110.9	1.47	.06 Miles West of East jct. Brickyard Rd. to Start o/p Quinebaug River	11/20/2022
11-N	SALEM	Ultra-Thin	10.38	17.8	7.42	SR-82 to SR-2	11/7/2023
11-S	SALEM	Ultra-Thin	10.38	17.8	7.42	SR-82 to SR-2	11/7/2023
12-N	Plainfield	VIP	23.44	26.29	2.85	Griswold TL to OP Mill Brook	6/5/2023
12-N	Killingly/ Putnam	VIP	39.81	44.65	4.84	Town Farm Road #2 to Heritage Road	12/1/2022
12-N	Plainfield	VIP	27.91	32.13	4.22	N. Jct Rte 14A Academy Hill Road to Rte 205 n/b Wauregan Road	11/28/2022
14-E	Plainfield	VIP	13.46	16.99	3.53	W. JCT RT. 14A TO 12	5/31/2023
82-E	SALEM	Chip-Seal	17.6	20.2	2.6	.03 MI E/O END ROUNDABOUT (NEW LONDON RD) TO RTE 354 (EB) (OLD COLCHESTER RD)	8/18/2022
163-N	MONTVILLE/ BOZRAH	VIP	7.46	12.56	5.1	RT. 82 TO SR-2 BOZRAH ST. EXT.	6/8/2023
164-N	Preston/ Griswold	VIP	0	7.83	7.83	Rte 2 Norwich Westerly Road to end of Route 164	12/9/2022
165-E	Norwich/ Preston	VIP	0	5.16	5.16	Rt 2 to Rt 164	6/7/2023
2A-E	Montville/ Preston	VIP	4.37	7.05	2.68	BGN OP I-395 TO RTE 12 (INCLUDE RAMPS)	9/30/2022
2A-E	Preston	VIP	7.35	9.91	2.56	Route 12 Military Hwy to End of Route 2A	9/29/2022
607-E	Killingly	VIP	0	2.54	2.54	RT. 12 TO SOUTH FRONTAGE RD.	11/21/2022
6-E	KILLINGLY	Traditional Epoxy	111.32	113.62	2.3	RT. 12 TO SR. 607 (Brickyard Rd)	Done by Another Contractor
12-N	NORWICH/ LISBON	Traditional Epoxy	15.2	19.55	4.35	RT. 97 TO NB. ACCESS TO I395	Done by Another Contractor

There were 16 sites selected for ground truth and pavement marking data collection which were scheduled for painting in 2022. As noted in Table 5-3, the painting schedule for six out of 16 sites was postponed to 2023 after data collection had already started. Thus, a comparison of ADAS lane marking detection capabilities in before-after permanent markings was not possible for these six sites. Moreover, there are two sites where permanent markings were installed by another contractor with an unknown final paint date. Without knowing the final paint date, the raw data cannot be categorized in groups for comparison. Thus, ground truth data from these sites also cannot be used for before-after comparison. The ripple effect of the adjusted painting schedule on the research project is a key lesson learned from multiple partners on this project. To prevent a situation like this from occurring in future efforts, a limited number of sites should be selected for data collection with a concrete painting schedule.

5.4 Linking AV Data with Routes

The ground truth data collected and provided by the CR team did not contain route information. The VBOX data contains longitude and latitude information which were later used to join route information with each data point. The research team needed to add route and milepost information to each data point collected to allow for a join with the paint schedule, therefore the Connecticut State Route Milepost geodatabase was collected from CTDOT Open Data portal. This data contains geolocation of milepost information at every 0.01 mile. The “Spatial Join” tool in ArcGIS Pro was used to join the data collected by the CR team with route mileposts, therefore adding the milepost information to every GPS data point collected by CR. The distribution of spatially joined data is presented in Table 5-4.

The “SiteID” in Table 5-4 was generated for the selected sites presented in Table 5-3 using site route information, construction type, and permanent paint date. The first part of the SiteID contains site route name, followed by construction type (VIP, UT= Ultra-Thin, TE= Traditional Epoxy, CS= Chip-Seal). The last part of the SiteID contains the final paint date in month and day. Any final paint date scheduled in 2023 were designated as “NC” (Not Completed) and routes painted by another vendor with unknown paint date were designated using “UN” (Unknown). The “%-LM” presents the count of observations where left lane marking was not detected per thousand observations and “%-RM” represents the count of observations where right lane marking was not detected per thousand observations.

The key takeaways from Table 5-4 can be summarized as follows:

- The temporal distribution of the ADAS ground truth data collected across selected vehicles for the targeted construction sites was not consistent, indicating unavailability of comparison data for each selected vehicle as well as across vehicles in Before-During Construction-After time slices. This finding resembles the temporal distribution noted in Table 5-1.
- The total amount of data collected using each selected vehicle on target construction sites was not consistent. Some vehicles were used more in collecting data whereas some vehicles were used only a few times.
- Comparing the number of data points available in day and night groups for each SiteID, it can be noted that only a very few sites had consistent number of data points in both day and night groups for each site. The number of data points in day and night groups is

significantly different in most sites and across vehicles. This finding suggests that there may not be comparable samples available in both day and night groups to compare lane marking detection capability in before, during and after construction period.

- Out of 16 sites, there were only four sites where data was available across all five vehicles that was processed by the UConn team. This finding suggests that a comparison in pavement marking detection capabilities across vehicles from different manufacturers may only be possible in these four sites.
- An overall comparison between %-LM and %-RM indicates that there is a significant difference in lane marking detection across vehicles. For example, the calculated value of %-LM for “12-N_VIP_1128” are 6.21, 7.45, 53.84, 2.06, and 12 for Vehicle 1 to Vehicle 5, respectively.

The exploration of ground truth data after linking with routes milepost was helpful to identify the extent of data availability for further analysis. The unavailability of data in comparison time slices across selected vehicles indicates that future studies should be designed with reliable paint schedule of construction study sites. The ground data collection should also be carefully monitored to assure the availability of comparison data based on the study design.

Table 5-4: Summary of Processed Data by Routes.

SiteID	Day/ Night	Vehicle 1			Vehicle 2			Vehicle 3			Vehicle 4			Vehicle 5		
		Count	%-LM	%-RM	Count	%-LM	%-RM	Count	%-LM	%-RM	Count	%-LM	%-RM	Count	%-LM	%-RM
11N_UT NC	Day	14626	0.00	0.00	5940	0.00	3.54	3440	72.09	55.81				9124	0.00	0.00
	Night	14482	0.00	0.00	7536	3.85	3.85	6858	12.10	0.00				15380	3.77	5.53
11S_UT NC	Day	23490	0.00	0.43	7479	5.21	10.83	6771	0.00	0.00				14629	117.23	68.84
	Night	15322	0.00	0.00	7488	7.88	7.88							15359	3.52	14.06
12N_TE UN	Day	16395	4.57	0.00	4454	170.86	202.51	2175	140.69	105.75				22940	74.06	112.38
	Night	16145	1.98	0.00	11622	74.94	81.31							29631	108.50	65.54
12N_VIP 1128	Day	16574	6.21	1.33	15432	7.45	6.74	11330	53.84	46.69	10659	2.06	2.06	23832	12.00	11.58
	Night	24232	138.37	0.00	13636	3.96	3.96	5858	0.00	0.00	11236	9.70	9.88	28686	5.58	24.30
12N_VIP 1201	Day	29465	3.33	3.67	14813	88.37	89.25	13221	186.07	128.21	12358	1.13	2.18	23981	44.83	62.09
	Night	30837	9.08	25.91	20943	26.93	32.33	3423	68.07	42.65	13642	8.87	8.80	35883	33.14	30.93
12N_VIP NC	Day	15835	4.36	6.32	7570	17.17	17.70	7247	106.25	30.36				17156	53.45	38.12
	Night	16775	7.45	6.44	8395	44.31	34.19							16870	189.75	84.71
14E_VIP NC	Day	10137	0.00	0.00	8410	42.33	31.27							9786	40.16	15.43
	Night	9508	0.00	0.00	9106	53.04	53.04							9676	20.15	25.73
163N_VIP NC	Day	54875	1.11	10.26	5639	95.58	89.55	1569	91.14	263.22				20517	165.42	141.25
	Night	27485	0.15	0.15	12964	71.27	71.20	3579	65.94	143.62				24109	35.26	179.02
164N_VIP 1209	Day	44372	0.00	225.32	15958	6.96	7.08	6858	122.34	125.40	20964	10.21	8.92	66476	7.07	12.41
	Night	42333	0.00	209.77	28297	35.69	170.34	12647	81.92	74.64	19463	1.59	2.00	65418	7.32	23.14
165E_VIP NC	Day	18468	0.00	0.00	10224	4.69	4.69	5557	0.00	6.12				39877	37.21	27.21
	Night	17823	0.00	1.46	14603	4.31	4.31							27858	28.07	21.86
2AE_VIP 0929	Day	7966	0.00	0.00	6896	151.83	159.22	1382	142.55	137.48				10346	64.08	73.55
	Night	9163	0.98	0.00	7022	57.68	56.54	1946	133.09	133.09				18428	50.79	36.03
2AE_VIP 0930	Day	18712	5.34	3.63	3582	81.24	97.71	4629	122.27	147.33	3871	36.42	36.42	14433	94.02	108.50
	Night	8860	27.65	6.21	4389	55.37	53.09	8466	146.94	122.73	4132	5.32	5.32	15003	72.25	83.72
607E_VIP 1121	Day	11216	0.00	0.62	4275	131.70	131.70							12019	96.01	159.41
	Night	11299	2.92	0.00	5254	105.06	105.06	2359	51.29	51.29				10651	22.63	57.83
6E_TE UN	Day	5000	3.40	4.00	1856	118.53	36.10							4523	77.38	41.34
	Night	4750	29.89	2.32	1497	82.83	64.80	1187	133.11	4.21				4286	81.66	54.83
6E_VIP 1120	Day	4427	43.37	14.91	1434	125.52	192.47							3097	195.03	43.59
	Night	5636	43.29	1.24	2752	83.21	139.90	2059	184.07	129.19				5775	196.88	73.59
82E_CS 0818	Day	25232	0.00	0.00	8724	121.96	116.46	3990	259.40	106.27	7082	29.23	29.23	16468	118.11	238.34
	Night	17762	0.00	0.00	8906	53.45	56.37	7289	68.18	61.87	7178	43.47	43.47	25770	18.70	39.15
Grand Total		589202	8.79	35.39	287096	46.09	60.50	123840	92.22	74.40	110585	10.79	10.74	657987	48.51	54.45

5.5 Evaluation of Pavement Marking Detection

To evaluate the effect of pavement marking characteristics on ADAS detection capability across selected vehicles, it is important to compare ADAS detection using a before-after study design. To do this, the data was processed into three groups: Before, During, and After. The "Before" period represents the data collected before the final paint was installed on the selected sites. The "During" period presents the data collected just before the installation of final paint and the "After" period represents the data was collected after the final paint was installed. Processed ADAS pavement marking detection tags over the length of the selected site need to be compared across defined groups to identify the effect of pavement marking characteristics on the ADAS pavement marking detection capabilities.

As reported in Table 5-4, there are only four sites where data from all five vehicles that was processed by the UConn team was available. It is important for the comparison to be conducted across vehicles to understand whether the ADAS detection capabilities of vehicles from different manufacturers are same or not. Thus, the data for the above-mentioned four sites were further explored to identify data availability across groups and during day and night. Table 5-5 shows the data availability from all five vehicles in before, during and after periods as well as the data collected during day and night.

The key takeaways from Table 5-5 can be summarized as follows:

- Out of all five vehicles, Vehicle 1 has the lowest "None Detected" events. Please note, these "None Detected" events include both left lane and right lane markings. Vehicle 1 has zero "None Detected" events in three out of four sites in both before and after periods. Thus, comparison using Vehicle 1 may not provide any meaningful results as there were no events where the pavement markings were not detected by the onboard ADAS.
- To conduct before-after comparison across vehicles from different manufactures, data should be available for all five vehicles in both before and after period with the same day/night tags. None of the four sites has consistent data for the before-after comparison across vehicles. Data is missing from at least one vehicle in all four sites for both day and night conditions. Thus, a before-after comparison across selected vehicles is not possible with the collected data.
- To conduct a before-after comparison for a specific vehicle, data needs to be available in both before and after periods with the same day/night tag. In most cases, data is not complete across the defined periods with the same day/night tag. For example, for 12N_VIP_1201 site, data is available in the before period collected during daytime, but data is only available in the after period collected during nighttime.

Table 5-5: Processed Data Availability by Temporal Groups.

SiteID	Period	Day/ Night	Vehicle 1				Vehicle 2				Vehicle 3				Vehicle 4				Vehicle 5			
			Date	Count	%-LM	%-RM	Date	Count	%-LM	%-RM	Date	Count	%-LM	%-RM	Date	Count	%-LM	%-RM	Date	Count	%-LM	%-RM
12N_ VIP 1128	Before	Day					6/21/22	4940	10.12	9.92	6/7/22	5697	51.61	46.16	6/9/22	5743	3.83	3.83				
		Night	6/29/22	5482	0	0	6/23/22	5376	0	0					6/9/22	5556	3.78	4.14	6/20/22	5671	16.40	8.29
	During	Day	9/14/22	2974	4.37	0													9/24/22	2119	8.97	0
		Night	9/15/22	3607	0	0	10/20/22	3577	0	0									9/23/22	1841	0	0
	After	Day	12/19/22	5451	0	0	12/5/22	5297	12.27	10.38	1/24/23	3640	0	0					1/11/23	5623	0	27.39
		Night	12/8/22	5946	0	0													1/17/23	5312	0	5.84
12N_ VIP 1201	Before	Day	6/24/22	6410	14.20	2.96	6/21/22	6235	114.03	123.66	6/7/22	6719	215.36	134.39	6/9/22	6863	2.04	3.93				
		Night	6/29/22	6362	0	0	6/23/22	6897	81.77	88.59					6/9/22	6628	4.07	3.92	6/20/22	6772	90.52	61.72
	During	Day	9/14/22	3869	0	0													9/24/22	3992	0	0
		Night	9/15/22	4903	0	15.91	10/20/22	7065	0	9.34									9/23/22	6866	10.34	9.18
	After	Day	12/19/22	6860	0	0	12/5/22	3386	48.73	48.73									1/17/23	7403	68.62	110.23
		Night	12/8/22	6628	0	0					1/24/23	668	28.44	28.44					1/11/23	7511	36.35	31.29
164N_ VIP 1209	Before	Day	6/24/22	9999	0	0	6/21/22	1842	13.57	14.66					6/9/22	10416	6.72	6.43	6/17/22	8179	15.53	14.55
		Night													6/9/22	10135	0	0.79	6/20/22	5691	2.81	5.62
	During	Day	9/30/22	8324	0	0	8/25/22	7898	0	0									9/27/22	9723	15.02	25.71
		Night	9/29/22	7612	0	0	8/25/22	10765	0	0									9/27/22	6844	7.89	60.78
	After	Day	12/19/22	11360	0	0					1/18/23	6858	122.34	125.40					1/11/23	10726	13.52	54.82
		Night	12/30/22	10888	0	0					1/24/23	6460	75.08	70.43					1/17/23	11382	10.28	8.43
2AE_ VIP 0930	Before	Day	6/2/22	6274	0	3.51	6/21/22	2784	93.39	100	6/6/22	3414	146.46	172.52	6/8/22	3217	43.83	43.83	6/17/22	2667	61.49	86.24
			6/24/22	3512	0	0													8/16/22	3448	160.67	67.00
		Night									6/6/22	3599	135.87	134.76	6/8/22	3480	6.32	6.32	6/20/22	3281	84.43	68.27
																			8/16/22	3012	47.81	48.47
	During	Day	9/30/22	3182	0	3.46													9/27/22	3258	109.88	113.26
		Night	9/29/22	3593	0.83	7.51	8/25/22	3509	31.92	31.92									9/27/22	2781	0	69.76
	After	Day	12/19/22	3311	21.44	2.42					1/18/23	613	107.67	83.20					1/17/23	3104	39.63	134.99
		Night	12/30/22	3515	68.28	3.13					1/24/23	3299	210.97	138.22					1/11/23	3329	126.76	64.88

5.5.1 Before-After Comparison for Specific Vehicle

As noted in the previous section, a before-after comparison across all eight vehicles utilized for this research project is not possible due to incomplete ground truth data in the before-after period with the same day/night tag. However, Table 5-5 also indicated that a before-after comparison is possible for a specific vehicle. Please note, the "During" period is not considered for comparison as the temporary marking date for a site is not known to the UConn team. Thus, data collected in before (at least two months before the final paint date) and after (data collected after the final paint date) periods with the same day/night tag was used for this analysis.

After carefully reviewing the data availability presented in Table 5-5, a before-after comparison was conducted for 12N_VIP_1201. This is a 4.84-mile-long VIP site on Route 12 in Killingly and Putnam, Connecticut. The final paint date for this site was December 1, 2022. For this site, data is available from Vehicle 2 that was collected during daytime in both before and after periods, and from Vehicle 5 that was collected during nighttime. The pavement marking characteristics collected using retroreflectometer was filtered for the selected site in both before and after final paint date.

To conduct this evaluation, the following figures were generated:

- A comparison of centerline and edgeline retroreflectivity readings in before and after period for 12N_VIP_1201 site. This comparison can indicate the improvements in the retroreflectivity values after the installation of the final paint. The centerline and edgeline retroreflectivity comparisons are provided in Figure 5-4 and Figure 5-5, respectively. Please note that the points and lines in both of these figures are plotted using actual data points collected using a retroreflectometer and the lines are generated using Local Regression (LOESS) method (ggplot2: LOESS Smoothing, 2009).
- A comparison of centerline lane marking stripe width and detected colors in before and after period for 12N_VIP_1201 site. This comparison can indicate the improvement in stripe width and colors detected by the retroreflectometer. The stripe width and color comparison is provided in Figure 5-6. Please note that the distribution of edgeline stripe width is almost identical to centerline stripe width.
- A comparison of centerline and edgeline contrast recorded by retroreflectometer in before and after period for 12N_VIP_1201 site. This comparison can indicate the improvement in the centerline and edgeline contrast value after the installation of the final paint. The comparison of centerline and edgeline contrast is provided in Figure 5-7 and Figure 5-8, respectively. Please note that the points and lines in both of these figures are plotted using actual data points collected using a retroreflectometer and the lines are generated using Local Regression (LOESS) method (ggplot2: LOESS Smoothing, 2009).
- A comparison of ADAS lane marking detection event distribution over the length of 12N_VIP_1201 from Vehicle 2 (Daytime) and Vehicle 5 (Nighttime) in before and after

period. Vehicle speed was also used to explore the relationship between ADAS detection events and vehicle speed. The comparison of lane marking detection events in Vehicle 2 and Vehicle 5 are presented in Figure 5-9 and Figure 5-10, respectively.

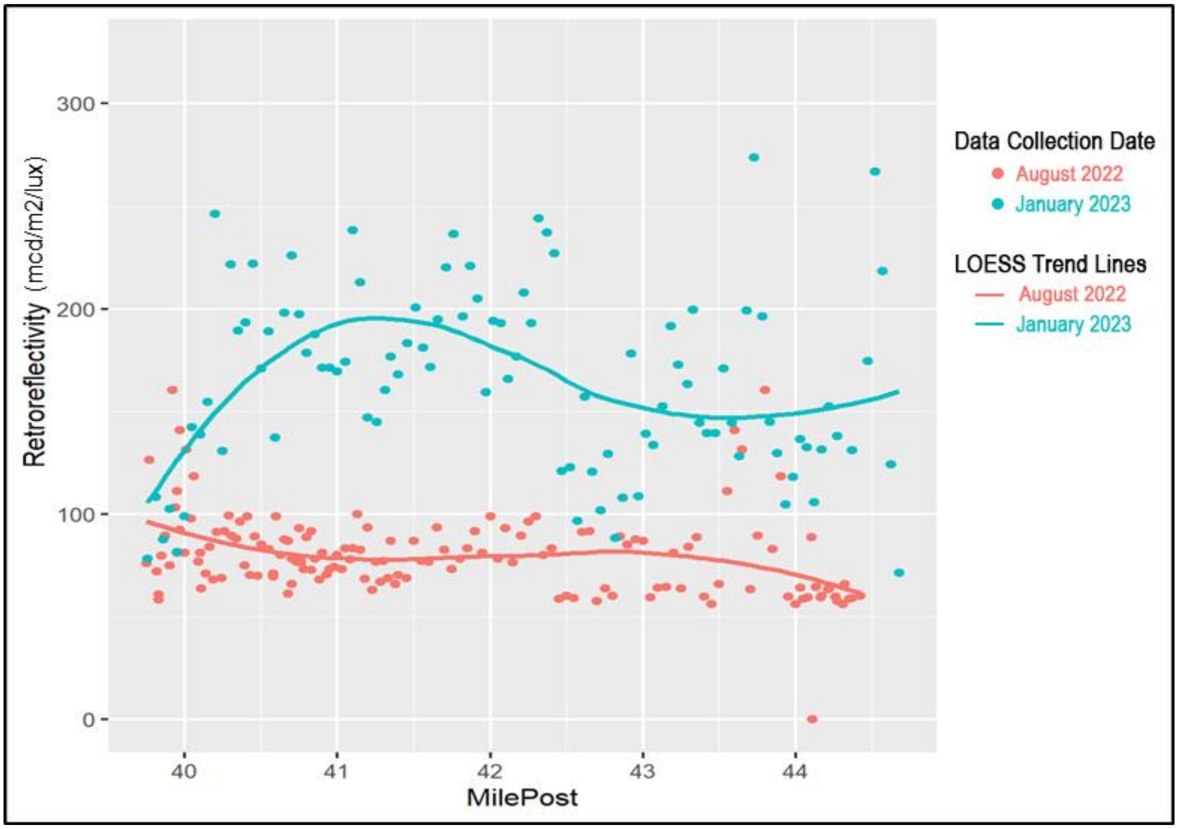


Figure 5-4: Centerline Retroreflectivity Distribution in Before and After Period on Route 12N_VIP_1201.

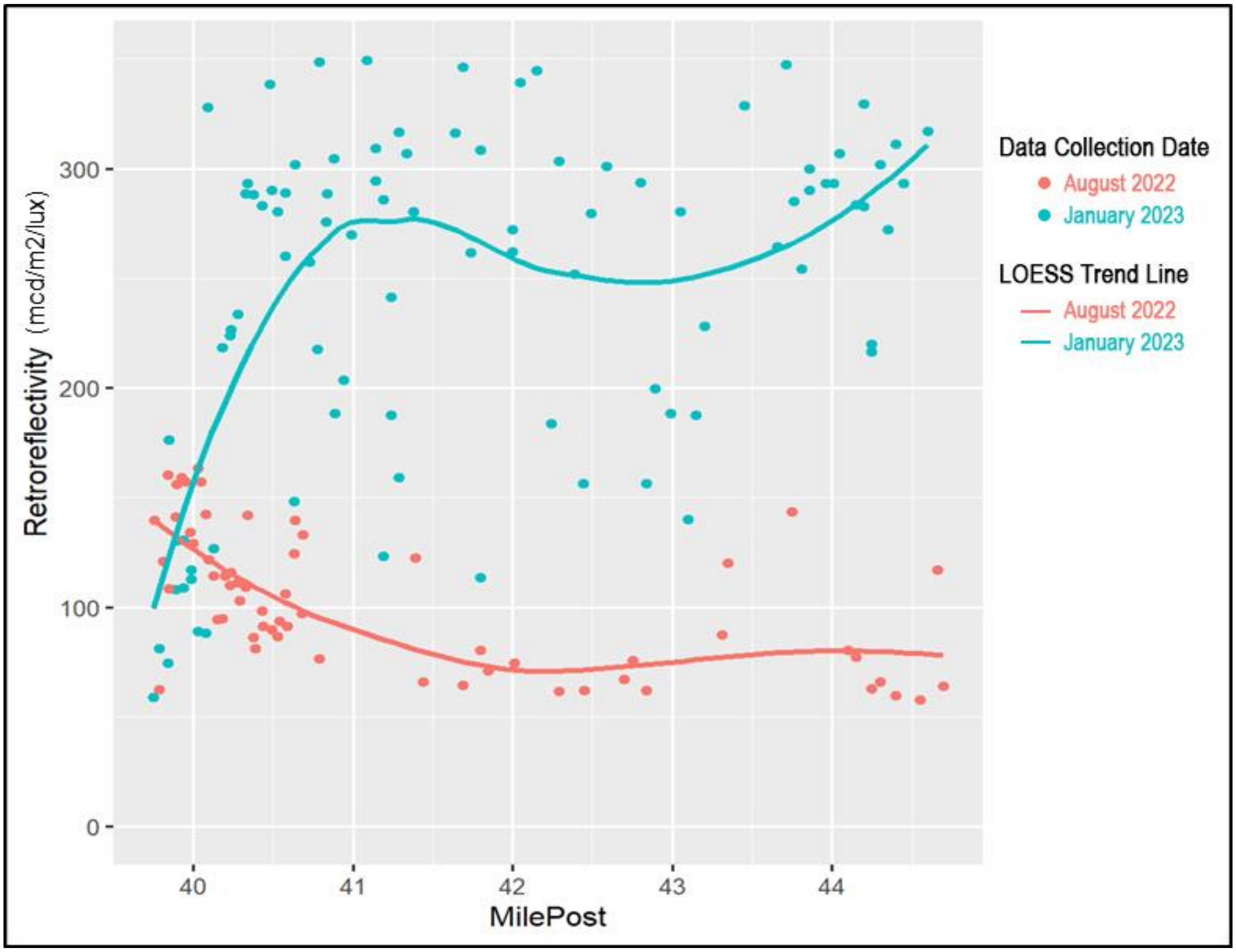


Figure 5-5: Edgeline Retroreflectivity Distribution in Before and After Period on Route 12N_VIP_1201.

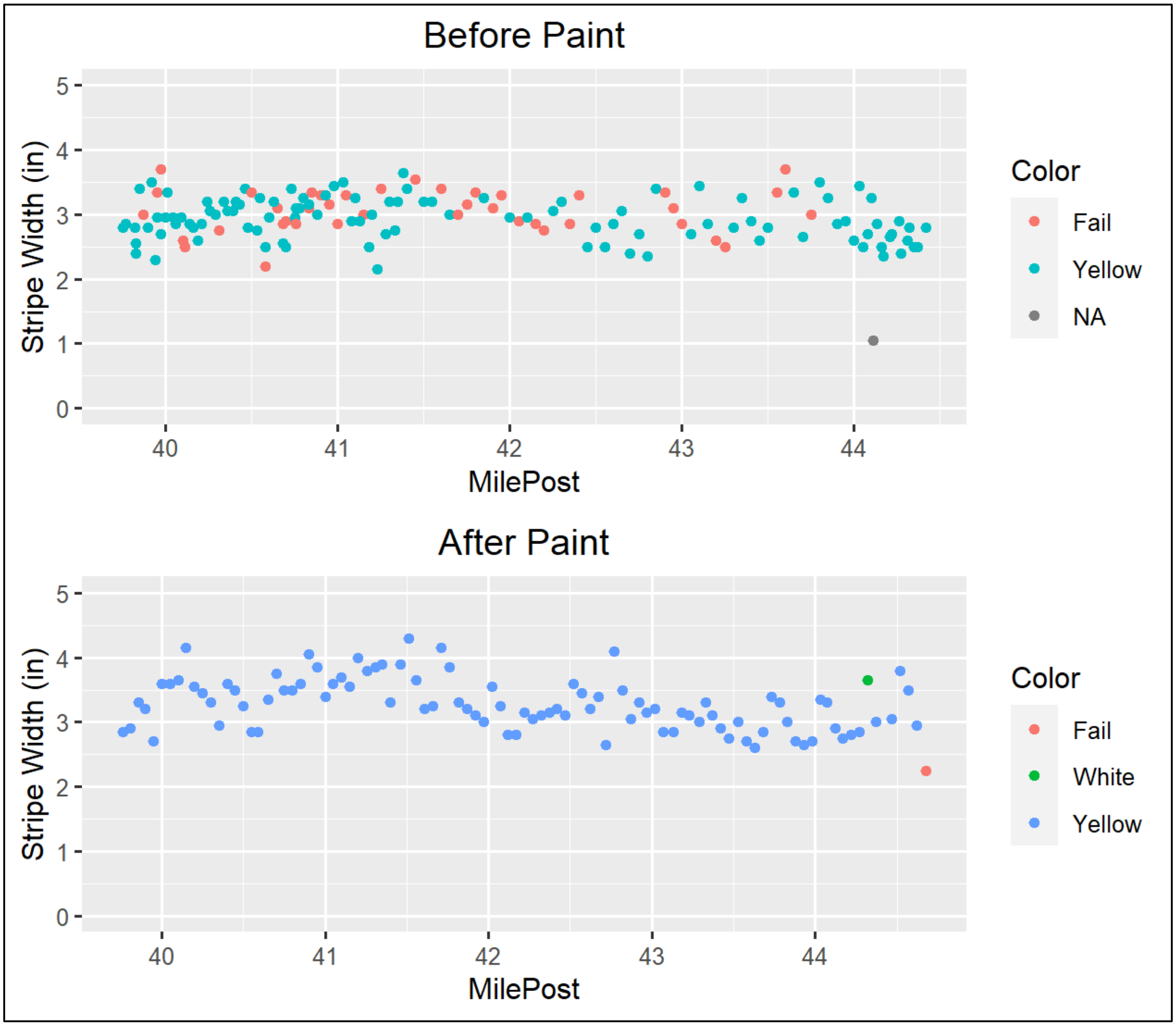


Figure 5-6: Comparison of Centerline Stripe Width and Color Distribution in Before and After Period on Route 12N_VIP_1201.

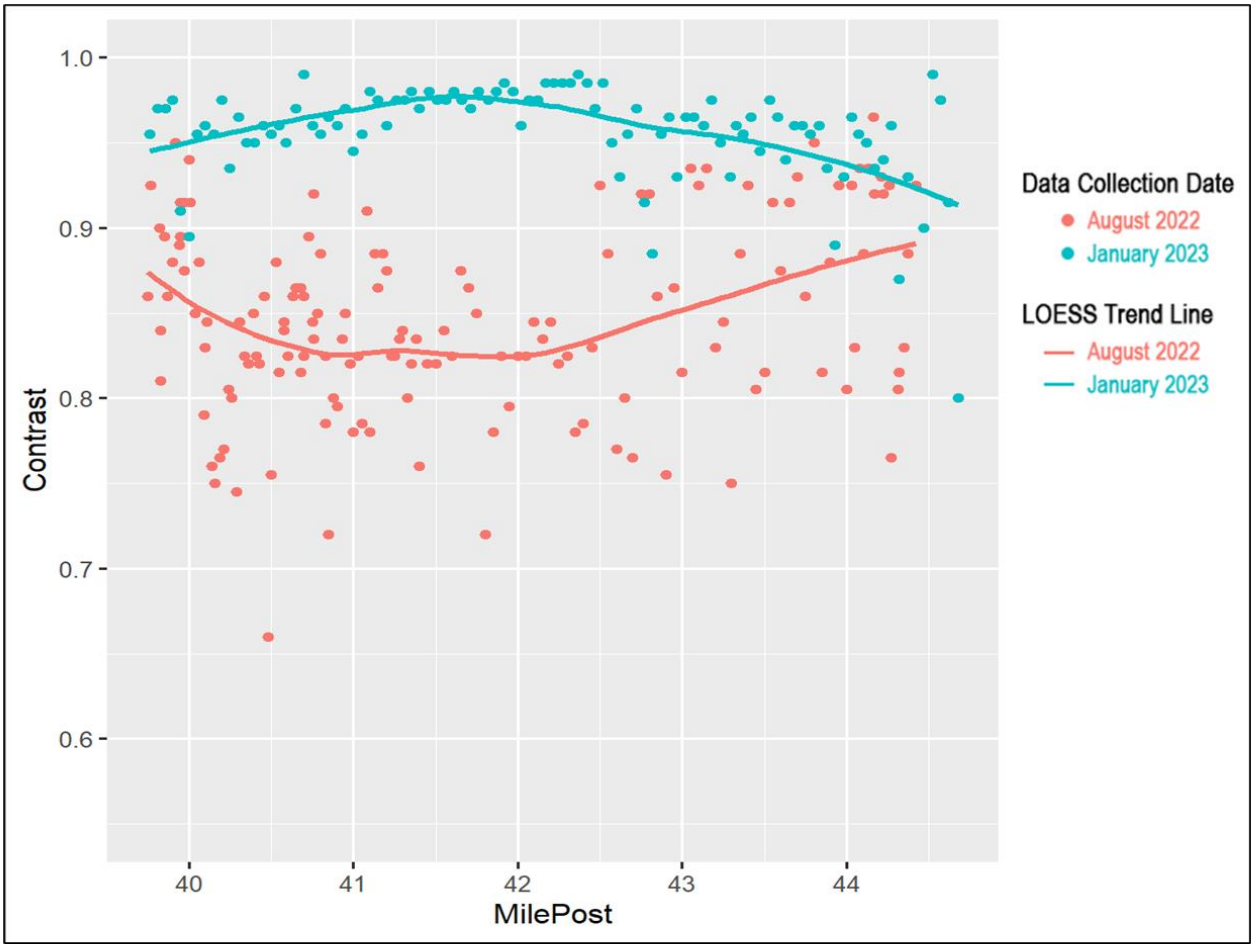


Figure 5-7 Comparison of Centerline Contrast Distribution in Before and After Period for Route 12N_VIP_1201.

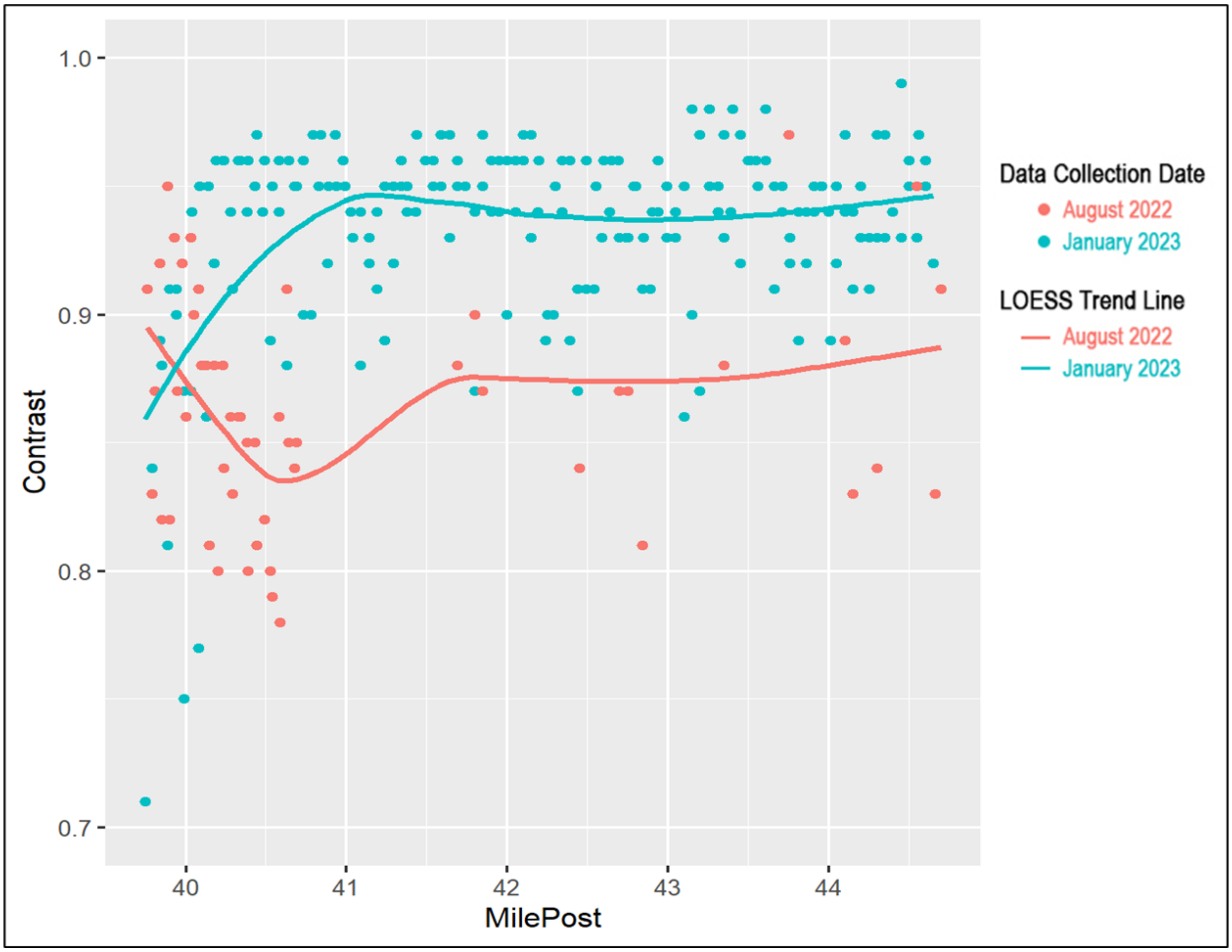


Figure 5-8 Comparison of Edgeline Contrast Distribution in Before and After Period for Route 12N_VIP_1201.

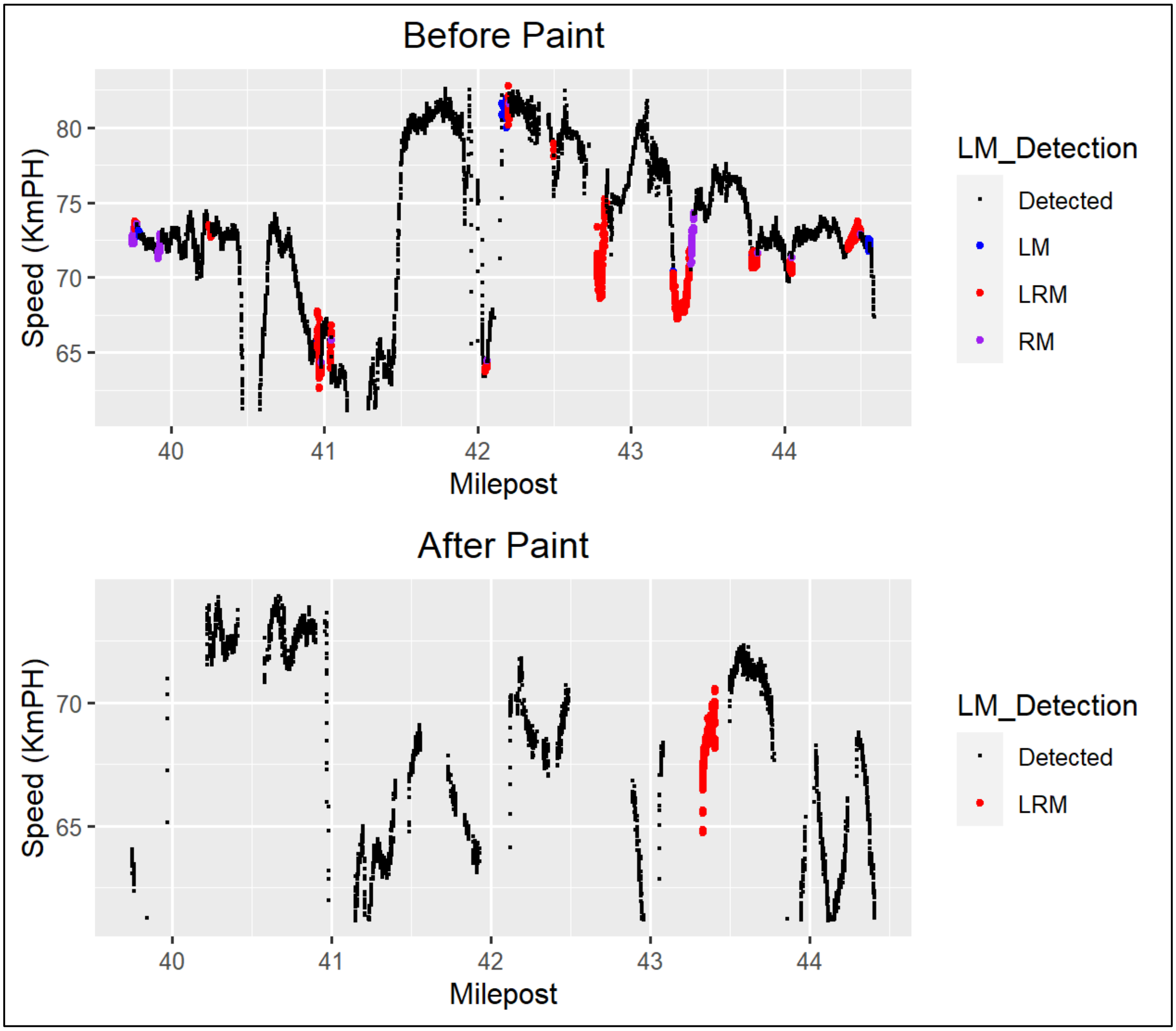


Figure 5-9: Comparison in Vehicle 2 ADAS Pavement Marking Detection in Before and After Period During Daytime on Route 12N_VIP_1201.

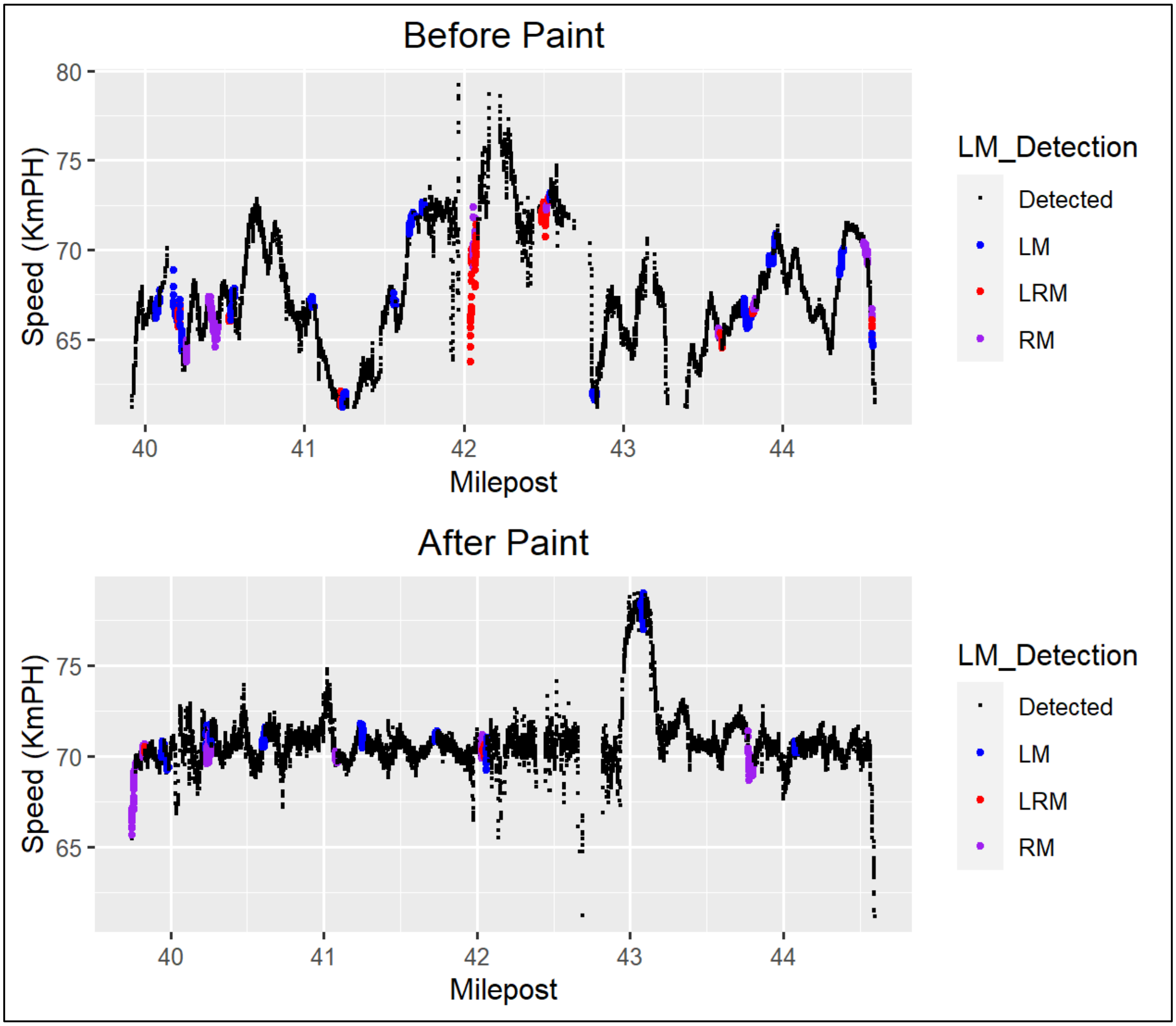


Figure 5-10: Comparison in Vehicle 5 ADAS Pavement Marking Detection in Before and After Period During Nighttime on Route 12N_VIP_1201.

The findings from the above exploration are summarized as follows:

- Both centerline and edgeline retroreflectivity improved after the installation of final paint. However, the improvements are not significant in both centerline and edgeline compared with the before period. While both centerline and edgeline retroreflectivity was found to be 50-100 mcd/m2/lux in the before period, it increased to only between 150-200 mcd/m2/lux for centerline and to only between 250-300 mcd/m2/lux for edgeline markings in the after period. It is possible that the retroreflective beads were not installed on the new pavement markings.
- The pavement marking stripe width slightly increased in the after period. However, the average stripe width measured using a retroreflectometer was found to be around 3 inches. While around 12% of the color readings failed in the before period, the retroreflectometer

was able to detect the marking color in all instances expect one in the after period.

- Both centerline and edgeline contrasts improved with the installation of new paint.
- The ADAS seems to detect pavement lane line markings with low retroreflectivity. The majority of the recorded retroreflectivity was between 50 and 100 mcd/m2/lux before the final application of paint on the analyzed site. The onboard ADAS from both Vehicle 2 and 5 was able to detect the majority of the pavement markings with low retroreflectivity.
- The travel speeds that the CR team operated the ADAS-equipped vehicles at the 12N_VIP_1201 site had no relation with the pavement marking detection capability of ADAS. The pavement marking "none detected" events do not seem to fall in either the lower or higher speed region, instead these events are spread across the range of the travel speed.
- The ADAS detection in both Vehicle 2 and Vehicle 5 seems to improve in the after period.
- With new lane markings, the ADAS still failed to detect lane markings in some instances for both vehicles. There was one location on the selected site where Vehicle 2 failed to detect lane markings in both before and after period. However, the Vehicle 5 ADAS "none detected" events were in exactly at the same locations in the after period compared with the before period.

The above findings indicate that the onboard ADAS from both vehicles during both day and night conditions can detect lane line markings with low retroreflectivity value as well as can detect 3-inch lane markings. The above exploration also indicated that vehicle speed may not have any effect on the ADAS lane marking detection capability. However, further investigation is needed to validate these findings as an in-depth investigation was not possible with the limited data available in this project. The ADAS lane marking "none detected" events may be associated with the limitations of onboard sensors and algorithms used to detect lane markings.

5.5.2 Comparison between Multiple Runs from Specific Vehicle

A comparison between multiple data collection runs from the same vehicle in the same data collection period was conducted to investigate whether the same vehicle can yield consistent lane marking detection or not. Based on the temporal distribution of processed data presented in Table 5-5, multiple runs from the same vehicle in the before period is available for Vehicle 5 on 2AE_VIP_930 site. There were two runs of data collected during daytime and two runs of data collected during nighttime in the before period using Vehicle 5. The distribution of ADAS lane line marking detection was generated over the length of the site for both daytime and nighttime to compare detection events during multiple runs using the same vehicle. Figure 5-11 and Figure 5-12 presents the distribution of lane marking detection events for daytime and nighttime, respectively.

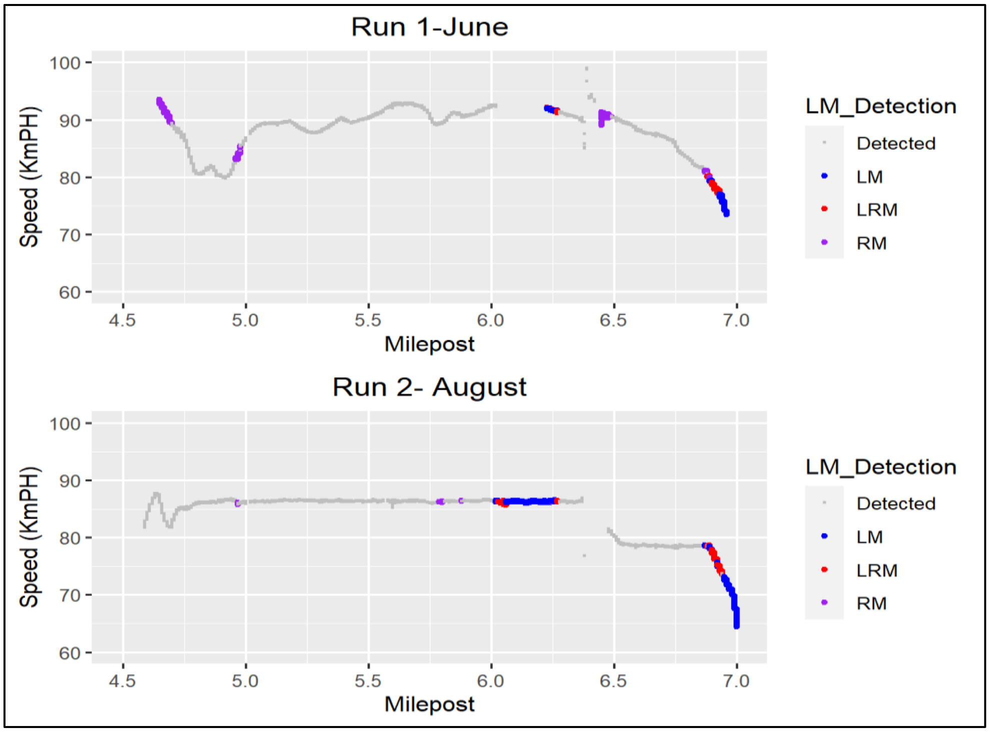


Figure 5-11: Distribution of Pavement Marking Detection Events for Two Consecutive Daytime Runs (Before Final Paint) on Route 2A-E_VIP_930 Site.

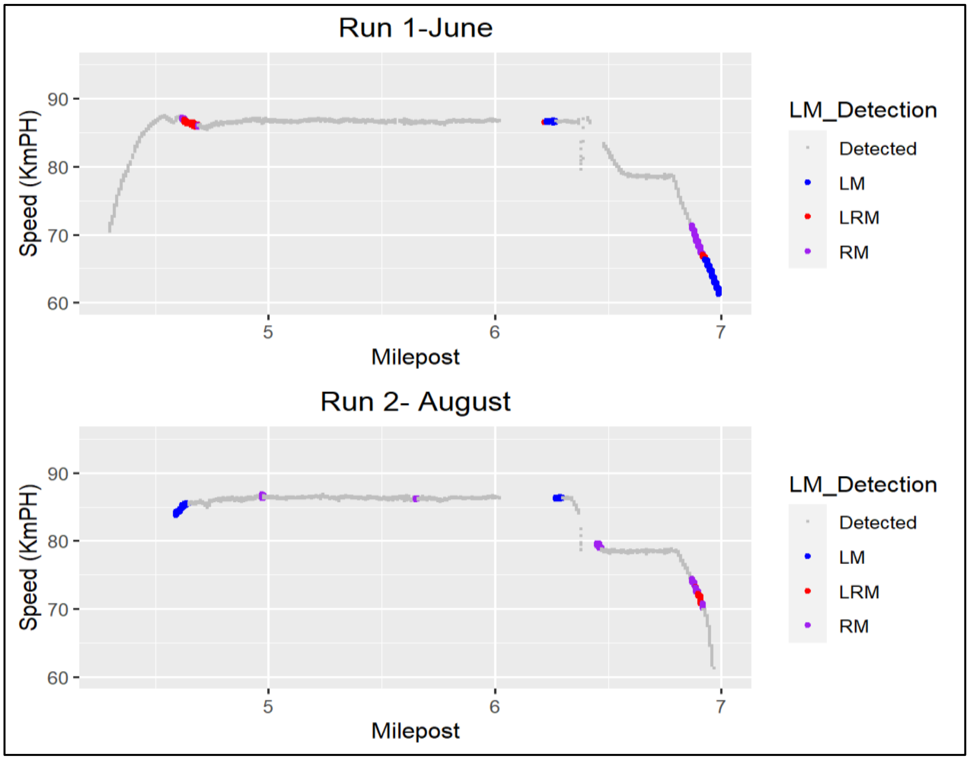


Figure 5-12: Distribution of Pavement Marking Detection Events for Two Consecutive Nighttime Runs (Before Final Paint) on Route 2A-E_VIP_930 Site.

The key findings from the above exploration can be summarized as follows:

- The distribution of "None Detected" events from both daytime and nighttime across multiple runs from before period did not occur at the same locations.
- The left marking was not detected in 61.49 out of 1000 observation in Run 1 which was conducted in June 2022 using Vehicle #5. Using same vehicle, there were 160.67 out of 1000 observations where the left marking was not detected in the run conducted in August.
- The right marking was not detected in 86.24 out of 1000 observation in Run 1 which was conducted in June 2022. Using the same vehicle, there were 67 out of 1000 observations where the right marking was not detected in the run conducted in August.
- Both "Detected" and "None Detected" events occurred at the same speed of the vehicle.

The above findings conform with the findings from the before-after comparison that emphasizes that the "None Detected" events may be related to onboard vehicle sensors and ADAS algorithms and may not be related to the lane marking characteristics. However, as mentioned earlier, the research team did not have access to the data collected by onboard sensors or how the proprietary ADAS algorithm works. Moreover, please note that the raw data collected by the CR team was processed only based on the information available from the driver instrument cluster considering the ADAS is engaged in all records with speed over 38 MPH. Any additional driver actions such as disengaging and reengaging ADAS, driving on lanes other than the rightmost lane, etc., were not considered while processing the data.

5.6 Special Scenarios

Based on experiences from raw data processing, a few special scenarios were noticed where the on-board ADAS either failed to detect existing pavement markings or detected lane markings where there are no pavement markings. These special scenarios were described below:

Scenario: Not Detected-Change in Lane Marking Types

As depicted in Figure 5-13, the on-board ADAS was unable to detect pavement marking of the left lane marking when it changes from a double-solid yellow line to a dashed white line. The on-board system continuously detected the double-solid yellow marking until it changed to a dashed white line. Another notable observation from the same run was that the on-board ADAS was able to re-engage in detecting pavement markings after 1-2 seconds. This observation indicates that the system has a time lag in re-engaging to detect lane line markings or the visual cues were provided after 1-2 seconds once the system re-engage in detecting pavement markings. Figure 5-14 presents the screen capture taken after three seconds since the instance presented in Figure 5-13.

Figure 5-13: Failure to Detect Lane Marking with Changes in Marking Type and Color.

(a)

(b)

Figure 5-14: Delay in Re-engaging Pavement Marking Detection; (a) Not Detected, (b) Detected After 3 Seconds.

Similar findings were also observed with only changes in lane marking type, even though the lane marking color was the same. As depicted in Figure 5-15, the on-board system was unable to detect lane markings when the lane line marking changed from solid white to dashed white. Interestingly, the onboard system was able to detect the changes in both lane marking type and color for the left marking in this case. This is counterintuitive from the finding described in the previous section. As the research team does not have access to the onboard sensor data, this scenario can’t be interpreted with valid evidence.

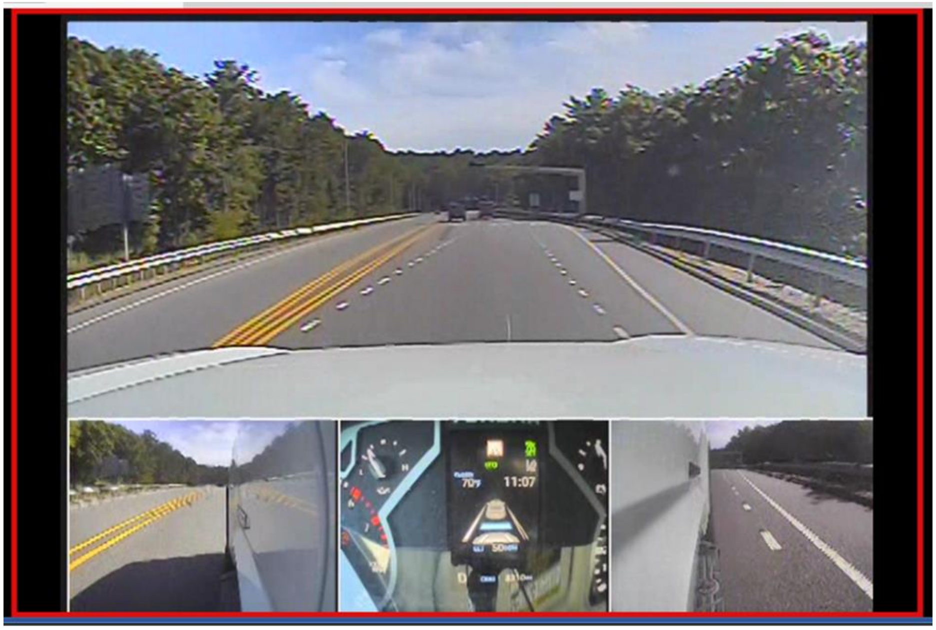


Figure 5-15: Failure to Detect Lane Marking with Changes in Marking Type.

Scenario: Not Detected-Object on the Road

The onboard ADAS sometimes failed to detect pavement markings in the presence of an object on the lane marking. As depicted in Figure 5-16, the onboard ADAS failed to detect pavement marking in the presence of an object on the marking.

Figure 5-16: Failure to Detect Lane Markings Due to Object on the Marking.

Scenario: Not Detected-Wide Lane

The onboard ADAS often failed to detect lane markings in case of wide lanes. These types of lanes often exist on the entrance of a highway or at lane drops. This limitation is also noted in the driver manual in some of the selected vehicles. A screen capture of right lane marking not detected due to wide lane is presented in Figure 5-17.

Figure 5-17: Failure to Detect Lane Marking in Wide Lane.

Scenario: Detected – Pavement Join

There are some situations during data collection which showed that the onboard ADAS is detecting pavement marking while there is no pavement marking present. As depicted in Figure 5-18, the onboard ADAS detected left lane marking while there were no markings present on the pavement. From the front and side view, it was assumed that the onboard ADAS is detecting pavement joint as a lane marking. A similar situation also occurred when there was no lane marking and the roadway had a raised curb with grass on the side which created a contrast with the pavement. This situation is presented in Figure 5-18 and Figure 5-19.

Figure 5-18: Detected Pavement Joint as Lane Marking.

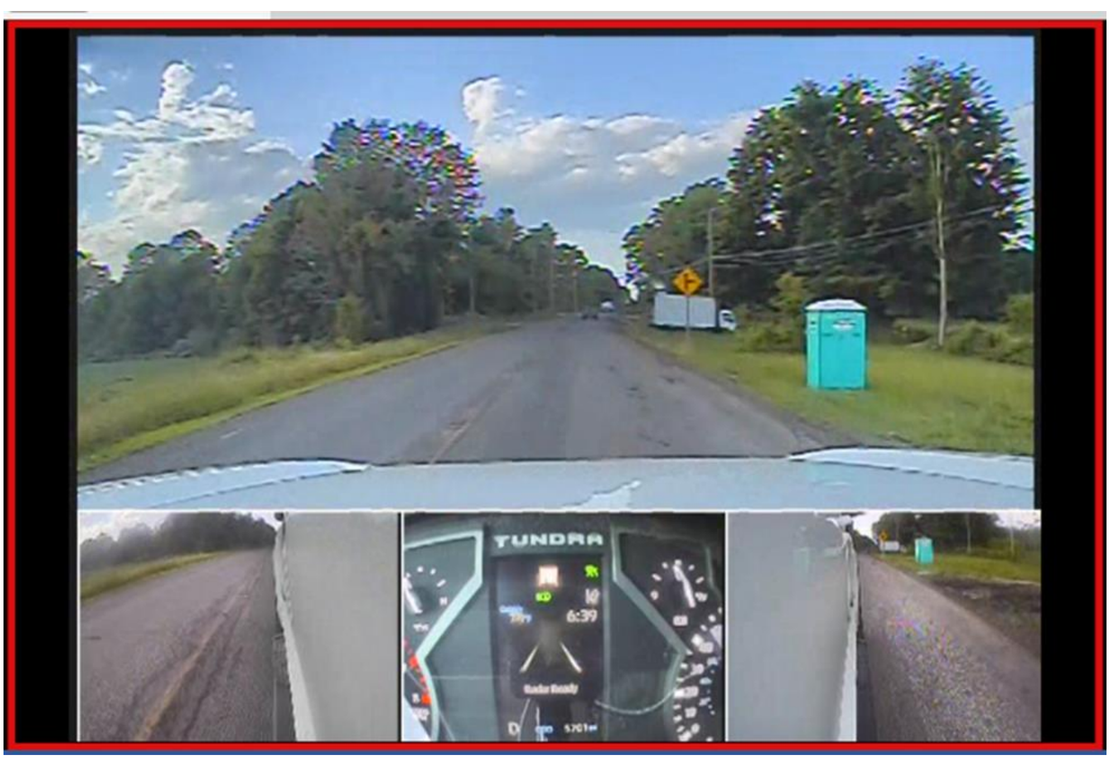


Figure 5-19: Detected Raised Curb as Pavement Marking.

The above exploration indicates that the onboard ADAS are mostly designed for ideal conditions. Most vehicles seem to have difficulty in detecting lane markings in special situations as described above. The limitations of ADAS lane marking detection features are also mentioned in the driver manual of these selected vehicles.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to evaluate the effect of longitudinal pavement marking quality, conditions, and design on the detectability of pavement markings by machine vision systems included in a cross section of light duty production vehicles operating on public roadways today. Pavement marking performance levels were varied using a range of in-service markings. Eight different light duty production vehicles equipped with their own machine vision and ADAS were used to collect ground truth data. The purpose of using multiple vehicles in this study was to identify if there are differences across makes, models, and technologies used to detect the presence of lane markings while a vehicle is operating with their ADAS machine vision engaged.

To achieve the project objectives, two classes of data were collected: pavement marking characteristics and lane marking detection events from each of the ADAS-equipped vehicles. The UConn team collected various pavement marking characteristics using a purchased vehicle-mounted retroreflectometer. The CR team drove each of the selected ADAS-equipped vehicles on the selected public roadways in Eastern Connecticut to collect ground truth on the machine vision detection capabilities of pavement lane line markings using a VBOX setup. The data collected by the CR team was processed by UConn and later analyzed to investigate the effect of pavement lane line marking characteristics on the ADAS lane marking detection. Real world data collection presents significant challenges not only in consistency of road, traffic, and weather conditions, but less control over equipment and variability in operating procedures when compared to test track or laboratory settings. Conducting the study in live traffic on roadways open to the public, where safety must be maintained at the highest standards, impacted data quality and consistency.

6.1 Summary of Data Analysis

Based on the processed data analysis, the results can be summarized as follows:

- No relationship was found between the pavement marking characteristics (retroreflectivity, stripe width, color, and contrast) and pavement marking detection capability of ADAS-equipped vehicles used in this study.
    - Vehicle ADAS tends to detect pavement lane line marking with retroreflectivity value below 100 mcd/m2/lux.
    - Vehicle ADAS was able to detect lane stripe width of 3 inches.
    - A similar trend was observed with pavement marking color and contrast.
- "None Detected" events where the vehicle ADAS failed to detect pavement lane line marking did not appear to be associated with normal vehicle operating speeds traveling on the secondary and express routes in the study. There were both lane marking detected and not detected events at the same speed over the longitudinal profile of the selected sites.
- A few special scenarios were identified where the onboard ADAS failed to detect lane markings due to changes in lane marking type and color, wide lane, object on the road. A

scenario was also identified where the onboard ADAS detected pavement joint and curb as lane marking.

- Driver education regarding the use of ADAS is paramount in effectively using these systems. The pavement lane line marking detection systems have limitations which can impact the system's effectiveness in certain scenarios. Being aware of these limitations can help drivers use the line marking system as a valuable aid while also exercising caution and attentiveness in various driving situations.

There were many limitations associated with the ground truth data collected and processed for analysis in this study.

A summary of the data issues is provided below:

- The CTDOT pavement contractor was removed which caused significant delays for data collection. The resulting data collection window was extremely small and provided the CR team an enormous challenge in collecting a massive amount of data in a short period of time. Incorporating weather delays which were out of the realm of influence further challenged data collection.
- Low quality of recorded video affected the accuracy of the data processed by the UConn team.
- A series of issues were experienced by the UConn team while processing the raw data. The lane marking detection tag was assigned based on manually processing the video recorded on the driver instrument cluster. Unavailability of the description of indicators on the instrument cluster may have compromised the accuracy of assigned tags.
- A significant number of videos were affected by sun glare, roadway lighting, and headlight glare. The glare often overexposed the instrument cluster which resulted in hard to process segments of the recordings.
- The GPS error (GPS lost connection with satellite) has been found to be a frequent issue associated with the majority of the VBOX files.
- The driver collecting the ground truth data did not consistently drive in the rightmost lane throughout the data collection.
- For the majority of the sites selected in this project, only one run of ground truth of ADAS detection data was collected. With only one run of data, the research team were not able to conduct before-after analysis for all selected sites and across all vehicles.
- Driver activity related to the driving task (e.g., pressing brakes, engaging/disengaging ADAS, etc.) were not collected during data collection. As noted by manufacturers, most ADAS disengages (if engaged) if brakes are pressed. Unavailability of braking, engaging/disengaging ADAS may have influenced the assigned lane marking detection tags processed from the video recordings.

6.2 Observations for Future Study Design

This study attempted to explore the effects of pavement marking characteristics on lane marking detection by ADAS using multiple ADAS-equipped vehicles from different manufacturers. As vehicle manufacturers have started incorporating ADAS features and sensors in their vehicles to further improve vehicle safety, this is a timely study that can provide insights on the detection capabilities of ADAS features in real-world roadway. While this study has experienced issues with data collection and processing, a series of lessons learned has been noted that can be incorporated in future study designs to guarantee the success of future studies. Ground truth data collection on ADAS machine vision detection on real-world roadway can suffer from a series of unexpected events. A ground truth data collection effort on real-world roadway needs to be meticulously designed and should be collected with validated equipment to control for the contextual factors as much as possible. The future recommendations from the lessons learned through this project are summarized as follows:

- To draw a validated conclusion or inference on the effect of different factors on the ADAS machine vision detection capability, multiple runs of data on each site are needed. Future studies should be designed to collect multiple runs of ground truth data on ADAS detection in a more controlled environment.
    - Multiple runs of data on the same site can be beneficial to compare the lane line marking detection capabilities from a specific vehicle.
    - Multiple runs at different speeds on the same site can be beneficial to evaluate the effect of speed on the machine vision detection capability.
    - Multiple runs of data on the same site with varying lane marking types and colors can help to evaluate the intrinsic limitations of the onboard ADAS in detecting different types of lane markings.
    - Multiple runs of data on the same site with varying pavement lane line marking retroreflectivity can help to evaluate the effect of retroreflectivity on the detection capability.
- Consistent ground truth data from multiple runs needs to be collected using vehicles from different manufacturers to thoroughly investigate the difference in detection capabilities across vehicles from different manufacturers.
- Ground truth data needs to be collected with a calibrated, well-tuned camera system with better graphics. High quality video data can be used to develop an automated system to process recorded video data.
- A high accuracy GPS should be used to collect data to minimize the effect of GPS connection loss on the collected data.
- Collecting ground truth data on the real-world roadway should be conducted on small sections of roadway with consistent roadway and pavement marking characteristics that will not need to driver to slow down due to intersection/ traffic.
- To evaluate the ADAS detection capabilities with changing lane marking types, ground

truth data collection study sites should be selected with variations in lane marking types within the same site.

- A data archiving guide should be developed before collecting data from real-world roadway.
- The data files which were tagged with route names did not use consistent route information. Using GIS to join ground truth data with route information may yield inaccurate route information in some cases as the joining solely depends on the accuracy of the GPS data.
- Finally, an AV data collection framework needs to be developed to guide future projects on designing and collecting ground truth data appropriately.

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APPENDIX

Examples of Lane Marking Detection Flags

Example	Tag	Description
	99	The definition and indication of line markings are interrupted by a service message, specifically one regarding the cruise control setting. It is not possible to ascertain with certainty whether the LKAS determines the road markings.
	99	The top layer of asphalt is removed from the road surface, and traffic cones are installed. In most cases, there are line markings on one side. However, old and intermittent (low-quality) line markings can also be present. In such situations, the system may become confused, incorrectly determining markings where they don't exist and failing to detect them where they should.
	NM	There are no lane markings due to freshly laid asphalt pavement.

		
	LM	Lane marking (left side) not defined by LKAS for unknown reason
	RM	Lane marking (right side) not defined by LKAS for unknown reason

		
	LRM	Lane marking (both sides) not defined by LKAS for unknown reason