DEPARTMENT OF TRANSPORTATION

Assessing Pavement Markings for Automated Vehicle Readiness

Adam Pike, Principal Investigator
Texas A&M Transportation Institute

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16. Abstract (Limit: 250 words)

New technologies are being added to vehicles at a growing rate to assist drivers and even fully take over the driving task in some situations. These technologies are generally camera-based and typically rely on pavement markings to maintain vehicle position and navigate the roadway. As drivers become more reliant on these systems, and for these systems to meet their potential safety benefits, the pavement marking infrastructure needs to be optimized to provide adequate roadway delineation. What is somewhat unknown is how different this optimized pavement marking system is from current practice and how different are the visibility needs of vehicle systems and the human eye. This project explores how various pavement marking configurations impact automated driving systems' ability to track the markings and maintain lane position. Evaluations take place in Texas and Minnesota on closed-course, open-road, and pavement marking test areas. Various camera-based systems are used to view the markings and generate feedback on the impact of the marking configurations and characteristics on the ability of the camera systems to track the markings. The research team analyzes the test results and provides recommendations to improve pavement markings to increase the function and reliability of camera-based pavement marking tracking driver assist features such as lane centering. The goal is to improve and maintain markings so the driver assist features can function reliably and yield safety improvements by reducing crashes, especially run-off-road crashes.

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Assessing Pavement Markings for Automated Vehicle Readiness

Final Report

Prepared by:

Adam Pike, P.E.
Maryam Shirinzad, Ph.D., P.E.
Texas A&M Transportation Institute
Texas A&M University System

Abhishek Nayak, Ph.D.
Sivakumar Rathinam, Ph.D.
Texas A&M University

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List of Abbreviations

ACC: Adaptive Cruise Control

ADAS: Advanced Driver Assistance System

ADS: Automated Driving System

ANOVA: Analysis Of Variance

ATSSA: American Traffic Safety Services Association

AV: Automated Vehicle

FHWA: Federal Highway Administration

LDW: Lane Departure Warning

LKA: Lane Keeping Assistance

MnDOT: Minnesota Department of Transportation

MUTCD: Manual on Uniform Traffic Control Devices

MV: Machine Vision

NCHRP: National Cooperative Highway Research Program

NCUTCD: National Committee on Uniform Traffic Control Devices

OEM: Original Equipment Manufacturer

PCC: Portland Cement Concrete

RMV: Reference Machine Vision

TAMU: Texas A&M University

TTI: Texas A&M Transportation Institute

Executive Summary

Automated Vehicles (AVs), Automated Driving Systems (ADS), and vehicles with Advanced Driver Assistance Systems (ADAS) all refer to vehicles that use various technologies to assist drivers or to replace drivers of vehicles. These systems have been under development for over a decade and have the potential to result in significant changes to vehicular transportation as we know it. These technologies have matured to the point where driverless vehicles are being tested on roads and most new vehicles come with some form of ADAS. These technologies are all feasible due to sensors that capture the driving environment in real-time and computer software to process and analyze the information from the sensors. These systems can be supplemented with mapping or other information that is not provided in real-time. What we do not fully know is what infrastructure and quality of infrastructure do these technologies require and how ready is our infrastructure to support the function of these emerging technologies. If infrastructure is not consistent or maintained at a high enough level, these technologies may not function properly and the benefits they provide may not be realized. Driver dissatisfaction and lower and slower adoption rates of the technologies may also occur if driver experience is less than optimal.

ADAS and ADS technologies offer the potential to save lives by reducing crashes caused by human error. Current ADAS have the capability to track pavement markings and potentially reduce lane-departure crashes which is beneficial, because lane departures are a leading cause of crashes. An increasing number of drivers have the option to use the ADAS features if the infrastructure can support them. Therefore, highway agencies should prepare their roadways to maximize the benefits of automated technologies by improving pavement marking uniformity, providing a higher level of maintenance, and potentially making changes to marking patterns and styles.

This research project looked at how pavement marking characteristics and configurations impact the functionality of camera-based, lane-tracking systems. The goal of the project was to recommend pavement marking practices to increase the functionality of these camera-based, lane-tracking systems, thus improving safety and reducing undesired outcomes from the utilization of the ADAS or ADS lane tracking functions.

The research team collected data in both Texas and Minnesota. The Texas data collection involved both closed-course and open-road evaluations. The Minnesota data collection involved data collection at a pavement marking test area and on open roads. The data collection efforts evaluated the markings during the day and at night using several different means of collecting the data.

The research team conducted closed-course testing in Texas to better understand how marking width, quality, and broken line marking to gap ratio impacted the ability of the camera system to track the pavement markings. Open-road evaluations in Texas were conducted to determine if contrast markings improved the ability of the camera system to track the markings during the day.

Minnesota data collection included testing at a pavement marking test area. This test area used a segment of roadway with specific pavement marking applications to evaluate different broken lane line configurations including changing line length, gap length, and cycle length. Open-road testing in Minnesota also used existing pavement markings. This allowed for testing in actual real-world conditions and allowed the research team to observe configurations that had not been evaluated in previous data collection efforts. The research team evaluated pavement markings at 37 different test areas in the Minneapolis area. The following list indicates the pavement marking configurations of interest to the project:

- Markings with varying levels of daytime and nighttime visibility
- 4-inch- vs 6-inch-wide markings
- Contrast markings
- Varying broken lane line configurations (skip length, gap length, cycle length)
- Line extensions across ramps and turn bays
- Gore areas

The research team acquired an aftermarket Mobileye 8 EyeQ4 test system with an extended output protocol. The Mobileye 8 EyeQ4 system was the most common ADAS sensor being installed in vehicles at the time. The aftermarket system acquired by the research team was a unique system that previously had not been available outside of vehicle original equipment manufacturers (OEMs). The aftermarket system allowed the research team to collect information from the system based on what the camera was observing. This allowed the research team to collect information such as the maximum distance the markings were tracked and marking detection confidence. The research team also used a camera-based, data-acquisition system to record images driving through each test area so that later those images could be annotated and run through lane tracking algorithms to determine how well the algorithms were able to track the markings in different marking test areas. In addition to the two camera systems with data output, the research team used four vehicles with varying levels of driver assist systems. All four vehicles were 2022 models. A Ford Explorer with Co-Pilot 360 Assist+, a Tesla Model Y with Autopilot, a Toyota RAV4 with Toyota Safety Sense 2.0 (TSS 2.0), and a Toyota 4Runner with Toyota Safety Sense P (TSS P) were evaluated. Each of these systems were able to operate in each of the 37 selected test areas near Minneapolis.

The research team collected and analyzed data to determine which pavement marking characteristics and configurations were most beneficial to improve conditions for the systems evaluated. The research team also reviewed recent changes to federal requirements and guidance concerning pavement markings. A summary of the most notable findings from all the testing includes the following:

- Closed Course Evaluation
    - Both day and night the 10-30 pattern had higher performance than the 10-40 pattern.
    - The markings that had higher retroreflectivity generally had higher detection.
    - The 6-inch-wide markings had similar nighttime performance but lower daytime performance than their 4-inch comparison markings. The impact of width on the daytime results was unexpected.

- Texas On-Road Evaluation
    - The line tracking results were always lower when sun glare was present.
    - The white marking followed by the black marking with or without sun glare performed better than white bordered by black or white markings only.
- Minnesota Test Deck Evaluation
    - Evaluations at the Minnesota test deck area indicated that the sections that had not been restriped had slightly lower performance data than the newer test deck markings or the restriped section. This indicated that well maintained markings are needed for the best detection by camera systems.
    - The maximum line detection distance was farther at night than during the day.
    - The Mobileye system generally had longer detection distances when more stripe was present on each skip line.
- Minnesota Open-Road Evaluation
    - A higher stripe to gap ratio showed improved marking detection from broken lane lines. The higher stripe to gap ratio also resulted in a statistically significant increase in end-of-line detection distance.
    - Broken lane line contrast markings with black following the white marking showed significant improvement in detection confidence.
    - The 6-inch-wide markings had similar end-of-line detection distance to the 4-inch-wide markings.
    - When considering the marking brightness (as evaluated from image grayscale analysis) the research team found a statistically significant increase in end-of-line detection distance with increased greyscale values.
    - The results showed that for the vehicle and roadway segments tested, the presence of dotted edge line extension did not have a statistically significant impact on lane position when passing a left-turn bay.
    - The results showed that for the vehicle and roadway segments tested, the presence of dotted edge line extension had a statistically significant beneficial impact on maintaining lane position when passing an exit ramp.
    - General observations indicated that the different broken lane line striping patterns did not have an impact on the operations of the systems evaluated as operation was normal in each of the test areas.
    - There were no results that indicated one style of contrast markings was better than the others.
    - In areas with lower-quality markings, there was some loss of tracking the markings by the systems both day and night.
    - Areas with turn bays and ramps (on or off) generated the majority of the non-desirable operations. In many cases, the vehicles either drifted toward or fully entered turn bays or ramps (both exit and entrance) when there were no dotted lane line extensions present. Even when dotted lane line extensions were present, there was still some drift toward some of the turn bays and exit ramps.

    - Dotted line extensions for turning movements from intersecting roads at large intersections and the markings on either end of MnRoad created some issues. The markings could be viewed, by ADAS, as the intended markings when they were more longitudinal than transverse and the vehicle would try to follow them.

The outcome of the research is recommended pavement marking practices that meet the research objectives. These recommendations cover pavement marking width, skip to gap pattern, dotted line extensions, gore areas, marking brightness and maintenance, and contrast markings. The specific recommendations are as follows:

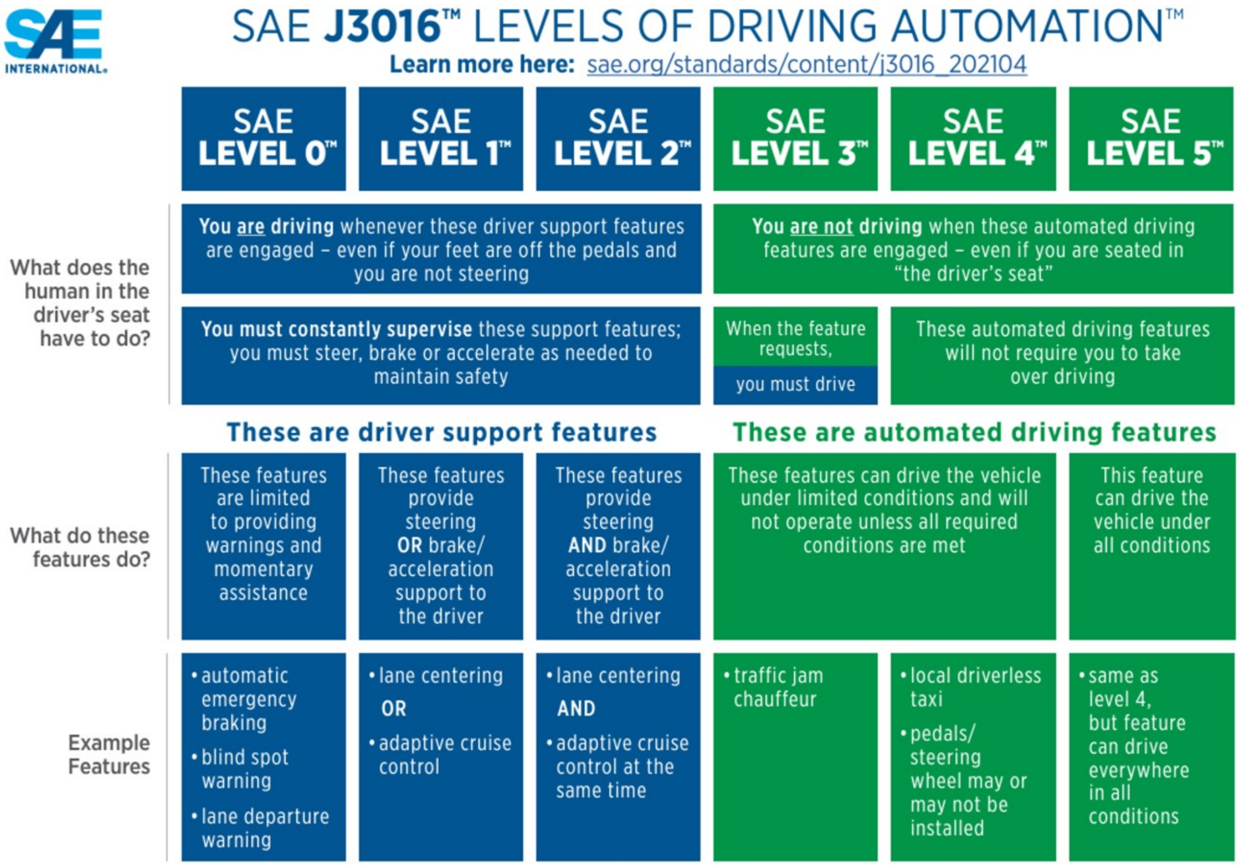
- Based on the data gathered in this study, the research team recommends MnDOT consider using 6-inch-wide markings as the normal width marking to better ensure high functionality of driver assist systems across a range of conditions and throughout the service life of the marking.
- The research team recommends MnDOT use a 12.5-37.5 stripe to gap broken lane line striping pattern.
- The research team recommends MnDOT use dotted line extension across all exit ramp areas and at turn bay entrance areas on roadways where utilization of driver lane-keeping assist systems is expected.
- The research team recommends MnDOT consider the use of dotted line extensions at on ramp areas but not extend them across the entire open area.
- The research team recommends MnDOT consider using dotted-line extensions for through movements across large intersections, especially when there is a shift in lane position across the intersection. The research team also recommends that MnDOT consider how dotted-line extensions for turning movements affect crossing traffic.
- The research team recommends well-maintained markings and dotted edge line extensions at exit ramp areas. The research team also recommends MnDOT consider adding chevron markings to long and wide gore areas where vehicle intrusions could be more common, due to geometric design or other circumstances, so that the vehicle system would disengage and not unintentionally follow between the gore makings.
- The research team recommends that MnDOT implement a pavement marking maintenance plan that ensures markings are visible both during the day and at night. This plan should exceed the requirements of Section 3A.05 Maintaining Minimum Pavement Marking Retroreflectivity of the 11th edition of the Manual on Uniform Traffic Control Devices (MUTCD). The research team recommends maintaining marking quality on all roads, not just those required by the MUTCD.
- Based on the data collected, the research team recommends, that when implemented, MnDOT use the white followed by black contrast marking pattern. The black contrast following the 12.5-foot-long skip line should be 10- or 12.5-feet long.
- The research team recommends implementing broken lane line contrast markings when the contrast between the combination of pavement surface and white marking material is low.

Chapter 1: Background and Literature Review

1.1 Introduction

AVs, ADS, and vehicles with ADAS all refer to vehicles that use various technologies to assist drivers or to replace drivers of vehicles. These systems have been under development for over a decade and have the potential to result in significant changes to vehicular transportation as we know it. These technologies have matured to the point where driverless vehicles are being tested on roads and many new vehicles come with some form of ADAS. These technologies have the potential to increase highway safety by supplementing or replacing the human driver, while at the same time, improving driver and passenger comfort, increasing driver productivity, and potentially reducing traffic delays. These technologies are all feasible due to sensors that capture the driving environment in real time and computer software to process and analyze the information from the sensors. These systems can be supplemented with mapping or other information that is not provided in real time. What we do not fully know is what infrastructure and what quality of infrastructure these technologies require and how ready our current infrastructure is to support the function of these emerging technologies. If infrastructure is not consistent or maintained at a high enough level, these technologies may not function properly and the benefits they provide may not be realized. Driver dissatisfaction and lower and slower adoption rates of the technologies may also occur if the driver experience is less than optimal.

SAE International has developed levels of driving automation, see Figure 1 [1]. These levels are based on the functions provided and the level of involvement of the driver. The lower levels of automation are considered ADAS. Features provided by ADAS may include — Adaptive Cruise Control (ACC), Blind Spot Monitoring (BSM), Forward Collision Warning (FCW), Traffic Sign Recognition (TSR), Automatic Emergency Braking (AEB), Automatic High Beam (AHB), Lane Departure Warning (LDW), Lane Keeping Assistance (LKA) and others [2, 3]. The lane-tracking functionalities highly depend on machine vision (MV) technology in terms of cameras located inside the car, against the front windshield behind the central rearview mirror [2]. The level 2 ADAS features are nearly automated driving, and some may claim they are level 3 functionality. Level 2 systems typically include cameras but may also include other sensors such as radar and lidar, as well as onboard high-definition maps of the roadway. Many vehicles today are being equipped with level 1 and level 2 technologies. Many level 2 systems are referred to by the vehicle manufacturer trade name such as autopilot, propilot, super cruise, etc. Level 3 technologies are not quite emerging on the market due in part to liability concerns if the driver is not paying attention to driving. Testing of fully autonomous systems such as the level 4 Waymo vehicle are occurring in specific locations around the country, but there is no expectation for widescale use in the near future.



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	SAE LEVEL 0™	SAE LEVEL 1™	SAE LEVEL 2™	SAE LEVEL 3™	SAE LEVEL 4™	SAE LEVEL 5™
What does the human in the driver's seat have to do?	**You are driving** whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			**You are not driving** when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	These are driver support features			**These are automated driving features**		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering **OR** brake/acceleration support to the driver	These features provide steering **AND** brake/acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• automatic emergency braking • blind spot warning • lane departure warning	• lane centering **OR** • adaptive cruise control	• lane centering **AND** • adaptive cruise control at the same time	• traffic jam chauffeur	• local driverless taxi • pedals/steering wheel may or may not be installed	• same as level 4, but feature can drive everywhere in all conditions

Figure 1. SAE International J3016 levels of driving automation graphic [1].

This document compiles a review of recent research studies and guidelines on machine vision systems and how they interact with infrastructure to provide lane tracking. Specifically, the function of pavement markings and how the camera technologies interpret them to provide their automated functions will be evaluated. The information gained in this review will help establish the work plan for the field data collection effort to evaluate specific areas of interest in the interaction between markings and machine vision technologies.

1.2 Highway Infrastructure to Support Automated Vehicles

Early predictions for the implementation of fully autonomous vehicles on roadways have proven to be much too optimistic. Current trends point to a focus on ADAS in the short term, with the gradual deployment of fully automated driving systems only within a narrow set of conditions [4]. ACC and LKA are becoming popular options and even standard features on vehicles. When used in combination, ACC and LKA provide level 2 autonomy. The market share of vehicles sold in the US in the first half of 2022 that had ADAS was approximately 70 percent [5]. Approximately 45 percent of vehicles had level 2 or 2+ technologies. These two ADAS features are useful in addressing roadway departure crashes, which are the largest category of crashes involving highway fatalities [6]. Agencies around the world are interested in understanding what highway infrastructure elements are essential for reliable AV and ADAS operation.

Highway infrastructure needs continue to be designed and built for human drivers but the design and maintenance must also consider the emerging ADAS technologies and future higher levels of AV. The Federal Highway Administration (FHWA) recently completed research that looked at the demands and potential impacts of AVs on current and future infrastructure assets [7]. Their primary goal was to develop practicable documentation for DOT stakeholders about AV-related infrastructure needs. As part of the project, researchers interviewed AV industry professionals and conducted nationwide workshops. The interviews and workshops identified that among all highway infrastructure categories (Physical Infrastructure, Traffic Control Devices, Transportation System Management and Operations (TSMO), Intelligent Transportation Systems (ITS) Infrastructure, and Urban Multimodal Infrastructure), updating inconsistent pavement markings should be given the highest priority. Recommendations to improve uniformity in the pavement markings across the United States would be the most beneficial infrastructure improvement right now because markings are currently being used by ADAS and are likely to be used by future fully automated vehicles. Infrastructure such as signs and signals are just starting to be used by ADS and research in these areas is just beginning. The research recognized that agencies are somewhat unready to support AV deployment due to a lack of standards and culture for innovation and funding. At the same time, improvements to marking uniformity and maintenance will be beneficial to human drivers. General recommendations included improved uniformity, improved design, and improved maintenance.

Standards for pavement markings were designed and developed based on human vision. In the US, marking widths (e.g., 4-inch versus 6-inch markings) and patterns (e.g., 10-foot marking with a 30-foot gap) vary between states and within states, which sometimes makes it difficult for AV technologies to provide a consistent level of performance. Poorly maintained markings are a challenge to AVs and vehicles with ADAS systems. The World Economic Forum rated the US transportation infrastructure system 12th in the 2014–2015 global competitiveness report [8]. According to a Reuters report, “Shoddy infrastructure has become a roadblock to the development of self-driving cars, vexing engineers, and adding time and cost. Poor markings and uneven signage on the three million miles of paved roads in the United States are forcing automakers to develop more sophisticated sensors and maps to compensate” [9]. National Cooperative Highway Research Program (NCHRP) research includes a summary of current state practices and provides recommendations for improvements to pavement markings to benefit ADAS and ADS [5].

Pape and Habtemichael [10] developed a framework for FHWA focusing on the required changes in the infrastructure components to support AV technologies. They also provided a list of initiatives to FHWA that may serve the deployment of AV technologies to reduce roadway departure crashes. The initiatives were developed based on the review of previous research, and discussions with technology developers, vehicle manufacturers, state and local DOT professionals, infrastructure officials, and other stakeholders. This research concluded that AV technologies’ most significant challenge would be the lack of standardization in signs and pavement markings. As marking patterns vary between states and within states, tight standardization is required for consistent, reliable, and higher-quality markings. Improved standards for lane markings would help MV systems correctly recognize and interpret pavement markings to ensure safe navigation of the vehicle.

1.3 Transportation Safety and Automated Vehicles

AVs and ADAS may reduce the possibility of crashes and their severity by addressing human error and distracted driving [11, 12, 13]. LDW systems provide a warning to a driver if the vehicle is in danger of departing its lane. The next automated functionality beyond LDW is LKA, which applies a momentary correction to the steering wheel or brake to bring the vehicle back into the driving lane if it begins to deviate [14]. Kockelman and Li evaluated the safety benefits of ADAS [15]. They estimated the annual economic cost savings from roadway departure crashes would be in the range of $6.6 billion to $12 billion. Alone, LDW could potentially prevent 483,000 crashes per year, including 87,000 nonfatal injury crashes and 10,345 fatal crashes, which represents 8 percent of all crashes and 30 percent of all road fatalities in the United States [16]. Jermakian [17] reported similar statistics, but Harper et al. estimated [13] about $42 billion in benefits from LDW systems as the technologies become more effective and widespread. Gordon et al. suggested a 47 percent reduction in lane-departure-related crashes, equivalent to reducing about 85,000 crashes annually [18]. A European study showed that ADAS could reduce the number of crashes in European countries by 14,000, assuming a 7-percent penetration rate by 2020 [19]. Kusano and Gabler estimated an 11 to 23 percent decrease in roadway departure crashes and a 13 to 22 percent reduction in driver fatalities, assuming all vehicles have lane-departure systems [20]. Scanlon et al. evaluated the effectiveness of LDW and LKA systems in preventing roadway departure crashes, assuming all vehicles have either system [21]. The study found that LDW systems can reduce crashes by 26.1 percent with a 20.7-percent reduction in severe injuries. On the other hand, LKA systems were predicted to reduce crashes by 32.7 to 51 percent with a 26.1- to 45.9-percent reduction in severe injuries. The baseline case considered that neither of the two driver assist systems were used. Kusano et al. estimated a 30-percent decrease in single-vehicle crashes and a 25-percent reduction in seriously injured drivers if vehicles were equipped with LDW systems [22].

Quantifying the safety benefits of AVs is difficult as these have been introduced only recently and are driven far fewer miles than conventional vehicles, and it is often unknown if the AV system was on or not and if it was properly functioning when a crash occurred. Kalra and Paddock conducted a study to learn how many miles of driving would be needed to evaluate the safety benefits of AVs more reliably [23]. Results suggested that potentially hundreds of millions or even hundreds of billions of miles would be needed to generate reliable data to show the safety effects of AVs compared to human drivers. They noted that safety advantages of new AV systems or features to improve safety performance could not be practically evaluated based on real-world testing. Therefore, researchers should focus on accelerated or virtual testing and simulations, mathematical modeling and analysis, scenario and behavioral testing, or extensive tests on hardware and software systems.

1.4 Pavement Marking Criteria for AV Technologies

MV systems use cameras to get images, which are then processed and analyzed using proprietary software to track the pavement markings and to measure other decision-making characteristics. Different manufacturers install different technologies to alert or assist drivers, for example, audible or visual warnings, steering wheel or seat vibrations, or by steering the vehicle. Some vehicles also have sensors such as LiDAR or radar to collect additional information about the driving environment. LiDAR and radar are mostly used for obstacle detection, whereas MV cameras are mainly used for lane detection [24]. MV uses different methods (e.g., feature-based, neural network-based, or probabilistic) to interpret the lane marking images to keep LDW, LKA, and other vehicle guidance system functions working [25]. Lane detection involves pre-processing of pavement marking images and feature extraction, followed by feature detection and model fitting [26].

LDW, LKA, and other vehicle guidance system technologies highly depend on well-maintained pavement markings and may not work correctly if the pavement markings fall below specific conditions. Several research studies have been completed or are going on to determine pavement marking characteristics that provide reliable machine-vision detection. Most of these studies indicate an empirical relation at best for how material characteristics influence MV systems; however, a universal standard is yet to be established. Researchers at Texas A&M Transportation Institute and Texas A&M University, College Station, Texas, have tested the effectiveness of lane markings as well as the vision algorithms through systematic development of lane detection metrics and testing of lane-detection algorithms in a robust test/vehicle environment [27]. Marr et al. [28] suggested that the luminance coefficient (Q_d) and retroreflectivity (R_L) are essential factors affecting machine vision's ability to detect pavement markings reliably. The luminance coefficient (Q_d) is considered a daytime visibility property and retroreflectivity (R_L) a nighttime visibility property. Nayak et al. tested lane markings using different state-of-the art lane detection algorithms and presented a systems approach for correlating the algorithm performance to the environmental factors, lane-marking types, color, material properties, and the retroreflectivity of pavement markings [29]. Hadi [30] explained that pavement markings with a very low retroreflectivity due to aging also have low daylight visibility. Pike et al. showed that "pavement markings with a higher R_L are expected to have a corresponding higher Q_d" [31]. Studies showed that glare has a negative impact on MV enabled lane-guidance functions [31, 32, 33, 34]. The contrast ratio between pavement substrate and markings is also a critical factor affecting MV performance. Kandarpa et al. [35] suggested a contrast ratio of 3:1 for reliable MV detection of pavement markings.

NCHRP sponsored a study to evaluate how pavement-marking characteristics impact marking detectability by MV systems [32]. The study evaluated pavement markings of various quality (e.g., color, retroreflectivity, solid, broken) at various speeds and in various conditions (e.g., day, night, sun glare, dry, wet). The study found that the marking characteristics and evaluation conditions could impact the detectability of the markings by the MV system. The study found that for most conditions the markings needed to have a contrast level compared to the surrounding pavement that was adequate for the system to detect the marking reliability. In most cases, a contrast level of 2.5 or greater would result in reliable detection. Contrast of marking luminance factor (CIE Y), dry retroreflectivity (R_L), and wet retroreflectivity were calculated. The findings also indicated that higher speeds and broken lane lines resulted in lower detection confidence levels. The impact of glare from the sun was the biggest factor in reducing detection confidence. The research recommended additional studies to evaluate the impact of marking width, marking contrast patterns, different road surface materials, and different MV technologies.

The American Traffic Safety Services Association (ATSSA) sponsored a closed-course study to evaluate the impact of 4-inch- and 6-inch-wide pavement markings on the ability of a MV system to track the markings across a range of conditions [31]. Research showed that 6-inch-wide markings were able to provide some improvement to the machine-vision detection under adverse visibility conditions. Based on the results of the NCHRP study, the 6-inch-wide pavement markings may be beneficial on high-speed roadways where detection of the markings is slightly reduced especially for broken lane line markings [32]. Other areas where wider markings may be beneficial include areas with previously removed markings scarring due to removal activities, blackout markings, crack seal, horizontal curves, or areas where glare is present.

Lundkvist & Fors [36] tested LDW systems for different types of lane markings (profiled/flat, new/worn) under different light conditions (day and nighttime) and different weather conditions (daytime and nighttime). This study did not consider the effect of different marking widths within 50 miles of the test loop. Primary roads had 99% functionality in both day and nighttime. However, functionality deteriorated in the wet nighttime condition, as well as during low opposing sun conditions. In the extreme opposing sun, the functionality decreased to 50%, while it was 92% during the nighttime with rain. The functionality was lower due to poor visibility of the road markings on secondary roads. LDW systems showed the best performance in both daytime and nighttime on dry roads. It found that roadways wider than 20 feet need to have a centerline to activate LDW systems. The study revealed that right road markings should have a minimum retroreflectivity of 70 mcd/m^2/lux in dry night conditions and 20 mcd/m^2/lux in wet night conditions. In dry daytime conditions, the luminance coefficient should be at least 5 mcd/m^2/lux higher than the pavement surface, where the luminance coefficient, Q_d, needs to be at least 85 mcd/m^2/lux.

A study by EuroRAP originally published in 2011 and later updated recommended that pavement markings should maintain minimum dry retroreflectivity of 150 mcd/m^2/lux, wet retroreflectivity of 35 mcd/m^2/lux, and a minimum width of 150 mm (6-inches) for MV detection [37]. The primary focus of the project was to investigate when markings need maintenance and how roads should be marked so that the markings are clear and visible. In November 2013, the European Union Road Federation (ERF) solidified EuroRAP's recommendations to increase highway safety accounting for both human and MV needs [38].

Davies [39, 40] studied the effect of markings’ retroreflectivity, contrast ratios, and widths on MV performance and how they vary from day to night and dry to wet conditions. The study used 8-foot long white and yellow pavement markings panels provided by the Potter Industry to simulate an edge line at distances of 24 to 60 feet in front of the test vehicle. These panels were positioned in front of an ADAS camera-equipped stationary vehicle. The pavement marking panels were 4-inches and 6-inches wide with varying levels of retroreflectivity from 131 to 394 mcd/m^2/lux. The study findings are as follows:

- Highest ADAS camera detection performance was found at a distance of 30 to 40 feet in front of the vehicle.
- MV detection ratings increased with the increase in retroreflectivity levels up to about 400 mcd/m^2/lux. Davies suggested to conduct more research to validate this statement and find the optimal retroreflectivity level.
- White markings were easier to detect than yellow markings.
- Six-inch markings outperformed four-inch markings, particularly at longer testing distances.
- ADAS camera detection performance dropped when the markings were wet. Researchers advised conducting more research regarding these issues.

Carlson and Poorsartep [41] collected ADAS camera performance data on 4-inch-wide flat markings (no profile). The results revealed that sometimes the MV detection ratings increased with an increase in contrast (luminance during the daytime and retroreflectivity during the nighttime). For example, the highest ADAS camera performance was found for center line markings with retroreflectivity levels of 50 to 225 mcd/m^2/lux during nighttime conditions. On the other hand, the lowest ADAS camera performance was found on markings with retroreflectivity levels of 50 to 75 mcd/m^2/lux. Research indicated that retroreflectivity alone was not always a good indicator of ADAS camera performance at night, as many other factors were also involved; for example, unavoidable environmental factors included low sun angles, rain, snow, and fog. On the other hand, shadows, lane marking removal/eradication scars, crack seal, and other pavement surface maintenance practices may contribute to failure of MV detection of pavement markings. Researchers noted ADAS cameras generally identified markings with retroreflectivity of at least 100 mcd/m^2/lux but may not provide any reliable detection.

Mobileye is a leading supplier of camera systems for ADS and ADAS technologies. It recommended removal of old markings and proper maintenance of existing and new markings for better MV performance [42]. In February 2018, Mobileye presented a summary of road-marking challenges and recommendations. It also asked to have more uniformity on marking width, avoiding narrow and very wide markings. It prefers 10-foot-long and 4-to 6-inch-wide markings and avoids 10-inch-wide markings. Other requests were as follows:

- New lane lines should be fully marked starting at the gore point.
- Ensure higher retroreflectivity levels in wet conditions.
- More uniformity on the shape and use of arrows, the width of Stop bars (15 to 20 inches), and speed-bump markings.
- Provide more apparent distinction between vehicle, bike, and pedestrian areas.

Subsequently, ATSSA also supported the following specific proposals made by Mobileye and the recommendations that were being developed at the time by the National Committee on Uniform Traffic Control Devices (NCUTCD), which included the following:

- 6-inch-wide longitudinal markings (edge lines, centerlines, and lane lines) shall be used on roads with a posted speed of 40 mph or greater.
- 15-feet-long lane-line markings with a gap of 25 feet shall be installed.
- Exit and entrance ramps shall be marked with dotted edge line extensions on roads with a posted speed of 40 mph or greater.
- Chevron markings shall be included in gore areas on roads with a posted speed of 40 mph or greater.
- Non-reflective pavement markers (Botts Dots) should be eliminated or only used when supplementing pavement markings.
- Contrast striping should be required on concrete roadways with a posted speed of 40 mph or greater.

In 2018, the Alliance of Automobile Manufacturers provided a list of suggestions for future pavement markings in response to the FHWA Automated Driving System Request for Information [28]. The Alliance's members include BMW Group, FCA US LLC, Ford Motor Company, General Motors Company, Jaguar, Land Rover, Mazda, Mercedes-Benz USA, Mitsubishi Motors, Porsche, Toyota, Volkswagen Group of America, and Volvo Cars North America. Their recommendations were as follows:

- Road markings should be well maintained and have a higher contrast ratio.
- Lane markings should be clear and uniform in width, color, length, and number of lines in High Occupancy Vehicle (HOV) lanes.
- Fewer parallel road surface markings for concrete expansion joints and tar lines so that ADS can reliably distinguish between real roads and others.
- New markings should be protected from erroneous marks (e.g., ghost markings) because there is a high chance that MV systems can mistakenly detect these as markings.
- Eliminate the use of Botts Dots. Correctly installed Botts Dots are adequate for current ADS technology; however, worn off or misaligned Botts Dots make it difficult for ADS camera algorithms to reliably detect them as lane markings.

1.5 NCUTCD Pavement Markings for ADS Recommendations

The NCUTCD develops recommendations that it sends to the FHWA for consideration in development of the MUTCD. The Marking Technical Committee (MTC) of the NCUTCD developed a task force to review available research and gather information from industry groups pertaining to pavement markings for ADS. A driving force for this effort was due to responses to the FHWA request for information (RFI) on integration of ADS into the highway transportation system. The FHWA RFI resulted in meetings that were held around the country on different topics to generate additional information. One of the key findings from meetings and the original RFI was the need for well-maintained and uniform infrastructure, especially the pavement markings.

As a result of their information review and discussions with industry groups, the MTC task force developed draft pavement marking criteria that would be beneficial to the function of ADAS while at the same time also being a benefit to human drivers [43]. The recommendations were approved at the January 2020 meeting and submitted to the FHWA for consideration in the next version of the MUTCD. The pavement marking criteria in the recommendations included suggestions to improve pavement marking uniformity, quality, and maintenance. Recommended changes to the MUTCD by NCUTCD is presented as following:

- Shall use 6-inch-wide markings on all freeways
- Shall use 6-inch-wide edge lines on highways with posted speed ≥ 55 mph and ≥6,000 vehicles/day
- Wide lines are 8 inches or more when used with 4-inch normal lines and 10 inches or more when used with 6-inch normal lines
- Should lengthen all broken lane lines on interstates, freeways, and expressways to 15 feet in length with a 25-foot gap (currently 10 feet with a 30-foot gap or similar ratio (1 to 3), MnDOT uses a 1 to 4 ratio)
- Shall use dotted line extensions across all exit ramps

The FHWA updated the MUTCD in December 2023 while this project was wrapping up [44]. Discussion of the MUTCD updates and how they compare to the MUTCD recommendations are discussed in the Conclusions and Recommendations chapter of this report.

1.6 State Practice

In October 2018, the U.S. DOT mentioned in its highly anticipated document, *Preparing for the Future of Transportation: Automated Vehicles 3.0 (AV3.0*), that the FHWA will pursue an update to the 2009 MUTCD, taking into consideration the needs of automated vehicle technologies [44]. At the time it was anticipated that FHWA may possibly include 6-inch-wide edge lines as the normal marking width and add minimum required pavement marking retroreflectivity levels, which had been a Congressional mandate since 1993. FHWA did incorporate guidance to use additional 6-inch-wide markings but did not require them in the MUTCD revision [44]. FHWA incorporated minimum maintained pavement marking retroreflectivity requirements into the MUTCD in 2022, and they remained in the full MUTCD revision [44]). FHWA established the requirement to implement a method to maintain markings above a 50 mcd/m^2/lux retroreflectivity level [44]. There were some exceptions to the requirement. Both wider markings and the maintenance of marking retro have already been evaluated to be beneficial in certain circumstances in different research studies for both human and machine drivers.

Some agencies have been improving their pavement markings prior to any federal requirements. For example, the Michigan, Tennessee, and Florida departments of transportation (DOTs) have been using 6-inch-wide markings for years to evolve their infrastructure to accommodate older drivers. Texas has started updating its pavement marking policies for serving future AV technologies, adopting 6-inch-wide markings statewide in 2022. Numerous other states are using a combination of 4-inch-wide and 6-inch-wide markings and are looking to widen their 4-inch markings to 6-inch markings statewide.

The California Department of Transportation (CalTrans) announced a change to its pavement-marking policy to serve the AV industry's increasing requirements after consultation with two major players in the autonomous vehicle industry — Tesla and Google [46]. The key changes were as follows:

- Discontinue two types of raised pavement markers on state highways: Type A, Botts Dots; and Type AY, non-reflective yellow dot
- Allow 6-inch longitudinal pavement markings for edge lines, center lines, and lane lines
- Prefer high-performance thermoplastic and tape over conventional (paint) pavement markings.

The Georgia Department of Transportation (GDOT) deployed AV-friendly lane markings on 13 miles of Interstate 85 in Troup County, from the Georgia-Alabama border to Exit 13-LaGrange. The design is specifically developed to work better with the sensors used by AVs and ADAS technologies under all lighting (daytime, nighttime) and weather (dry, wet) conditions [4747].

1.7 Literature Review Summary

ADAS and AV technologies offer the potential to save lives by reducing crashes caused by human error. Current ADAS have the capability to track pavement markings and thus reduce lane departure crashes, which are a leading cause of crashes. By 2025, most new cars will be equipped with ADAS functionalities. An increasing number of drivers have the option to use the ADAS features if the infrastructure can support them. Therefore, highway agencies should prepare their roadways to maximize the benefits of AV technologies by improving pavement marking uniformity, providing a high level of maintenance, and potentially making changes to marking patterns and styles.

Different studies have recommended different criteria for pavement markings and showed compelling evidence of each criterion’s benefit. While the studies may have some differences in specific marking characteristic levels or implementation locations, they all seek to improve pavement marking maintenance. This improved maintenance will provide markings that are easier for AV systems to track, while at the same time, improving markings for human drivers. Some areas where the research is lacking and recommendations have been minimal concern contrast pavement markings and the best patterns or where to install them, pavement marking width on center lines and lower speed/volume roadways, combinations of broken lane line width and cycle pattern changes, long range (distance) requirements for nighttime visibility of the markings (retroreflectivity), lane line extensions through intersections, and the necessity of additional treatments at gore areas or turn lanes. A major consideration regardless of what changes are made is to work toward adopting a minimum uniform policy for pavement marking implementation and maintenance. This will help prepare highways for current and future AVs and vehicles with ADAS features to help promote their use and increase highway safety.

Chapter 2: Data Collection

The research team collected data in both Texas and Minnesota. The Texas data collection involved both closed-course and open-road evaluations. The Minnesota data collection involved data collection at a pavement marking test area and on open roads. The data collection efforts evaluated the markings during the day and at night using several different means of collecting the data. This chapter describes the data collected during each of the data collection efforts.

2.1 Texas Evaluations

2.1.1 Closed-Course Evaluations

The research team initially conducted closed-course testing to better understand how marking width, quality, and broken line marking to gap ratio impacted the ability of the camera system to track the pavement markings. Testing was conducted at the Texas A&M-RELLIS campus in Bryan-College Station, TX. Table 1 indicates the pavement marking properties for the 6 pavement marking types evaluated. The pavement marking panels were laid out in a normal tangent lane configuration with 10 foot long skip markings with gaps of 30 or 40 feet. The markings were laid out as 4 or 6 inch wide markings for the various tests. One set of markings were placed on each side of the lane and three separate longitudinal test areas were setup for each pass with the camera system. Data were collected during the day and at night. Figure 2 provides an example of the setup of the markings during the evaluations.

Table 1. Pavement marking material characteristic data, reflectivity and color

Group	Marking Code	Marking Width (in.)	Measurement Direction	R_L	Q_D	x	y	Y
Set 1 – L	01W-4	4	NB	94	203	0.3297	0.3504	51.99
Set 1 – L	01W-4	4	SB	84	199	0.3297	0.3504	51.99
Set 1 – L	N/A	N/A	Pavement	18	86	0.3680	0.3678	18.59
Set 1 – R	08W-4	4	NB	1404	184	0.3256	0.3447	58.15
Set 1 – R	08W-4	4	SB	1045	192	0.3256	0.3447	58.15
Set 1 – R	N/A	N/A	Pavement	18	78	0.3690	0.37	20.08
Set 2 – L	02W-6	6	NB	136	179	0.3227	0.3419	43.48
Set 2 – L	02W-6	6	SB	127	181	0.3227	0.3419	43.48
Set 2 – L	N/A	N/A	Pavement	20	90	0.3687	0.3681	21.17
Set 2 – R	06W-6	6	NB	312	171	0.3227	0.3419	43.48
Set 2 – R	06W-6	6	SB	279	171	0.3227	0.3419	43.48
Set 2 – R	N/A	N/A	Pavement	18	77	0.3649	0.37	18.46
Set 3 – L	02W-4	4	NB	141	178	0.3221	0.3413	43.06
Set 3 – L	02W-4	4	SB	126	181	0.3221	0.3413	43.06
Set 3 – L	N/A	N/A	Pavement	19	86	0.3686	0.3693	22.20

Group	Marking Code	Marking Width (in.)	Measurement Direction	R_L	Q_D	x	y	Y
Set 3 – R	06W	4	NB	313	173	0.3237	0.3428	38.27
Set 3 – R	06W	4	SB	288	172	0.3237	0.3428	38.27
Set 3 – R	N/A	N/A	Pavement	17	71	0.3738	0.3714	21.41

Figure 2. Images of 10-40 gap pavement markings (Set 2: 06W-6 on left and 02W-6 on right) during day (above) and (Set 2: 08W on left and 01W on right) at night (below)

Video data were collected using the TTI/TAMU Reference Machine Vision (RMV) system. The RMV system was being developed as part of research project [27], "Reference Machine Vision for ADAS Functions." With the objectives of this MnDOT project in mind, specific test scenarios were developed to evaluate the impact of changing the markings and to evaluate the function of the RMV system. The RMV system utilizes a forward-facing camera connected to a laptop. The camera is used to collect images of the forward scene that are later processed in image analysis software. The image analysis software is used to annotate the images for the actual location of the markings and then an algorithm that tracks the markings is run on the image set. The difference between the annotated locations and where the algorithm thinks the markings are located is used to calculate how well the algorithm tracks the markings. It is anticipated that better markings will result in higher levels of agreement between the marking tracking by the lane tracking algorithm and the annotated locations. The system is used to generate quantitative data on tracking markings and serves as an alternative to being able to collect data with actual advanced driver assist systems in vehicles. Figure 3 shows the RMV system camera installed in the test vehicle.

Figure 3. TTI/TAMU RMV system.

Video data were collected using the RMV system during daytime (clear sky conditions, around 10 a.m.) and nighttime (using high beam and low beam separately). Data were collected by driving in two different directions (northbound and southbound). Table 2 identifies the different testing conditions under which the video data were collected.

Table 2. Combinations of driving conditions for pavement marking panel data collection

Vehicle Driving Direction	Marking Spacing	Driving Conditions
Northbound	10-30	Daylight
		Night High Beam
		Night Low Beam
	10-40	Daylight
		Night High Beam
		Night Low Beam
Southbound	10-30	Daylight
		Night High Beam
		Night Low Beam
	10-40	Daylight
		Night High Beam
		Night Low Beam

2.1.2 Open-Road Evaluations

Open-road evaluations in Texas were conducted to determine if contrast markings improved the ability of the RMV system to track the markings during the day. US-290 outside of Houston, TX consists of several contrast marking patterns which could result in varying levels of lane detection performance. The TTI team collected video data using the RMV system during morning driving eastbound. Driving east during the morning hours results in the sun being directly over the horizon adding glare on the camera sensor. The effect of glare is absent when driving westbound.

Some of the contrast marking patterns encountered on US290 include:

1. White pavement marking followed by black (WB) [Figure 4, Figure 5]
2. White pavement markings with a black border (BWB) [Figure 6, Figure 7]
3. Combination of 4-inch and 6-inch-wide white markings (White)

Figure 4. Image of a road segment with white pavement marking followed by black (driving westbound).

Figure 5. Image of a road segment with white pavement marking followed by black (driving eastbound).

Figure 6. Image of a road segment with white pavement markings with a black border (driving westbound).

Figure 7. Image of a road segment with white pavement markings with a black border (driving eastbound).

2.2 Moorhead Area Evaluations

2.2.1 Test Areas

The research team in conjunction with significant efforts from MnDOT project technical liaison Ethan Peterson and MnDOT District 4 personnel, identified an area in MnDOT District 4 that was suitable for the MnDOT sponsored research project titled, “Pavement Marking Patterns and Widths – Human Factor Study.” This same test area was used to test how automated vehicle systems evaluated the markings. The selected roadway was State Highway 336 just east of Moorhead, Minnesota. This highway was scheduled for resurfacing during summer 2022. This made it a good location to test various pavement marking combinations, since the test areas would be eliminated during the resurfacing process.

MN 336 is approximately 2-miles long and connects I-94 on the south end to US10 on the north end. The roadway is 4-lanes divided along most of its length. MN 336 runs mostly north and south with a few minor roadway connections along its length. The pavement surface is Portland cement concrete (PCC) with 4-inch-wide pavement markings. A westbound segment of I-94 was added to the study route to evaluate additional marking configurations. The I-94 segment is a four or six-lane freeway with on and off ramps. Existing pavement markings on I-94 were 4-inches wide. The pavement surface on I-94 was asphalt in Minnesota and PCC in North Dakota. Table 3 provides additional details about the test segments. Figure 8 provides a high-level satellite image of the test segments locations.

The human factors research project was specifically looking at changes to the broken lane line pavement markings. The existing yellow and white edge lines were left in place along MN 336. During the week of May 15, 2022, MnDOT contracted a striping project on the road as part of the research project. The contractors restriped over the northbound broken lane line markings with white 6-inch-wide markings following the patterns as indicated in Table 3. The same was done for the second two southbound segments, except that black contrast markings were also added to these two segments. Segments 1 and 2 southbound required the removal of the existing broken lane line markings due to the change in cycle length of the markings. After removal was completed the new broken lane line markings were applied as indicated in Table 3. The removal of the preexisting markings was very good leaving minor changes to the pavement surface that were not easily noticeable after the new marking patterns were installed. All applied markings were standard paint and beads. The markings along I-94 were all 4-inch-wide markings and were not modified for the study. While the study was being conducted, MnDOT restriped the I-94 WB1 test area as part of their planned restriping activities. This resulted in a portion of the data being collected on an older marking and the other portion of the data being collected on a whiter and brighter marking.

Table 3. Pavement marking test area descriptions

Roadway	Direction	Segment #	Length (approximate in miles)	Marking Cycle Spacing (ft) (marking-gap)	Test Marking Width	Pavement Surface	Additional Information
MN 336	SB	1	0.57	10-30	6-inch	PCC	Removal of current broken lane line stripe required due to new 40 ft cycle length
MN 336	SB	2	0.49	15-25	6-inch	PCC	Removal of current broken lane line stripe required due to new 40 ft cycle length
MN 336	SB	3	0.47	10-40	6-inch	PCC	Application of black bordered contrast (~2-inch black border on the left and right side of the white marking)
MN 336	SB	4	0.66	10-40	6-inch	PCC	Application of black trailing contrast (6-inch black 10 ft long marking after the white marking)
MN 336	NB	1	0.67	12.5-37.5	6-inch	PCC	

Roadway	Direction	Segment #	Length (approximate in miles)	Marking Cycle Spacing (ft) (marking-gap)	Test Marking Width	Pavement Surface	Additional Information
MN 336	NB	2	0.5	20-30	6-inch	PCC	
MN 336	NB	3	0.48	15-35	6-inch	PCC	
MN 336	NB	4	0.44	10-40	6-inch	PCC	
I-94	WB	1	0.5	10-40	4-inch	Asphalt	In Minnesota
I-94	WB	2	0.5	10-30	4-inch	PCC	In North Dakota
I-94	WB	3	0.5	10-30	4-inch	PCC	In North Dakota, black trailing contrast (4-inch black 10 ft long marking after white marking)

Figure 8. Test area layout.

Figure 9 through Figure 19 show images of the pavement markings at the different test areas during the day and at night. The research team was able to capture images while stationary on MN 336, whereas on I-94 the images were captured at highway speed.

Figure 9. Segment 1 SB day (left) and night (right) images.

Figure 10. Segment 2 SB day (left) and night (right) images.

Figure 11. Segment 3 SB day (left) and night (right) images.

Figure 12. Segment 4 SB day (left) and night (right) images.

Figure 13. Segment 1 NB day (left) and night (right) images.

Figure 14. Segment 2 NB day (left) and night (right) images.

Figure 15. Segment 3 NB day (left) and night (right) images.

Figure 16. Segment 4 NB day (left) and night (right) images.

Figure 17. I-94 WB1 day (left) and night (right) images.

Figure 18. I-94 WB2 day (left) and night (right) images.

Figure 19. I-94 WB3 day (left) and night (right) images.

The research team used a handheld (portable) reflectometer to collect reflectivity values on the markings and surrounding pavement along the MN 336 test area. Table 4 provides the average retroreflectivity values (R_L – used as a nighttime visibility surrogate measurement) and the average daytime reflection (Qd - luminance coefficient under diffuse illumination, daytime or nighttime under overhead illumination reflection measurement) for the test markings in each segment. The test markings were only the broken lane line markings. The research team also evaluated R_L and Qd for the other markings and the pavement surface along the test area. Table 5 provides the results of those measurements.

Table 4. MN 336 test area, test marking reflectivity levels

Direction	Segment #	Average Nighttime Retroreflectivity (R_L) (mcd/m^2/lux)	Average Daytime Reflection (Qd) (mcd/m^2/lux)
SB	1	411	199
SB	2	383	197
SB	3	342	190
SB	4	425	202

Direction	Segment #	Average Nighttime Retroreflectivity (R_L) (mcd/m^2/lux)	Average Daytime Reflection (Qd) (mcd/m^2/lux)
NB	1	306	192
NB	2	352	201
NB	3	291	193
NB	4	303	187

Table 5. MN 336 test area, other reflectivity levels

Measurement	Average Nighttime Retroreflectivity (R_L) (mcd/m^2/lux)	Average Daytime Reflection (Qd) (mcd/m^2/lux)
White Edge	123	184
Yellow Edge	69	167
Black Marking	2	83
Pavement Surface	17	100

2.2.2 Evaluation System

The research team acquired an aftermarket Mobileye 8 EyeQ4 test system with extended output protocol. The Mobileye 8 EyeQ4 system was the most common ADAS sensor being installed in vehicles at the time. The aftermarket system acquired by the research team is a unique system that previously had not been available outside of vehicle OEMs. The aftermarket system allowed the research team to collect information from the system based on what the camera was observing. This allowed the research team to collect information such as maximum distance the markings are tracked and marking detection confidence. Both of these metrics are anticipated to positively correlate with marking visibility from the camera system. Figure 20 shows the aftermarket Mobileye system installed next to the OEM system in a 2022 Ford Explorer. Figure 20 is looking toward the windshield from outside the vehicle. The software is run on a laptop and is connected to the camera system with a USB cord. The software collects real-time data as the vehicle is driven through the test areas. The data later needs to be processed to determine the output values.

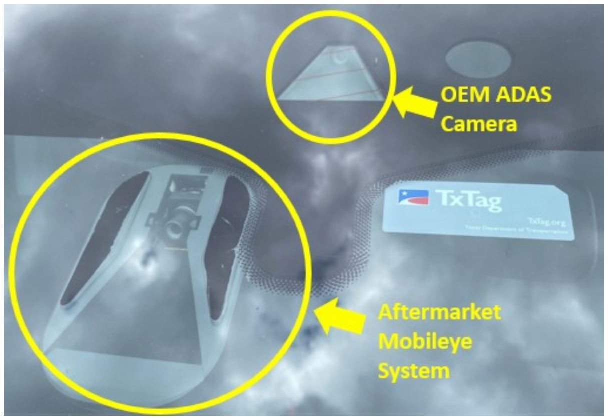


Figure 20. Aftermarket and OEM ADAS.

2.2.3 Evaluations Conducted

The research team used the Mobileye system to evaluate the markings in each test segment. The test vehicle was driven at highway speeds through each segment while data were being collected. Due to traffic during data collection, multiple runs were conducted such that a clear road ahead was observed and vehicles in adjacent lanes did not affect the markings being observed. Passes through the test segments where other vehicles interfered with the forward view of the markings from the camera were removed from the data set. Data were collected in tangent sections only.

2.3 Minneapolis Area Evaluations

This portion of the testing was conducted on open roads utilizing existing pavement markings. This allowed for testing in actual real-world conditions and allowed the research team to observe configurations that had not been evaluated during previous data collection efforts. The following list indicates the pavement marking configurations of interest to the project:

- Markings with varying levels of daytime and nighttime visibility
- 4-inch vs 6-inch wide markings
- Contrast markings
- Varying broken lane line configurations (skip length, gap length, cycle length)
- Line extensions across ramps and turn bays
- Gore areas

The research team requested specific test areas from the research project’s Technical Advisory Panel to include in the testing. The locations the panel provided were evaluated in addition to other test areas the research team found while viewing satellite imagery and while driving around during the first day of testing.

2.3.1 Test Locations

The research team evaluated pavement markings at 37 different test areas in the Minneapolis area. Figure 21 shows the approximate location of these test areas. The test areas ranged in length between a few tenths of a mile to several miles in length.

Table 6 provides details about the pavement marking test areas. Information includes the factors of interest at each test area, details about the location, and which lane was driven in during the data collection.

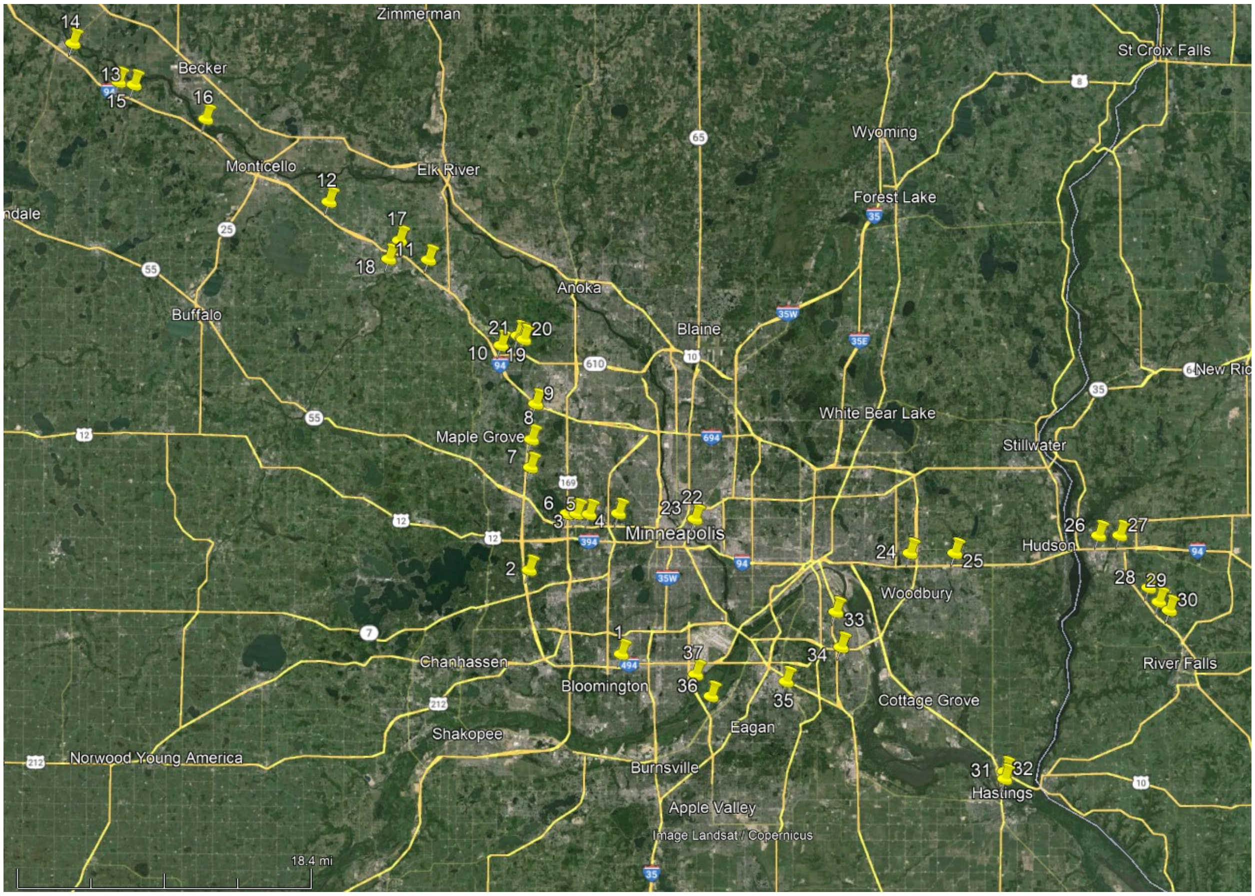


Figure 21. Minneapolis area test site locations.

2.3.1.1 Retroreflectivity Data Collection

The research team was unable to collect handheld retroreflectivity at the test location due to traffic. The research team was unable to bring its mobile retroreflectometer because it requires a different vehicle than the test vehicle used during the data collection. The research team worked with MnDOT's pavement marking condition specialist to collect the retroreflectivity data. MnDOT was able to collect mobile pavement marking retroreflectivity data at several of the locations. This data was used to rate the quality of the markings at night to help identify differences in the resulting lane tracking data. MnDOT was only able to collect retroreflectivity data on a few of the sites. The research team utilized image analysis to gather grayscale levels of the images collected in these sections to develop a brightness scale based on the collected retroreflectivity data. The grayscale analysis allowed the research team to approximate the brightness level of the markings in all sections.

Table 6. Minneapolis area test site information

Site Number	Roadway	Travel Direction	Lane Driven In	Start	End	Factors Evaluated
1	I-494	WB	2nd from left	Bridge before exit 6	exit 7a ramp	width, cycle, quality
2	I-494	NB	2nd from left	MN 7 bridge	Minnetonka bridge	width, cycle, quality, contrast
3	MN 55	EB	left	US 169 bridge	just after Boone	quality, left turn bays
4	MN 55	EB	left	MN 100 bridge	Theodore Wirth	left turn bays
5	MN 55	WB	left	Glenwood ave	Shore drive	quality, left turn bays
6	MN 55	WB	left	Glenwood ave	Shore drive	quality, left turn bays
7	I-494	NB	right	0.2 mi before exit 23 ramp	after exit 23 on ramp ends	ramp area
8	I-494	NB	2nd from left	overhead CMS	top of hill	width, cycle, quality, contrast
9	I-494	NB	2nd from left	at dash marks on left for 494/94 interchange	after merge with I-94 WB	interchange area
10	I-94	WB	2nd from left	maple groove bridge	610 bridge	width, cycle, quality, contrast
11	I-94	WB	2nd from left	CMS just before mile marker 206	exit 205 ramp	width, cycle, quality, contrast
12	I-94	WB	left lane	0.2 mi before MnRoad split	after MnRoad merge	MnRoad merges
13	I-94	WB	right lane	exit 183 1/2 mile sign	exit 183 bridge	ramp area, quality
14	I-94	EB	2nd from left	after exit 178 on ramp	top of hill	width, cycle, quality, contrast
15	I-94	EB	right lane	mile marker 183 (just before exit 183 Hasty silver creek)	just past off ramp	ramp area
16	I-94	EB	2nd from left	mile marker 190	exit 193 2 miles sign	width, cycle, quality, contrast
17	I-94	EB	2nd from left	at over head CMS	exit 205 1/2 mile sign	width, cycle, quality, contrast
18	MN 241	EB	left	Edgewood dr	oakwood pkwy	left turn bays
19	CR 81	EB	right	before maple grove turn lanes	after tunnel	intersection, gore area
20	CR 81	EB	right	before maple grove turn lanes	fenbrook	gore area
21	CR 81	WB	left	before fernbrook turn lanes	after maple grove	intersection, left turn bay
22	I-35W	NB	2nd from left	after work zone area ends	university ave bridge	width, cycle, quality, contrast

Site Number	Roadway	Travel Direction	Lane Driven In	Start	End	Factors Evaluated
23	I-35W	SB	2nd from left	university ave bridge	before work zone area begins	width, cycle, quality, contrast
24	I-94	EB	2nd from left	MN 120 bridge	I-494 SB exit ramp	width, cycle, quality, contrast
25	I-94	EB	2nd from left	Radio dr bridge	Woodbury dr bridge	width, cycle, quality, contrast
26	I-94	EB	2nd from left to right ramp	Exit 2 ramp	after merge with WI 35	width, cycle, quality, contrast
27	I-94	EB	3rd from left to right ramp	Exit 2 ramp	after merge with WI 35	width, cycle, quality, contrast
28	WI 35	SB	right	0.25 mi before Glover	radio dr ramp	right turn bay
29	WI 35	SB	right	radio dr ramp	after radio dr on ramp	ramp area
30	WI 35	NB	right	0.25 mi before radio exit	after radio on ramp	ramp area
31	US 61	SB	right	at Hastings sign	at traffic light after bridge	width, cycle, quality, contrast, right turn bay
32	US 61	NB	right	after traffic light before bridge	at bridge over railroad tracks	width, cycle, quality, contrast, right turn bay
33	US 52	NB	right	0.25 mi before Wentworth exit	after Wentworth on ramp	off ramp area
34	US 52	SB	2nd from left	at exit 125A exit ramp	after Upper 55th st on ramp	on ramp area
35	Yankee Doodle Rd	WB	right	Elrene rd	Lexington Ave	width, cycle, quality, turn bay
36	US 77	NB	right	at cliff rd bridge	new asphalt pavement on other side of lake	width, cycle, quality, ramp area
37	US 77	NB	right	new asphalt pavement on other side of lake	Killebrew dr exit ramp	width, cycle, quality

2.3.2 Evaluation Systems

The research team used six camera-based systems to evaluate the markings in the Minneapolis area. These included the previously described Mobileye 8 EyeQ4 system and the TTI/TAMU RMV system. In addition to these systems the research team used four vehicles with varying levels of driver assist systems. All four vehicles were 2022 model year vehicles. A Ford Explorer with Co-Pilot 360 Assist+ system, a Tesla Model Y with Autopilot lane centering, a Toyota RAV4 with Toyota Safety Sense 2.0 (TSS 2.0) lane centering, and a Toyota 4Runner with Toyota Safety Sense P (TSS P) lane departure warning system were evaluated. Each of these systems were able to operate in each of the selected test areas. The research team sought to test a hands-free driver assist system such as General Motors Super Cruise or Ford's Blue Cruise. The research team was unable to evaluate either of these systems. These systems were unlikely to be functional on all of the test sections due to the varying roadway classifications included in the testing.

2.3.2.1 Ford Co-Pilot 360 Assist+

The research team used a 2022 Ford Explorer with a Co-Pilot 360 Assist+ system to evaluate the markings. Figure 20 shows the OEM camera used for the Co-Pilot 360 Assist+ system. The Co-Pilot 360 Assist+ system provides lane centering capability when the system is active and the markings are able to be tracked. The vehicle operator maintained a light touch on the steering wheel to keep the system active but allowed the vehicle to provide the steering during testing. The research team used two GoPro cameras to record the forward scene and the instrument cluster. The instrument cluster indicated when the system was active and if lane centering functions were working. Figure 22 shows the instrument cluster with the Co-Pilot 360 Assist+ system active and tracking the markings. The system is active and tracking the markings when the lines are green. The lines are gray when it is not tracking.

Figure 22. Ford Co-Pilot 360 Assist+ gauge cluster.

2.3.2.2 Tesla Autopilot

The research team used a 2022 Tesla Model Y to evaluate the pavement marking test areas. The Tesla Autopilot system is one of the most advanced systems in a production vehicle. The system uses multiple forward-facing cameras to provide lane centering features. Figure 23 provides an image of the Tesla forward facing cameras. The Tesla was driven with Autopilot enabled. This allowed the vehicle to provide lane centering functions. The vehicle operator maintained a light touch on the steering wheel to keep the system active but allowed the vehicle to provide the steering during testing. An interior video camera was used to monitor the vehicle's steering as it proceeded through the test areas. Figure 24 shows the Tesla interior with the interior camera setup. Yellow tape was placed on the steering wheel to help observe system input to the steering of the vehicle. Figure 25 shows the Tesla information screen while markings are being tracked and lane centering functions are active as indicated by the blue lines on the screen.

Figure 23. Tesla front facing cameras.

Figure 24. Tesla interior.

Figure 25. Tesla information screen.

2.3.2.3 Toyota Safety Sense 2.0 (TSS 2.0)

The research team used a 2022 Toyota RAV4 to evaluate most of the pavement marking test areas. The RAV4 uses a single forward-facing camera like the 4Runner described in the next section. The evaluated system provides lane centering driver assistance when the system is active. Figure 26 provides an image of the RAV4 instrument gauge cluster. The lane centering feature is active when both the white bars and blue bars are indicated as is displayed in Figure 26. If the blue bars are not present, then lane centering is not functioning. If only the white bars are present, then the system will only provide lane keeping assistance. If neither the white or blue bars are present then the system is not providing any steering assistance. The vehicle operator maintained a light touch on the steering wheel to keep the system active but allowed the vehicle to provide the steering during testing. An interior video camera was used to monitor the vehicle steering as it proceeded through the test areas.

Figure 26. Toyota TSS 2.0 gauge cluster.

2.3.2.4 Toyota Safety Sense P (TSS P)

The research team used a 2022 Toyota 4Runner to evaluate most of the pavement marking test areas. The 4Runner has a lower level of ADAS compared to other test vehicles. The 4Runner uses a single forward-facing camera as displayed in Figure 27. The evaluated system only provides lane departure warning when the system senses the vehicle leaving the lane. Figure 28 provides several images of the 4Runner instrument gauge cluster. The top image shows the lane departure warning system when no markings are being tracked as indicated by the empty lines. The middle image shows the system when it is tracking markings on both sides of the vehicle as indicated with the filled in white lines. The bottom image shows the system when the warning is being provided for a lane departure with the orange line. When operating the vehicle the operator maintained steering of the vehicle but allowed the vehicle to encroach on markings to test when the system would sense a lane departure. An interior video camera was used to monitor the vehicle steering as it proceeded through the test areas.

Figure 27. Toyota forward facing camera.

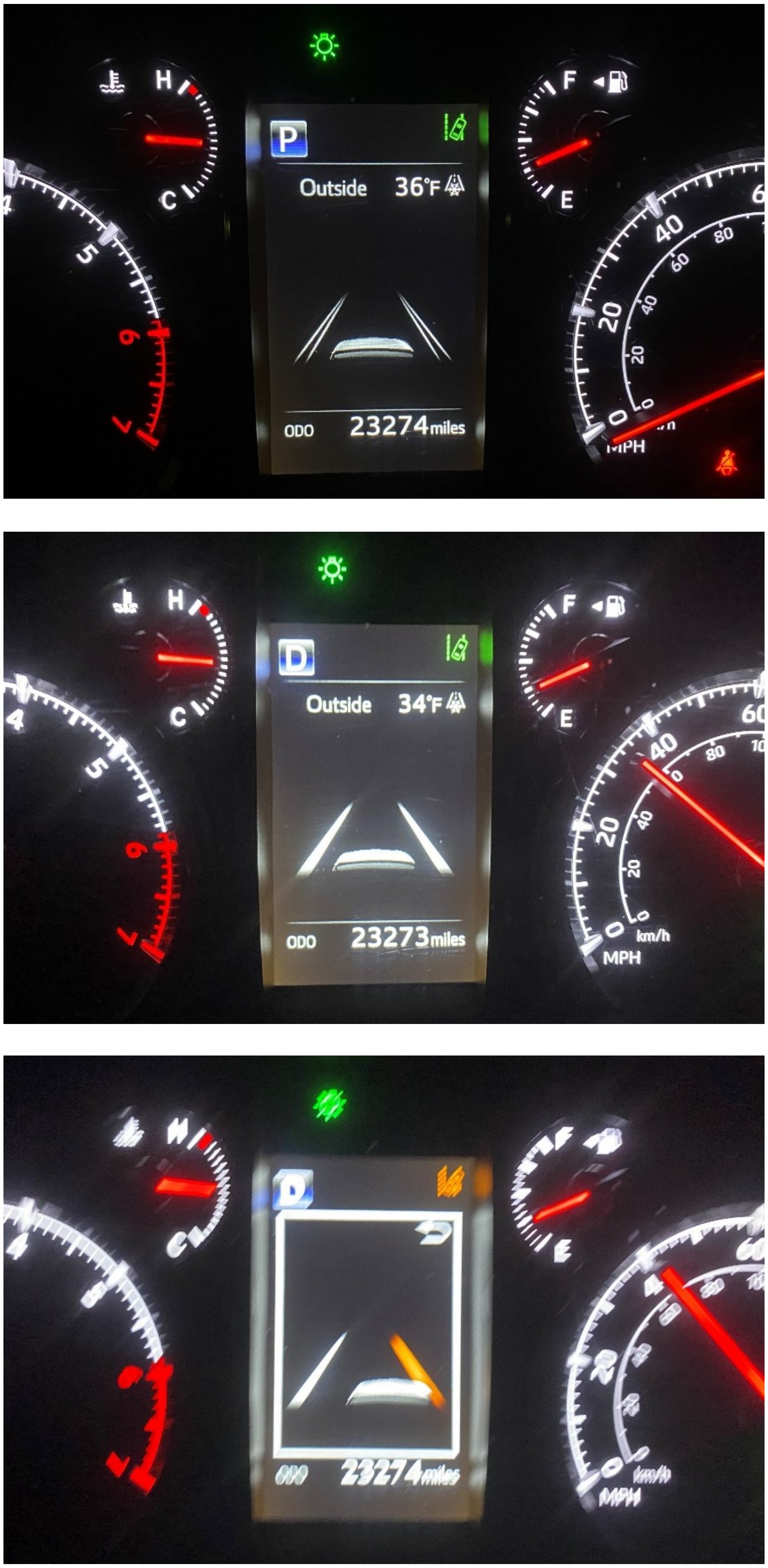


Figure 28. Toyota TSS P gauge cluster.

2.4 Evaluations Conducted

The research team used the six data collection systems to evaluate the marking test areas. The Mobileye 8, RMV, Ford Co-pilot, and Tesla Autopilot systems were used to evaluate each of the test areas. The two Toyota systems were used to evaluate the majority of the test areas. Due to the number of test areas all of the data could not be collected with each system within the time allotted for data collection efforts.

Evaluations were conducted during the day and at night. Daytime data collection occurred with the lighting conditions present. This resulted in some data being collected during cloudy days and other data being collected during sunny days. Some data were specifically collected with sun glare conditions. All nighttime evaluations were conducted under low beam illumination. Multiple runs were conducted in some sections if traffic conflicts, traffic signals, or other obstructions limited the data collection efforts. During all testing the vehicle operator maintained a light touch on the steering wheel to keep the systems active but allowed the vehicle to provide the steering during testing. The goal was to test the ADAS ability to use the markings provided to guide the vehicle through the test areas.

Chapter 3: Data Analysis

3.1 Texas Data Analysis

The research team analyzed the data collected on the pavement marking samples on the closed course and open-road test areas. The main areas of interest were how the marking width, quality, broken line marking to gap ratio, and contrast pattern impacted the RMV camera systems ability to track the pavement markings during the day and at night.

3.1.1 Measures of Effectiveness

The RMV system algorithm performance is measured in terms of the conventional pixel-accuracy based performance metrics such as True Positives (TP), False Positive (FP), False Negative (FN), and F-Measure. To evaluate if a lane marking is successfully detected, the lane markings are detected as lines with width equal to 30 pixels. The intersection-over-union (IoU) metric is calculated between the ground truth annotation (images collected during data collection that were manually annotated to indicate the location of the markings) and the lane prediction from the algorithm. The lane predictions where IoUs are larger than 0.5 are viewed as TP. Performance of the algorithms is related to Precision (P), Recall (R), and F1 scores on a linear scale. Higher scores represent better lane detection performance of the algorithms, i.e. the algorithm correctly predicts the lane position in comparison to the actual lane position.

Based on the predictions, the F-Measure is calculated as:

$$F - measure = \frac{(1+\beta^2)(P * R)}{\beta^2(P+R)}$$

Where,

$$Precision\ (P) = \frac{TP}{(TP+FP)} = \frac{True\ Positives}{Total\ Detections\ Marked\ Positive}$$

$$Recall\ (R) = \frac{TP}{(TP+FN)} = \frac{True\ Positives}{Total\ Positives\ in\ Ground\ truth}$$

β = 1, which gives the harmonic mean (F1-measure).

3.1.2 Closed Course Evaluation Results

The following factors were considered by the research team to evaluate the performance of markings using the RMV system.

- Factor 1: Lane line spacing configuration: 10-30 vs 10-40. (Compare typical MUTCD spacing to typical MnDOT spacing)
- Factor 2: Lighting Conditions: daytime vs nighttime (high beam headlamps [HB] vs low beam headlamps [LB])
- Factor 3: Marking Material & Width [01W-4, 02W-4, 02W-6, 06W-4, 06W-6, 08W-4]

A statistical analysis approach was selected to analyze the closed course data and investigate the effect of different marking and evaluation conditions on LD performance. All of the factors for the RMV system development study [27] were included in an analysis of variance (ANOVA) model to analyze the individual factors as well as the effect of two-way interactions to identify factors with statistical significance. Table 7 lists the factors and levels that were considered in the ANOVA model with F1 scores as the response variable. Driving direction and evaluation area were not investigated further for the MnDOT research project. The analysis was carried out using the JMP software suite. ANOVA was conducted separately for nighttime and daytime data. Factors without statistical significance in their two-way interaction were removed from consideration in the final ANOVA model.

Table 8 and Table 9 list the statistically significant factors as predicted by the ANOVA model for the nighttime and daytime testing. These are the full results from the RMV system development study [27]. The factor level testing results applicable to the MnDOT study are also provided in the following subsections.

Table 7. Factors considered in the ANOVA model

Factor	Level
Spacing	10-30 spacing, 10-40 spacing
Lighting Condition	Day, Night-LB, Night-HB
Driving Direction	SB, NB
Evaluation Area	Near, Full Length, Far
Marking and Width	01W-4, 02W-4, 02W-6, 06W-4, 06W-6, 08W-4

Table 8. Statistically significant factors during nighttime based on ANOVA model for LD performance (F1-scores)

Source	Parameters	Degrees of Freedom	Sum of Squares	F Ratio	Prob > F
Spacing	1	1	0.74899927	682.2828	< 0.0001*
Lighting Condition	1	1	0.00107002	0.9747	0.3255
Driving Direction	1	1	0.02126749	19.3731	< 0.0001*

Source	Parameters	Degrees of Freedom	Sum of Squares	F Ratio	Prob > F
Evaluation Area	2	2	0.04663060	21.2385	< 0.0001*
Marking	5	5	0.02830087	5.1560	0.0003*
Spacing*Light	1	1	0.00490784	4.4707	0.0365*
Spacing*Driving Direction	1	1	0.02145441	19.5434	< 0.0001*
Spacing*Marking	5	5	0.13685526	24.9330	< 0.0001*
Light*Marking	5	5	0.01803733	3.2861	0.0081*

Note: The * in the Prob > F column indicates statistically significant results at a 95% confidence level.

Table 9. Statistically significant factors during daytime based on ANOVA model for LD performance (F1-scores)

Source	Parameters	Degrees of Freedom	Sum of Squares	F Ratio	Prob > F
Spacing	1	1	0.08099427	62.8570	< 0.0001*
Driving Direction	1	1	0.03735097	28.9868	< 0.0001*
Evaluation Area	2	2	0.14112119	54.7597	< 0.0001*
Marking	5	5	0.03871050	6.0084	0.0002*
Spacing*Driving Direction	1	1	0.04192916	32.5398	< 0.0001*
Spacing*Marking	5	5	0.02143691	3.3273	0.0106*

Note: The * in the Prob > F column indicates statistically significant results at a 95% confidence level.

3.1.2.1 Factor 1: Lane line spacing configuration: 10-30 vs 10-40:

Figure 29 shows that LD performance was higher for the 10-30 configuration as compared to 10-40 configuration during both day and night. This is likely due to the fact that closer lane markings result in more marking for the LD algorithms to detect, leading to higher LD performance. Table 10 lists the least square mean value of F1 scores output for the different spacing configurations. Figure 30 and Figure 31 provide the results of the 2-way interaction of spacing and marking material for LD performance during daytime and nighttime respectively.

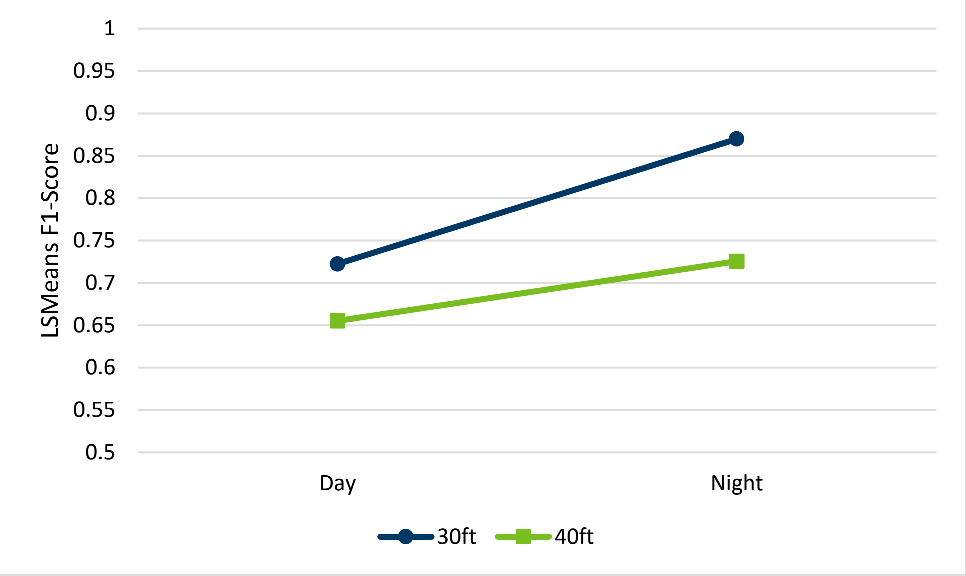


Figure 29. Effect of marking spacing and lighting condition on LD performance.

Table 10. Least square means table comparing the effect of marking spacing and lighting condition on LD performance

Level	Least Sq Mean	Std Error	Mean
10-30 – Daytime	0.72230940	0.00598273	0.722309
10-40 – Daytime	0.65522973	0.00598273	0.655230
10-30 – Nighttime	0.86972840	0.00406634	0.869728
10-40 – Nighttime	0.72548716	0.00406634	0.725487

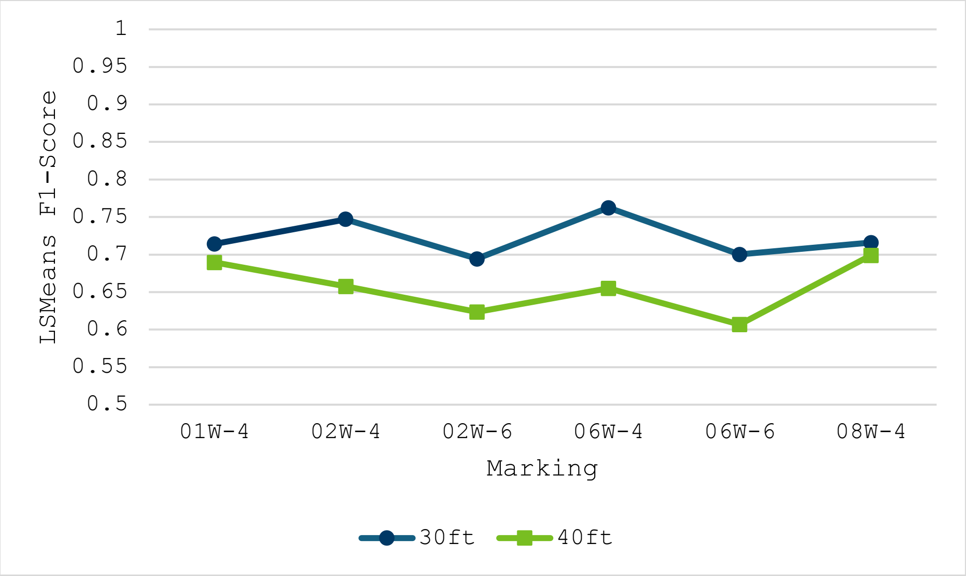


Figure 30. Effect of two-way interaction of marking spacing on marking material for daytime LD performance.

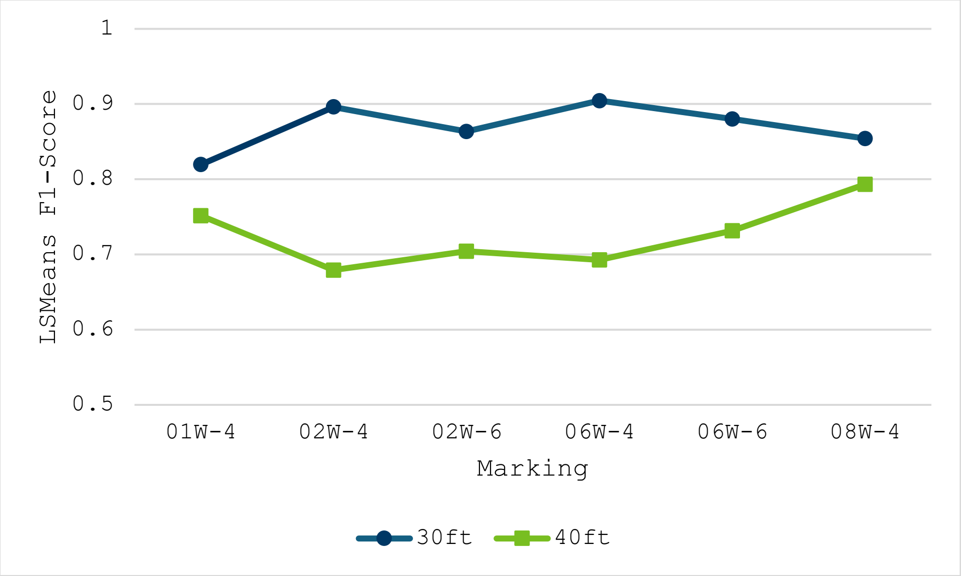


Figure 31. Effect of two-way interaction of marking spacing on marking material for nighttime LD performance.

3.1.2.2 Factor 2: Lighting Condition – Day vs Night (High Beam Headlamps vs Low Beam Headlamps):

Overall the nighttime LD performance was observed to be better compared to the daytime performance (Figure 29). Figure 32 displays the effects of marking spacing and nighttime illumination (high beam vs. low beam vehicle headlamps). The spacing has a much larger effect than nighttime illumination.

Figure 33 captures the effect of the two-way interaction of nighttime illumination on marking material LD performance. Marking 08W is expected to have the highest LD performance, whereas 01W is expected to have the lowest LD performance based on retroreflectivity levels. Even though there is a general increasing trend for both high beam and low beam data, the 08W LMS F1 score for low beam illumination is comparatively lower.

Within each pair of markings, the markings with higher R_L values generally resulted in better LD performance (had higher F1 scores as compared to markings with lower R_L values) for pairwise evaluations during nighttime(See Figure 33).

Table 11 shows the least square means table comparing the effect of nighttime illumination on LD performance. The performance difference between high and low beam is negligible.

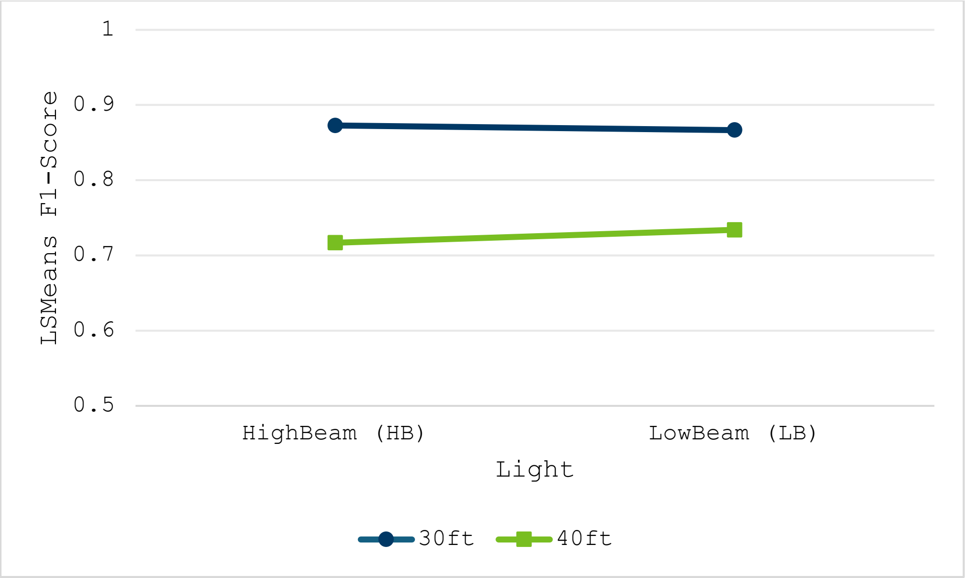


Figure 32. Effect of nighttime illumination on LD performance.

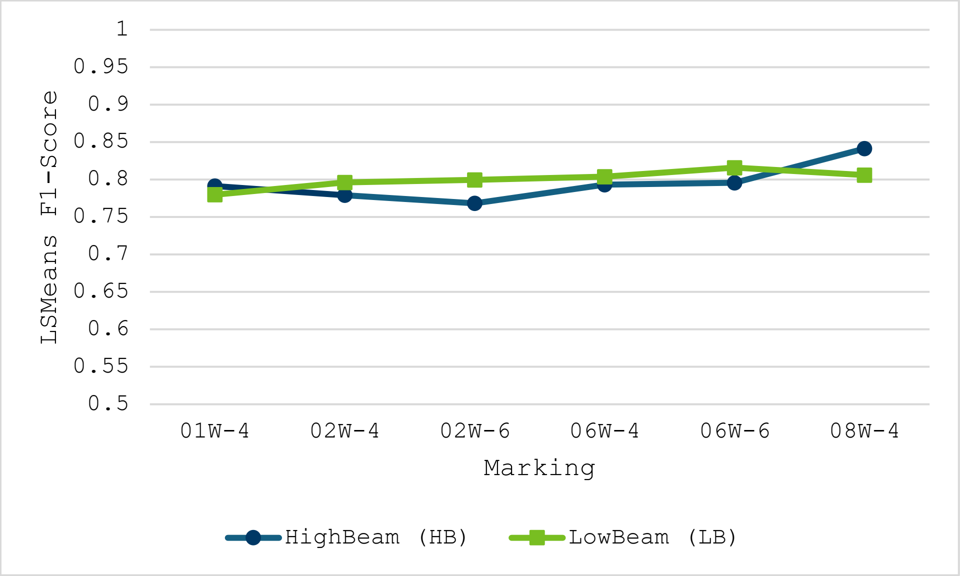


Figure 33. Effect of two-way interaction of nighttime illumination on marking material for LD performance.

Table 11. Least square means table comparing the effect of nighttime illumination on LD performance

Level	F1 Score (LS Mean)	Std Error	Mean
High Beam (HB)	0.79488186	0.00390474	0.794882
Low Beam (LB)	0.80033371	0.00390474	0.800334

3.1.2.3 Factor 3: Marking Material [01W, 02W, 06W, 08W]

Lane markings with higher R_L values generally exhibited better LD performance during the nighttime (higher F1 scores). Markings 01W, 02W, 06W, and 08W had R_L values that increased as their marking code number increased (Table 12). The increase in F1 score can be observed in Figure 34, where nighttime F1 scores appear to be increasing with increasing retroreflectivity (R_L) values from 01W to 08W (Figure 34).

Set 1 contains 08W-4 marking material panels, which have the highest R_L value (~1200) and 01W-4 marking material panels, which have the lowest R_L value (~90). The resulting LD performance of 08W-4 was observed to be just 5% better than that of 01W-4 (see Table 12). There could be several factors that may have influenced this behavior.

- The increase in R_L values may not necessarily convert to improved LD performance by similar magnitudes.
- F1 scores for individual performances of 01W and 08W were extracted by processing an image collected as the vehicle drove between 01W and 08W (Set 1). There may exist some co-operative interactions between 01W and 08W that improved the individual F1 score of 01W marking, or conversely, 08W's performance may have been reduced due to 01W, leading to the two markings having similar F1 scores. Further investigations are required to better understand this observation.

During the daytime, all 4-inch-wide markings had similar F1 scores. This result is likely influenced by the Q_d value, which is a property that may affect LD performance during the daytime. The Q_d values are similar (Q_d ~ 170 to 200 as seen in Table 1) for these markings. A limitation of this evaluation is that the Q_d values of the samples chosen do not vary much between samples.

LD performance of the 6-inch-wide markings were observed to be generally lower than that of the 4-inch-wide markings during daytime (Figure 34). Researchers expected that the performance of the LD algorithms would be higher with the wider 6-inch markings since the wider markings provide the algorithm more features to detect lanes. However, this trend was not clearly observed based on the limited set of data collected.

Table 12. Least square means comparing the effect of marking material and width on LD performance, day (top) and night (bottom)

Level (Day)	F1 Score (LS Mean)	Std Error	Mean
01W-4	0.702	0.0104	0.702
02W-4	0.702	0.0104	0.702
02W-6	0.659	0.0104	0.659
06W-4	0.709	0.0104	0.709
06W-6	0.654	0.0104	0.653
08W-4	0.707	0.0104	0.707

Level (Night)	F1-Score (LS Mean)	Std Error	Mean
01W-4	0.786	0.00676	0.786
02W-4	0.788	0.00676	0.788
02W-6	0.784	0.00676	0.784
06W-4	0.799	0.00676	0.799
06W-6	0.806	0.00676	0.806
08W-4	0.824	0.00676	0.824

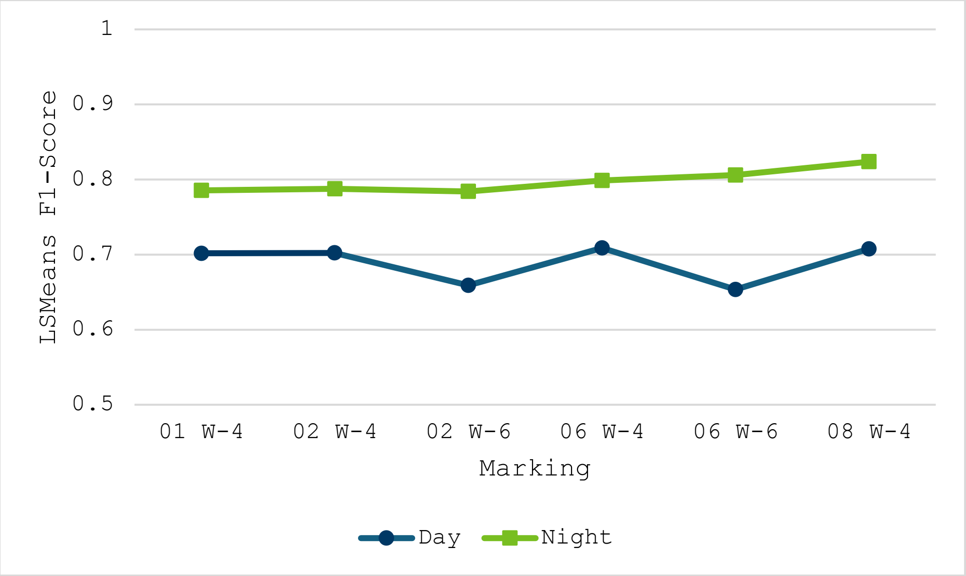


Figure 34. Effect of marking material for LD performance.

3.1.3 On-road Contrast Marking Evaluations

The results of the performance of contrast marking on the RMV system are presented in Table 13. LD performance was observed to be lower while driving east as compared to driving west for all the contrast marking patterns. The WB marking pattern, white followed by black, was observed to perform the best among all the type of contrast marking patterns observed on US290.

Table 13. LD performance of different pavement marking on US 290

Marking	Driving Direction	Precision (P)	Recall (R)	F1 - Measure
BWB	East	0.56824	0.63833	0.601249226
BWB	West	0.59065	0.648249	0.618110551
WB	East	0.576458	0.785637	0.6649855310
WB	West	0.849475	0.917485	0.882171153
White only	East	0.506709	0.521368	0.513933991

3.2 Moorhead Area Data Analysis

The Mobileye system used in this study collects several parameters including detection confidence and end of line distance for both left side and right side pavement markings. The research team used these values to determine how well the pavement markings on the test deck performed. Detection confidence is presented as a percentage and shows how well the Mobileye system detects the pavement marking. Detection confidence values for left side markings were used to see how well the Mobileye system was able to detect the test pavement markings when data were collected from the right lane.

3.2.1 Detection Confidence Data Analysis

Figure 35 shows the detection confidence values for the pavement marking test areas. Table 14 shows average detection distance values during the day and night. We can see that WB1 had lower values prior to restriping. The first westbound segment was restriped during the study and WB1 represents before restriping conditions while WB1New represents after restriping conditions. Pavement markings at WB1 were not very reflective and this resulted in the slightly low nighttime detection confidence value. The other WB areas had slightly lower values than the north and southbound areas on the test deck, likely due to the older markings. SB1 is notably lower than the other test deck marking results. This segment had a slight curve which resulted in the shortest tangent section. The smaller sample size may have affected the results.

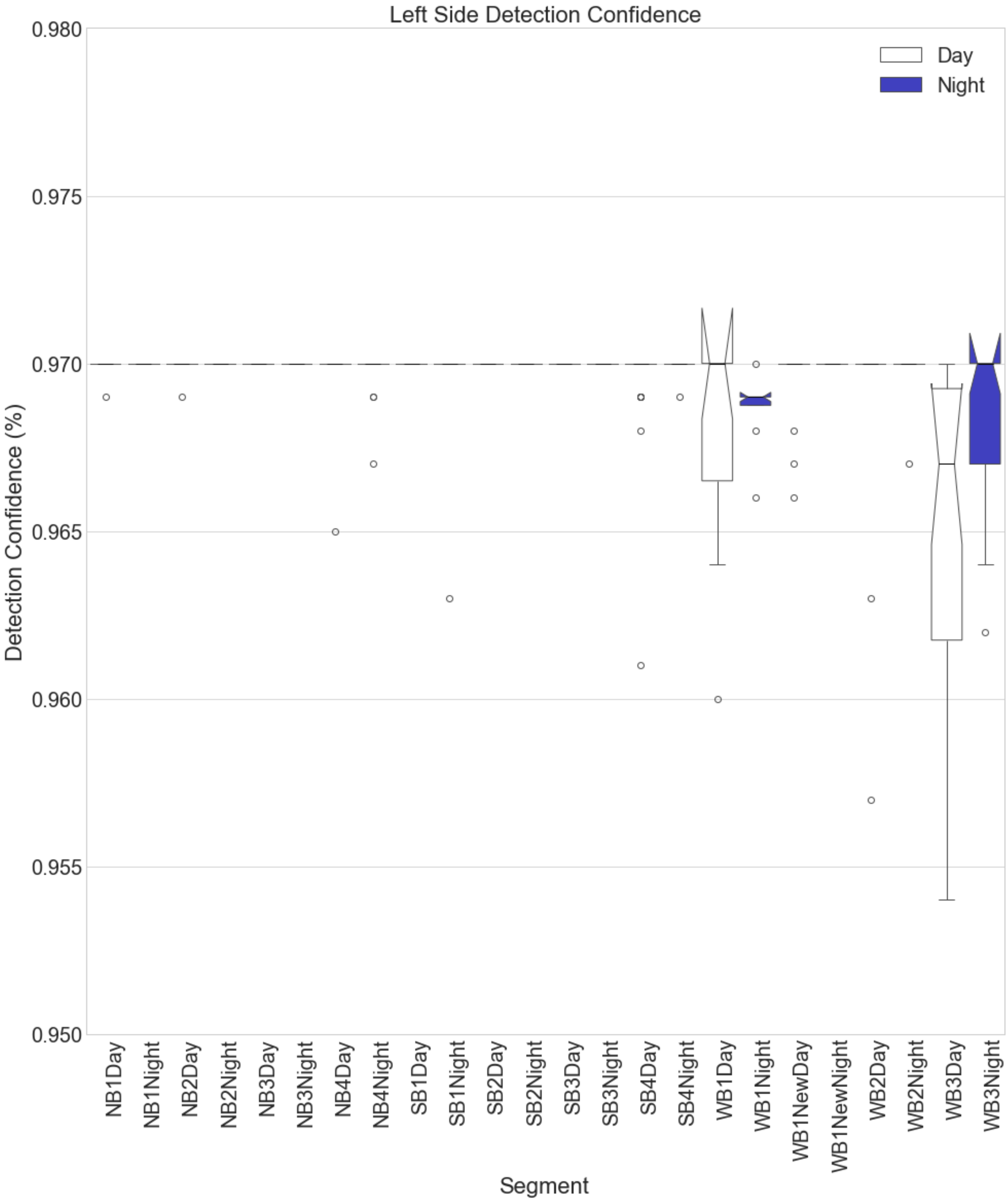


Figure 35. Left side detection confidence values in the range of (0.95, 0.98) in study segments.

Table 14. Average left side detection confidence, day and night

Segment	Day	Night	Average
NB1	0.9700	0.9700	0.9700
NB2	0.9700	0.9700	0.9700
NB3	0.9700	0.9700	0.9700
NB4	0.9698	0.9698	0.9698
SB1	0.9601	0.9658	0.9629
SB2	0.9700	0.9700	0.9700
SB3	0.9700	0.9700	0.9700
SB4	0.9695	0.9700	0.9697
WB1	0.9664	0.9686	0.9673
WB1New	0.9695	0.9700	0.9697
WB2	0.9693	0.9699	0.9696
WB3	0.9625	0.9684	0.9656
Average	0.9682	0.9672	0.9677

The study team observed that the data for all segments were highly skewed with the majority of values being 0.96 and 0.97. Figure 36 shows the histogram of left side detection confidence values.

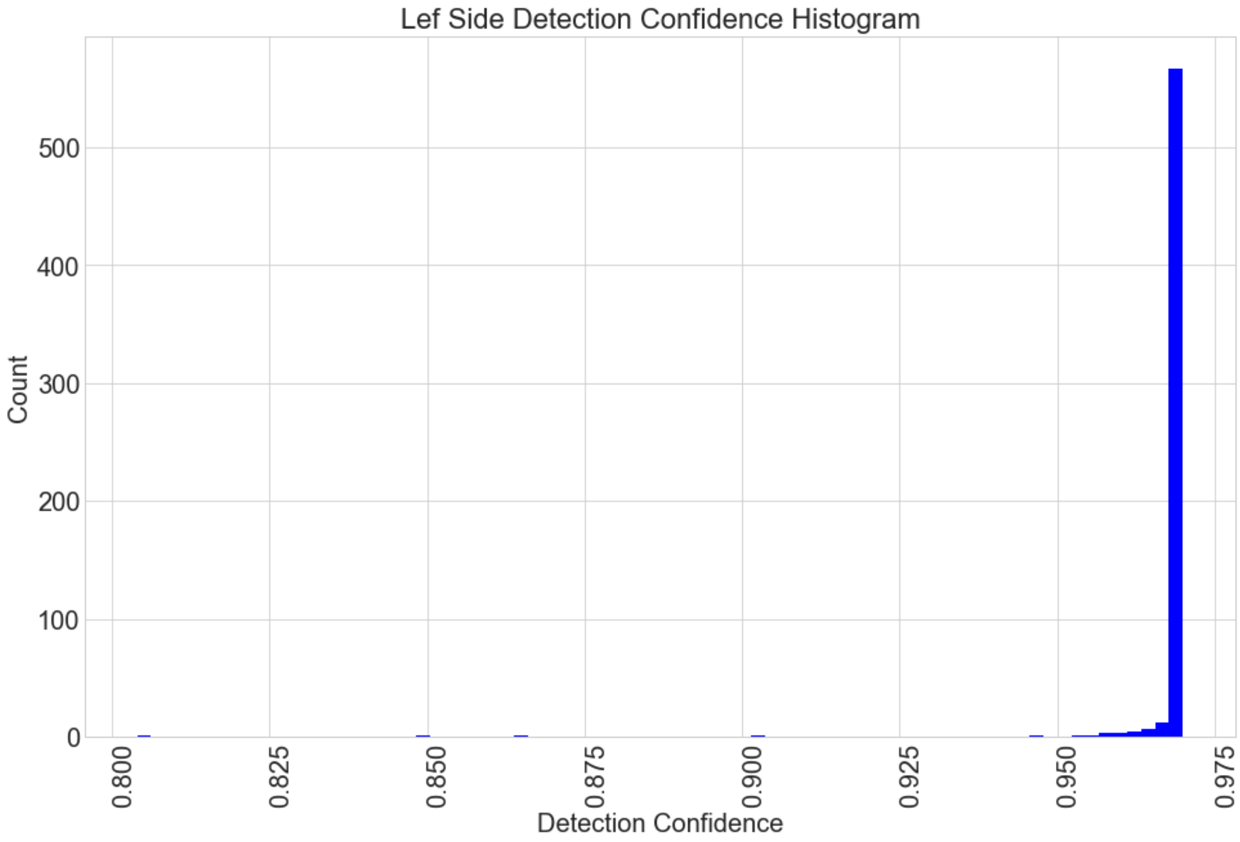


Figure 36. Left side detection confidence histogram.

Transforming the data still resulted in skewed distributions. Although the shape of the histogram implies non-normality, a Shapiro-Wilk test was conducted to confirm that the data were not normally distributed. The results of the Shapiro-Wilk test are shown in Table 15 and show that the data were not normally distributed.

Table 15. Shapiro-Wilk normality test results for left side detection confidence

Test statistic	p-value
0.05213	0.00000

Many of the statistical methods such as linear regression, Anova, Tukey's HSD and t-test have a normality assumption, but it has been shown that these methods could be robust against non-normality except when the response variable is highly skewed. Since the response variable (left side detection confidence) has a skewed distribution with a long tail, the study team did not use these methods to analyze the data. While distribution of the left side detection confidence values did not allow formal analysis of the data, the fact that different period (day/night), segment, cycle length, and other factors generally had high detection confidence values, implies that the markings evaluated were not overly dependent of these factors given the condition of the markings. As mentioned earlier most of the segments' pavement markings were in good condition and there is not enough data from different pavement conditions to draw conclusions that the configuration or pattern impacted the results.

3.2.2 End of Line Detection Distance Data Analysis

In addition to detection confidence, the study team investigated the impact of the independent variables on the end of line detection distance values for the test markings. The end of line values show how far ahead the Mobileye system is capable of detecting the pavement markings and is presented in meters. Figure 37 shows a boxplot of the end of line values for day and night. Figure 38 shows a histogram of the left side end of line values.

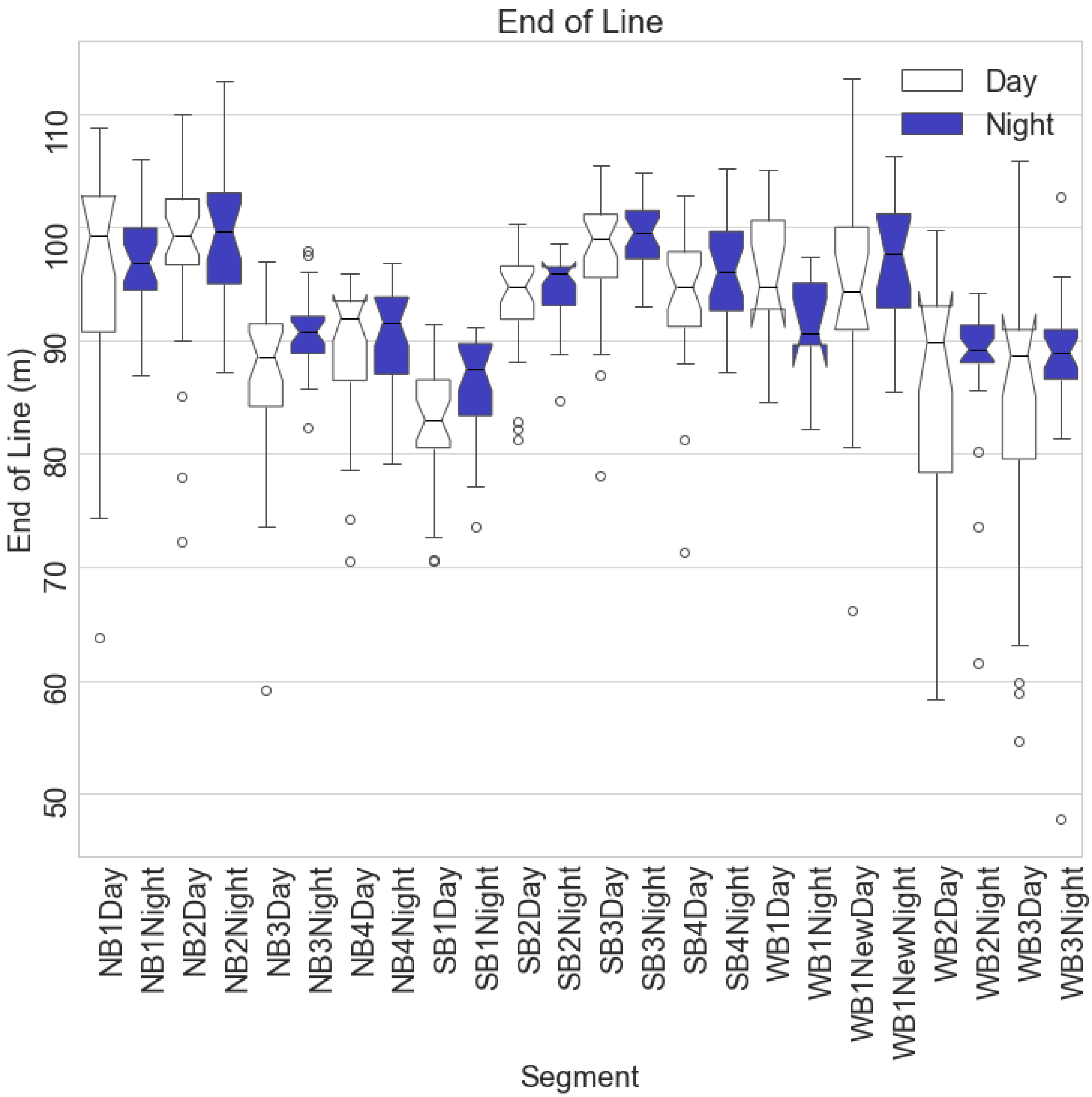


Figure 37. Left side end of line values in study segments.

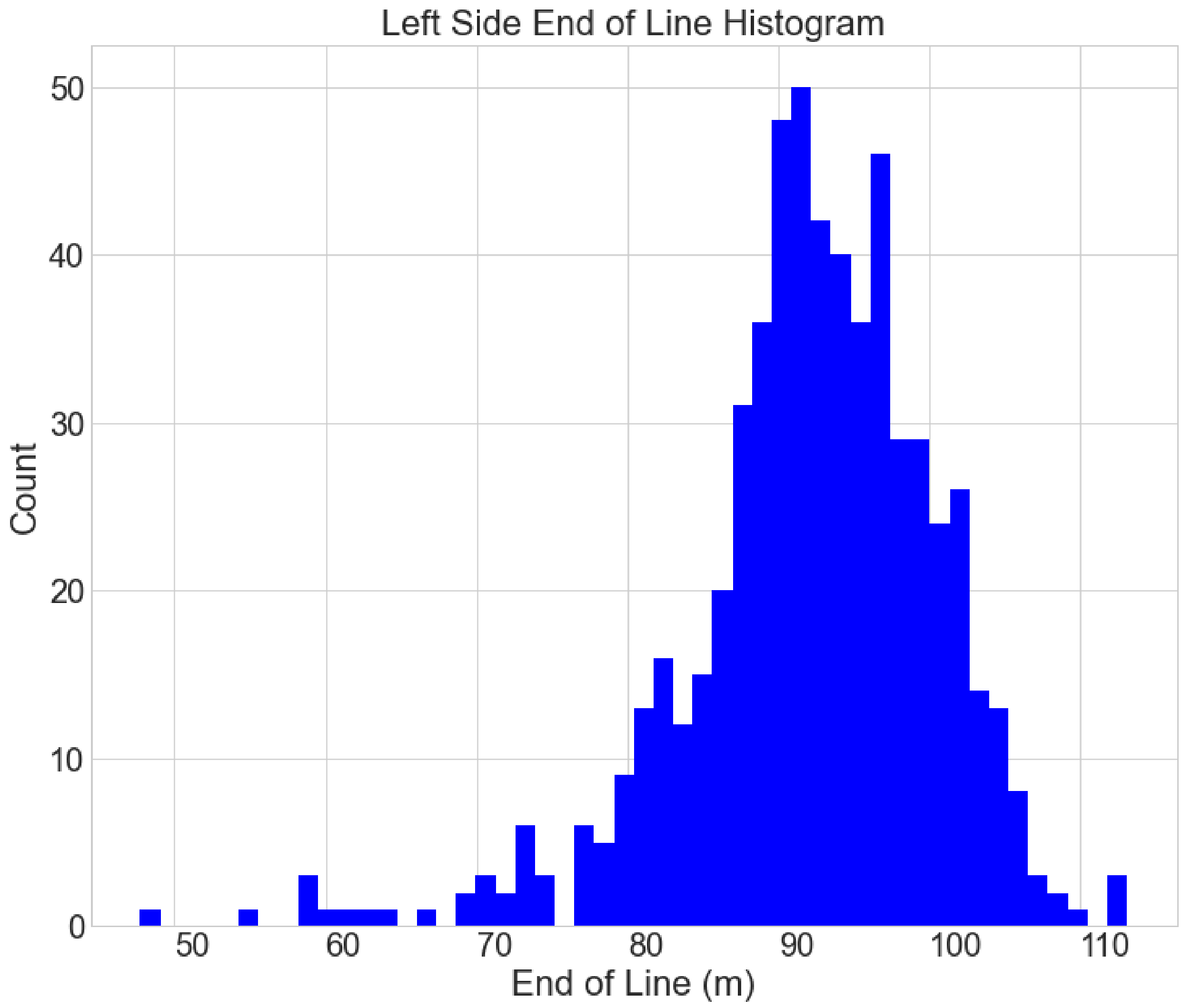


Figure 38. Left side end of line histogram.

Although the distribution of the values resembles a bell shape, upon conducting a Shapiro-Wilk test, it was found that the data were not normally distributed. Results of the Shapiro-Wilk normality test are shown in Table 16 and show that the data were not normally distributed. Although the data were not normally distributed, research has shown that these methods are robust to the violations of normality. The research team conducted an initial linear regression before applying a t-test comparison of the means method to examine the impact of period (day/night) and an Anova and a post-hoc Tukey's HSD test to study the impact of segment of left side end of line.

Table 16. Shapiro-Wilk normality test results for left side end of line

Test statistic	p-value
0.91293	0.00000

3.2.2.1 Initial Linear Regression

An initial linear regression was conducted to investigate the impact of period (day or night) and segment on left side end of line. Table 17 and Table 18 provide the regression fit statistics and initial regression results.

Table 17. Regression fit statistics for left side end of line

Dep. Variable: EndOfLine_Left	R-squared (uncentered): 0.349
Adj. R-squared (uncentered): 0.336	No. Observations: 603
Df Residuals: 590	Df Model: 12

Table 18. Initial regression results for left side end of line

Segment	coef	Std err	t	P>|t|
Segment_NB1	17.6509	0.913	19.339	0
Segment_NB2	19.5064	0.905	21.553	0
Segment_NB3	9.4807	0.905	10.475	0
Segment_NB4	10.4312	0.905	11.525	0
Segment_SB1	5.2753	0.898	5.877	0
Segment_SB2	14.8702	0.898	16.567	0
Segment_SB3	19.2518	0.898	21.449	0
Segment_SB4	15.7704	0.898	17.57	0
Segment_WB1	15.0493	1.5	10.034	0
Segment_WB1New	16.4987	1.103	14.954	0
Segment_WB2	7.565	0.913	8.288	0
Segment_WB3	6.8608	0.937	7.318	0
Period_Day	78.0617	0.375	208.342	0
Period_Night	80.149	0.388	206.56	0

To find out which group(s) are significantly different from other groups a post-hoc Tukey’s HSD (honestly significant difference) test was used. The Tukey’s HSD test makes pairwise comparisons among all groups. In this study there were 12 study segments which led to 66 pairs of comparison. The study team grouped the segments that were not significantly different from each other. Table 19 shows the 8 groups based on the ANOVA analysis results. Segments connected with the same group letter are not significantly different. The results show many segments with different configurations have similar results.

Table 19. ANOVA segment groups for left side end of line

Segment	Group a	Group b	Group c	Group d	Group e	Group f	Group g	Group h	Least Mean Squares	Standard Error
NB1 Day						f	g	h	96.355	1.318
NB1 Night						f	g	h	97.109	1.368
NB2 Day								h	97.914	1.295
NB2 Night								h	99.270	1.368
NB3 Day	a	b	c						86.413	1.295
NB3 Night		b	c	d	e	f			90.889	1.368
NB4 Day	a	b	c	d	e				88.826	1.295
NB4 Night		b	c	d	e	f			90.209	1.368
SB1 Day	a								82.624	1.295
SB1 Night	a	b							86.190	1.342
SB2 Day				d	e	f	g	h	93.342	1.295
SB2 Night					e	f	g	h	94.579	1.342
SB3 Day							g	h	97.534	1.295
SB3 Night								h	99.164	1.342
SB4 Day				d	e	f	g	h	93.736	1.295
SB4 Night						f	g	h	96.023	1.342
WB1 Day				d	e	f	g	h	95.897	2.103
WB1 Night	a	b	c	d	e	f	g	h	91.367	2.465
WB1New Day			c	d	e	f	g	h	94.051	1.644
WB1New Night						f	g	h	97.158	1.644
WB2 Day	a	b							85.462	1.342
WB2 Night	a	b	c	d	e				87.878	1.342
WB3 Day	a	b							84.224	1.423
WB3 Night	a	b	c	d					87.631	1.342

3.3 Minneapolis Minnesota Data Analysis

3.3.1 Test Locations

The research team evaluated pavement markings at over 30 test areas in the Minneapolis area. Table 6 provides details about the pavement marking test areas. Information includes the factors of interest at each test area, details about the location, and which lane was driven in during the data collection. Table 20 includes additional details about each test area including the pavement and pavement marking characteristics.

Table 20. Minneapolis area test site marking information

Site Number	Roadway	Travel Direction	Lane Driven In	Factors Evaluated	Left Marking	Right Marking	Marking Skip Configuration	Marking Width	Edge line Extension	Contrast Pattern	Pavement
1	I-494	WB	2nd from left	width, cycle, quality	skip	skip	10-40	4	N/A	none	asphalt
2	I-494	NB	2nd from left	width, cycle, quality, contrast	skip	skip	10-40	6	N/A	bordered	concrete
3	MN 55	EB	left	quality, left turn bays	solid	skip	10-40	4	no	none	asphalt
4	MN 55	EB	left	left turn bays	solid	skip	10-40	4	no	none	asphalt
5	MN 55	WB	left	quality, left turn bays	solid	skip	10-40	4	no	none	asphalt
6	MN 55	WB	left	quality, left turn bays	solid	skip	10-40	4	no	none	asphalt
7	I-494	NB	right	ramp area	skip	solid	10-40	4	no	bordered	concrete
8	I-494	NB	2nd from left	width, cycle, quality, contrast	skip	skip	10-40	4	N/A	bordered	concrete
9	I-494	NB	2nd from left	interchange area	mix	mix	mix	mix	no	bordered	concrete
10	I-94	WB	2nd from left	width, cycle, quality, contrast	skip	skip	10-40	6	N/A	bordered	concrete
11	I-94	WB	2nd from left	width, cycle, quality, contrast	skip	skip	10-40	4	N/A	bordered	concrete
12	I-94	WB	left lane	MnRoad merges	solid	skip	10-40	4	no	none	asphalt
13	I-94	WB	right lane	ramp area, quality	skip	solid	20-30	6	yes	bordered	concrete
14	I-94	EB	2nd from left	width, cycle, quality, contrast	skip	skip	20-30	6	N/A	none	asphalt
15	I-94	EB	right lane	ramp area	skip	solid	20-30	6	yes	none	asphalt
16	I-94	EB	2nd from left	width, cycle, quality, contrast	skip	skip	20-30	6	N/A	bordered	concrete
17	I-94	EB	2nd from left	width, cycle, quality, contrast	skip	skip	10-40	6	N/A	bordered	concrete
18	MN 241	EB	left	left turn bays	solid	skip	10-40	4	yes	none	concrete
19	CR 81	EB	right	intersection, gore area	skip	solid	10-40	4	no	none	asphalt
20	CR 81	EB	right	gore area	skip	solid	10-40	4	no	none	asphalt
21	CR 81	WB	left	intersection, left turn bay	solid	skip	10-40	4	no	none	asphalt
22	I-35W	NB	2nd from left	width, cycle, quality, contrast	skip	skip	10-40	4	N/A	shadow	concrete
23	I-35W	SB	2nd from left	width, cycle, quality, contrast	skip	skip	10-40	4	N/A	shadow	concrete
24	I-94	EB	2nd from left	width, cycle, quality, contrast	skip	skip	10-40	4	N/A	bordered	concrete
25	I-94	EB	2nd from left	width, cycle, quality, contrast	skip	skip	10-40	4	N/A	bordered	concrete

Site Number	Roadway	Travel Direction	Lane Driven In	Factors Evaluated	Left Marking	Right Marking	Marking Skip Configuration	Marking Width	Edge line Extension	Contrast Pattern	Pavement
26	I-94	EB	2nd from left to right ramp	width, cycle, quality, contrast	skip	skip	12.5-37.5	4	N/A	bordered	concrete
27	I-94	EB	3rd from left to right ramp	width, cycle, quality, contrast	skip	solid	12.5-37.5	4	N/A	bordered	concrete
28	WI 35	SB	right	right turn bay	skip	solid	12.5-37.5	4	no	none	concrete
29	WI 35	SB	right	ramp area	skip	solid	12.5-37.5	4	yes	none	concrete
30	WI 35	NB	right	ramp area	skip	solid	12.5-37.5	4	yes	none	concrete
31	US 61	SB	right	width, cycle, quality, contrast, right turn bay	skip	solid	10-40	4	no	mix	mix
32	US 61	NB	right	width, cycle, quality, contrast, right turn bay	skip	solid	10-40	4	no	mix	mix
33	US 52	NB	right	off ramp area	skip	solid	10-40	4	yes	none	asphalt
34	US 52	SB	2nd from left	on ramp area	skip	solid	10-40	4	no	none	asphalt
35	Yankee Doodle Rd	WB	right	width, cycle, quality, turn bay	skip	solid	10-40	4	no	none	asphalt
36	US 77	NB	right	width, cycle, quality, ramp area	skip	solid	10-40	4	no	mix	mix
37	US 77	NB	right	width, cycle, quality	skip	solid	10-40	6	N/A	none	asphalt

3.3.2 Nighttime Marking Quality Data Analysis

3.3.2.1 Process

The research team measured grayscale values from the nighttime captured images at each test area of interest. Figure 39 and Figure 40 provide images of lower and higher brightness markings. The images were captured with the RMV system with the same settings in each test area. One issue that arises is the presence or absence of overhead lighting in each section as that lighting will impact the light on the markings and thus the grayscale values.

The process involved selecting 10 images along the length of each site. The images were selected such that the markings of interest were centered approximately 100 feet away from the vehicle (see Figure 41). To analyze the marking, the research zoomed in on the markings that were 100 feet away and recorded the grayscale value of the marking (see Figure 42). The middle portion along the length of the marking was used to capture the grayscale values, because areas along the edge could be shared pixels with the pavement resulting in falsely low values. Separate grayscale values were recorded for the markings on either side of the vehicle. It is important to note that the research team tried to avoid any images that may have been affected by direct overhead lighting or headlights from other vehicles as the extra illumination on the pavement markings would affect the measurements.

Figure 39. Lower brightness markings example.

Figure 40. Higher brightness markings example.

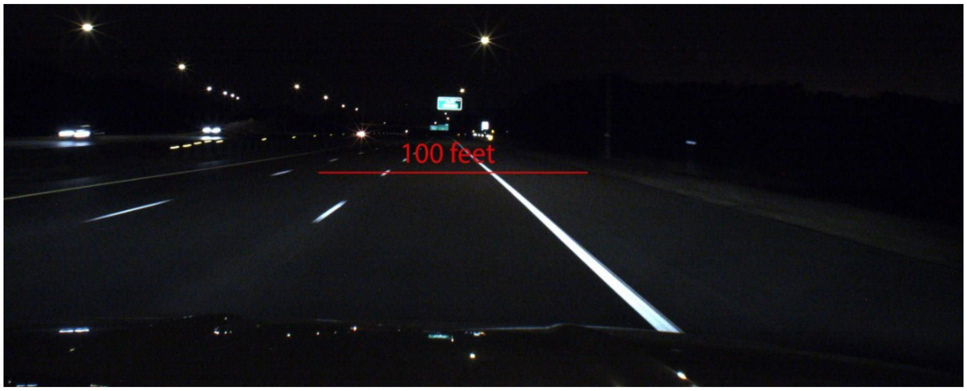
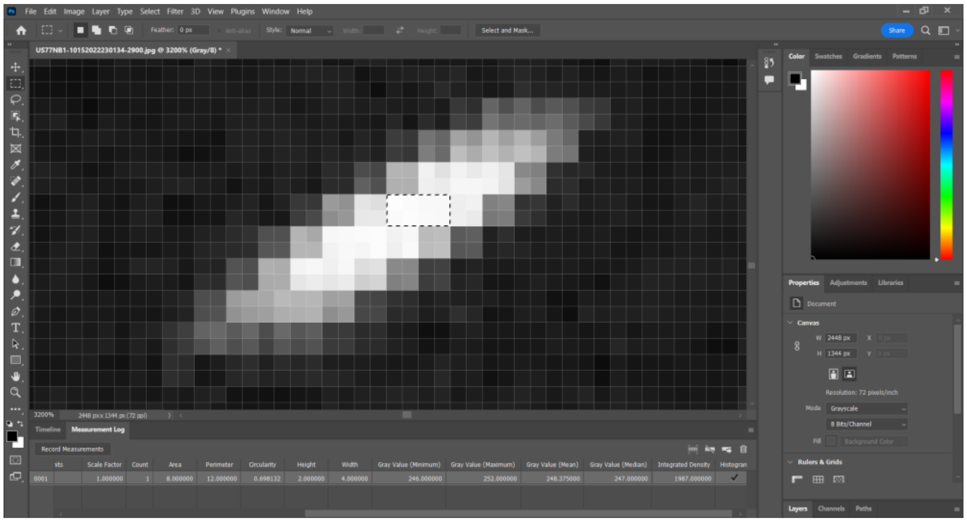


Figure 41. Reference distance for brightness evaluation.



US77NB1-10152022230134-2900.jpg @ 3200% (Gray/8) *

Feather: 0 px

Style: Normal

3200%

2448 px x 1344 px (72 ppi)

W 2448 px

H 1344 px

Resolution: 72 pixels/inch

Mode Grayscale

8 Bits/Channel

	its	Scale Factor	Count	Area	Perimeter	Circularity	Height	Width	Gray Value (Minimum)	Gray Value (Maximum)	Gray Value (Mean)	Gray Value (Median)	Integrated Density	Histogran
0001		1.000000	1	8.000000	12.000000	0.698132	2.000000	4.000000	246.000000	252.000000	248.375000	247.000000	1987.000000	✓

Figure 42. Zoomed image of marking being analyzed.

3.3.2.2 Nighttime Images of Test Areas

Example images from each test area where grayscale values were captured are provided in Figure 43 through Figure 76. Some test areas were broken up into smaller subsections because the quality of the pavement markings was obviously different, the marking configurations changes, or the pavement changed. Not all test areas were evaluated for marking brightness level, as some test areas were only evaluated for their marking configurations.

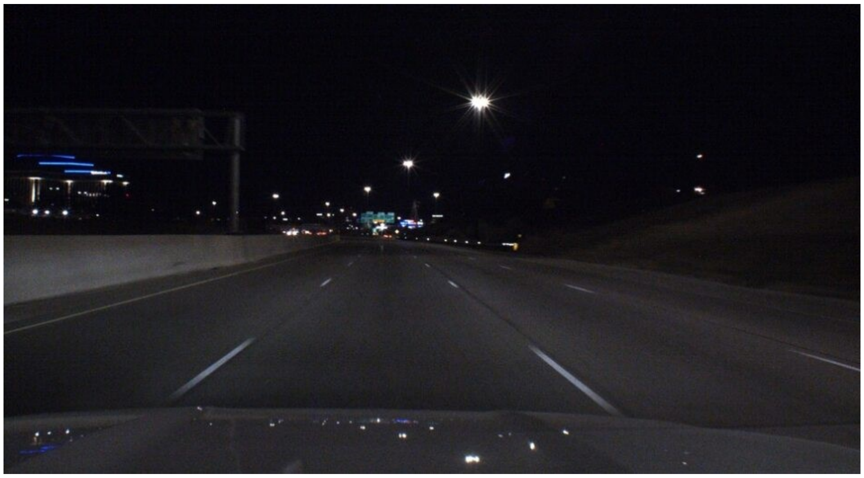


Figure 43. Test site 1.

Figure 44. Test site 2.

Figure 45. Test site 3.

Figure 46. Test site 4b.

Figure 47. Test site 5a.

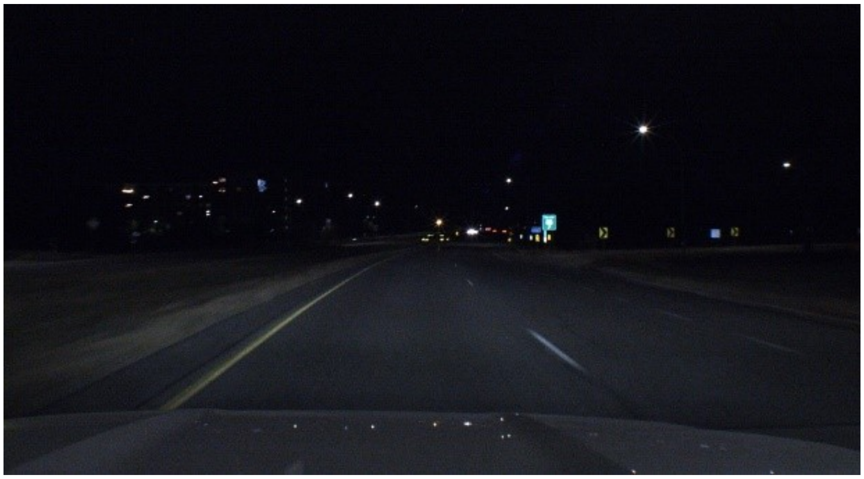


Figure 48. Test site 6a.

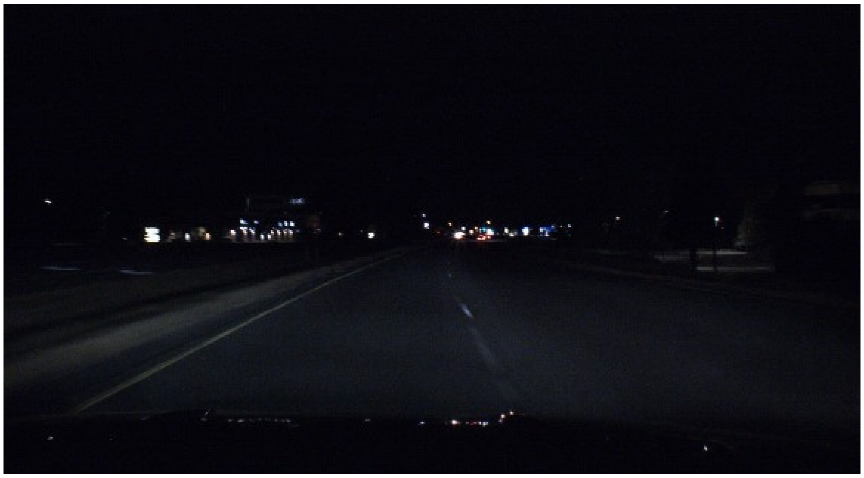


Figure 49. Test site 6b.

Figure 50. Test site 8.

Figure 51. Test site 10.

Figure 52. Test site 11a.

Figure 53. Test site 11b.

Figure 54. Test site 14.

Figure 55. Test site 16.

Figure 56. Test site 17.

Figure 57. Test site 22a.

Figure 58. Test site 22b.

Figure 59. Test site 23.

Figure 60. Test site 24.

Figure 61. Test site 25.

Figure 62. Test site 26.

Figure 63. Test site 28a.

Figure 64. Test site 28b.

Figure 65. Test site 31a.

Figure 66. Test site 31c.

Figure 67. Test site 32a.

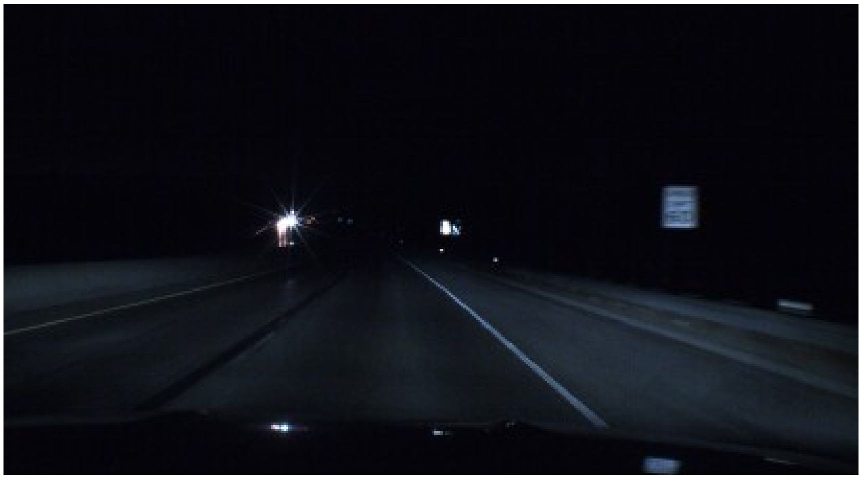


Figure 68. Test site 32b.

Figure 69. Test site 32c.

Figure 70. Test site 35.

Figure 71. Test site 36a.

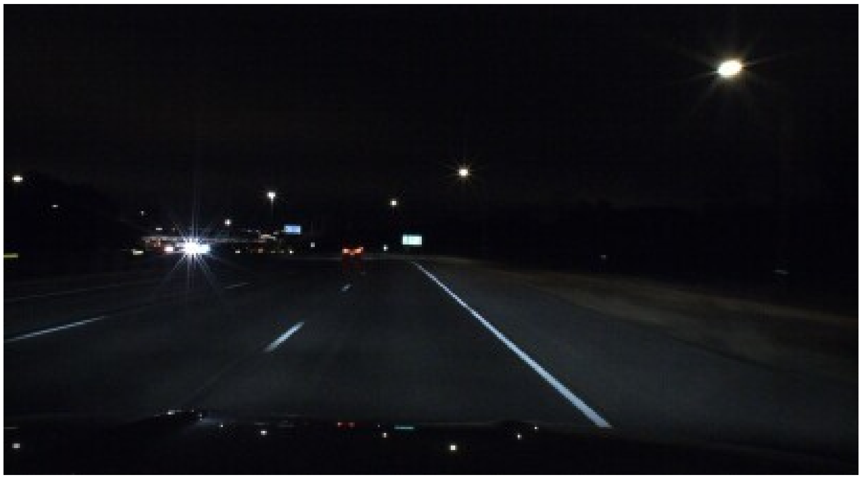


Figure 72. Test site 36b.

Figure 73. Test site 36d.

Figure 74. Test site 36e.

Figure 75. Test site 36f.

Figure 76. Test site 37.

3.3.2.3 Test Section Nighttime Brightness Summary Data

Table 21 provides the summary of the grayscale data gathered from the images taken at the various sites. The average and standard deviations of the left and right markings refer to the 10 images evaluated per site. The maximum possible grayscale value is 256. Markings with grayscale values near this level are near saturation or over saturated, meaning that their true brightness as compared to the others may not be fully captured. Utilizing the same camera setting for each test area required the exposure levels to be such that the low visibility markings were able to be captured but resulted in oversaturation for the brighter markings.

Table 21. Average grayscale values for sections of interest

Site Number	Average Left Value	Average Right Value	Left Standard Deviation	Right Standard Deviation
1	86.3	112.9	11.84	6.90
2	79.5	108.3	8.00	9.18
3	47.9	115.0	5.20	13.59
4b	65.2	85.6	7.60	7.12
5a	90.4	250.3	8.42	1.34
6a	44.8	58.5	5.18	9.86
6b	38.4	72.6	2.72	18.77
8	83.9	117.5	9.64	8.97
10	250.8	251.4	0.79	0.70
11a	69.4	102.1	4.58	4.53
11b	72.5	249.5	6.90	1.72
14	249.6	250.8	2.07	0.79
16	250.5	250.9	0.85	0.88
17	246.5	251.0	2.92	1.15

Site Number	Average Left Value	Average Right Value	Left Standard Deviation	Right Standard Deviation
22a	63.3	77.5	5.52	10.34
22b	79.1	120.0	9.64	11.58
23	63.8	62.2	8.34	10.28
24	89.6	120.9	11.41	9.28
25	58.2	72.2	4.32	5.20
26	129.9	N/A	9.53	N/A
27	167.1	50.4	12.54	5.52
28b	189.7	226.0	9.38	6.90
31a	45.9	117.5	5.11	11.71
31c	251.0	247.3	0.82	3.77
32a	238.9	200.4	4.84	17.34
32b	54.2	105.7	7.11	13.80
32c	72.0	137.9	16.14	13.44
35	58.9	91.2	11.78	15.74
36a	74.1	71.8	9.00	6.78
36b	78.8	94.1	10.25	11.16
36d	75.9	63.4	5.59	5.70
36e	246.1	191.4	3.31	7.69
36f	53.9	84.8	14.28	12.68
37	239.1	250.2	4.91	1.75

The average grayscale values for the six test sites where mobile retroreflectivity were captured are summarized in Table 22. These data are plotted in Figure 77. The exponential trendline fitting the data shows very high correlation between the data. One issue is that the high retroreflectivity site is saturated as the grayscale value is over 250. This means the actual correlation between the grayscale value and the high retroreflectivity value is unknown. When the data are plotted without the high grayscale value, see Figure 78, the correlation is not as strong. The greyscale data still provide some level of nighttime marking brightness information, though not as accurate or equitable compared to a measured retroreflectivity value. The research team utilized the grayscale values for each test site due to lack of a better measure of nighttime marking quality.

Table 22. Grayscale value and measured retroreflectivity averages

Site	Average Left Grayscale Value	Left Marking Average Retroreflectivity (mcd/m^2/lux)
1	86	97
2	80	83
3	48	80
10	251	996
24	90	157
25	58	73

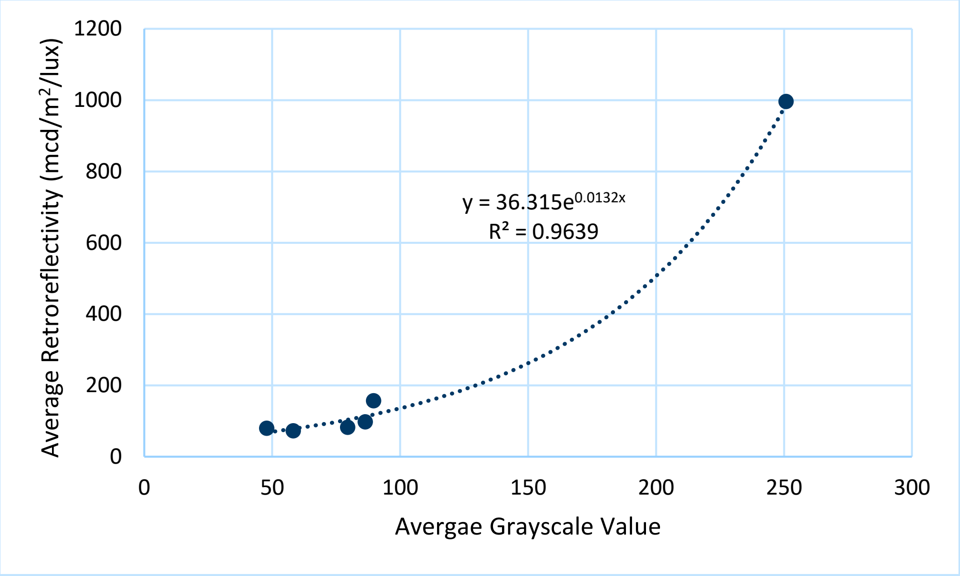


Figure 77. Grayscale value vs measured retroreflectivity.

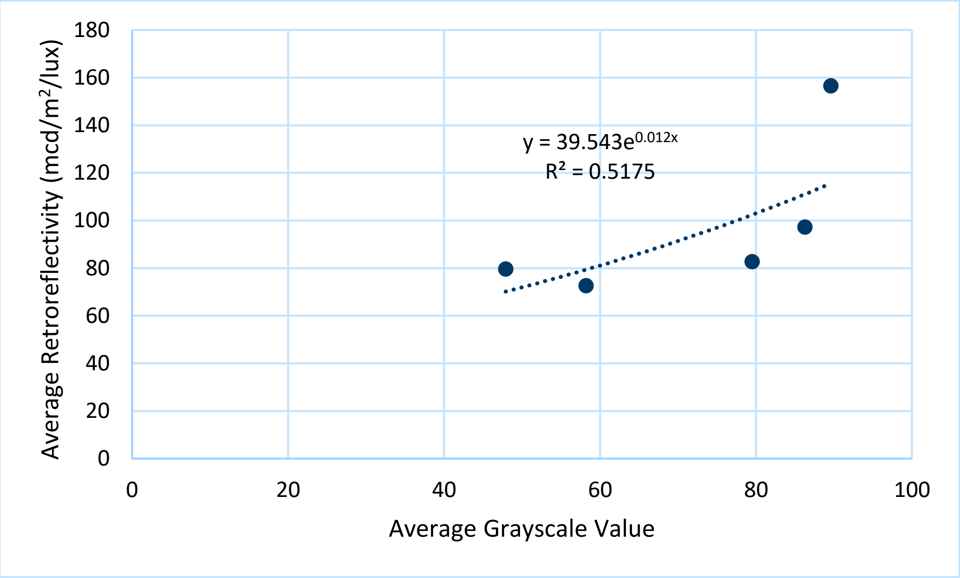


Figure 78. Grayscale value vs measured retroreflectivity (reduced).

3.3.3 Minneapolis Mobileye 8 EyeQ4 Data Analysis

3.3.3.1 Evaluation of Marking Properties on Detection

The research team used regression analysis to investigate the impact of collected parameters on detection confidence and end of line detection distance for the test sites near Minneapolis. Detection confidence is a number between 0 and 1 and represents the confidence level at which the Mobileye system detected the pavement marking type. For each segment, two detection confidence levels were given by the Mobileye system to represent the confidence level of detecting the marking on either side of the driving lane. The study team added a new variable "Side" and re-arranged the database such that one datapoint for each side of the study segment was considered. End of line is the farthest distance (in meters) from the Mobileye camera that the Mobileye system is tracking the pavement marking. End of line is important because higher quality visibility conditions (a factor of contrast, pavement marking quality, lighting conditions, roadway geometry, etc.) should result in larger end of line detection distance values. Figure 79 through Figure 82 display the day and night detection confidence and end of line values.

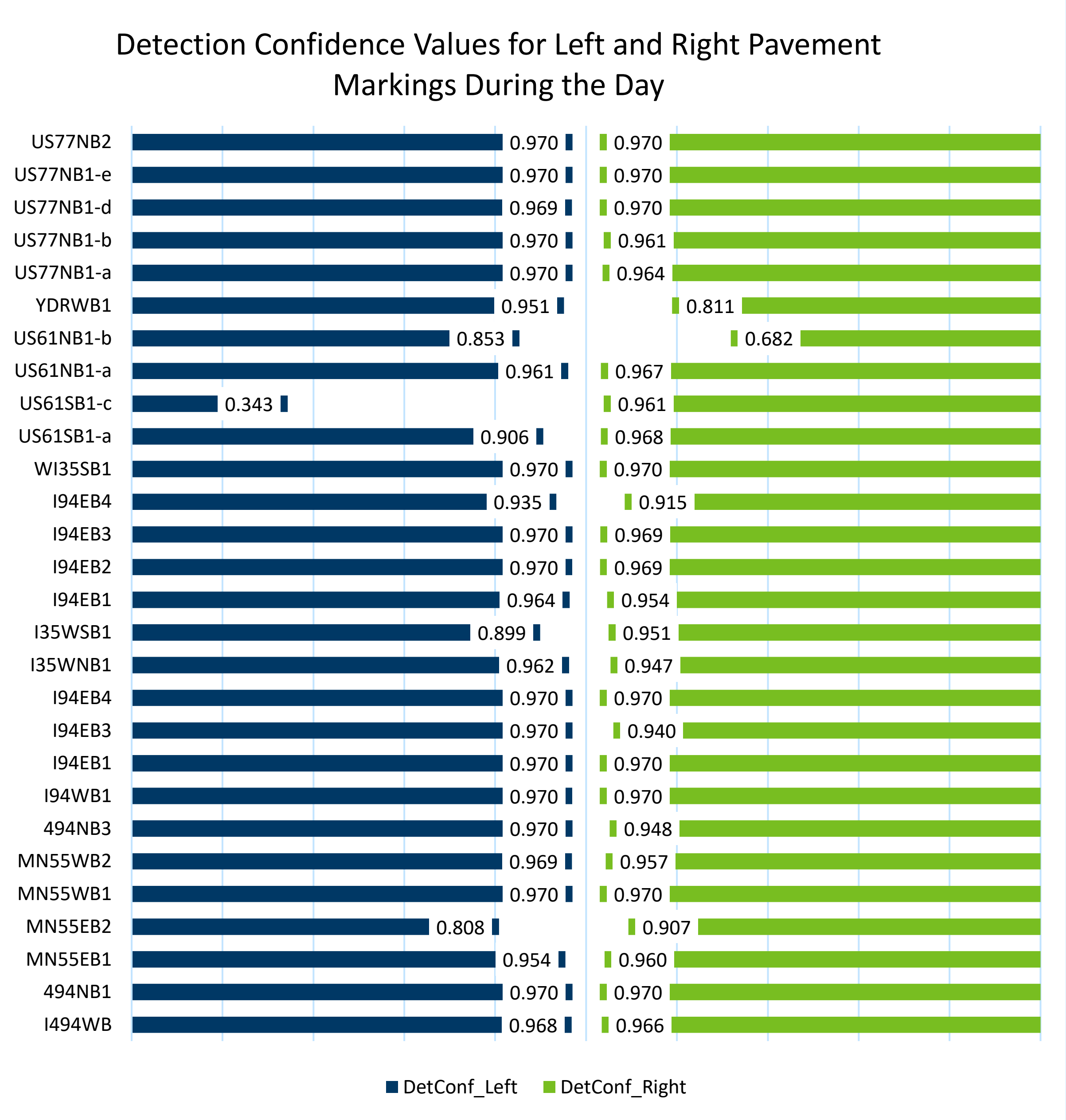


Figure 79. Detection confidence values for left and right pavement markings during the day.

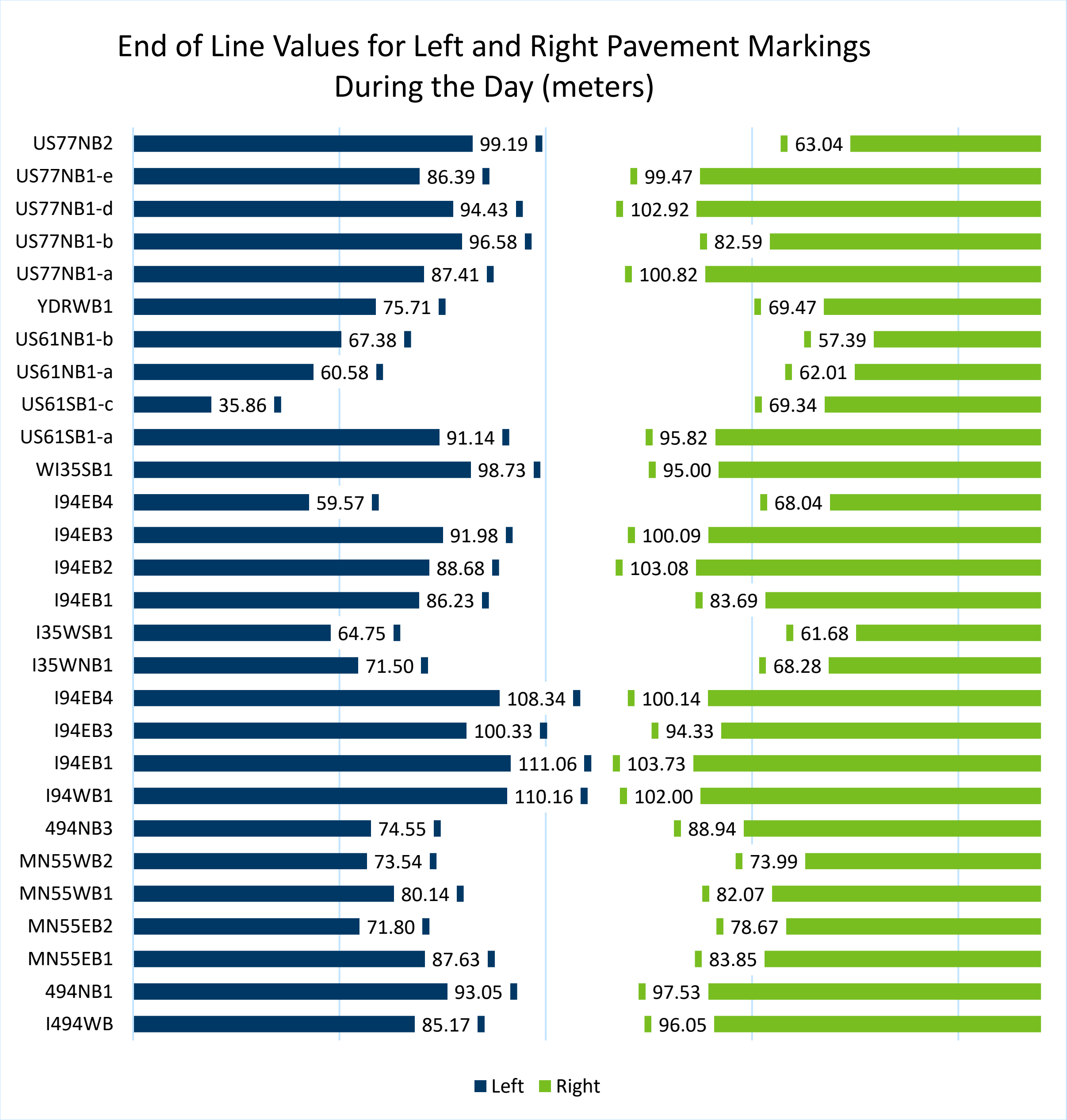


Figure 80. End of line values for left and right pavement markings during the day.

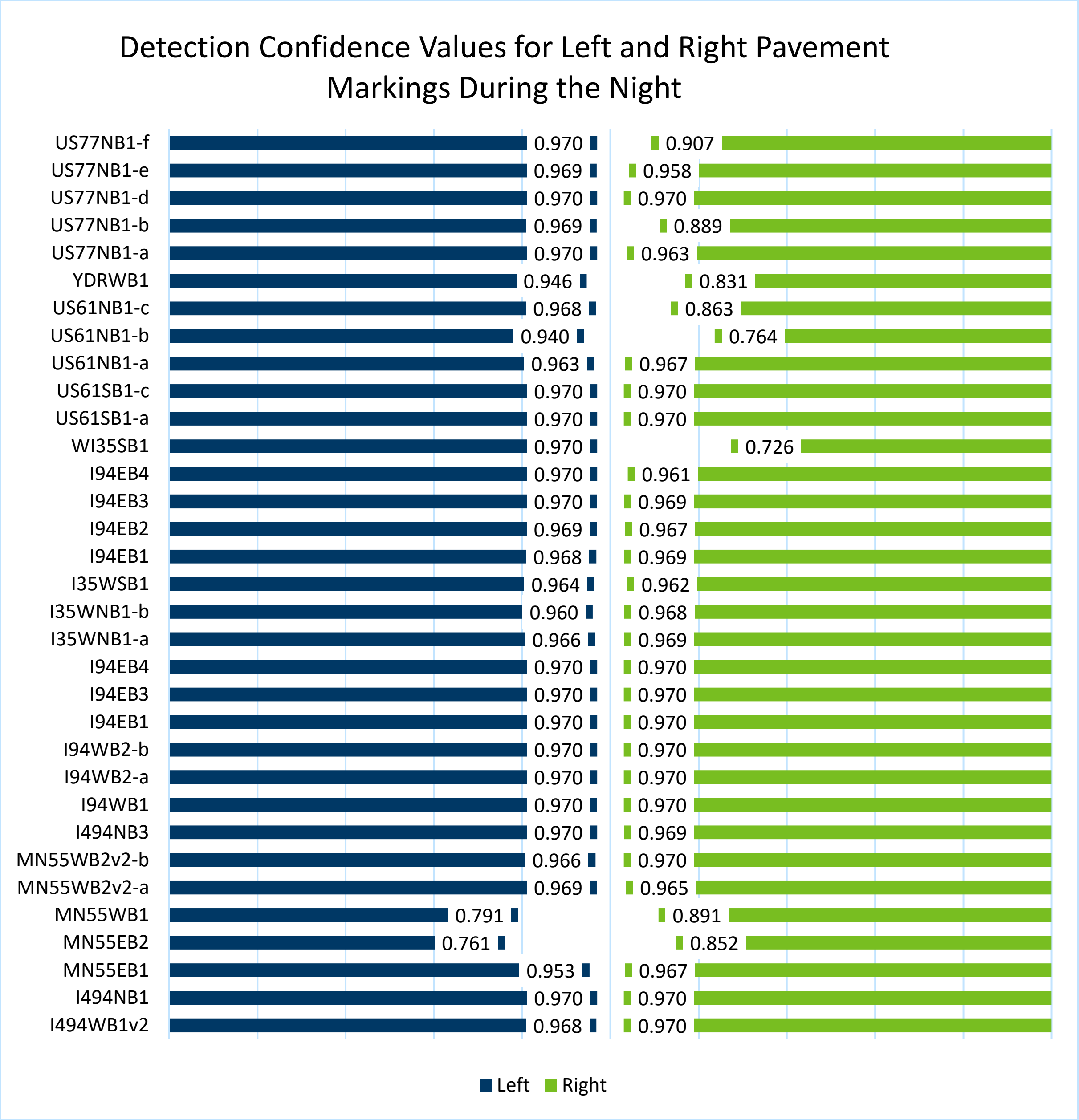


Figure 81.Detection confidence values for left and right pavement markings during the night.

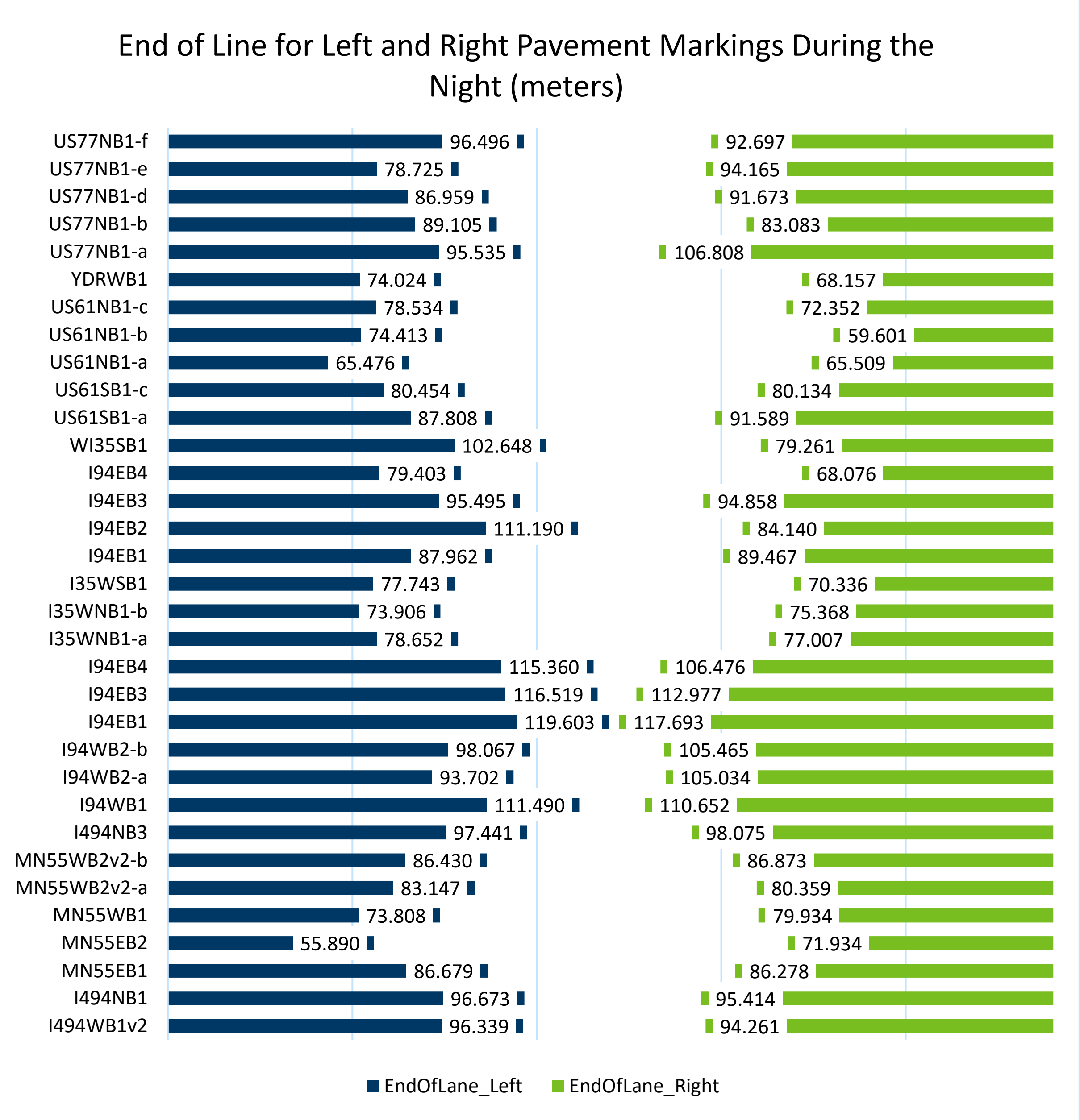


Figure 82. End of line values for left and right pavement markings during the night.

To model detection confidence the following parameters were used as independent variables:

- DayNight (whether the data were collected during the day or at night)
- Marking (marking type, skip, solid, or mix)
- Skip_Configuration (spacing of skip markings, 10-40, 20-30, 12.5-37.5)
- Marking_Width (4 or 6 inch)
- Contrast_Pattern (shadow, bordered, mix, or none)
- Grayscale value (nighttime brightness values between 0 and 256)

The results are presented in Table 23. A brief look at the regression results show that detection confidence was not impacted by the study parameters. This could be due to the fact that all detection confidence parameters were very high in all conditions regardless of study segment characteristics. Fit statistics for this model are listed in Table 24.

Table 23. Regression results for detection confidence for combined day and night

Source	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	0.931	0.024	38.09	<2e-16
DayNightNight	0.026	0.020	1.341	0.183
SideRight	-0.010	0.017	-0.611	0.542
Markingsolid	-0.018	0.019	-0.975	0.332
Skip_Configuration12.5-37.5	0.037	0.040	0.904	0.368
Skip_Configuration20-30	0.016	0.025	0.617	0.538
Markign_Width6	0.009	0.024	0.371	0.711
Contrast_Patternmix	-0.020	0.025	-0.781	0.437
Contrast_Patternnone	-0.003	0.021	-0.132	0.896
Contrast_Patternshadow	0.008	0.031	0.266	0.79

Table 24. Fit statistics for detection confidence model for combined day and night

Residual standard error: 0.076 on 112 degrees of freedom	
Multiple R-squared: 0.108288,	Adjusted R-squared: 0.009187
F-statistic: 1.125 on 9 and 112 DF, p-value: 0.3514	

The research team repeated the regression analysis by assuming end of line as the response variable.

Table 25. Regression results for end of line for combined day and night

Source	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	89.826	4.242	21.176	<2E-16
DayNightNight	5.725	3.363	1.702	0.092
SideRight	-2.509	2.936	-0.855	0.395
Markingsolid	-1.567	3.208	-0.488	0.626
Skip_Configuration12.5-37.5	20.994	7.943	2.643	0.009
Skip_Configuration20-30	12.131	4.425	2.741	0.007
Markign_Width6	-1.828	4.219	-0.433	0.666
Contrast_Patternmix	-3.846	4.959	-0.776	0.440
Contrast_Patternnone	-4.172	3.697	-1.128	0.262
Contrast_Patternshadow	-7.194	8.505	-0.846	0.399

The results of the regression model for end of line are show in Table 25 and fit statistics are listed in Table 26.

Table 26. Fit statistics for end of line model for combined day and night

Residual standard error: 13.05 on 110 degrees of freedom	
Multiple R-squared: 0.3581,	Adjusted R-squared: 0.2939
F-statistic: 5.578 on 11 and 110 DF	p-value: 4.752e-07

Side, Marking type, Marking width and contrast pattern did not impact End of line while time of day and skip configuration significantly impacted End of line. The results show that assuming similar conditions, End of line is almost 6 meters (~19 feet) longer at night. 12.5-37.5 skip configuration increased detection confidence by almost 21 meters (~68 feet) and 20-30 skip configuration increased detection confidence by 12 meters (~ 40 feet)

The research team also collected the grayscale values as a surrogate for retroreflectivity measurements. This data is only useful for nighttime detection as it is a measure of marking brightness during the nighttime viewing conditions. To include the grayscale values in the analysis, the research team filtered the nighttime data and added grayscale values and repeated the analysis to model detection confidence and End of line for nighttime taking grayscale values into account. Figure 83 indicates the grayscale values used in the analysis.

Other parameters are similar to parameters used in modeling the combined model except the time of day (Day/Night) variable needed to be removed since only nighttime values were in the analysis. The research team first constructed a regression model to investigate the impact of study parameters on detection confidence. The results of the model are listed in

Table 27 and fit statistics of the model are shown in Table 28. *We can see that Grayscale is not a significant variable to predict detection confidence. This is likely due to the majority of the sections having high detection confidence regardless of the grayscale value.*

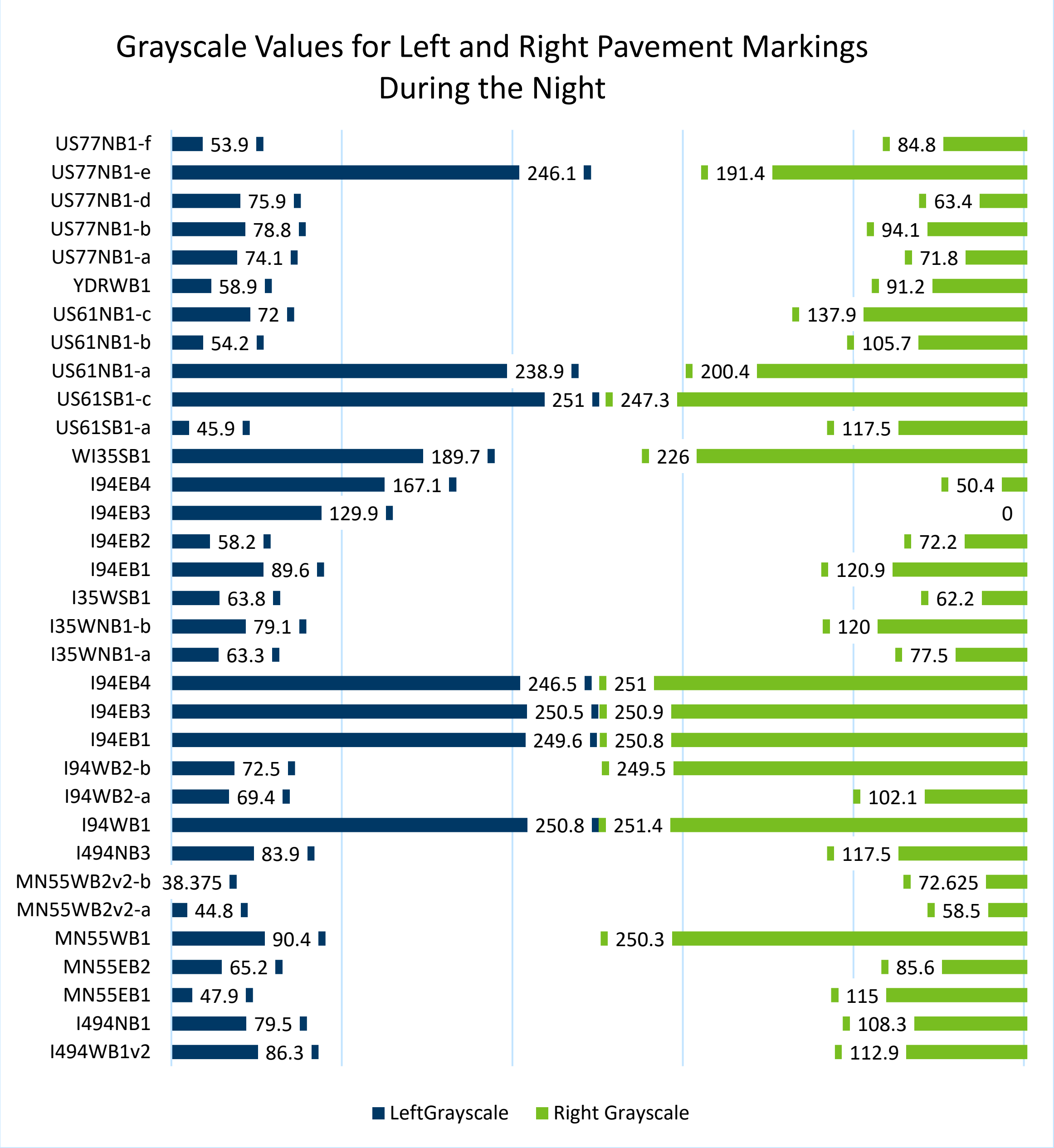


Figure 83. Grayscale values for left and right pavement markings during the night.

Table 27. Regression results for detection confidence for night (grayscale included)

Source	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	0.998	4.69E-02	21.294	<2e-16
SideRight	-0.008	1.45E-02	-0.556	0.581
Markingsolid	-0.039	1.87E-02	-2.114	0.039
Skip_Configuration20-30	-0.010	4.87E-02	-0.211	0.833
Skip_Configuration10-40	-0.038	4.13E-02	-0.917	0.363
Markign_Width6	-0.007	2.43E-02	-0.27	0.788
Contrast_Patternmix	-0.001	2.43E-02	-0.056	0.956
Contrast_Patternnone	-0.003	2.18E-02	-0.121	0.905
Contrast_Patternshadow	0.011	3.08E-02	0.351	0.727
Grayscale	0.000	1.04E-04	-0.205	0.839

Table 28. Fit statistics for detection confidence model for night (grayscale included)

Residual standard error: 0.05503 on 56 degrees of freedom	
Multiple R-squared: 0.168,	Adjusted R-squared: 0.03048
F-statistic: 1. 23 on 9 and 56 DF,	p-value: 0.2959

The study team conducted a similar analysis for the End of line. The results and fit statistics for this model are shown in Table 29 and

Table 30 respectively. *We can see that at night, Grayscale is a significant parameter in predicting End of line. This means that the marking nighttime quality will impact the maximum distance at which the system is able to detect the markings.*

Table 29. Regression results for end of line for night (grayscale included)

Source	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	89.65004	10.96338	8.177	3.95E-11
SideRight	-2.12806	3.39887	-0.626	0.53379
Markingsolid	-2.05668	4.36574	-0.471	0.6394
Skip_Configuration20-30	7.31803	11.39991	0.642	0.52353
Skip_Configuration40-10	0.05149	9.65931	0.005	0.99577
Markign_Width6	-4.14772	5.6749	-0.731	0.46789
Contrast_Patternmix	-15.49532	5.69205	-2.722	0.00863
Contrast_Patternnone	-2.50885	5.09449	-0.492	0.62432
Contrast_Patternshadow	-14.58724	7.1921	-2.028	0.0473
Grayscale	0.05691	0.02429	2.343	0.02272

Table 30. Fit statistics for end of line for night (grayscale included).

Residual standard error: 12.87 on 56 degrees of freedom	
Multiple R-squared: 0.3553,	Adjusted R-squared: 0.2516
F-statistic: 3.429 on 9 and 56 DF,	p-value: 0.002016

3.3.3.2 Evaluation of Marking Configurations at Ramps and Turn Bay Areas

The research team utilized their 2022 Ford Explorer with Co-Pilot 360 Assist+ system and Mobileye 8 EyeQ4 system to evaluate areas where the pavement marking configuration may influence lane position of vehicles with autonomous or ADAS features. The vehicle operator had the vehicle set to lane centering mode and only provided enough steering wheel input to keep the system active. The lane centering feature was fully allowed to steer the vehicle through the test areas. The goal of testing at these specific test sites is to better understand if the presence of dotted line extension pavement markings made a difference in lateral position of the vehicle. Test areas included turn bays and exit and entrance ramp areas. Some of the test sites had gaps in the markings whereas others had dotted line extensions going across the lane where the vehicles were supposed to cross. In segments where the change in lane function takes place, absence of dotted markings means that the through lane has varying lane width along the segment. If dotted pavement markings are present, the through lane width along the transition segments maintains a relatively constant lane width.

DATA PREPARATION

The Mobileye system was used to collect vehicle lateral position, while the Co-Pilot 360 Assist+ was used to guide the vehicle through the test area.

The following steps were taken to compose the database used for data analysis:

1- Processing Mobileye® output to extract lane position data.
2- Mapping the extracted data on Google Earth®.
3- Using Google Earth® to select target sub segments.
4- Using target subsegment data to calculate study parameters.
5- Compile the study parameters in a single database.

Each of the 5 mentioned steps are explained in more detail in the following paragraphs.

1- Processing Mobileye® output to extract lane position data.

The Mobileye system processes images captured by a camera installed behind the windshield at the center line of the vehicle and outputs data in hexadecimal digits. The research team was provided a protocol to convert the raw output to meaningful numbers. The research team collected the following parameters from the Mobileye output:

- Time Stamp.
- Latitude and Longitude.

  - Side of the road (this information was included as a checkpoint but was not used for analysis).
  - Detection Confidence on either side of the road. (used for analysis described in previous section)
  - End of line on either side of the road. (used for analysis described in previous section)
  - Lane position (distance from the camera to pavement marking on either side, used in this analysis).
2- Mapping the extracted data on Google Earth®.

The research team used the latitude and longitude data to map the Mobileye data on Google Earth. This step was required since the study team needed to use site specific characteristics such as beginning of solid pavement marking, beginning of the taper, presence, or absence of the dotted lines, etc. to select subsegments in the next step. Study site locations are shown in Figure 84 with roadway and direction of travel written in boxes next to each site/group of sites.

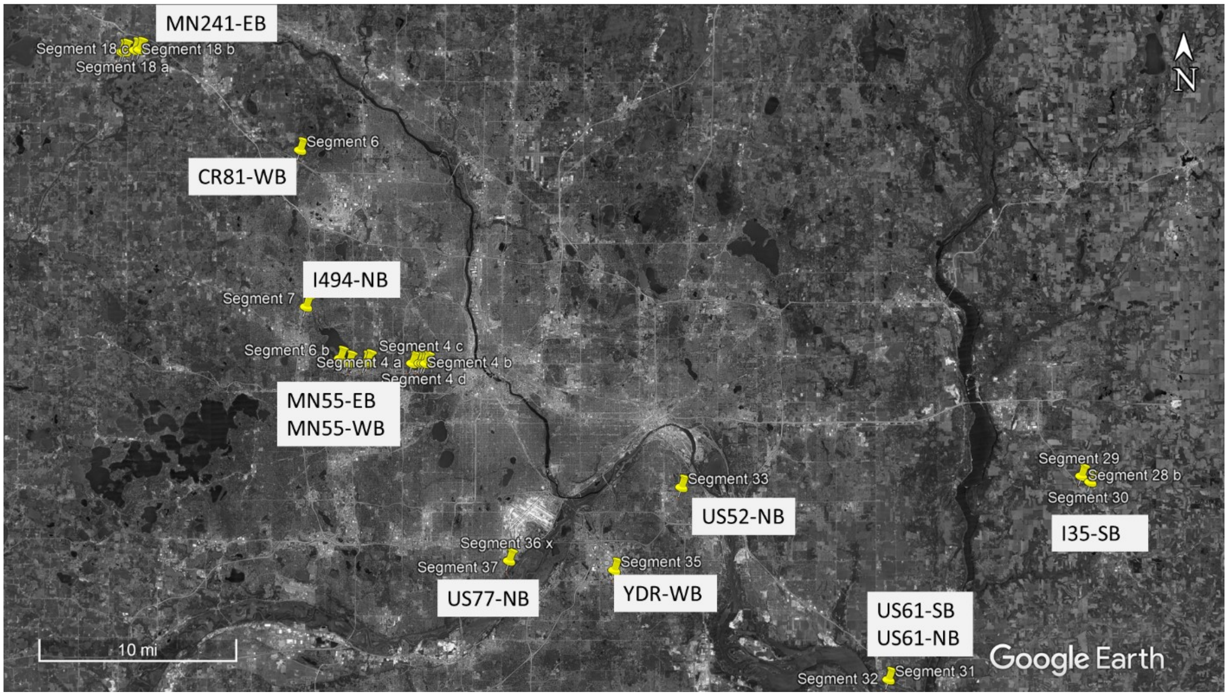


Figure 84. Study site locations.

3- Using Google Earth to select target subsegments.

For each study site, the research team selected two subsegments: A subsegment where the transition took place, (e.g. addition of a left turn bay of the left side of the road or addition of a tapered off-ramp on the right side of the road) and a subsegment immediately upstream of the transition subsegment.

The transition subsegment was selected using the following protocol and depicted in Figure 85.

  a- The start point of the tapered pavement marking was identified (Point A).
  b- A point approximately 100 ft upstream of the Point A was selected (Point B).

c- The distance from Point B to the end of transition segment (Point C) was measured. Transition subsegment is the subsegment between Point B and Point C.

d- The upstream segment was selected immediately upstream of transition segment with equal length as transition segment.

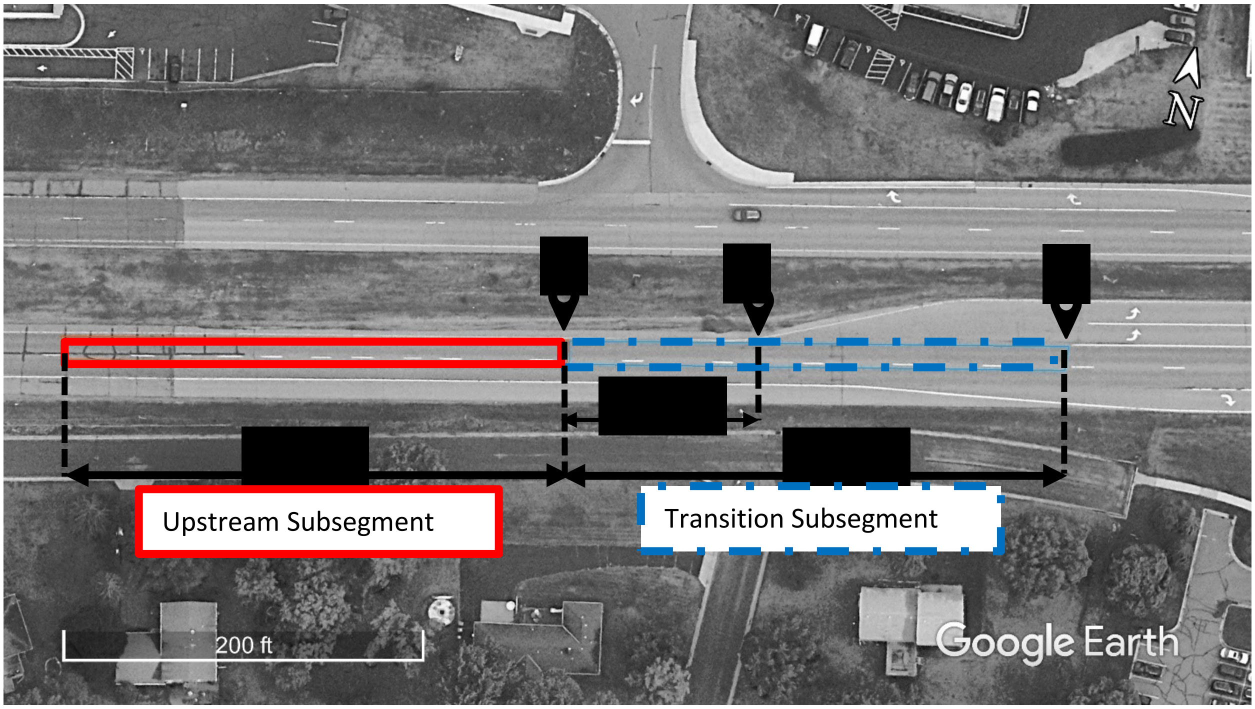


Figure 85. Transition subsegment and upstream subsegment selection process.

4- Using target subsegment data to calculate study parameters.

After subsegments were selected, their respective data points were identified in the individual processed files (Step 1) and extracted to calculate lateral position ratio, LPR.

Distance from left values were stored as negative numbers while distance from right values were stored as positive numbers. The “Lateral Position Ratio” (LPR) was calculated as:

$$LPR = \frac{|Distance\ from\ left|}{Distance\ from\ right}$$

The lateral position ratio shows if the vehicle is in the middle of the lane or is left or right of center. LPR values under 1 indicate that the vehicle is at the right side of the centerline of the lane, while values over 1 indicate that vehicle is located to the left of the centerline. When LPR is close to 1, the vehicle is at the centerline. After calculating LPR for each point, the following parameters were calculated for each transition and upstream subsegment and stored in a new database:

- Subsegment Length
- Standard deviation of LPR

- Average LPR
- Coefficient of Variation of LPR
- Average Distance from Left (DL)
- Average of top 10% values of Distance from Left (Later used for right-side off-ramps)
- Average Lane Width (Later used for right-side off-ramps)
- Average of top 10% values of Lane Width
- Average Distance from Right (DR) (Later used for left-side off-ramps)
- Average of top 10% values of Distance from Right (Later used for left-side off-ramps)

5- Compile the study parameters in a single database.

After parameters in step 4 were calculated they are stored in a database along with other information such as type of transition (left turn bay, right-side off-ramp, etc.), segment name, number of through lanes in the segment, the driving lane, etc. Each line of data represented a subsegment. The output file was later used to conduct the analysis. This database was later filtered, and two distinct sets of data were selected for analysis.

DATA ANALYSIS

DESCRIPTIVE STATISTICS

The compiled database had two rows per each study site. One row for the transition subsegment and one row for the upstream subsegment. Table 31 and

Table 32 list descriptive statistics for study parameters for left turn lane and right side off ramps respectively. The study team chose the following study site types and studied them independently:

1- Study sites with left-turn bays.
2- Study sites with off-ramps at the right-side of the road.

Table 31. Descriptive statistics for left turn lane study sites

Variable Name	Variable Type	Min	Max	Mean	St.Dev
DottedPMatTransition	Binary	0	1	0.269	0.444
LeftPM	Binary	0	1	0.635	0.482
SegmentType	Categorical	Upstream (26) Transition (26)			
Day.Night	Categorical	Day (22) Night (30)			
LPR.Mean	Numerical	-1.448	-0.620	-1.047	0.170
DL10Mean	Numerical	-3.855	-1.511	-2.028	0.355
DLMean	Numerical	-2.275	-1.370	-1.823	0.148
LWMean	Numerical	1.609	3.489	2.361	0.443
LW10Mean	Numerical	3.528	5.475	3.762	0.339
DRMean	Numerical	1.460	2.211	1.782	0.158
DR10Mean	Numerical	1.515	2.433	1.929	0.189
Length	Numerical	70	462	172.192	112.455

Table 32. Descriptive statistics for right side off ramp study sites

Variable Name	Variable Type	Min	Max	Mean	St.Dev
DottedPMatTransition	Binary	0	1	0.5294	0.4991
RightPM	Binary	0	1	0.7647	0.4242
SegmentType	Categorical	Upstream (17) Transition (17)			
LPR.Mean	Numerical	-2.596	-0.616	-1.223	0.429
DLMean	Numerical	-2.379	-1.231	-1.845	0.235
DL10Mean	Numerical	-3.039	2.490	-1.850	0.820
LWMean	Numerical	1.453	3.380	1.913	0.443
LW10Mean	Numerical	3.272	4.108	3.560	0.173
DRMean	Numerical	1.150	2.001	1.624	0.204
DR10Mean	Numerical	1.444	2.587	1.811	0.195
Length	Numerical	77	364.15	164.62	118.00

For segments with left turn bays, the increment in lane width in the transition subsegment takes place on the left side of the road. For segments with an exit ramp on the right, the increment in lane width in the transition subsegment takes place on the right side of the vehicle. In other words, if the through lane is not marked by dotted pavement markings it seems like the lane width increases gradually. Figure 86 shows an example of this situation for left turn bays. Figure 87 shows an example of this situation for exit ramps. These two situations need to be evaluated separately and compared to sections that have dotted line extensions through the transition subsegment.

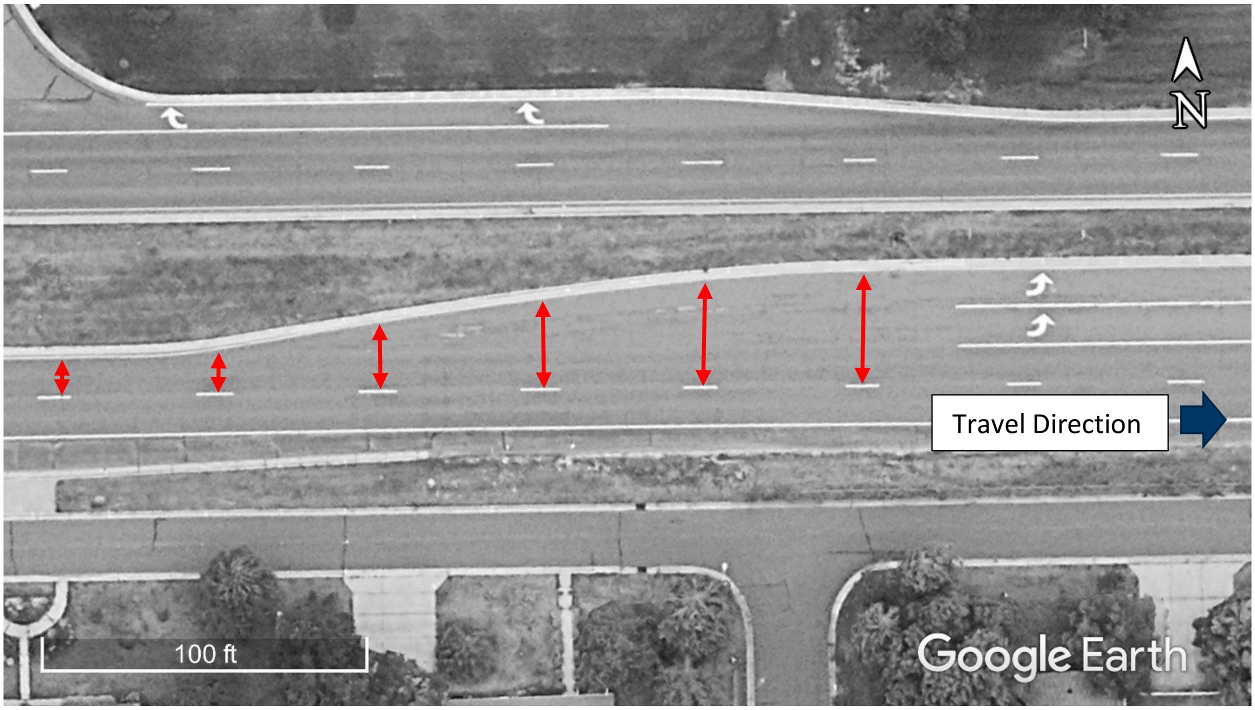


Figure 86. Increment of distance between two pavement markings at transition segments in left turn lanes.

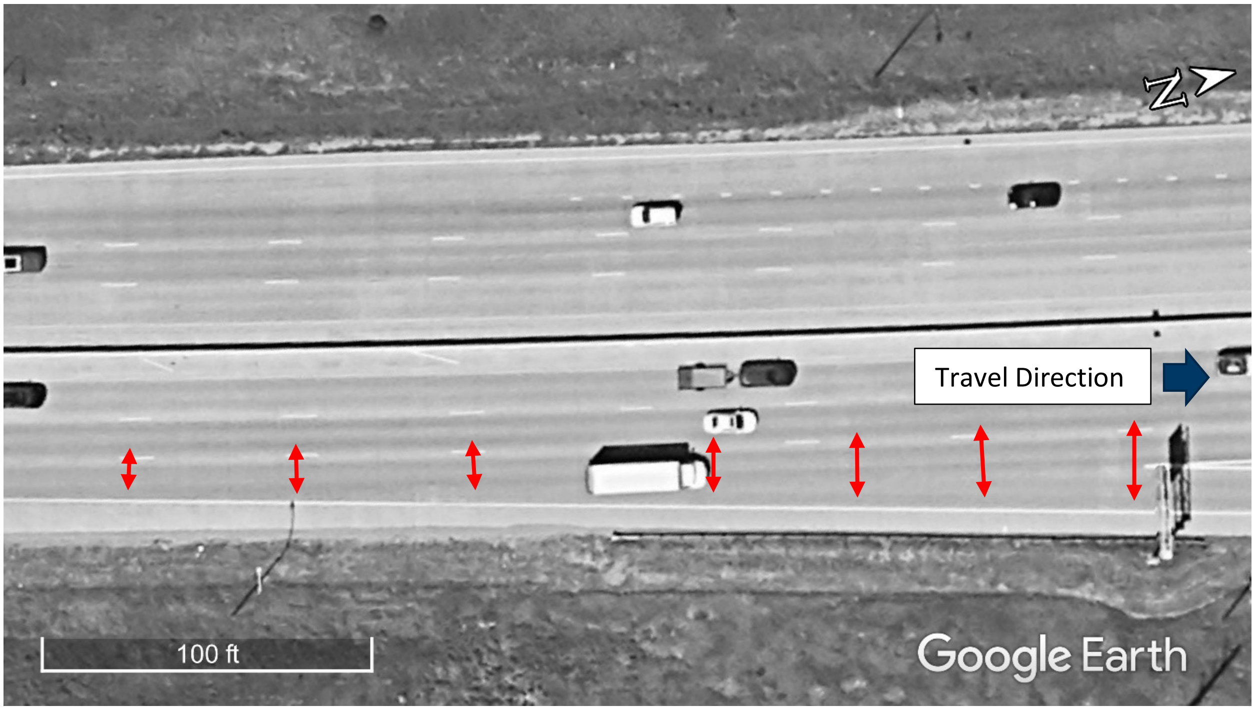


Figure 87. Increment of distance between two pavement markings at transition segments for right side off ramp study sites.

According to the Manual on Uniform Traffic Control Devices (MUTCD) “a dotted line used as a lane line or edge line extension guides vehicles through an intersection, a taper area, or an interchange ramp area.” Some study segments had dotted line extension pavement markings while some did not and this provided the opportunity to compare lateral position of the test vehicle at different locations to evaluate the impact of these pavement markings on the lane keeping capabilities of the evaluated system.

SEGMENTS WITH LEFT TURN BAYS

For segments with left turn bays, the distance from right values for the two subsegments (transition subsegments and upstream segment) were compared. As previously mentioned, choosing the distance from right was due to the fact that the increment in the lane width for transition subsegments without dotted pavement markings happens on the left side of the driving lane and keeping a consistent distance from the right side of the driving lane is synonymous to maintaining lane position. To investigate if the presence of the dotted pavement markings impacted the lateral position of the vehicles, a two-way ANOVA test was used. The two factors considered in the two-way ANOVA, were:

- Subsegment type (Upstream vs transition segment).
- Presence of dotted pavement markings on the left side of the subsegment.

Two different dependent variables were chosen to represent the lateral position:

- Distance from right in two forms:
    - Mean distance from right for all of the datapoints at each subsegment.
    - Mean of highest 10% of distance from right values at each subsegment.
- LPR as defined previously.

DISTANCE FROM RIGHT

As explained earlier, for left turn bays, keeping a consistent distance from the right side pavement marking is synonymous to maintaining lane position, thus comparing average distances from right for different subsegments could indicate how dotted pavement markings impacted distances from the right. For each study site, data for two subsegments were collected, making it possible to compare each transition subsegment to its upstream subsegment. In all study sites upstream subsegment had pavement markings at both sides of the driving lanes (making the distance from both sides relatively similar and consistent), while on transition subsegments, where dotted pavement markings were not used, the distance from right would increase. An ANOVA test with “SubsegmentType”, “LeftPM”, and “Length” as independent variables and “DRMean” as the dependent variable was conducted. “SubsegmentType” was a categorical parameter with two options namely “Transition” and “Upstream”. “LeftPM” was a binary variable with 0 representing no dotted pavement marking on the left side, and 1 representing dotted pavement markings on the left side. “Length” was segment length measured in feet. “Day.Night” was a categorical variable that showed the time period in which the data were collected. The results are shown in Table 33 and show no significant relationship between any of the independent variables on the average distance from right.

Table 33. ANOVA table for average distance from right at left turn bays

Source	Df	Sum Sq	Mean Sq	F Value	Pr(>F)
SegmentType	1	0	0	0	0.9942
LeftPM	1	0.0009	0.00087	0.036	0.851
Length	1	0.0909	0.09087	3.765	0.0621
Day.Night	1	0.0236	0.02363	0.979	0.3306
Residuals	29	0.6999	0.02413		

The study team repeated this test by replacing the dependent variable with the average of top 10% of distance from right values. The independent variables were similar to the previous test, and the results are listed in Table 34. Again, the results show no significant relationship between any of the independent variables on the average distance from right. The LeftPM variable did have a larger impact when just looking at the top 10% values.

Table 34. ANOVA table for average of top 10% distance from right at left turn bays.

Source	Df	Sum Sq	Mean Sq	F Value	Pr(>F)
SegmentType	1	0.0246	0.02461	0.769	0.3876
LeftPM	1	0.0701	0.07012	2.192	0.1495
Length	1	0.0192	0.01922	0.601	0.4446
Day.Night	1	0.1027	0.10268	3.21	0.0836

Residuals	29	0.9276	0.03198		

LANE POSITION RATIO

The study team investigated if LPR was impacted by segment or the presence of dotted pavement markings. Using ANOVA analysis "SubsegmentType" and "LeftPM" as independent variables and "LPR.Mean" as the dependent variable, the results showed that we could not reject the null hypothesis indicating no statistically significant impacts.

Table 35. ANOVA table for average LPR at left turn bays

Source	Df	Sum Sq	Mean Sq	F Value	Pr(>F)
SegmentType	1	0.0054	0.00535	0.18	0.6742
LeftPM	1	0.0074	0.00741	0.249	0.6212
Length	1	0.1234	0.12336	4.155	0.0507
Day.Night	1	0.0172	0.01724	0.58	0.4523
Residuals	29	0.8611	0.02969		

The results of the above tests all indicate that the system evaluated was generally capable of maintaining its lane position when passing by a left turn bay with or without dotted line extension pavement markings. It is important to note that the length of subsegments in this study were relatively short. Figure 88 shows the distribution of lengths for transition subsegments. Although "Length" was considered as one of the independent variables in the ANOVA tests, it would be useful to study longer subsegments and see if the vehicle is still capable of maintaining lane position and capable of maintaining the active lane centering feature for an extended length of the road. It is also important to note that this detailed evaluation is for a single vehicle type. This vehicle and three others were driven through the same test areas and subjective analysis on the vehicles ability to maintain lane position was evaluated (discussed later in this report).

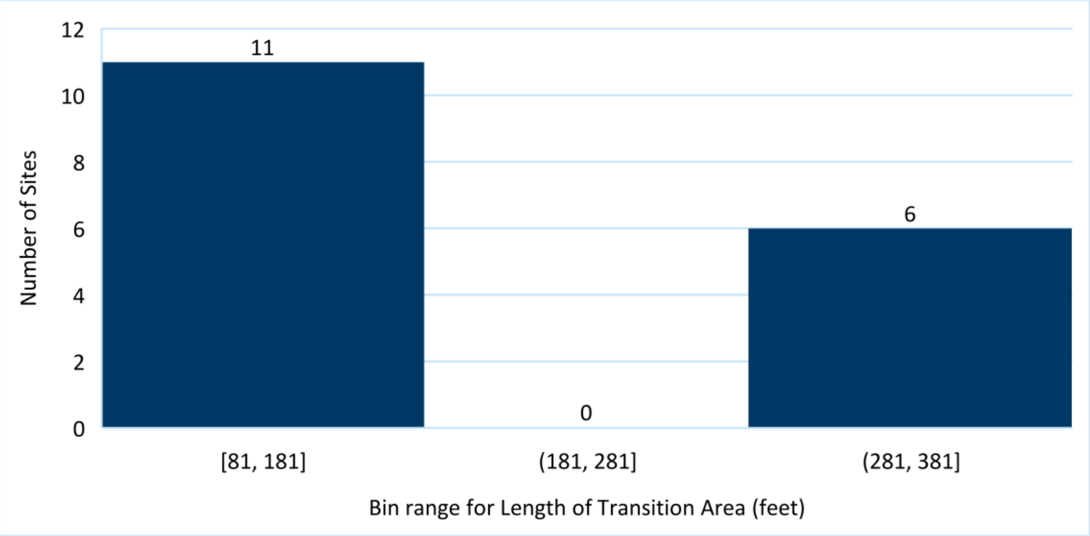


Figure 88. Transition segment length distribution for left turn lanes.

OFF RAMP SUBSEGMENTS

The research team repeated the tests for the study sites that had an off ramp on the right side of the road. Instead of distance from right, the study team chose distance from left as the dependent variable because in these locations maintaining lane position in the right lane was synonymous to keeping a consistent distance from the left pavement marking. Instead of adding a new column that showed presence of dotted pavement marking on the left side of the road, the new parameter showed presence of dotted pavement marking on the right side of the road.

DISTANCE FROM LEFT

Similar to the left turn lanes, the study team conducted an ANOVA test with “SegmentType”, “RightPM”, “Length”, and “Day.Night” as independent variables and “DLMean” as the dependent variable. “SegmentType” was a categorical variable that showed if the measurement belonged to the transition subsegment or the upstream subsegment. “RightPM” was a binary variable that was set to 1 if there was pavement markings (solid, broken or dotted) on the right side of the lane and “Length” was segment length in feet. “Day.Night” showed the time period that the data were collected in. “DLMean” showed the average distance from left for each segment. The ANOVA test results are listed in Table 36 and show that both length and RightPM had significant impact on the average distance from left. To understand this impact, a linear regression model was fitted, and the results were studied further as shown in Table 37. Fit statistics for the linear regression are listed in Table 38.

Table 36. ANOVA table for average distance from left at off ramp locations

Source	Df	Sum Sq	Mean Sq	F Value	Pr(>F)
SegmentType	1	0.1769	0.17685	6.115	0.0243
RightPM	1	0.1817	0.18173	6.283	0.0226
Length	1	0.2051	0.20506	7.09	0.0164
Day.Night	1	0.0066	0.00659	0.228	0.6392
Residuals	17	0.4917	0.02892		

Table 37. Regression parameters for distance from left model at off ramp locations

Source	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-2.2195952	0.1107781	-20.036	2.91E-13
SegmentTypeUp	0.0699427	0.0823644	0.849	0.4076
RightPM	0.2955097	0.1071986	2.757	0.0135
Length	0.000769	0.0002851	2.697	0.0153
Day.NightNT	-0.0349843	0.0732808	-0.477	0.6392

Table 38. Fit statistics for distance from left model at off ramp locations

Residual standard error: 0.1701 on 17 degrees of freedom	
Multiple R-squared: 0.537	Adjusted R-squared: 0.428

F-statistic: 4.929 on 4 and 17 DF	p-value: 0.007998

The results show a significant impact of “RightPM” on the average distance from left. The coefficient estimate for the “RightPM” was positive, meaning that the average distance from left was lower when there was pavement marking present on the right side of the road, indicating the vehicle maintained its position better than when there was no marking present. The length of the segments seemed to have a significant impact on the distance from left, but the coefficient estimate was very small and negligible. It is also important to note that the Adjusted R-Squared value (0.428) was relatively small. Length distribution for off ramp positions is shown in Figure 89. It is important to note that this detailed evaluation is for a single vehicle type. This vehicle and three others were driven through the same test areas and subjective analysis on the vehicles ability to maintain lane position was evaluated (discussed later in this report).

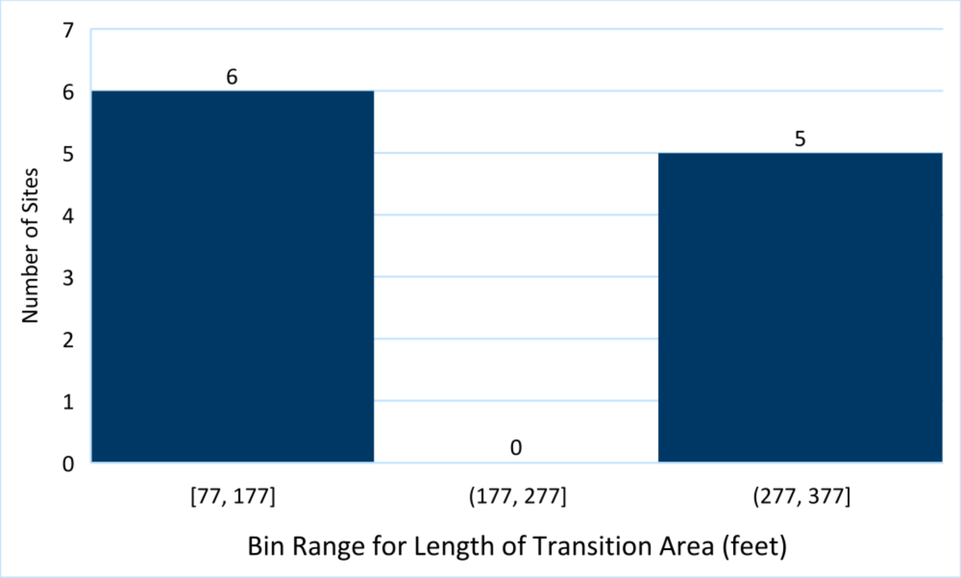


Figure 89. Transition segment length distribution for off ramp locations.

Lane Position Ratio:

The study team chose LPR as the dependent variable and conducted an ANOVA test. Similar to Distance from Left ANOVA test, the results showed that Presence of dotted pavement markings on the right side of the driving lane, impacted lane position ratio.

Table 39. ANOVA table for average LPR at off ramp locations

Source	Df	Sum Sq	Mean Sq	F Value	Pr(>F)
SegmentType	1	0.5649	0.5649	6.114	0.0243
RightPM	1	0.7637	0.7637	8.266	0.0105
Length	1	0.0183	0.0183	0.198	0.6618
Day.Night	1	0.1801	0.1801	1.949	0.1806
Residuals	17	1.5706	0.0924		

3.3.4 Minneapolis Observation of Vehicle Operations

The research team used 4 vehicles with varying levels of ADAS to drive through each of the test sites to observe how the vehicles operated with the different pavement marking conditions. Each vehicle was operated in a similar manner. The ADAS features were fully enabled, and the steering wheel was only used to keep the system active. The ADAS features were allowed to steer the vehicle though the test sites. The Toyota TSS P system does not provide steering assist, it only provides lane departure warning. The other three systems provide Level 2 autonomy and have lane centering functions. Each vehicle was operated day and night. At night only low beam headlamp illumination was used. Not all vehicles drove through each test area due to time constraints.

The researchers used forward facing cameras to monitor the drive through the test sites including how the steering wheel moved and audio recordings from the researchers conducting the tests. The researchers noted how the system guided the vehicle, when marking detection was dropped, and when issues came up. When needed the driver took over full operation of the vehicle to maintain a safe operating environment. Notes from each of the test sites are provided in the following tables. Table 40 provides the observations during the day and Table 41 provides the observations at night.

General observations indicate that the different broken lane line striping patterns did not have an impact on the operations of the systems evaluated as operation was normal in those test areas. There were no results from the on-road observations of vehicle operations that indicated one style of contrast markings were better than the other. In areas with lower quality markings there was some loss of tracking the markings by the systems both day and night.

Areas with turn bays and ramps (on or off) generated the majority of the non-desirable operations. In some cases, the vehicles either drifted toward or fully entered turn bays or ramps when there were not dotted lane line extensions present. Even when dotted lane line extension were present there was still some drift toward some of the turn bays and ramps. The drift toward these areas is an operational issue as ideally the vehicle would maintain a similar position along the centerline of the lane. In the cases where the vehicle left the lane, safety becomes a major issue, as the driver may not be expecting the vehicle to depart the lane toward the turn bay or ramp area. In some cases, the systems deactivated after leaving the lane. This type of movement was of particular interest as the system may still function outside of its intended course and an unobservant driver may not correct in time.

The operation of these systems in combination with gore areas was also of interest. The research team typically found that the systems did not want to cross markings to enter gore areas (where markings were in good condition). The systems would deactivate if forced out of the lane by the driver and would stay in the lane otherwise. In a couple cases the vehicle followed the edge line marking and started to exit before correcting into the gore area and disengaging the system. The systems can drive in the gore area if they can get in and track the markings on either side. It is no different than engaging the system on the shoulder of a road. If the system can track a marking it will try to guide the vehicle alongside it. Providing good markings at gore areas and dotted line extensions to help keep vehicles in their intended lanes at exit ramp areas is desirable. Dotted line extensions at turn bays are also desirable to help keep vehicles in their intended lanes. Minimizing the opening width between an on ramp and the trough lane at on ramp areas is desirable to improve vehicle operations by keeping the main lane vehicles along the centerline of their intended lane.

Another area where issues arose was in areas where markings not intended for the direction of travel the vehicle was going went across the traveled lane. These included dotted line extension markings from intersecting roads at large intersections and the markings on either end of MnRoad. The markings may be viewed as the intended markings if they are more longitudinal than transverse and the vehicle may try to follow them. The vehicles attempting to follow these markings resulted in the driver having to manually take over the vehicle operations to potentially avoid a crash.

Table 40. Observations of vehicle operations through each test site during the day

Site Number	Roadway	Factors Evaluated	Ford Co-Pilot 360 Assist+	Tesla Autopilot	Toyota TSS 2.0	Toyota TSS P
1	I-494	width, cycle, quality	Normal operation	Normal operation	Normal operation	Normal operation
2	I-494	width, cycle, quality, contrast	Normal operation	Normal operation	Normal operation	Normal operation
3	MN 55	quality, left turn bays	Normal operation	Normal operation	Normal operation	Normal operation
4	MN 55	left turn bays	Pulled left and deactivated at turn bay	Some pull into turn bays	Pulled left at first turn bay, deactivated at some turn bays.	System lost line detection at turn bays and intersections.
5	MN 55	quality, left turn bays	System cancelled at intersection with cat tracks from side street movement	Driver disengaged system when vehicle jerked due to crossing cat tracks	Lost lane detection at intersection, crossing cat tracks had no impact	Lost lane detection at intersection, crossing cat tracks had no impact
6	MN 55	quality, left turn bays	Pulled left and deactivated at turn bay	Normal operation	System lost line detection at some gaps and pulled left into some turn bays	System lost line detection at gaps and some poor marking areas
7	I-494	ramp area	Pulled right toward ramp before correcting	Normal operation	Normal operation	Dropped right line marking when passing ramp
8	I-494	width, cycle, quality, contrast	Normal operation	Normal operation	Normal operation	Normal operation
9	I-494	interchange area	Went to left roadway following left skip line	Normal operation	System kept disengaging	Dropped right line at split
10	I-94	width, cycle, quality, contrast	Normal operation	Normal operation	Lane centering was drifting	Normal operation

Site Number	Roadway	Factors Evaluated	Ford Co-Pilot 360 Assist+	Tesla Autopilot	Toyota TSS 2.0	Toyota TSS P
11	I-94	width, cycle, quality, contrast	Normal operation	Normal operation	Normal operation	Normal operation
12	I-94	MnRoad merges	-	Vehicle tried to exit left into barriers following the edge line instead of crossing skip line to go right	Vehicle tried to exit left into barriers following the edge line instead of crossing skip line to go right	Did not like where skip lines cross road at MNDOT ends
13	I-94	ramp area, quality	Normal operation	Normal operation	-	-
14	I-94	width, cycle, quality, contrast	-	Normal operation	-	-
15	I-94	ramp area	-	Normal operation	-	-
16	I-94	width, cycle, quality, contrast	Normal operation	Normal operation	-	-
17	I-94	width, cycle, quality, contrast	Normal operation	Normal operation	Normal operation	Normal operation
18	MN 241	left turn bays	Normal operation	Normal operation	Dropped lane tracking at turn bays and would pull vehicle into the turn bays.	Dropped left lane markings at turn bays when solid line goes to skips momentarily, then picks the skips up.
19	CR 81	intersection, gore area	Pulled right to turn bay	Pulled right then corrected	Pulled right into turn bay	Lost tracking at turn bays
20	CR 81	gore area	system cancelled	system cancelled when forced into gore area	-	-
21	CR 81	intersection, left turn bay	-	system did not like the loss of markings near merge area	Pulled left then canceled at left hand turn bay	-

Site Number	Roadway	Factors Evaluated	Ford Co-Pilot 360 Assist+	Tesla Autopilot	Toyota TSS 2.0	Toyota TSS P
22	I-35W	width, cycle, quality, contrast	Normal operation	Normal operation	System had trouble detecting lane lines throughout, had to manually steer to avoid leaving the lane.	-
23	I-35W	width, cycle, quality, contrast	Normal operation	Normal operation	System had trouble detecting lane lines throughout, had to manually steer to avoid leaving the lane.	-
24	I-94	width, cycle, quality, contrast	Normal operation	Normal operation	-	-
25	I-94	width, cycle, quality, contrast	Normal operation	Normal operation	-	-
26	I-94	width, cycle, quality, contrast	Normal operation	Normal operation	-	-
27	I-94	width, cycle, quality, contrast	system cancelled at ramp area due to glare	-	-	-
28	WI 35	right turn bay	Pulled right to some turn bays	Pulled right to some turn bays	-	-
29	WI 35	ramp area	Normal operation	Normal operation	-	-
30	WI 35	ramp area	Normal operation	Normal operation at off ramp with dashes, but pulled right at on ramp	-	-
31	US 61	width, cycle, quality, contrast, right turn bay	pulled right at turn bay, system cancelled on bridge	Normal operation	-	-

Site Number	Roadway	Factors Evaluated	Ford Co-Pilot 360 Assist+	Tesla Autopilot	Toyota TSS 2.0	Toyota TSS P
32	US 61	width, cycle, quality, contrast, right turn bay	Normal operation	Normal operation	-	-
33	US 52	off ramp area	-	Normal operation	-	-
34	US 52	on ramp area	Pulled right at ramp areas	Pulled right at ramp areas	Some pull toward ramps.	Dropped right lane line at ramps.
35	Yankee Doodle Road	width, cycle, quality, turn bay	system cancelled at turn bays, inconsistent operation	Normal operation	Pulled toward turn bays, had trouble tracking markings	Dropped lane lines at turn bays and intersections, struggled with left skip lines.
36	US 77	width, cycle, quality, ramp area	Normal operation	Normal operation	Normal operation	Difficulty picking up poor lane lines, no other issues.
37	US 77	width, cycle, quality	Normal operation	Normal operation	Normal operation	Normal operation

- Indicates the section was not evaluated with that vehicle.

Table 41. Observations of vehicle operations through each test site at night

Site Number	Roadway	Factors Evaluated	Ford Co-Pilot 360 Assist+	Tesla Autopilot	Toyota TSS 2.0	Toyota TSS P
1	I-494	width, cycle, quality	Normal operation	Normal operation	Normal operation	Normal operation
2	I-494	width, cycle, quality, contrast	Normal operation	Normal operation	Normal operation	Normal operation
3	MN 55	quality, left turn bays	Normal operation	Normal operation	Normal operation	Dropped tracking at turn bays and intersections

Site Number	Roadway	Factors Evaluated	Ford Co-Pilot 360 Assist+	Tesla Autopilot	Toyota TSS 2.0	Toyota TSS P
4	MN 55	left turn bays	Pulled left at turn bays and deactivated	pulled toward turn bay	Pulls toward some turn bays	Dropped tracking at turn bays and intersections
5	MN 55	quality, left turn bays	System cancelled at intersection with cat tracks from side street movement	Some vehicle wander at intersection, tried to follow diagonal cross cat tracks then corrected, and turn bays	Pulls toward some turn bays, loses tracking at big intersection.	Dropped tracking at turn bays and intersections, and areas with poor markings
6	MN 55	quality, left turn bays	Pulled left at turn bays	Normal operation	Some loss of tracking due to poor markings	Some loss of tracking due to poor markings
7	I-494	ramp area	Pulled right toward ramp and into gore area before system deactivated	Normal operation	Pulled right onto ramp	Dropped right marking at ramp
8	I-494	width, cycle, quality, contrast	Normal operation	Normal operation	Normal operation	Normal operation
9	I-494	interchange area	Went to left roadway following left skip line	Went to left roadway following left skip line	Pulled right toward right split but stayed left	Dropped right line at split
10	I-94	width, cycle, quality, contrast	Normal operation	Normal operation	Normal operation	Normal operation
11	I-94	width, cycle, quality, contrast	Normal operation	Normal operation	Normal operation	Normal operation

Site Number	Roadway	Factors Evaluated	Ford Co-Pilot 360 Assist+	Tesla Autopilot	Toyota TSS 2.0	Toyota TSS P
12	I-94	MnRoad merges	-	Vehicle tried to exit left into barriers following the edge line instead of crossing skip line to go right. At the other end vehicle needlessly changed lanes when skip marking crossed lane.	Vehicle tried to left exit where skip lines crossed the road at MNDOT closed road area, had to take over manually. In left lane at end of section, briefly loses tracking, keeps in left lane.	-
13	I-94	ramp area, quality	Normal operation	Drifted right at on ramp	-	-
14	I-94	width, cycle, quality, contrast	Normal operation	Normal operation	-	-
15	I-94	ramp area	Normal operation	Normal operation	-	-
16	I-94	width, cycle, quality, contrast	Normal operation	Normal operation	-	-
17	I-94	width, cycle, quality, contrast	Normal operation	Normal operation	Normal operation	Normal operation
18	MN 241	left turn bays	Pulled toward first turn bay good otherwise	Normal operation	Would drop left line tracking and pull toward turn bays some.	Dropped left lane markings at turn bays when solid line goes to skips momentarily, then picks the skips up.
19	CR 81	intersection, gore area	Pulled right toward turn bays	Pulled right into turn bay	Pulled right into turn bay	Normal operation
20	CR 81	gore area	System cancelled when forced into gore area	System deactivated when forced into gore area	Pulled vehicle into turn bay, had to manually steer through gore area.	System was able to be activated in gore area

Site Number	Roadway	Factors Evaluated	Ford Co-Pilot 360 Assist+	Tesla Autopilot	Toyota TSS 2.0	Toyota TSS P
21	CR 81	intersection, left turn bay	System cancelled when lane markings dropped at merge area	vehicle pulled right and left when markings were dropped at merge area	Poor tracking in area where markings drop	Normal operation
22	I-35W	width, cycle, quality, contrast	Normal operation	Normal operation	System had trouble detecting lane lines throughout, had to manually steer to avoid leaving the lane.	-
23	I-35W	width, cycle, quality, contrast	Normal operation	Normal operation	System had trouble detecting lane lines throughout, had to manually steer to avoid leaving the lane.	-
24	I-94	width, cycle, quality, contrast	Normal operation	Normal operation	-	-
25	I-94	width, cycle, quality, contrast	Normal operation	Normal operation	-	-
26	I-94	width, cycle, quality, contrast	System deactivated at ramp area due to poor markings	Normal operation	-	-
27	I-94	width, cycle, quality, contrast	System deactivated at ramp area due to poor markings	Normal operation	-	-
28	WI 35	right turn bay	system pulled toward turn bays without dashes	system pulled toward turn bays without dashes	-	-
29	WI 35	ramp area	Normal operation	Normal operation	-	-

Site Number	Roadway	Factors Evaluated	Ford Co-Pilot 360 Assist+	Tesla Autopilot	Toyota TSS 2.0	Toyota TSS P
30	WI 35	ramp area	-	-	-	-
31	US 61	width, cycle, quality, contrast, right turn bay	pulled right at turn bay, system cancelled on bridge	Normal operation	-	-
32	US 61	width, cycle, quality, contrast, right turn bay	system slow to activate, pulled right toward turn bay	Normal operation	-	-
33	US 52	off ramp area	Normal operation	Normal operation	-	-
34	US 52	on ramp area	Normal operation	Pulled toward on ramps	No issues at ramps, but had trouble tracking the poor condition markings	Dropped right lane line at ramps
35	Yankee Doodle Road	width, cycle, quality, turn bay	Pulled right toward turn bays, cancelled at one turn bay	Pulled toward turn bays	Had difficulty reading the poor lane lines. Pulled into/toward turn bays on right.	Difficulty tracking poor quality markings
36	US 77	width, cycle, quality, ramp area	Normal operation	Normal operation	Normal operation	Mostly normal operation, some brief loss of tracking the low quality markings
37	US 77	width, cycle, quality	Normal operation	Normal operation	Normal operation	Normal operation

- Indicates the section was not evaluated with that vehicle.

Chapter 4: Conclusions and Recommendations

4.1 Findings

The research team collected and analyzed data to determine which pavement marking characteristics and configurations were most beneficial to improve conditions for advanced driver assist and automated driving systems. The research team also reviewed recent changes to federal requirements and guidance concerning pavement markings. The findings discussed in the following sections are used to determine the recommended pavement marking practices that meet the objective of the research.

4.1.1 Closed-Course Evaluation Findings

The closed-course evaluations took place in a controlled environment and evaluated variations in pavement marking quality, width, and pattern. These tests took place during the day and at night. The results showed the lane line pattern had a significant effect on the results. During both day and night, the 10-30 pattern had higher performance than the 10-40 pattern. The markings that had higher retroreflectivity generally had higher detection. The 6-inch-wide markings had similar nighttime performance but lower daytime performance than their 4-inch comparison markings. The impact of width on the daytime results was unexpected.

4.1.2 On-Road Evaluation Findings

On-road evaluations took place in three distinct areas. The first test area was in Texas where contrast markings were examined. The second test area was at a pavement marking test deck in Minnesota. The third test area was on roads around the Minneapolis area.

4.1.2.1 Contrast Marking Evaluation in Texas

Areas of multi-lane highway with and without contrast markings were examined with and without sun glare. The line tracking results were always lower when the sun glare was present. The white marking followed by the black marking with or without the sun glare performed better than white bordered by black or white markings only.

4.1.2.2 Pavement Marking Test Deck in Minnesota

A series of 6-inch-wide broken lane line markings with different patterns were installed on MN 336. These markings only varied in the length of the stripe and gap, and in some cases, the inclusion of black contrast. Three additional areas of 4-inch-wide markings on I94 were also evaluated. One of the I94 segments was restriped with a new 4-inch-wide marking between tests. The detection confidence of the Mobileye system when evaluating the markings was similar for each test area. The noticeable exceptions were the segments on I 94 that were not restriped. These segments had slightly lower data than the newer test deck markings or the restriped segment on I94. This indicated that well-maintained markings are needed for the best detection by camera systems. The maximum line detection distance was farther at night than during the day. The older 4-inch markings on concrete had shorter maximum detection distances than the newer 6-inch markings. The Mobileye system generally had longer detection distances when more stripe was present on each skip line.

4.1.2.3 Open-Road Evaluations in Minnesota

The open-road evaluations took place on more than 30 segments around Minneapolis. The evaluations consisted of driving through each test area with the Mobileye ADAS logging data and driving through the test areas with 4 different ADAS equipped vehicles. The Mobileye system was used to evaluate marking detection confidence, maximum marking detection distance, and vehicle position within the lane. The ADAS equipped vehicles were driven with minor inputs from the driver to allow the ADAS to assist as much as possible. The ADAS equipped vehicles were monitored to see how the systems operated the vehicle through the test areas.

MOBILEYE SYSTEM EVALUATIONS

The Mobileye system evaluations revealed that several marking characteristics showed improvements in marking detection, some of which were significant. A higher stripe to gap ratio showed improved marking detection from broken lane lines. The higher stripe to gap ratio also resulted in a statistically significant increase in end-of-line detection distance. Broken lane line contrast markings with black following the white marking showed significant improvement in detection confidence. Contrast markings did not show an increase in end-of-line detection distance, instead they showed a decrease that was not statistically significant. Six-inch-wide markings compared to 4-inch-wide markings resulted in a small, not statistically significant, improvement in detection confidence. The 6-inch-wide markings had similar end-of-line detection distance to the 4-inch-wide markings. When considering the marking brightness (as evaluated from image grayscale analysis) the research team found a statistically significant increase in end-of-line detection distance with increased greyscale values.

The Mobileye system was also used to evaluate the position of the vehicle as turn bays and exit ramps were passed during data collection. Some of these turn bays and exit ramps had dotted edge line extensions whereas others did not. The research team compared the position of the vehicle upstream of the target area and the position of the vehicle when passing the target area. The results showed that for the vehicle and roadway segments tested, the presence of dotted edge line extensions did not have a statistically significant impact on lane position when passing a left-turn bay. Many of the evaluated turn-bay gaps were short and on tangent sections. These characteristics may have minimized the benefit of having the dotted edge line extensions. The results showed that for the vehicle and roadway segments tested, the presence of dotted edge line extension had a statistically significant beneficial impact on maintaining lane position when passing an exit ramp. Many of the ramp opening areas were short but some of the ramps both with and without the dotted edge line extensions had some horizontal curvature. The presence of the curve may have been a reason the dotted edge line extension saw a statistically significant benefit.

VEHICLE ADAS OPERATION ASSESSMENTS

The observation of the ADAS operation through the test areas was not to assess differences between or to rate the quality of the ADAS, but rather to monitor how the different systems reacted to the different marking configurations. The main observation was to determine if the vehicle navigated through the test areas as expected or if undesirable operations were detected by the vehicle operators.

General observations indicated that the different broken lane line striping patterns did not have an impact on the operations of the systems evaluated as operation was normal in each of the test areas. There were no results that indicated one style of contrast markings was better than the others. In areas with lower-quality markings, there was some loss of tracking the markings by the systems both during the day and night.

Areas with turn bays and ramps (on or off) generated the majority of the non-desirable operations. In many cases, the vehicles either drifted toward or fully entered turn bays or ramps (both exit and entrance) when there were no dotted lane line extensions present. Even when dotted lane line extensions were present, there was still some drift toward some of the turn bays and exit ramps. The drift toward these areas is an operational issue; ideally the vehicle maintains a similar position along the centerline of the lane. In cases where the vehicle left the lane, safety becomes a major issue, as the driver may not be expecting the vehicle to depart the lane and enter the turn bay or ramp area. In some cases, the systems deactivated after leaving the lane. This type of movement was of particular interest as the system can still function outside of its intended course and an unobservant driver may not correct in time. The operation of these systems in combination with gore areas was also of interest. The research team typically found that the systems did not want to cross markings to enter gore areas (where markings were in good condition). The systems would deactivate if forced out of the lane by the driver and would stay in the lane otherwise. In a couple cases, the vehicle followed the edge line marking and started to exit before correcting into the gore area and disengaging the system. The systems can drive in the gore area if they can get in and track the markings on either side. It is no different than engaging the system on the shoulder of a road. If the system can track a marking it will try to guide the vehicle alongside it. Keeping vehicles out of undesired locations with well-maintained markings is essential.

One other circumstance where issues arose was in those areas where markings not intended for the direction of travel the vehicle was going went across the traveled lane. These included dotted line extensions for turning movements from intersecting roads at large intersections and the markings on either end of MnRoad. The markings could be viewed, by ADAS, as the intended markings, if they were more longitudinal than transverse, and the vehicle might try to follow them. The vehicles attempting to follow these markings resulted in the driver having to manually take over the vehicle’s operations to potentially avoid a crash.

4.1.3 Changes to the MUTCD

Over the course of this project, the Federal MUTCD was undergoing revisions. One of the recommendations the NCUTCD made to the FHWA was to update the MUTCD to provide better markings for not only human drivers but also for the next generation of autonomous and driver assistance systems. These recommendations included:

- Shall use 6-inch-wide markings on all freeways.
- Shall use 6-inch-wide edge lines on highways with posted speed ≥ 55 mph and ≥6,000 vehicles/day.
- Wide lines are 8 inches or more when used with 4-inch normal lines and 10 inches or more when used with 6-inch normal lines.
- Should lengthen all broken lane lines on interstates, freeways, and expressways to 15 feet in length with a 25-foot gap.
- Shall use dotted line extensions across all exit ramps.

The NCUTCD recommendations were considered by the FHWA, and during December 2020, the Notice of Proposed Amendment (NPA) to the MUTCD was published by the FHWA. The NPA covered all proposed changes to the MUTCD. The changes made to the MUTCD considering the above mentioned NCUTCD recommendations went beyond what was recommended. There was a much greater emphasis on using wider markings on a wider range of roadways. The MUTCD used a lower speed threshold (40 mph vs 55 mph) and did not have criteria for traffic volume. The changes in the NPA included:

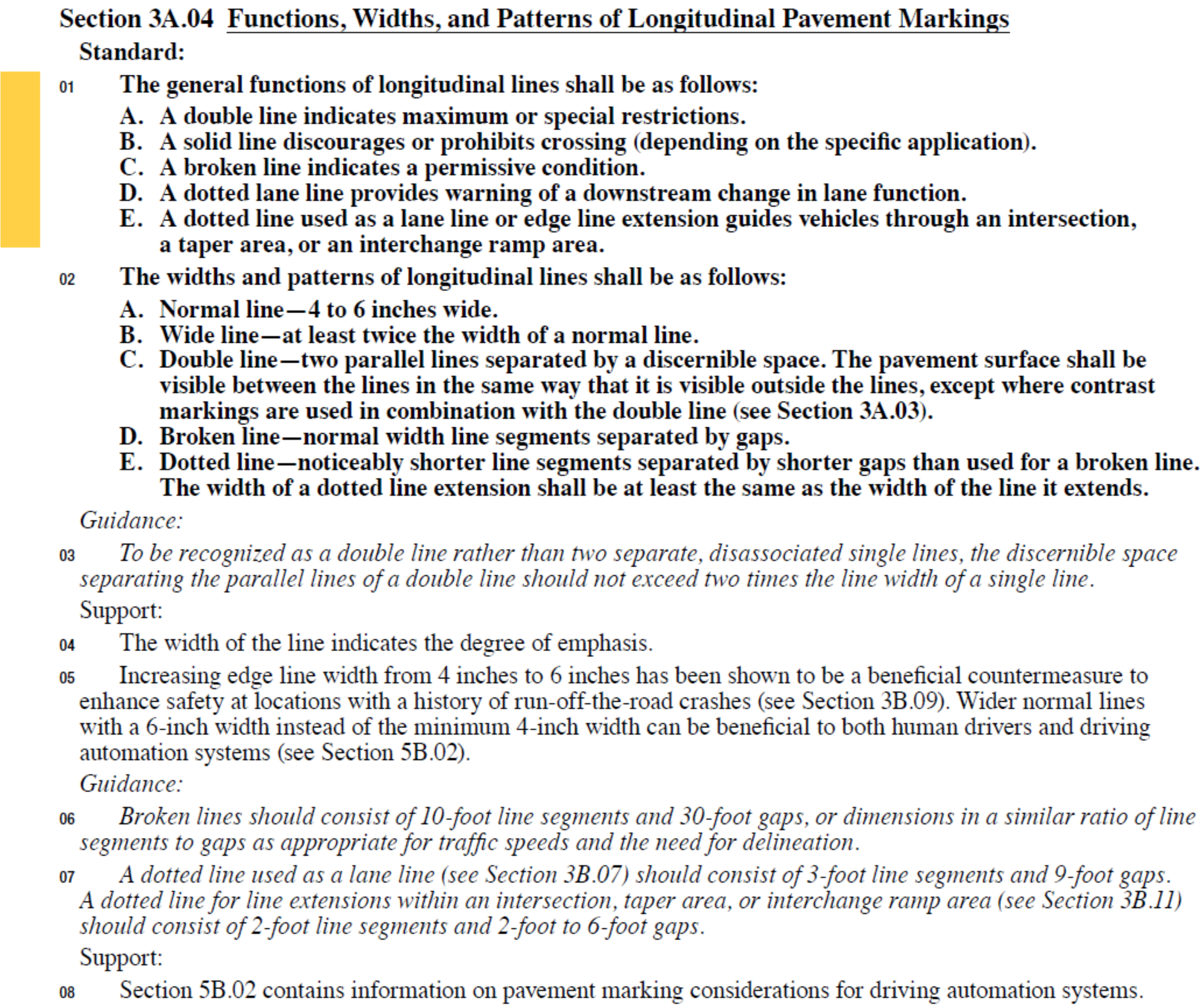
- Normal width line – 6-inches wide for freeways, expressway, and ramps; 6-inches wide for all other roadways with speed limits > 40 mph, 4 to 6 inches for all other roadways.
- Wide line – at least 8 inches in width if 4-inch or 5-inch normal width lines are used and at least 10 inches in width if 6-inch normal width lines are used.
- There were no changes to the length of broken lane lines in part 3, but FHWA included new material in a revised part 5 (see below).
- Dotted line extensions were changed from “may” to “shall” for exit and entrance ramps.
- Guidance: regardless of the width of the normal line used on the roadway, edge lines on two-lane roadways should be at least 6 inches wide.

The NPA included a new part 5 developed to cover automated vehicles. This part is intended for consideration of traffic control devices that are specifically being designed to accommodate automated vehicles capable of performing partial or full real-time operational functions in general traffic on a sustained basis. This part does not require an agency to do anything.

Section 5B.02 covers markings. Many items in this section reiterate changes made in part 3 and suggest additional expansion of those changes. The section indicates greater use of 6-inch-wide markings including on all freeways, expressways, and ramps, and use of 6-inch-wide edge lines on roadways with posted speeds greater than 40 mph. This greater use of 6-inch-wide markings benefits AV operations while also benefiting, or at least not detracting from the performance of the human operator. The section provides additional guidance for normal width markings to be at least 6 inches wide on conventional roadways, and edge lines of at least 6 inches in width on conventional roadways with posted speed limits of 40 mph or less. The guidance also calls for dotted edge line extension along all entrance and exit ramps, all auxiliary lanes, and all tapers where a deceleration or auxiliary lane is added. Consideration of adding chevron markings in the neutral areas of exit gore to distinguish them from travel lanes is included as guidance. A recommended change from the NCUTCD was a longer broken lane line marking with a shorter gap. This was not addressed in part 3 but is in part 5. The guidance indicates consideration of broken lines of at least 10 feet in length with a maximum gap of 30 feet. The guidance also indicates the use of uniform contrast markings on light-colored pavements to create greater contrast.

In December 2023, the FHWA published the 11th edition of the MUTCD [44]. There were several changes to part 3 concerning the material discussed from the NCUTCD recommendations and what was provided in the NPA. The biggest change is that the added language in the NPA to require increased use of 6-inch-wide markings was removed from part 3, see Figure 90. The section on functions, widths, and patterns of longitudinal pavement markings has only a few changes from what was in the 10th edition of the MUTCD. The FHWA did add in a support statement that says, “Increasing edge line width from 4 inches to 6 inches has been shown to be a beneficial countermeasure to enhance safety at locations with a history of run-off-the-road crashes. Wider normal lines with a 6-inch width instead of the minimum 4-inch width can be beneficial to both human drivers and driving autonomous systems.” This support statement does not require an increased use of 6-inch-wide markings but provides support to do so.

The reasoning FHWA provided for removing the requirements for increased use of 6-inch-wide marking is as follows, “The FHWA received several comments opposed to the new requirement for 6-inch-wide normal lines due to the additional cost. Commenters suggested that the budgetary impact was underrepresented since the change was not a one-time cost but also increased life-cycle costs related to ongoing maintenance with pavement resurfacing and marking “refreshing.” Some commenters also suggested that the extent of the proposed 6-inch requirement was not supported by research. A number of agencies stated they might decide not to install markings at all on roadways that do not meet the warrants for centerlines and edge lines in Sections 3B.02 and 3B.10 based on the increased cost of 6-inch markings, which could result in increased crashes.” The justification is reasonable because of the language used in the NPA. Had the FHWA followed the recommendations of the NCUTCD some of the comments received would not have been an issue, i.e., requirements for 6-inch markings where markings are not warranted and 6-inch markings not required on as many roadways.



Section 3A.04 Functions, Widths, and Patterns of Longitudinal Pavement Markings

Standard:

01 **The general functions of longitudinal lines shall be as follows:**

A. A double line indicates maximum or special restrictions.
B. A solid line discourages or prohibits crossing (depending on the specific application).
C. A broken line indicates a permissive condition.
D. A dotted lane line provides warning of a downstream change in lane function.
E. A dotted line used as a lane line or edge line extension guides vehicles through an intersection, a taper area, or an interchange ramp area.

02 **The widths and patterns of longitudinal lines shall be as follows:**

A. Normal line—4 to 6 inches wide.
B. Wide line—at least twice the width of a normal line.
C. Double line—two parallel lines separated by a discernible space. The pavement surface shall be visible between the lines in the same way that it is visible outside the lines, except where contrast markings are used in combination with the double line (see Section 3A.03).
D. Broken line—normal width line segments separated by gaps.
E. Dotted line—noticeably shorter line segments separated by shorter gaps than used for a broken line. The width of a dotted line extension shall be at least the same as the width of the line it extends.

Guidance:

03 *To be recognized as a double line rather than two separate, disassociated single lines, the discernible space separating the parallel lines of a double line should not exceed two times the line width of a single line.*

Support:

04 The width of the line indicates the degree of emphasis.

05 Increasing edge line width from 4 inches to 6 inches has been shown to be a beneficial countermeasure to enhance safety at locations with a history of run-off-the-road crashes (see Section 3B.09). Wider normal lines with a 6-inch width instead of the minimum 4-inch width can be beneficial to both human drivers and driving automation systems (see Section 5B.02).

Guidance:

06 *Broken lines should consist of 10-foot line segments and 30-foot gaps, or dimensions in a similar ratio of line segments to gaps as appropriate for traffic speeds and the need for delineation.*

07 *A dotted line used as a lane line (see Section 3B.07) should consist of 3-foot line segments and 9-foot gaps. A dotted line for line extensions within an intersection, taper area, or interchange ramp area (see Section 3B.11) should consist of 2-foot line segments and 2-foot to 6-foot gaps.*

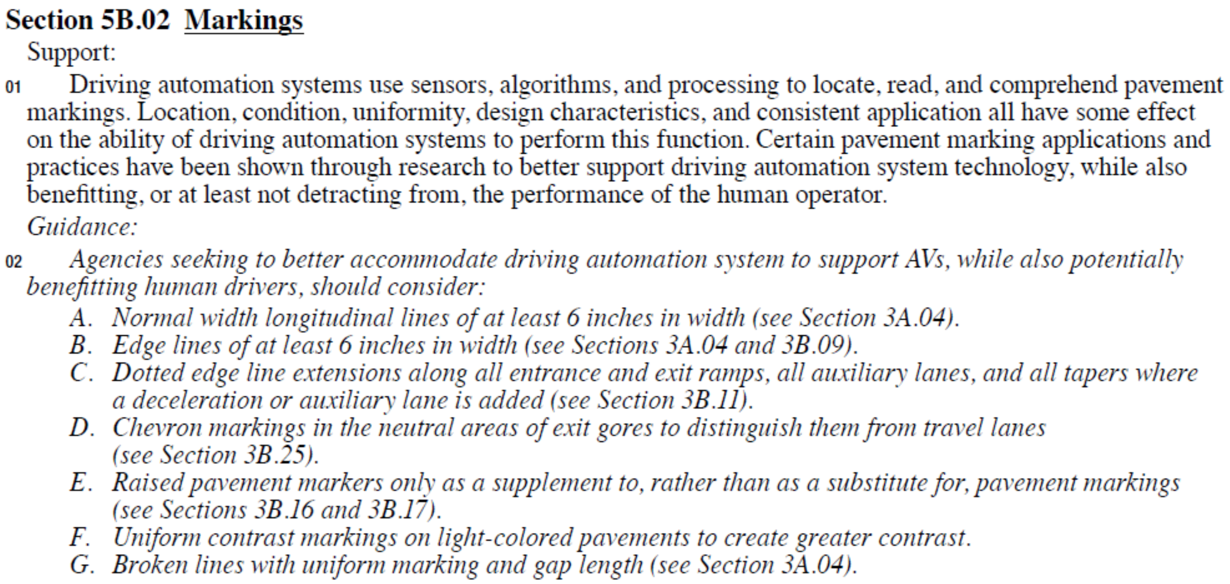
Support:

08 Section 5B.02 contains information on pavement marking considerations for driving automation systems.

Figure 90. 11th Edition MUTCD Section 3A.04 [44].

The 11th edition of the MUTCD does require the use of a normal width dotted line across exit ramps and leaves it as an option to use a normal width dotted line across entrance ramps. Part 3 of the 11th edition of the MUTCD does not change the guidance for the dimensions of broken lines, they are still indicated as 10-foot line segments and 30-foot gaps, or dimensions in a similar ratio.

Part 5 of the 11th edition of the MUTCD has less information than what was provided in the NPA. Figure 91 shows the 11th edition of the MUTCD part 5 section 5B.02. FHWA removed some repeated content and the suggestion to use broken lines of at least 10 feet in length with a maximum gap of 30 feet.



Section 5B.02 Markings

Support:

01 Driving automation systems use sensors, algorithms, and processing to locate, read, and comprehend pavement markings. Location, condition, uniformity, design characteristics, and consistent application all have some effect on the ability of driving automation systems to perform this function. Certain pavement marking applications and practices have been shown through research to better support driving automation system technology, while also benefitting, or at least not detracting from, the performance of the human operator.

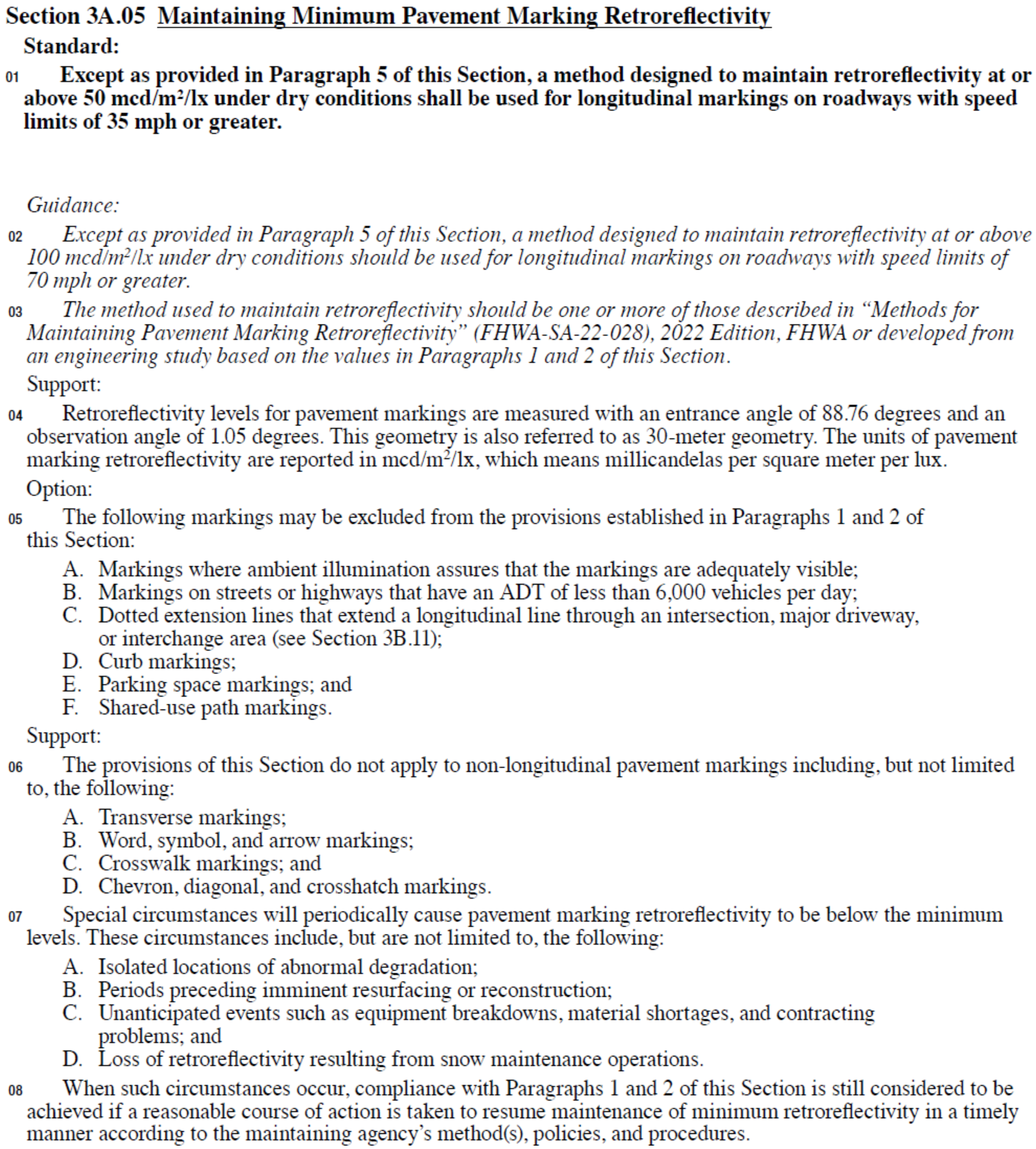
Guidance:

02 *Agencies seeking to better accommodate driving automation system to support AVs, while also potentially benefitting human drivers, should consider:*

- A. *Normal width longitudinal lines of at least 6 inches in width (see Section 3A.04).*
- B. *Edge lines of at least 6 inches in width (see Sections 3A.04 and 3B.09).*
- C. *Dotted edge line extensions along all entrance and exit ramps, all auxiliary lanes, and all tapers where a deceleration or auxiliary lane is added (see Section 3B.11).*
- D. *Chevron markings in the neutral areas of exit gores to distinguish them from travel lanes (see Section 3B.25).*
- E. *Raised pavement markers only as a supplement to, rather than as a substitute for, pavement markings (see Sections 3B.16 and 3B.17).*
- F. *Uniform contrast markings on light-colored pavements to create greater contrast.*
- G. *Broken lines with uniform marking and gap length (see Section 3A.04).*

Figure 91. 11th Edition MUTCD Part 5 Section 5B.02 [44].

Between publishing the NPA and the 11th edition of the MUTCD, the FHWA published a revised version of the 10th edition (2009 edition) of the MUTCD. This was the 3rd revision of the document. The revision included the addition of a section on maintaining minimum pavement marking retroreflectivity. This section requires agencies to implement a method to maintain their pavement marking retroreflectivity (on applicable markings) above required levels. This section was carried over to the 11th edition of the MUTCD with only editorial changes [44]. Figure 92 provides the section of the MUTCD.



Section 3A.05 Maintaining Minimum Pavement Marking Retroreflectivity

Standard:

01 **Except as provided in Paragraph 5 of this Section, a method designed to maintain retroreflectivity at or above 50 mcd/m^2/lx under dry conditions shall be used for longitudinal markings on roadways with speed limits of 35 mph or greater.**

Guidance:

02 *Except as provided in Paragraph 5 of this Section, a method designed to maintain retroreflectivity at or above 100 mcd/m^2/lx under dry conditions should be used for longitudinal markings on roadways with speed limits of 70 mph or greater.*

03 *The method used to maintain retroreflectivity should be one or more of those described in "Methods for Maintaining Pavement Marking Retroreflectivity" (FHWA-SA-22-028), 2022 Edition, FHWA or developed from an engineering study based on the values in Paragraphs 1 and 2 of this Section.*

Support:

04 Retroreflectivity levels for pavement markings are measured with an entrance angle of 88.76 degrees and an observation angle of 1.05 degrees. This geometry is also referred to as 30-meter geometry. The units of pavement marking retroreflectivity are reported in mcd/m^2/lx, which means millicandelas per square meter per lux.

Option:

05 The following markings may be excluded from the provisions established in Paragraphs 1 and 2 of this Section:

A. Markings where ambient illumination assures that the markings are adequately visible;
B. Markings on streets or highways that have an ADT of less than 6,000 vehicles per day;
C. Dotted extension lines that extend a longitudinal line through an intersection, major driveway, or interchange area (see Section 3B.11);
D. Curb markings;
E. Parking space markings; and
F. Shared-use path markings.

Support:

06 The provisions of this Section do not apply to non-longitudinal pavement markings including, but not limited to, the following:

A. Transverse markings;
B. Word, symbol, and arrow markings;
C. Crosswalk markings; and
D. Chevron, diagonal, and crosshatch markings.

07 Special circumstances will periodically cause pavement marking retroreflectivity to be below the minimum levels. These circumstances include, but are not limited to, the following:

A. Isolated locations of abnormal degradation;
B. Periods preceding imminent resurfacing or reconstruction;
C. Unanticipated events such as equipment breakdowns, material shortages, and contracting problems; and
D. Loss of retroreflectivity resulting from snow maintenance operations.

08 When such circumstances occur, compliance with Paragraphs 1 and 2 of this Section is still considered to be achieved if a reasonable course of action is taken to resume maintenance of minimum retroreflectivity in a timely manner according to the maintaining agency's method(s), policies, and procedures.

Figure 92. 11th Edition MUTCD Part 3 Section 3A.05 [44].

4.2 Recommendations

The outcome of the research is to recommend pavement marking practices that meet the research objectives. These recommendations cover pavement marking width, skip to gap pattern, dotted line extensions, gore areas, marking brightness and maintenance, and contrast markings. The specific recommendations are in the following subsections.

4.2.1 Pavement Marking Width

Closed-course testing did not show much detection difference by the camera system between 4- and 6-inch-wide markings. Testing at the Minnesota test deck showed that the newer 6-inch markings were detected at a greater distance than the older 4-inch markings. That testing also showed a substantial improvement in detection when an older 4-inch marking was restriped with new material but still 4 inches in width. Open-road evaluations in Minnesota indicated 4- and 6-inch markings had similar detection distances by the Mobileye system. Based on the testing conducted, it appears that well maintained 4-inch markings have similar detection levels by the camera systems evaluated as 6-inch-wide markings. Unfortunately, the research team was unable to test low-performing (low retroreflectivity or poor presence) 6-inch-wide markings. Areas with low-performing 4-inch markings were not detected as well as areas with better-performing 4-inch markings or the 6-inch marking test areas. It is expected that a low-performing 6-inch-wide marking will be more detectable by camera systems than an equivalent 4-inch-wide marking. Six-inch-wide markings should benefit camera detection in areas where conflicting signals may cause confusion for the tracking algorithm, i.e, work zones, areas with pavement joints, areas with ghost markings, and areas with glare conditions on the road.

Based on the data gathered in this study, the research team recommends that MnDOT consider using 6-inch-wide markings as the normal width marking to better ensure high functionality of driver assist systems across a range of conditions and throughout the service life of the marking. This research is not conclusive on the benefit of 6-inch-wide normal markings for camera-based lane-detection systems. The data indicate that 4-inch and 6-inch markings provide similar levels of detection and visibility when the markings are good. The inability to evaluate poor-performing 6-inch markings to determine if they provide benefits over poor-performing 4-inch markings limits a definitive recommendation. This recommendation is similar to the recommendation provided in the *Pavement Marking Patterns and Widths – Human Factor Study* research project. That project recommended using 6-inch-wide markings as they were preferred by drivers and have been shown to improve safety. Using 6-inch-wide markings is supported by the NCUTCD pavement marking committee and the new Part 5 of the 11th edition of the MUTCD.

4.2.2 Broken Lane Line Skip to Gap Pattern

Closed-course testing showed higher detection performance by the camera system when evaluating the 10-30 pattern compared to the 10-40 pattern. Testing at the Minnesota test deck did not show significant differences between some of the different broken lane line patterns, but generally showed that the camera system was able to see the markings at greater distances when more stripe was present. Open-road evaluation in Minnesota showed that the Mobileye system showed improved marking detection from broken lane lines with higher stripe to gap ratio. The higher stripe to gap ratio also resulted in a statistically significant increase in end-of-line detection distance by the system.

The research team recommends MnDOT use a 12.5-37.5 stripe to gap broken lane line stripping pattern. The 12.5-37.5 pattern showed better performance than the current 10-40 pattern while maintaining the 50-foot cycle pattern. Maintaining the 50-foot cycle length is also preferred to reduce complexities with implementation. This recommendation agrees with the recommendation provided in the *Pavement Marking Patterns and Widths – Human Factor Study* research project. This recommendation also meets FHWA guidance on stripe to gap ratio.

4.2.3 Dotted Line Extensions

Open-road testing in Minnesota showed that the presence of dotted line extensions can help with driver assist system functionality in areas with turn bays and ramps. Situations with roadway curvature saw the most benefit from the presence of dotted line extensions across the opening areas to turn bays and ramp areas. The dotted lines reduced unwanted vehicle movement away from the main lane toward the open turn bay or ramp area. The presence of dotted line extensions for turning movements in intersections caused some undesirable reactions from the driver assist systems when going straight through the intersections. These dotted line extensions crossed the through lane and were picked up by some systems causing the vehicle to react with undesired movement.

The research team recommends MnDOT use dotted line extensions across all exit ramp areas and at turn bay entrance areas on roadways where use of driver lane keeping assist systems is expected. These types of roadways may include roadways with higher speeds or more free-flow traffic. *The research team recommends MnDOT consider using dotted line extensions at on ramp areas but not extend them across the entire open area.* Inclusion of additional dotted line extensions across some, but not the entire area, of the on ramp open area will help reduce undesired lane wander for main-lane traffic using lane-centering systems. An area needs to be left open so that entering vehicles using driver assist features do not try to track the dotted line extension as the left edge marking and potentially force an undesired movement to the shoulder or cause unintended system deactivation. The testing here did not identify the gap requirements needed for the traffic entering the highway. The 11th edition of the MUTCD now requires dotted line extensions across exit ramp areas but leaves them as an option for on ramps and turn bays.

Application of dotted line extensions for turning movements at intersections are good for human drivers making turns but may cause confusion for camera systems that are going straight through those intersections. Application of dotted line extensions at intersections to allow greater functionality of driver assist systems needs to consider the roadway types where these systems are more likely to be used. These types of roadways may include roadways with higher speeds or more free-flow traffic. *The research team recommends MnDOT consider dotted line extensions for through movements across large intersections, especially if there is a shift in lane position across the intersection. The research team also recommends that MnDOT consider how dotted line extensions for turning movements will affect crossing* *traffic.* If there is potential that a crossing vehicle may detect the turning lane dotted line extension, then application of that turning movement dotted line extension needs to be considered. Potentially a gap in the dotted line extension could be created as it passes the through movement lanes.

4.2.4 Gore Areas

During testing, a driver assist system that followed the exit ramp markings brought the vehicle toward the gore area before deactivating the system. Providing good markings at gore areas and dotted line extensions to help keep vehicles in their intended lanes at exit ramp areas is desirable. The driver assist systems will track any longitudinal markings. Those markings could be the left and right markings of a gore area or an edge line marking while the vehicle is driving on the shoulder of the road. *The research team recommends well-maintained markings and dotted edge line extensions at exit ramp areas. The research team also recommends MnDOT consider the addition of chevron markings to long and wide gore areas where vehicle intrusions may be more common, due to geometric design or other circumstances, so that the vehicle system would disengage and not unintentionally follow between the gore makings.*

4.2.5 Marking Brightness and Maintenance

Closed-course testing indicated that markings with higher retroreflectivity had higher detection. Testing at the Minnesota test deck showed better detection of the restriped 4-inch-wide marking and newer 6-inch-wide markings compared to the older 4-inch-wide markings. Open-road testing in Minnesota found a statistically significant increase in maximum detection distance with increased marking brightness. Open-road testing also indicated that some of the evaluated ADAS systems lost functionality in the areas noted as having lower pavement marking quality.

The testing did not cover a wide enough range of daytime and nighttime pavement marking performance levels to establish specific pavement marking performance levels for maintenance purposes. The testing did find that adequate maintenance of markings is needed to ensure reliable performance of the driver assist systems and that higher-performing markings generated higher detection confidence and detection distances than lower-performing markings. *The research team recommends that MnDOT implement a pavement marking maintenance plan that ensures markings are visible both during the day and at night. This plan should exceed the requirements of Section 3A.05 Maintaining Minimum Pavement Marking Retroreflectivity of the 11th edition of the MUTCD. The research team recommends maintaining marking quality on all roads not just those required by the MUTCD.*

4.2.6 Contrast Markings

Open-road evaluations in Texas found that the contrast pattern of white followed by black performed slightly better than white bordered by black and better than white markings alone. Testing at the Minnesota test deck did not find any preference toward one contrast design or the other. Open-road testing in Minnesota showed that the Mobileye system detected the white followed by black contrast marking better than other marking types on PCC pavements but did not see that marking type farther down the road.

Based on the data collected the research team recommends, that when implemented, MnDOT use the white followed by black contrast marking pattern. The black contrast following the 12.5-foot-long skip line should be 10- or 12.5-feet long. This recommendation is different than the recommendation provided in the *Pavement Marking Patterns and Widths – Human Factor Study* research project. That research did not find a preferred pattern based on driver input.

This research did not generate enough data to recommend specific roadway types or situations for implementation of contrast markings beyond what is recommended in part 5 of the 11th edition of MUTCD. The MUTCD provides guidance, “to better accommodate driving automation system to support AVs, while also potentially benefitting human drivers, should consider”… “F. Uniform contrast markings on light-colored pavement to create greater contrast.” The type of pavements used in addition to its age and condition will affect the pavement color. The specific type of marking material and its age will affect how bright and white the marking looks during the day. *The research team recommends implementing broken lane line contrast markings when the contrast between the combination of pavement surface and white marking material is low.*

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