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EVALUATION OF NJDOT HARDENED TRAFFIC PAINT MARKINGS AND STRIPES PERFORMANCE
FINAL REPORT

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Submitted by

Mohammad Jalayer, Ph.D.
Associate Professor
Department of Civil and Environmental Engineering
Rowan University

Subasish Das, Ph.D.
Assistant Professor
Department of Civil and Environmental Engineering
Texas State University

Adam Pike, P.E.
Associate Research Engineer
Texas A & M Transportation Institute

Yusuf Mehta, Ph.D., P.E.
Professor
Department of Civil and Environmental Engineering
Rowan University

NJDOT Research Project Manager
Giri Venkiteela

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16. Abstract

Pavement markings are essential for guiding drivers, enhancing roadway safety, and supporting Advanced Driver Assistance Systems (ADAS) and automated driving technologies. Their effectiveness depends on visibility under all conditions, day or night, clear or adverse weather. While retroreflectivity is a standard metric for nighttime visibility, it does not account for other critical factors such as pavement background color, marking width, or observational conditions, nor does it reflect daytime performance. Degradation is often accelerated by weather, traffic volume, poor surface preparation, and inadequate drying time or thickness. Some newly applied markings fail prematurely, highlighting the need for routine performance evaluation. This study analyzes technical and performance data of various pavement marking materials to identify those best suited for New Jersey's conditions. It also assesses drying time, durability, cost benefits, and the role of temporary markings, while proposing alternative testing protocols and specifications for quick deployment in case of supply chain disruptions. The findings aim to improve installation practices, enhance maintenance strategies, and ensure markings meet visibility needs for both human drivers and autonomous vehicle sensors.

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EXECUTIVE SUMMARY

Pavement markings are fundamental to roadway safety and navigation, serving as the primary method for agencies to provide longitudinal guidance to drivers. Their role has become increasingly critical with the growth of Advanced Driver Assistance Systems (ADAS) and automated driving technologies, which depend on clear, consistent, and visible markings for accurate lane detection and control. To ensure effectiveness, markings must remain visible under varying lighting and weather conditions. Traditionally, retroreflectivity has been used to assess nighttime visibility, but it does not capture all factors affecting performance. Pavement color, marking width and color, surface texture, driver viewing conditions, and environmental factors also impact visibility. Additionally, some markings deteriorate quickly due to poor application, inadequate surface preparation, high traffic volumes, and unsuitable material choices.

Recognizing these limitations, this project evaluated the performance of various pavement marking materials across New Jersey. Technical and field data were collected to determine which materials can withstand the state's traffic and environmental conditions. The study also assessed drying times, cost-effectiveness, and supply chain reliability, identifying the need for temporary or rapidly deployable marking solutions during shortages. Findings guided the selection of suitable products, improvements to installation specifications and maintenance practices, and updates to testing protocols and specifications for quick application when supply issues arise. Consideration was also given to autonomous vehicle sensing requirements to ensure future compatibility.

To further inform the evaluation, the team conducted interviews with state DOTs, agencies, manufacturers, and autonomous vehicle industry stakeholders. These discussions provided insights into marking types, durability testing, material formulations, supply chain challenges, and alignment with AV sensor requirements. A three-year field investigation (2023–2025) across New Jersey used video-based technologies and computational methods to monitor real-world marking performance.

A significant focus was the compatibility of pavement markings with connected and autonomous vehicle (CAV) sensing systems. As these technologies advance, ensuring that roadway infrastructure is machine-readable is critical for safety and operational reliability. The study also reviewed and proposed updates to existing testing methods and specifications to meet modern and future-ready standards.

Ultimately, the project offers actionable guidance for transportation agencies, including improved installation techniques, maintenance strategies, and specifications, supporting longer-lasting, more visible, and technologically compatible pavement markings that enhance safety and prepare New Jersey's infrastructure for connected and automated mobility.

BACKGROUND

Pavement markings are a critical component of roadway safety, providing essential guidance to drivers while supporting the functionality of ADAS and emerging automated driving technologies that depend on clear and consistent lane delineation. To be effective, these markings must remain visible under all lighting and weather conditions, yet their performance is influenced by multiple factors beyond the commonly measured retroreflectivity used to assess nighttime visibility. Elements such as pavement background color, marking width and color, surface texture, viewing conditions, and environmental exposure can significantly impact visibility, while adverse weather, high traffic volumes, poor surface preparation, and suboptimal material application often accelerate deterioration. Recognizing these challenges, the NJDOT commissioned a comprehensive evaluation of pavement marking materials to determine which products best withstand the state's traffic demands and environmental conditions, while also addressing issues such as drying time, durability, cost-effectiveness, and supply chain resilience. The study incorporates technical data analysis, multi-year field performance monitoring, and the development of alternative specifications for rapid deployment during material shortages. A key focus is ensuring compatibility with CAV sensing systems, requiring markings to be both human- and machine-readable. To inform this work, structured interviews were conducted with state DOTs, manufacturers, and AV industry stakeholders to gather insights on materials, application methods, testing protocols, and emerging technology requirements. Field evaluations across diverse roadway types and regions of New Jersey utilized mobile and stationary retroreflectivity measurements, colorimetric analysis, and advanced image processing to assess marking visibility, durability, and presence over time. The outcomes of this research will guide NJDOT in refining installation specifications, improving maintenance strategies, and adopting testing protocols that ensure long-lasting, cost-effective, and technologically compatible pavement markings, thereby enhancing safety, reducing life-cycle costs, and preparing New Jersey's transportation infrastructure for the demands of future mobility.

OBJECTIVE

1. Identify product(s) to stripe various roadway surfaces to withstand the NJ weather and traffic conditions.
2. Develop durable and cost-effective guidance and recommendations to improve marking installation specifications and maintenance practices.
3. Evaluate drying time issues, alternative testing protocols, durability issues, cost benefits, and temporary markings.
4. Develop an alternative specification for quick application of paints when supply chain issues arise.
5. Provide guidance and recommendations to improve new marking installation specifications and techniques, improve marking maintenance practices, and evaluate the current specifications and requirements for road markings and stripes paint with respect to sensing capabilities of autonomous vehicles for operational purposes.

The outcome of this study will provide guidance and recommendations to improve new marking installation specifications and techniques, improve marking maintenance practices, and evaluate the current specifications and requirements for road markings and stripe paint with respect to the sensing capabilities of autonomous vehicles for operational purposes.

LIST OF ABBREVIATIONS AND SYMBOLS

AADT	Average Annual Daily Traffic
ACAT	Advanced Crash Avoidance Technologies
ACC	Asphalt Cement Concrete
ADAS	Advanced Driver Assistance Systems
ADS	Automated Driving Systems
ATM	Advance Traffic Marking
AI	Artificial Intelligence
ASTM	American Society for Testing and Materials
ATSSA	American Traffic Safety Services Association
AV	Autonomous Vehicle
AWP	All-Weather Paint
CIE	Commission Internationale de l'Éclairage (International Commission on Illumination)
CNN	Convolutional Neural Network
DAS	Driving Automation System
DOT	Department of Transportation
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
HSIP	Highway Safety Improvement Program
IDEA	Innovations Deserving Exploratory Analysis
IRB	Institutional Review Board
LD	Lane Detection
LDW	Lane Departure Warning
LKA	Lane Keep Assist
LTPP	Long-Term Pavement Performance
MMA	Methyl Methacrylate
MUTCD	Manual on Uniform Traffic Control Devices
NHSTA	National Highway Traffic Safety Administration
NCHRP	National Cooperative Highway Research Program
NTPEP	National Transportation Product Evaluation Program
NJDOT	New Jersey Department of Transportation
OCR	Optical Character Recognition
RFI	Request for Information
R_L	Coefficient of Retro-reflected Luminance
SAE	Society of Automotive Engineers
SCSP	Smart Cities Symposium Prague
SLD	Straight Line Diagram
TCD	Traffic Control Device
TRB	Transportation Research Board
TRPM	Temporary Raised Pavement Marker
USDOT	United States Department of Transportation

VOC	Volatile Organic Compounds
WAC	Washington Administrative Code
YOLOv8	You Only Look Once version 8 (a real-time object detection model)

CHAPTER 1: REVIEW THE CURRENT STATE OF PRACTICE AND ART, LESSONS LEARNED

Introduction

Pavement markings serve as visual cues for motorists, guiding roadways. They are designed to be visible during daylight hours and have retroreflective properties for nighttime visibility, ultimately reducing crashes in different weather conditions. (1) Various types of pavement markings exist, including longitudinal markings (e.g., edge lines, center lines, and lane lines), transverse markings (e.g., stop lines, yield lines, and crosswalk markings), and auxiliary markings (e.g., arrows, words, symbol markings, and parking lot stripes). The Manual on Uniform Traffic Control Devices (MUTCD) outlined the circumstances when pavement marking is necessary to inform and guide the road user. In the 3A.03 section of MUTCD, it is stated that "materials used for marking should provide the specified color throughout their useful life" and that "consideration should be given to selecting pavement marking materials that minimize tripping or loss of traction for pedestrians and bicyclists". The useful pavement marking material life is typically three months to seven years; they need to be restriped or replaced multiple times as the pavement on which it is painted has a life expectancy are 12 to 20 years. (2) As pavement marking material bears an installation cost at every restriping and guides the motorist to ameliorate the traffic system's safety, low cost, long life, high reflectivity, and short drying time are the desirable characteristics of selecting a reliable pavement marking material. (3) Thus, to evaluate pavement marking based on those desirable characteristics, multiple performance matrices like durability, retroreflectivity, and daytime color are considered. (2) This research project aims to collect and analyze technical and performance data of different pavement marking materials, focusing on identifying products that can withstand the weather and traffic conditions in New Jersey. Additionally, the project will evaluate drying time, alternative testing protocols, durability, cost benefits, and temporary markings, and develop alternative specifications for the quick application of paints during supply chain disruptions. The study will also assess the sensing capabilities of AVs for operational purposes to provide recommendations to improve marking installation specifications, maintenance practices, and current requirements for road markings and stripe paints. The following sections provide a literature review on pavement marking materials and performance, including a discussion of commonly used materials in the USA, key attributes contributing to performance, previous degradation modeling studies, and material selection tools and strategies for transportation agencies. The literature search was mainly based on the following five categories:

- Performance of the products regarding drying time issues, alternative testing protocols, durability issues, and cost benefits.
- Products suitable for striping various roadway surfaces to withstand inclement weather conditions.
- Temporary markings and alternative specifications in case of supply chain issues.
- Current specifications and requirements for road markings and stripes paints for automated vehicle (AV) operation.
- Review of state practices on the key issues of hardened traffic paint markings and stripes performance.

Pavement Marking Materials

Traffic paint, polyester, epoxy, Methyl methacrylate (MMA), Polyurea, and thermoplastic are the regularly used pavement marking materials in the United States. In newly paved surface marking, materials of high durability like thermoplastic and epoxy are used, whereas non-durable polyesters and traffic paints are used for restriping. In the subsequent section, all the commonly used marking materials will be briefly discussed.

Traffic Paint

The cost-effectiveness of traffic paint makes it a popular pavement marking material in the United States. On top of its user and environment-friendly nature provides more acceptance among people than solvent-based paints. Among the two types of paints, solvent-based paint is incorporated with dissolved resin in a solvent, whereas emulsion resins are the components of waterborne paint. There are four types of traffic paint, focusing on drying time. Instant-drying paints have a dry time of less than 30 seconds, and for the quick-drying paint, the value is 30 to 120 seconds. Drying time of 2 to 7 minutes is for fast dry paints, and if the drying time is more than 7 minutes, the paint is known as conventional paint. (4) Faster drying paints are recommended because they can lessen construction-related accidents, traffic delays, and labor expenses. Traffic paint is often applied at a thickness of 15 or 20 mils. Traffic paint is thought to be less durable than other pavement marking materials; nevertheless, it fades more quickly. Because of this, it is frequently used on highways with light to moderate traffic volume and needs regular restriping. There have been speculations that some more recent high-build traffic paint formulations, which contain an acrylic cross-linking emulsion and are applied at a thickness of 30 mils, offer better performance. (5)

Polyester

Polyester is a thermosetting pavement marking material that consists of two components: a resin and a catalyst. These two components are mixed just before application. Typically, organic peroxide is used as the catalyst. It’s important to handle the catalyst with care, as its fumes can be hazardous and can cause burns upon contact with the skin. (6) Polyester is usually applied at a thickness of 15 mils, and to enhance retroreflectivity, glass beads are dropped onto the surface of the stripe while the material is still wet. Polyester is commonly used on asphalt pavements and can be applied over existing markings, making it a versatile option. Polyester paint has a service life of two to three years. For optimal results, the air temperature should be at least 50°F (10°C), and the application should be delayed for 2 weeks after paving, unless a primer is applied. Polyester paint was examined to have a low retroreflective value in one of the studies from Michigan, but it is widely used as a marking material in Ohio. Careful consideration of the specific climate, application requirements, and regulations of each state is necessary when deciding on the most suitable pavement marking material for a given project.

Epoxy

Epoxy is a two-component thermosetting pavement marking material that consists of a resin mixture containing pigments, extenders, and fillers in the first component, and a hardener that acts as a catalyst to accelerate the setting or drying process in the second component. In new condition, it is durable in both Portland Cement Concrete(PCC) and

Asphalt Cement Concrete (ACC) pavement. (7) There are two types of epoxies available: slow-curing epoxies with drying times exceeding 40 minutes, and rapid-setting epoxies that can dry in less than 30 seconds, but are generally more expensive. (8) There are some potential drawbacks associated with using epoxy as a pavement marking material. For instance, it may exhibit low durability in weaving areas, color instability when exposed to intense ultraviolet light, and a lack of compatibility with existing pavement markings, which limits its use as a restriping material. (8) Typically, epoxies are applied at a thickness of 20 mils. They can be applied at ambient and surface temperatures as low as 35°F (2°C) and even when the pavement surfaces are slightly wet. Proper cleaning of the pavement surface is essential for achieving good bonding with epoxy markings. Some epoxy manufacturers also recommend installing this material in a groove to protect it from traffic and snow plowing. In recent years, there have been advancements in epoxy formulations, with the addition of polymers to create hybridized epoxy or hybridized polymer pavement markings. This product is marketed as a material that combines the durability of epoxies in terms of resistance to traffic with the ultraviolet-light-resistance of polymers. This has made epoxy-based pavement markings more versatile and easier to apply using standard epoxy equipment. (8) It's important to carefully consider the specific requirements of each pavement marking project, including factors such as climate, pavement surface condition, and compatibility with existing markings, when choosing the most appropriate pavement marking material, including epoxy or its hybridized variants.

Methyl Methacrylate (MMA)

MMA is a thermosetting polymer that possesses unique characteristics like high tensile strength, great adherence to a variety of surfaces, and exceptional resistance to UV deterioration, chemicals, and wear. Due to its outstanding qualities, MMA is the perfect choice for pavement markings that must withstand high traffic volumes, severe weather, and harsh environmental exposure. It is a relatively new product that has undergone extensive testing and has been used in cold climates like Alaska and Eastern Europe. In recent years, the transportation industry has grown increasingly fond of it because of its exceptional performance and superior qualities as a pavement marking material. MMA-based pavement marking materials have an expected lifespan of two to seven years and are made to endure harsh environmental conditions, including heavy snowplow areas, mountain passes, and locations with high traffic. Methyl methacrylate monomer, colors, fillers, glass beads, and silica make up the first half of the two-part MMA system, while benzyl peroxide dissolved in plasticizer makes up the second. This allows for customization of composition and formulation to achieve particular performance characteristics, such as better adhesion, retroreflectivity, and drying time. The two parts are combined in a 4:1 ratio and then sprayed or coated onto the pavement. Spray, extrusion, and prefabricated markings are some of the different ways that MMA-based pavement marking solutions can be applied. The MMA-based compound is sprayed onto the road surface using a popular technique called spray application, leaving a smooth, even coating. As opposed to extrusion, which involves applying the material using an extrusion gun to produce raised markings, extrusion is known to provide markings with a longer lifespan. Preformed markings, which are used on PCC and ACC pavements, are pre-cut patterns applied to the road surface. Although the sprayed version is frequently selected for its affordability, the extruded version is noted for its durability. Although reasonably dry conditions are required for installation, it should be noted that MMA may not be as effective in high-humidity environments. [9] The variety of MMA's applications is one of its main benefits. It is appropriate for a variety of climatic circumstances since it may be used at ambient temperatures and even at zero degrees Fahrenheit if there is no frost. [9] Methacrylate may be sprayed at varied thicknesses, ranging from 30 to 120 mil, and is well recognized for its quick drying characteristics, with a no-track time of around 20 minutes. [10] Additionally, MMA-based polymers are renowned for being highly visible in low-light and slick circumstances, improving traffic safety. Although there are no volatile organic compound (VOC) issues with MMA, stripping workers may still face health risks owing to little volatilization when applying chemicals to heated pavement or when spraying the substance. [9] Innovative application techniques with improved visibility and visual appeal, such as contoured marks, bespoke patterns, and 3D markings made from MMA-based materials, have drawn attention lately. These cutting-edge application techniques have the potential to significantly enhance the functionality and appearance of pavement markings made from MMA, demonstrating the ongoing innovation and adaptability of this relatively young product in the sector of transportation infrastructure.

Thermoplastic

Thermoplastic is a combination of resins and pigments that become liquid when heated. To provide retroreflectivity, drop-on glass beads and fillers are frequently combined in with it. In a factory, they are combined, and then they are brought to the project site as solid blocks or granular powder. Glass beads can either be added to the thermoplastic before they are applied to the pavement or just placed upon it. Extrusion and spraying are the two main techniques used to apply thermoplastic pavement markings. Spray thermoplastic is applied to a thinner thickness and is used for both new and restriping applications. The minimum application thickness for extruded thermoplastic on new pavements is 90 mils. Alkyd and hydrocarbon thermoplastics are the two main varieties of thermoplastics that are accessible. The latter contains a naturally occurring resin that is resistant to oil but sensitive to heat, in contrast to the former, which is generated from petroleum and may be susceptible to oil. As a result, while applying alkyd thermoplastics, rigorous temperature control is necessary. The pavement surface needs to be carefully cleaned to get rid of debris, moisture, dust, and other impurities before thermoplastic markings are applied. In order to guarantee optimum cooling and adhesion, the pavement and air temperatures must both be at least 50°F and rising. Even while thermoplastics have often been proven to operate satisfactorily on asphalt pavements, several jurisdictions have prohibitions on their usage on concrete pavements due to durability worries. [1]

Polyurea

Polyurea is a two-component pavement marking substance that cures rapidly. It consists of an isocyanate and a resin, which are amalgamated immediately prior to application. It is noted for its rapid setting, allowing traffic to resume promptly after application. Polyurea is exceptionally durable and resistant to abrasion, making it suitable for high-traffic areas. It maintains its color and retroreflectivity effectively over time, enhancing its performance under adverse weather conditions. Polyurea markings are typically applied at a thickness of 15 mils and exhibit considerable durability, particularly in harsh weather conditions. Its longevity typically ranges from two to five years, dependent upon traffic volume and other environmental factors. It is essential to note that polyurea may be affected by the ambient air temperature during application. Optimal results require a temperature of no less than 50°F (10°C).[10]

Tape

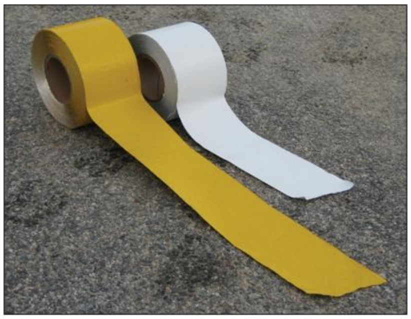
Pavement marking tape is a preformed, durable material used to create highly visible markings on roadways. It is made of an acrylic or vinyl material and is typically applied using a heat-activated adhesive. Tape markings offer instant trafficability after application, making it ideal for situations requiring minimal downtime. Unlike liquid paints, tape provides consistent thickness and sharp edges, leading to more precise and uniform markings. It is particularly useful in areas with heavy traffic or where markings need to be easily replaceable. Reflective glass beads are often embedded in the tape's surface to improve its retroreflectivity. Tape is widely used for temporary or emergency markings, and while it typically lasts 1 to 3 years, it may require periodic maintenance in high-traffic areas. [11]

Temporary Pavement Marking Material

Temporary Tape is another option for pavement markings in work zones. It consists of preformed strips of plastic with adhesive backing. It can be easily removed by pulling it up without requiring heat or mechanical methods. However, it is only suitable for short-term use of up to 6 months, as it may strongly adhere to the pavement after that period. It also contains retro-reflective material (See Figure 1a).

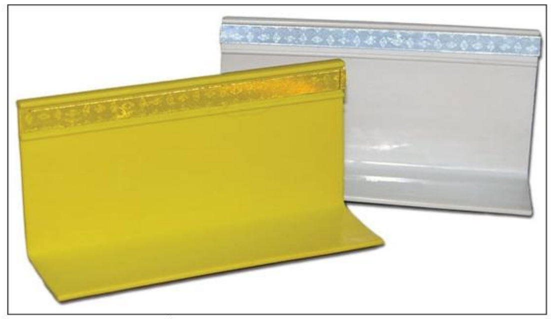
TRPMs are commonly used in construction zones and can be attached to the pavement using adhesive or peel-and-stick backing.

- Tabs are strips of plastic with a reflective strip built into them, providing flexibility to resist impact. They can simulate a continuous or dashed line and are suitable for supplementing flat line markings in conditions such as rain. However, they require regular inspection and replacement if damaged (See Figure 1b).
- Buttons are similar to tabs and are rounded domes that can be glued to the pavement. They are manufactured from plastic or ceramic materials and may be used to simulate dashed lines. However, they are less impact-resistant than tabs and are not typically used in areas where snowplowing is possible (See Figure 1c).
- Epoxy and thermoplastic materials are usually used for long-term work zones with high traffic volumes. These materials are highly durable and can withstand extreme abuse from traffic or other situation-specific conditions. They are appropriate for areas where a visible line is needed for many months or years and where permanent markings will eventually be applied.



Source: Safety Flag

a



Source: TransLine

b

Source: ATSSA 2014

c

Figure 1. a) Temporary Tapes, b) TRPMs: Tabs, c) TRPMs: Buttons

Special Colored Pavement Markings

One of the challenges related to pavement markings in work zones is the presence of ghost markings, which can cause confusion for drivers. These ghost markings remain after old pavement markings are removed. One solution to this issue is the use of special marking colors, such as orange, which are used in some European countries like Switzerland, Slovakia, and Austria, and the Canadian province of Ontario. [11] **Error! Reference source not found.** shows commonly used temporary orange pavement marking materials.

(a) (b) (c)

Figure 2. Orange pavement marking materials: (a) nonwet reflective tape, (b) wet reflective tape, and (c) spray-applied MMA [11]

In the United States, there have been experiments with the use of special color markings through color recognition studies, driver surveys, and field evaluations. For instance, a color recognition study on Type I and Type II fluorescent orange retroreflective RPMs found that 100% of test subjects accurately interpreted the marking color during daytime.

Moreover, the marking color was correctly understood by 84% of test subjects for Type I markings and 75% of test subjects for Type II markings during nighttime (Finley et al., 2005). Wisconsin also sponsored research on the use of orange pavement marking tapes. The Wisconsin Department of Transportation (WisDOT) conducted experiments with orange markings in work zones, specifically on a large and complex freeway-to-freeway interchange reconstruction project in Milwaukee. While driver acceptance was good, it was challenging to distinguish the effects of orange markings from other work zone management strategies due to the complex traffic flow characteristics and frequent configuration changes at the site. To further evaluate the impact of orange markings on driver behavior, a matched-pairs study was conducted on two bridge re-decking projects on I-94 near Oconomowoc, Wisconsin, which offered a simpler environment. Analysis of vehicle positioning and speed data indicated that there was very little difference in driver behavior between the two colors. However, driver surveys and interviews with project field engineers revealed a preference for the orange marking when lateral lane shifts are necessary. (11)

Characteristics of Pavement Markings

When deciding on the type of pavement marking material, several factors need to be taken into consideration. One of the most crucial factors is the duration of the project. In some cases, road projects require frequent adjustments, which makes the use of easily removable pavement marking materials such as temporary tape or TRPMs a more viable option than traffic paint. This is because the mobilization of equipment such as stripers, truck-mounted attenuators, and brooms needed for traffic paint can be costly and time-consuming. Weather conditions can also impact the decision on the type of pavement marking material to use. In inclement weather conditions, such as during heavy rainfall, the use of TRPMs is often more appropriate than traffic paint. This is because moisture during applications is not as significant an issue as it is with traffic paint. In addition, traffic paint does not provide sufficient retro-reflectivity during wet weather conditions, unless wet reflective beads are added. TRPMs can provide better visibility during inclement weather, making them a safer option for drivers. High traffic volume is another factor that can impact the choice of pavement marking material. In areas with high traffic volume, pavement markings are subject to significant wear and tear. Traffic paint is likely to be worn quickly under these conditions, especially if traffic is driving directly on the stripe. Other pavement marking types, such as epoxy or thermoplastic, are more durable and can provide long-lasting pavement markings for high-volume work zones, thereby reducing the need for frequent re-marking during the project. However, it is important to note that even TRPMs are not highly durable devices and need to be monitored closely. Table 1 provides an overview of the commonly used pavement marking materials. (12)

Table 1 - Characteristics of temporary pavement markings (44)

Materials	Application	Durability	Pros	Cons
Paint	Machine	1 year or less	Low cost \$0.10-0.15/foot; wet-reflective	Low durability under heavy traffic,

Materials	Application	Durability	Pros	Cons
			elements can be added	low quality under wet weather
Thermoplastic	Machine	3 to 5 years	High durability	High cost $0.70-3.00/foot, medium wet weather recovery; difficult to remove
Epoxy	Machine	3 to 5 years	High Durability	High cost $0.70-3.00/foot, medium wet weather recovery, and contrast hard to see on new concrete
TRPM: Tabs	Installed by hand	Less than 1 year; less than 1 month under heavy traffic	Low cost, high visibility under wet weather, flexible installation	Possible littering, vandalism, best in warm weather application
TRPM: Buttons	Installed by hand or by machine	1 year	Low cost, audible and tactile clue to driver	Not conducive for snowplows, small target value

Performances Matrices of Pavement Markings and Strips

Testing Protocols

The testing protocols for the performance matrices of pavement markings and strips need to be summarized to know about the existing protocols and alternatives. A summary of the protocols is described in this section.

Protocols on Test Deck

Transverse test decks are the field method used by the National Transportation Product Evaluation Program (NTPEP). NTPEP test decks are located around the country, and the data are pooled to be used by any transportation agency. The procedures for conducting a test deck are based on ASTM D713.

A data collection protocol to determine the durability of the pavement markings on the test decks so that when combined with typical marking installation costs, the overall cost effectiveness of the tested pavement markings could be determined. As part of the data collection protocol, retroreflectivity measurements and photographic should be collected for each pavement marking along the edge line, lane line, and transverse line. Data should be typically collected as soon as possible after the winter season, twice during the middle of the year, and as late as possible prior to the next winter season.

Transverse test decks should be installed using the protocol established by the NTPEP standards and best practices according to the National Transportation Product Evaluation Program (1999). This protocol indicates the design of the test deck, appropriate installation conditions, and when and how to collect data after installation.

Protocols on Measuring Retroreflectivity

The data collection protocol was designed to yield enough data to obtain a statistically valid representation of the pavement markings while keeping the exposure of the data collection team to a minimum. The data collection protocol for this project was partially modeled after that described in ASTM D6359. All retroreflective devices meet the criteria set in ASTM E1710-05.[12] All data collection devices were properly calibrated prior to data collection.

Image segmentation is the process of assigning a set of image pixels to regions that have common characteristics. The proposed system tries to segment images of white or yellow pavement markings into foreground (marking) and background (pavement) parts. The system then objectively reports the presence by calculating the percentage of white and yellow paint in the total image area. The system assumes that the image being processed complies with the general rules specified by the transportation department protocol (i.e., image resolution, image dimensions, and the number of images taken for a specific segment length) used for detecting presence.

Protocols on Various Properties

The protocol on various properties includes density, settling properties, X-ray Diffraction, etc. Protocols for testing general properties of pavement markings are listed in Table 2. Protocols for testing general properties of pavement markings.

Table 2 - Protocols for testing general properties of pavement markings

Density	ASTM D 1475
Settling Properties	ASTM D 869
X-Ray Diffraction	Dried Film Scan

Paint Protocol

The protocol for paints includes several physical properties like viscosity, density, dispersion, and % weight. All the test methods for the paint properties are listed in Table 3.

Table 3 - Test methods for paint properties

Paint Property	**Test Method**
Viscosity at 25 ± 1 °C (Stormer)	ASTM D562A
Density/wt per gal, g/ml @ 25°C (or lb/gal)	ASTM D1475
Fineness of grind/dispersion, Hegman	ASTM D1210
Nonvolatile/total solids, by weight%	ASTM D2369
Pigment content, by weight %	ASTM D3723
%nonvolatile in vehicle (vehicle solids)	ASTM D2369

Paint Property	Test Method
Dry to no pickup time , without beads	ASTM D711
Initial daytime color, D65/2°, Y, x, y, & YI (E313)	ASTM D1729
Dry opacity @10 mil wet (or 5 mil dry)	Fed 141/4121.1

Protocols for Performed Tapes

Performed tape paint property, including mechanical properties like tensile strength, ultimate elongation. There are also various test methods for retroreflectivity, whiteness index, adhesion, skid resistance, etc. The test methods for all the properties are shown in Table 4.

Table 4 - Test methods for various tape properties

Performed Tape Paint Property	Test Method
Tensile Strength	ASTM D 3759
Ultimate Elongation	ASTM D 3759
Retroreflectivity	ASTM D 4505
Whiteness Index	ASTM E 313
Adhesion	ASTM D 4505
Skid Resistance	ASTM D 4505
Wear Index	Fed. Test Method 141 & 6192.1

Protocols for Epoxy

Epoxy properties include drying time, adhesion to concrete, hardness, abrasion resistance, color yellowness index, etc. The test methods for all the properties are listed in Table 5.

Table 5 - Test methods for epoxy

Epoxy Paint Property	Test Method
Drying Time	ASTM D 711
Epoxide Number	ASTM D 1652
Adhesion to Concrete	ACI Method 503
Hardness	ASTM D 2240
Abrasion Resistance	ASTM D 501
Color	ASTM G 53
Yellowness Index	ASTM D 1925

Protocols for Waterborne Paints

Waterborne paints properties include viscosity, heat stability, and freeze-thaw stability. Pigment content, opacity, and water resistance. The test methods for all the properties are listed in Table 6.

Table 6 - Test methods for various performed tape properties

Waterborne Paint Property	Test Method
Viscosity	ASTM D 562
No Track Dry Time	ASTM D 711
Total Solids	ASTM D 2369
Pigment Content	ASTM D 3723
Heat Stability	ASTM D 562
Freeze-Thaw Stability	ASTM D 562
Water Resistance	ASTM D 562
Opacity	Leneta Form 2C Opacity chart

Durability

The durability of pavement marking material is the measure of its ability to physically withstand external loading (e.g., traffic, weather) without being displaced from the pavement. Typically, the minimum requirement for a pavement marking to be functional is at least 75% existence of its initial material per unit length and a minimum of 100 millicandelas per square meter per lux (mcd/m^2/lux), which represents its service life. Any pavement marking system's lifespan can vary greatly and is influenced by a number of variables. Monitoring a marking's performance over the course of its life is the only real way to ascertain how durable it will be. Even then, only that specific set of variables are applicable to the service life of that specific marking. One of the main factors affecting the service life of a pavement marking system is traffic volume. Other important factors include the type of roadway surface, the quality of installation, and winter maintenance activities. The proportion of heavy vehicles, application conditions, weather conditions, marking orientation, roadway geometry, marking thickness, type of retroreflective optics used, and criteria for determining the end of the service life are additional variables that can affect service life. The service life may differ from one site to another, where the same marking has been applied, depending on the specific circumstances at each location. Thus, presence is one of the performance matrices for pavement marking material evaluation. Table 7 demonstrates the durability value of different marking materials when used as different kinds of marking lines in a 2-lane route of Belmont County.

Table 7 - Two-year durability at State Route 9 (2-lane) in Belmont County (13)

Section	Line	Direction	Continuous/ Dashed	Surface	Durability	Pass/Fail
Polyester (Section 1)	Edge Line	NB	Continuous	Grinding	10	Pass
	Center Line	NB	Dashed	Restriping	10	Pass
	Center Line	SB	Dashed	Restriping	10	Pass
	Edge Line	SB	Continuous	Grinding	10	Pass
	Edge Line	NB	Continuous	Restriping	10	Pass
	Center Line	NB	Dashed	Restriping	10	Pass
	Center Line	SB	Dashed	Restriping	10	Pass
	Edge Line	SB	Continuous	Restriping	10	Pass

Section	Line	Direction	Continuous/ Dashed	Surface	Durability	Pass/Fail
Epoxy (Section 2)	Edge Line	NB	Continuous	Grinding	10	Pass
	Edge Line	SB	Continuous	Grinding	10	Pass
Thermoplastic (Section 3)	Edge Line	NB	Continuous	Grinding	10	Pass
	Edge Line	SB	Continuous	Grinding	10	Pass
Paint (Section 4)	Edge Line	NB	Continuous	Grinding	9	Pass
	Center Line	NB	Continuous	Restriping	10	Pass
	Center Line	SB	Continuous	Restriping	10	Pass
	Edge Line	SB	Continuous	Grinding	9	Pass
	Edge Line	NB	Continuous	Restriping	8	Pass
	Center Line	NB	Continuous	Restriping	8	Pass
	Center Line	SB	Continuous	Restriping	9	Pass
	Edge Line	SB	Continuous	Restriping	9	Pass

The durability of a pavement marking material can be easily assessed following the NTPEP guideline. A wheel will be rolled over the tested marking material strips, and the percentage of area that remains will be observed and will be rated on a one (1) to ten (10) scale. While one represents the least durable, ten represent the best. In an alternative way, it can also be quantified using binary image analysis. Photos of the test area need to be captured at standardized lighting and fed to any image analysis software. The software can come up with the presence value by computing the percentage of area where the material is missing.

Durability = 10 Durability = 9

Figure 3. Evaluation of marking material durability [14]

The result of this experiment will give a gross idea about the amount of binder that is present in the evaluated test bed. The toughness of the pavement marking material can be determined using the result of this analysis. Although pavement marking will always start with the maximum value of ten, it deteriorates over time. The large drop usually occurs during the winter due to the snowplow blades' abrasion. Durability values of 10 to 8, 7 to 6, and 5 to 1 are considered as Good, Fair and Poor as performance ratings of the marking material. If any pavement marking shows poor criteria in this test, it is most likely that one needs a restripe.

Drying Time

There have been several studies conducted to investigate the drying time of pavement marking materials. The drying time of pavement marking materials is an important factor that affects the performance and durability of markings, as it determines when the markings can be opened to traffic without the risk of smudging or damage. Clark and Sanders (1993) investigated the drying time of polyester pavement markings. The study found that the drying time of polyester markings varied depending on factors such as temperature, humidity, and thickness of the material. (2) The drying time of polyurea-based markings ranged from 5 min to 20 min, depending on the environmental conditions. The drying time of epoxy-based markings usually ranges from 5 minutes to 1 hour if the temperature is between 60 to 80 °F; it also could shift up to several hours if the temperature is below 60.(2) The drying time of waterborne paint was found to be around one minute, depending on factors such as temperature, humidity, and ventilation. In general, higher temperatures and lower humidity levels resulted in faster drying times. The drying time of MMA pavement markings applied with different thicknesses. The study found that the drying time of thermoplastic markings varied depending on the thickness of the material, with thicker markings taking longer to dry. The drying time of MMA marking is around 20 minutes, depending on the thickness of the material and environmental conditions. In summary, the drying time of pavement marking materials varies depending on factors such as temperature, the type of marking material used (e.g., waterborne paint, thermoplastic, epoxy-based, or polyurea-based), the thickness of the material applied, the level of humidity, and the amount of ventilation in the environment. For instance, waterborne paint typically has a shorter drying time compared to thermoplastic or epoxy-based materials. Waterborne paint markings can often dry to the touch in a very short time under optimal conditions and may be opened to less than an hour. Thermoplastic markings, on the other hand, may take longer to dry, depending on the thickness of the material and environmental conditions. Epoxy-based and polyester markings also tend to have longer drying times, depending on the specific material and environmental conditions. It is important to note that the recommended drying time for pavement markings may vary based on local specifications, manufacturer recommendations, and environmental conditions. Properly allowing the markings to fully dry before opening to traffic is crucial to ensure their durability, performance, and visibility. Opening the markings to traffic too soon can result in smudging, premature wear, and reduced retroreflectivity, which can compromise the effectiveness of the markings in guiding road users and enhancing traffic safety.

Day Time Color

The measurement of daytime color of pavement marking materials is typically completed using the National Transportation Product Evaluation Program (NTPEP) method, which specifies the use of a spectrophotometer according to ASTM D 6628, Standard Specification for Color of Pavement Marking Materials. This method records data in the Commission Internationale de l'Éclairage (CIE) Y, x, y color space using a 2-degree observer and a D65 illuminant, as specified in the NTPEP Committee Work Plan for the

Field Evaluation of Pavement Marking Materials. The CIE Y, x, y color space is divided into two parts: lightness (Y) and hue (xy). Lightness is a measure of how light or dark a color appears, while hue refers to the classification of a color, such as red, yellow, blue, and so on. The CIE x, y chromaticity diagram is used to represent the hue of colors. The use of spectrophotometers and the CIE Y, x, y color space allows for accurate and standardized measurement of pavement marking material color during daylight conditions. Spectrophotometers are capable of measuring the reflectance or transmittance of light at various wavelengths, and the CIE Y, x, y color space provides a mathematical representation of color that can be objectively quantified and compared.

By following the NTPEP method and using spectrophotometers in accordance with ASTM D 6628, transportation agencies and researchers can obtain consistent and reliable data on the daytime color of pavement marking materials. This information can be useful in evaluating the performance, durability, and visibility of different pavement marking materials, as well as ensuring compliance with established standards and guidelines for road safety. According to ASTM D 6628, the minimum in-service daytime lightness (Y) limit for white is 35, and the limit for yellow is 25. Additionally, the color coordinates of a pavement marking material must remain within the specified chromaticity limits for the duration of its service life. The analysis of NTPEP daytime color data involves several steps. First, the lightness values (Y) are checked to ensure they meet the minimum requirements. Then, the hue values (x, y) are plotted on the chromaticity diagram, and any values that fall outside the appropriate limits are marked. It is worth noting that lightness (Y) values can sometimes drop below the established minimum in one test and then rise back up in subsequent tests. Similarly, hue (xy) data may exhibit similar trends, but it is more likely for hue values to continue to fall outside the chromaticity limits over time. The overall color performance rating takes into consideration both lightness and hue. Marking materials that fully comply with ASTM D 6628 and have no failures are rated as “Good”. Materials that have one or two failures for at least one or both attributes are rated as “Fair”, while materials that have three or more failed data points for one or both attributes are rated as “Poor”. For example, a marking material that has two lightness values and two hue values that fall outside the established limits would receive a “Fair” color performance rating. Among the different pavement types, epoxy on asphalt performed the worst in terms of lightness for white materials but performed well on concrete. Yellow materials, both epoxies and polyurea, performed poorly on both pavement types. Thermoplastic materials generally performed well, except for a pair of white and yellow counterparts on concrete pavement from the Minnesota site.

Retroreflectivity

Pavement marking retroreflectivity (R_L) refers to the phenomenon where incident light from a vehicle’s headlight beams is reflected back to the driver’s eyes after striking a pavement marking. This is typically achieved by incorporating round, transparent glass beads into the marking material. The performance of these glass beads depends on various properties, such as their size, refraction index, clarity, roundness, the rate of bead application, and the quality of the installation. It is generally believed that optimal R_L is achieved when around fifty to sixty percent of the glass bead diameter is embedded in the marking material. The coefficient of retro-reflected luminance, R_L, is commonly used to represent R_L, and it is expressed in units of mcd/m^2/lux. R_L is calculated by dividing the luminance, which refers to the amount of available or reflected light in a particular direction, by the luminous flux, which represents the rate of flow of light over time. (15)

Methods of Measuring Retroreflectivity

Retroreflectivity measurements of pavement markings can be obtained using handheld or mobile reflectometers. [1] These reflectometers typically employ the standard 30-meter geometry for measuring nighttime retroreflectivity. This geometry is based on the driver's ability to view the marking at a location that is 30 meters ahead of the vehicle.

Handheld

Historically, the retroreflectivity of pavement markings has been evaluated using handheld retroreflectometers.(12) These devices have the advantage of being portable and relatively easy to use. However, there are some disadvantages associated with handheld retroreflectometers. One limitation is that data can only be collected at discrete locations, which may not provide a comprehensive representation of the overall retroreflectivity performance of the pavement markings. (10) ASTM E2832 covers a method for evaluating pavement marking retroreflectivity using a portable instrument in a condition of continuous wetting, simulated rain conditions. Furthermore, testing with handheld retroreflectometers can be labor-intensive and potentially hazardous to the operator and to the traveling public, as it requires maintenance of traffic during testing. (35)

Mobile

Mobile retroreflectometers have been developed as an alternative method for evaluating the retroreflectivity of pavement markings. (14) Mobile retroreflectometers are typically mounted on vehicles and can measure retroreflectivity continuously and at highway speeds, providing a more comprehensive assessment of pavement marking performance. Choubane et al. (2010) found that at a 95% significance level, there is no statistical difference or bias in retroreflectivity value (range 200 to 800 mcd/m^2/lux) measured in handheld and mobile retroreflectivity measurement devices.

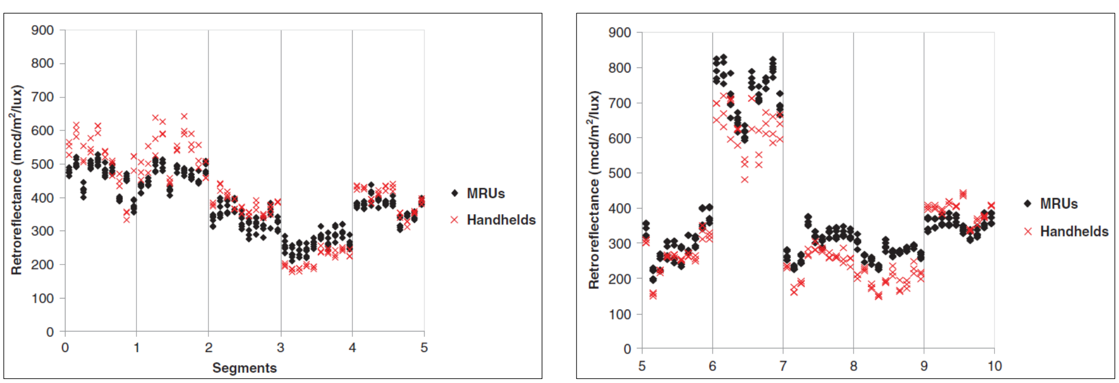


Figure 4. Retroreflectivity of handheld and mobile units (14)

These devices are equipped with sophisticated measurement technologies, such as spectrophotometry, which allow for accurate and efficient data collection.(14) The use of mobile retroreflectometers for pavement marking evaluation has several advantages over handheld retroreflectometers. First, mobile retroreflectometers allow for continuous data collection, providing a more comprehensive and representative assessment of retroreflectivity performance. (17) Second, they reduce the need for manual labor and maintenance of traffic during testing, making the process safer and more efficient. (17) Third, mobile retroreflectometers can cover a larger area in a shorter amount of time, which is particularly beneficial for large-scale pavement marking assessment projects. Mobile retroreflectometers have become a popular choice for pavement marking assessment projects due to their efficiency and accuracy in measuring retroreflectivity on roadways. (17)

Figure 5. Mobile retroreflectivity unit of FDOT (14)

AASHTO T 398-22 provides guidelines for measuring pavement marking retroreflectivity with mobile units at roadway speeds, enabling efficient, large-scale data collection without traffic disruption.(16) ASTM E3320-21 is the standard test method for measurement of retroreflective pavement marking materials using a mobile retroreflectometer unit (MRU).(17)

Retroreflectivity of Temporary Pavement Marking

According to Section 6F.77 of the MUTCD, pavement markings in work zones must be visible during daylight, twilight, and nighttime periods. Traffic paint is typically used for long-term stationary work, while temporary tape, buttons, and TRPMs may be required for other situations, such as chip-sealed surfaces or short- and intermediate-term work zones. (18) In Section 6G.02, all temporary markings in long-term work zones must be retroreflective, and missing or defective devices can be replaced to restore retroreflectivity. However, retroreflectivity can diminish over time due to exposure to weather, debris, dirt, and traffic, which can affect nighttime driving. Therefore, factors such as degradation of reflectivity, glare on the roadway surface, other pavement treatments, missing or damaged temporary devices, and wearing of traffic paint should be considered when choosing pavement markings. Practitioners should also take into account the impact of retroreflectivity during the day, not just at night. (19)

Some DOTs have minimum retroreflectivity requirements for temporary pavement markings. Maryland requires a minimum retroreflectivity of 250 mcd/m^2/lx for white markings and 150 mcd/m^2/lx for yellow markings.[18] Indiana also requires temporary markings to meet the performance specifications of permanent markings, except that the contractor does not need to measure retroreflectivity of temporary markings, and quality adjustments are not made.[19] Delaware mandates that temporary pavement markings should adhere to the retroreflectivity standards specified in Table 8.

Table 8 - Delaware retroreflectivity requirement for temporary latex paint and temporary tape [20]

Pavement Marking Material	Pavement Marking Color	Minimum Retroreflectivity – 1 mcd/ft^2/footcandle = 1mcd/m^2/lx
Latex paint (temporary or permanent)	White	150
Latex paint (temporary or permanent)	Yellow	125
Temporary tape	White	750
Temporary tape	Yellow	450

In a study conducted by Hawkins et al. (2012), the effectiveness of different removable pavement marking products was evaluated in terms of their daytime presence, retroreflectivity, and removability. The study was conducted in an active work zone in central Iowa and included both white and yellow edge-line markings within the taper and crossover sections of the work zone. Several common products were tested, including Advance Traffic Marking (ATM), SWARCO Temporary Pavement Marking Tape, and 3M Wet Reflective Removable Tape. The study found that the temporary pavement marking tapes performed satisfactorily in terms of retroreflectivity over the 56-day period. Table 9 provides a summary of the dry retroreflectivity readings measured using a standard 30-meter geometry retro-reflectometer in units of mcd/m^2/lux.

Table 9 - Retroreflectivity measurements for standard paint and removable tape in Florida [21]

Product	Location	Line	@15 Days	@46 Days	@56 Days
ATM	Taper	White edge line	716	407	NA
3M	Taper	White edge line	695	362	NA
SWARCO	Taper	White edge line	333	284	NA

Product	Location	Line	@15 Days	@46 Days	@56 Days
Paint	Tangent	White edge line	398	NA	NA
ATM	Cross-over (leading section)	White edge line	767	NA	NA
SWARCO	Cross-over (leading section)	White edge line	280	NA	NA
3M	Cross-over (leading section)	White edge line	445	NA	397
3M	Cross-over (leading section)	Yellow edge Line	447	NA	290
SWARCO	Cross-over (leading section)	Yellow edge Line	421	NA	267
Paint	Cross-over	White edge line	281	NA	NA
Paint	Cross-over	Yellow edge Line	34	NA	NA
3M	Cross-over (trailing section)	White edge line	548	NA	NA
SWARCO	Cross-over (trailing section)	Yellow edge Line	624	NA	507
3M	Cross-over (trailing section)	Yellow edge Line	382	NA	238

Temporary pavement markings pose a challenge due to reduced visibility during wet and nighttime conditions. To address this challenge, research studies have evaluated different products like paint, tape, and permanent markings. One such product is the all-weather paint (AWP) developed by 3M, which maintains retroreflective properties even when covered with a film of water. This is achieved through specially developed elements that provide retroreflection in both dry and wet conditions. After spraying the AWP on the road surface, 3M bonded core elements are dropped, followed by a second drop of conventional glass beads. Compared to standard pavement marking, the AWP is visibly more retroreflective, as demonstrated in Figure 6 during a typical rain event in North Carolina. In a two-phase project by Cunningham et al. (2013), the AWP was evaluated for use in work zones. The AWP was compared to a standard pavement marking based on four measures of effectiveness, including retroreflectivity, vehicle travel speed, rate of lane encroachments, and linear lane displacement. While the retroreflectivity values for the AWP markings were inconsistent, they were generally higher than those of the conventional markings.

Figure 6. Wet weather comparison of standard pavement marking (left) and the AWP (right) pavement markings [22]

Suitability for Inclement Weather

Pavement markings are particularly helpful for drivers during restricted vision and slippery surfaces during inclement weather conditions. One of the key challenges for the evaluation of the pavement marking material properties is the suitability of those in inclement weather conditions. Regarding the testing procedures, no pavement marking should be applied 24 hours after inclement weather conditions like rain and snow. The pavement marking evaluation needs additional time and requirements in adverse climate conditions.

Changing weather conditions can affect drying time and bead embedment depths. Changes in marking temperature can have the same effect. [23, 24, 25] This improved retro-reflectivity in wet environments is achievable because the larger bead is less likely to be submerged in water and thus retains some retroreflective qualities; in contrast, a smaller glass bead that becomes submerged in water no longer retains any retroreflective features.

The thickness of the marking binder affects both retroreflectivity and durability. All pavement marking systems degrade over time as a result of exposure to weather and traffic. Waterborne pigments typically have a lower initial retroreflectivity value and degrade more quickly than other marking materials. This is in part due to the application's slim thickness.

The states of Colorado, New Mexico, and Texas have modified methods for conducting accelerated weathering experiments to ensure that materials can withstand exposure to sunlight and moisture. Colorado conducts weathering experiments on epoxy, while New Mexico and Texas conduct them on thermoplastic. It was observed that adding accelerated weathering test requirements or tighter daytime chromaticity requirements to material specifications, primarily for epoxy, promotes better color performance (Colorado, New Mexico, Texas).

Embedded beads increase the retroreflectivity of pavement materials, while the weather is the key issue for them to embed. Hence, care should be taken to address this situation by scheduling the installation with weather alerts. Some thermoplastics can adhere more in adverse weather conditions. Several environmental conditions have been identified as problematic for LDW systems. Existing literature, documents the presence of adverse weather conditions, such as fog or rain, as problematic scenarios for vision-based detection systems. [8,26,27] This is because (a) moist markings have significantly lower retroreflectivity than dry markings, and (b) detection ratings increase as retroreflectivity increases.

Retroreflectivity has also been shown to significantly impact detectability in instances of moderate and heavy rainfall [28,54,29]. According to a report from Europe, a suitable road marking should have a minimum dry retroreflectivity of 150 mcd/m^2/lux, a minimum wet retroreflectivity of 35 mcd/m^2/lux, and a minimum line width of 150 mm. [30] Another European report reveals that the required retroreflectivity for LDW to function is 70 mcd/m^2/lx in dry night conditions, 20 mcd/m^2/lx in damp night conditions, and a marking luminance coefficient 5 mcd/m^2/lx greater than the pavement surface in daylight conditions. [31] There are no environmental conditions that the system must meet. The performance testing should be conducted in areas where the visibility range exceeds 1 km.[32] The FHWA LDW test procedure document mandates the use of high-contrast and uniform pavement, adherence to the lane marking specifications outlined in the MUTCD (e.g., standard marking widths of 4–6 inches), and ensuring that they are in good condition. [26,27] Additionally, the document recommends avoiding LDW tests in inclement weather conditions such as rain, fog, snow, hail, smoke, or ash. [54]

Service life

A literature review and agency surveys have shown that the expected service life of pavement markings varies considerably across the United States. Table 10 shows the range of values for assorted pavement marking types. The large ranges demonstrate the need to use historical retroreflectivity data based on your agency's or your state's conditions.

Table 10 - Service life of different marking materials

Pavement Markings Material Type	Range of Service Life (Years)
Water-based paints	0.5 to 3.0
Alkyl-based paints	0.25 to 3.0
Epoxy	2.0 to 5.0
Thermoplastics	1.0 to 7.0
Preformed tapes	2.0 to 8.0
Methyl methacrylate	2.0 to 7.0
Polyurea	3.0 to 4.0

In the context of this particular project, it was determined that a pavement marking system could be considered to have a remaining service life if it was able to sustain a satisfactory level of presence (i.e. greater than 75 percent remaining) as determined through subjective evaluation in situ, with ASTM D913 serving as a reference point. Additionally, the retroreflectivity of the marking system needed to be at least 100 mcd/m2/lux.[55] The durability of a pavement marking system is subject to significant variability and contingent upon a multitude of factors. To accurately assess the longevity of a marking, it is imperative to consistently evaluate its performance over its entire lifespan. However, it should be noted that the longevity of said marking is solely relevant to the specific set of parameters in question. The longevity of pavement marking is significantly impacted by various factors, including traffic volume, the type of roadway surface, the standard of installation, and the extent of winter maintenance operations.

Modeling of Retroreflectivity Degradation

In 2001, Migletz et al. used linear, quadratic, and exponential models to analyze a range of pavement marking materials, including epoxy, polyester, methyl methacrylate, and thermoplastic. They discovered that almost 92% of the marking lines, linear and decay models, offered the greatest fit. However, there was a sizable amount of difference in service life forecast between various sites within a state for the same material types and related types. [(33)] Using a natural logarithmic model, Abboud and Bowman examined traffic paint and thermoplastic in 2002.[(34)] For the examination of flat and contoured thermoplastic markings in 2003, Lindly and Wijesundera utilized linear and exponential models but found no distinction between the two. [(35)] Thamizharasan et al., (2003) observed variations in retroreflectivity over time due to restriping and snowplowing in 2003 using a linear model for older thermoplastic and epoxy materials and a nonlinear model for newly put marking materials. [(36)] In 2004, Kopf used linear, exponential, and natural logarithmic models to examine solvent-based and water-based traffic paint. He found that there was a sizable difference in performance between routes with comparable Average Annual Daily Traffic (AADT) and environmental circumstances. They concluded that it is uncommon to accurately forecast pavement marking performance using statistics. [(37)] It was discovered in 2007 that for both yellow and white markings, centerline markings deteriorate more quickly than edge line markings. In addition to weighted and unweighted ANOVA, Craig et al. (2007) did an average value analysis on thermoplastic markings in the colors white and yellow. Sathyanarayanan et al. (2008) used Weibull distribution to study water-based road paint and discovered that white pavement markings had a longer service life than yellow markings. In 2009, Abbas et al. used linear, power, exponential, natural logarithmic, and inverse polynomial models to evaluate traffic paint, thermoplastics, epoxy, polyurea, modified urethane, and methyl methacrylate. They claimed that when applied to Portland cement concrete bridge decks, linear and exponential models offered the highest coefficient of determination for all materials. [(13)] Each snowplow occurrence was comparable to a 3.22 mcd/m^2/lux drop in pavement marking retroreflectivity, according to Mull and Sitzabee's analysis of traffic paint using mixed stepwise selection in 2012. They also discovered that AADT had a marginal but significant impact on the retroreflectivity deterioration of traffic paints. [(38)] The same year, Robertson et al. (2013) used stepwise regression analysis and percent difference models to examine high-build aqueous and waterborne traffic paint. The researchers discovered that pavement marking age, traffic volume, lane width, and shoulder width significantly influenced waterborne paint, while pavement marking age and traffic volume significantly influenced high-build paint. In their 2014 study of thermoplastic utilizing stepwise regression analysis (full and reduced models), Ozelim and Turochy discovered that initial retroreflectivity might not be a significant feature for the assessment of future retroreflectivity.

Cost-Benefits of Pavement Markings

The overall projected cost of pavement marking materials depends on some variables, including the cost per unit of material, traffic volume, completion of the construction phase, and actual service life. Given the vast range of marking performances, choosing the most economical traffic marking material was a frequent challenge for practitioners. [39] Approximately 3% of the global Gross Domestic Product was said to have been lost because of the significant financial costs associated with automobile accidents. [40] According to estimates by Wijnen et al. (2019), preventing a road death could cost as low as 0.04% - 4.20% of the expenses related to one. This is the safety benefit of hardened pavement marking.

The attainment of the most cost-effective pavement marking involves various factors. A straightforward approach involves evaluating the current expenses associated with the installed marking against the anticipated lifespan of each potential marking option. The durability of various pavement marking compounds was tested in different environmental conditions by a team of researchers. The regression equation for each line type determined the marking's service life at varying retroreflectivity levels. The investigators calculated the annual costs of each marking style across all retroreflectivity levels using the cost data. Retroreflectivity degradation curves help to determine the markings' ages at various levels. The retroreflectivity levels were chosen to incrementally indicate a marking reaching lower sustained retroreflectivity. The marker needs to be replaced when its retroreflectivity goes below a specified threshold.

The figures show the cost of the marking per mile per year of service and its age at the retroreflectivity levels indicated. Due to extreme winter circumstances that caused most materials to lose retroreflectivity after one winter season, the Alaska test deck dataset is inappropriate for comparison. In these cases, agencies must evaluate road marking benefits. These features include providing daylight direction and modeling marking reapplication after winter.

The markings in the Nashville and Tusculum, Tennessee, test decks showed good presence and retroreflectivity over time. During the 4-year assessment period, certain markings' retroreflectivity dropped below 100 mcd/m^2/lux, the project's minimum criteria. Only two portions are unmarked, which is unacceptable. The Nashville test deck's acrylic paint and extruded thermoplastic markings were the most cost-effective. At the Tusculum test deck, acrylic paint, extruded thermoplastic, and modified urethane marks were more cost-effective than others. The section 2 TN-T extruded MMA marking was durable. Its original expense made it uneconomical. Markings in a deep groove did not extend operating longevity, making them uneconomical. Only sections 4 TN-N and 2 TN-T b show the cost-effectiveness of deep grooved marking over shallow grooved marking. Section 4 TN-N thermoplastic extrusion is cost-effective.

However, the regression equation does not match real service life. Because the grooved marking deteriorated slowly during the inspection, the regression model predicted a long service life. Regression study shows that markings cannot last 44 to 125 years, emphasizing the need for continuing review. Section 2 TN-T b was the least cost-effective

Tennessee test deck designation. In this case, significant indentations extended the operational longevity, justifying the additional cost. The delays and safety risks of applying and reapplying stripes, measuring retroreflectivity, and inspecting a pavement marking system may also affect its overall cost efficiency. The categorization of the roadway, traffic volume, and marking material installation and drying time determine the above costs. An organization may include the perceived brightness of road markings under damp nighttime conditions as an indirect expense. Superior materials may not need delineators or higher retroreflective pavement markers. The current and restriping materials must be compatible when picking a marker. When choosing a material, consider surface preparation and installation weather conditions.

Cost of Temporary Pavement Markings

Highway agencies must factor in the cost of temporary pavement markings, including it in the overall project expenses, as the cost of the various products used can differ. For instance, traffic paint can cost between $0.05 to $0.15 per foot installed, whereas epoxy or thermoplastic can range from $0.10 to $0.35 per foot installed, which are more durable but come at a higher cost. Temporary tape is comparatively more expensive, according to unpublished average bid-price data from Massachusetts DOT, which indicates that it costs four to five times more than temporary paint.[19] Similarly, data from the Vermont Agency of Transportation's 5-year average price list shows that temporary tape is more expensive than temporary paint, with only minor variations in costs for 4-in. and 6-in. markings. (17) These findings were reported in recent research conducted by Brown and Edara (2021), as listed in Table 11.

Table 11 - Average unit prices for temporary pavement markings (41,42)

Item Description	Units (Linear Foot, LF)	Average Price	Contract Occurrence
Temporary 4-In. White Line	LF	$0.19	18
Temporary 4-In. White Line, Temporary Pavement Marking Tape	LF	$1.38	4
Temporary 4-In. White Line, Paint	LF	$0.10	79
Temporary 4-In. Yellow Line	LF	$0.19	17
Temporary 4-In. Yellow Line, Temporary Pavement Marking Tape	LF	$2.49	2
Temporary 4-In. Yellow Line, Paint	LF	$0.11	78
Temporary 6-In. White Line	LF	$0.50	2
Temporary 6-In. White Line, Temporary Pavement Marking Tape	LF	$1.08	7
Temporary 6-In. White Line, Paint	LF	$0.12	27
Temporary 6-In. Yellow Line	LF	$0.50	1
Temporary 6-In. Yellow Line, Temporary Pavement Marking Tape	LF	$0.86	5

Temporary 6-In. Yellow Line, Paint	LF	$0.11	19

Ullman et al. (2008) developed several matrices to aid in selecting the most suitable temporary pavement marking materials for work zones. [43] These matrices, depicted in Figure 7, provide the lowest total cost for temporary pavement markings for different scenarios at the 15th, 50th, and 85th percentile total cost computations. For instance, the study found that for project phase durations of approximately two years at AADT levels of 10,000 vpd to 19,000 vpd, the median total costs of thermoplastics and traffic buttons on asphalt pavements were almost equal and reported as "T/B" in Figure 7. Generally, the research suggests that for work zones with lower AADT and shorter project durations, paint is more cost-effective. However, for longer project durations and higher AADT levels, thermoplastic and traffic buttons are more effective in terms of cost.

(a) Asphalt Surface

15th Percentile Cost

Lane ADT	Phase Length (days) 90	180	360	540	720
3000	P	P	P	P	P
4000	P	P	P	P	P
5000	P	P	P	P	P
6000	P	P	P	P	P
7000	P	P	P	P	P
8000	P	P	P	P	P
9000	P	P	P	P	P
10000	P	P	P	P	T/B
11000	P	P	P	P	T/B
12000	P	P	P	P	T/B
13000	P	P	P	T	T/B
14000	P	P	P	T	T/B
15000	P	P	P	T	T/B
16000	P	P	P	T	T/B
17000	P	P	T	T	T/B
18000	P	P	T	T	T/B
19000	P	P	T	B	T/B
20000	P	P	T	B	T/B
21000	P	P	T	B	T/B
22000	P	P	T	B	T/B
23000	P	P	T	B	T/B
24000	P	P	T	B	T/B

Median Cost

Lane ADT	Phase Length (days) 90	180	360	540	720
3000	P	P	P	P	P
4000	P	P	P	P	P
5000	P	P	P	P	P
6000	P	P	P	P	P
7000	P	P	P	P	P
8000	P	P	P	P	P
9000	P	P	P	P	P
10000	P	P	P	T	T/B
11000	P	P	P	T	T/B
12000	P	P	T	T	T/B
13000	P	P	T	T	T/B
14000	P	P	T	B	T/B
15000	P	P	T	B	T/B
16000	P	P	T	B	T/B
17000	P	P	T	B	T/B
18000	P	P	T	B	T/B
19000	P	T	B	B	T/B
20000	P	T	B	B	B
21000	P	T	B	B	B
22000	P	T	B	B	B
23000	P	T	B	B	B
24000	P	T	B	B	B

85th Percentile Cost

Lane ADT	Phase Length (days) 90	180	360	540	720
3000	P	P	P	P	T
4000	P	P	P	P	T
5000	P	P	P	T	T
6000	P	P	T	T	T/B
7000	P	P	T	T	T/B
8000	P	P	T	T	T/B
9000	P	P	T	B	T/B
10000	P	P	T	B	T/B
11000	P	T	B	B	T/B
12000	P	T	B	B	T/B
13000	P	T	B	B	B
14000	P	T	B	B	B
15000	P	T	B	B	B
16000	P	T	B	B	B
17000	P	T	B	B	B
18000	P	T	B	B	B
19000	T	T	B	B	B
20000	T	B	B	B	B
21000	T	B	B	B	B
22000	T	B	B	B	B
23000	T	B	B	B	B
24000	T	B	B	B	B

(b) Concrete Surface

15th Percentile Cost

Lane ADT	Phase Length (days) 90	180	360	540	720
3000	P	P	P	P	P
4000	P	P	P	P	P
5000	P	P	P	P	P
6000	P	P	P	P	P
7000	P	P	P	P	P
8000	P	P	P	P	P
9000	P	P	P	P	P
10000	P	P	P	P	P
11000	P	P	P	P	P/B
12000	P	P	P	P	P/B
13000	P	P	P	P	P/B
14000	P	P	P	P	P/B
15000	P	P	P	B	P/B
16000	P	P	P	B	P/B
17000	P	P	P	B	P/B
18000	P	P	P	B	P/B
19000	P	P	T	B	P/B
20000	P	P	T	B	P/B
21000	P	P	T	B	P/B
22000	P	P	T	B	P/B
23000	P	P	T	B	P/B
24000	P	P	T	B	P/B

Median Cost

Lane ADT	Phase Length (days) 90	180	360	540	720
3000	P	P	P	P	P
4000	P	P	P	P	P
5000	P	P	P	P	P
6000	P	P	P	P	P
7000	P	P	P	P	P
8000	P	P	P	P	P
9000	P	P	P	P	P
10000	P	P	P	P	P
11000	P	P	P	P	P/B
12000	P	P	P	P	P/B
13000	P	P	P	B	P/B
14000	P	P	P	B	P/B
15000	P	P	P	B	P/B
16000	P	P	B	B	P/B
17000	P	P	B	B	P/B
18000	P	P	B	B	P/B
19000	P	P	B	B	B
20000	P	P	B	B	B
21000	P	P	B	B	B
22000	P	P	B	B	B
23000	P	P	B	B	B
24000	P	P	B	B	B

85th Percentile Cost

Lane ADT	Phase Length (days) 90	180	360	540	720
3000	P	P	P	P	P
4000	P	P	P	P	P
5000	P	P	P	P	P
6000	P	P	P	P/B	P/B
7000	P	P	P	P/B	P/B
8000	P	P	P	P/B	P/B
9000	P	P	P	P/B	P/B
10000	P	P	P	P/B	P/B
11000	P	P	P	P/B	P/B
12000	P	P	P	P/B	P/B
13000	P	P	B	P/B	P/B
14000	P	P	B	P/B	B
15000	P	T	B	P/B	B
16000	P	T	B	P/B	B
17000	P	T	B	P/B	B
18000	P	T	B	P/B	B
19000	P	T	B	B	B
20000	P	B	B	B	B
21000	P	B	B	B	B
22000	P	B	B	B	B
23000	P	B	B	B	B
24000	P	B	B	B	B

Notes: P = Paint, T = Thermoplastic, and B = Button

Figure 7. Most cost-effective marking material. a) asphalt pavement, b) concrete pavement [43]

Pavement Marking Removal

There are various methods available to contractors for removing pavement markings, with the most commonly used being chemical removal, grinding, high-pressure water jet, hot compressed air burning, oxygen burning, hydro blasting, shot blasting, sand blasting, and temporary taping. However, these methods can create problems such as damage to the road and scarring of the pavement, which can cause confusion for motorists, especially in wet weather conditions at night. "Ghost stripes," the image of the old marking, can be left behind as scars, making it difficult to completely remove the marking without causing any damage. To minimize pavement scarring, agencies are advised to avoid painting over existing markings with black paint or asphalt, as stated in Section 6F.77 of the MUTCD. Grinding is a popular method of removing pavement markings, although other methods are permitted by most agencies. Cho et al. (2011) conducted a comprehensive study on the effectiveness study on temporary pavement marking removal methods. A list of available removal methods described in this study is provided in Table 12.

Table 12 - Pavement Marking Removal Techniques [44,45]

Technique of Removal	**Description**	**Performance**
Water blasting	Water shot at 10,000 psi; relatively high cost; relatively long time for removal; standard practice by agencies.	Rated best for removal especially on concrete; slower than most other treatments; very effective for tape
Grinding	Relatively fast method: most common treatment used; scars pavement.	Grinding leaves 1/8 to 1/4 inch groove for thermoplastic; concrete pavement is bright to look like permanent marking
Shot Blasting	Uses small steel balls shot at high speed to remove markings.	Dry pavement only; effective for thinner lines; recycle shot; slower process
Sand Blasting	Similar to sand blasting; very fine materials are propelled at high speed to remove markings	Slow and can scar pavement; performance is highly tied to operator.
Hydro-blasting	Combination of water and sand; can leave scars but effective; water and sand can be recycled	Effective due to the ability to recycle sand and water, but can leave scars
Hot Compressed Air Burning (HCAB)	Mix of propane and air to vaporize material, found effective with temporary tape,	Relatively slow rate
Excess oxygen burning	Similar to HCAB; slow removal for thicker materials	Scarring may fade quickly
Dry Ice Blasting	Application of solid carbon dioxide;	Effective but costly

Chemical	Environmentally friendly – does not contain Methylene Chloride (MeCl); Still needs to be power washed at 400 psi	Best at removing stripe without scarring on concrete and asphalt

Pike and Miles (2013) conducted a study to determine the most effective, cost-efficient, and environmentally friendly method for removing pavement markings in work zones. This study evaluated various pavement marking removal methods listed in

Table 13 and their effectiveness with respect to the marking material. The table includes references to the specific literature where new information or gaps were filled. The table indicates whether a removal method can adequately remove the pavement marking (labeled as "good") or remove it at a slower speed (labeled as "slow"). The study concluded that high-pressure water blasting has significantly improved over time, with equipment that can now be loaded on a mobile platform and operating pressures ranging in excess of 40,000 psi.

This improvement has made high-pressure water blasting more competitive in terms of effectiveness and cost compared to grinding methods. Blasting systems tend to remove all markings without leaving a deep scar, but may result in shadow lines. On the other hand, grinding tends to leave a scar to remove all markings. Both methods can create dust and debris, which need to be cleaned or vacuumed to ensure a safe driving and work environment. However, wet grinding and water blasting do not generate dust. Grinding is generally faster and cheaper than blasting techniques.

Table 13 - Effectiveness of removal method with respect to pavement marking material (46)

Removal Method	**Paint**	**Thermoplastic**	**Epoxy**	**Tape**	**Foil Tape**
High-Pressure Water	Good (47,48)	Good (48)	Good (47,48)	Good	Ineffective
Sand Blasting	Good	Slow	Good	Ineffective	Very Slow
Hydroblasting	Good	Slow	Good	Ineffective	Ineffective
Soda Blasting	Slow (45,47)	Slow (45,47)			
Dry Ice Blasting	Slow (45,47)	Slow (47)	Slow (45)		
Shot Blasting	Good				
Grinding	Good (45,47,48)	Good (48)	Good (47,48)	Ineffective	Ineffective
Excess-Oxygen Burningb	Thin Only	Ineffective	Ineffective	Ineffective	Good
Laserb	Slow (49)				
Chemicalsb	Slow (45)	Ineffective	Ineffective	Ineffective	Ineffective
Hand Removal	Very Slow	Very Slow	Ineffective		

State Practices

Different state departments of transportation have specific specifications and procedures; loss should not exceed 5% [50], while the Oregon DOT permits only a 5% reduction of thermoplastic and methyl methacrylate material during the 180-day acceptance period. The Pennsylvania DOT allows a 15% reduction in longitudinal durable materials for the 3-year warranty period and a 10% reduction for word and symbol markings for intersections and mid-block areas during the 6-month warranty period [52].

NCHRP 306 has investigated long-term pavement marking practices and provided a list of specifications published by ASTM and CEN that define retroreflectivity and the procedures for measuring it. [1] The following are the listed specifications:

- E 1710-97 - Standard Test Method for Measurement of Retroreflective Pavement Marking Materials with CEN-Prescribed Geometry Using a Portable Retroreflectometer (1998).
- D 6359-98 - Standard Specification for Minimum Retroreflectance of Newly Applied Pavement Marking Using Portable Hand-Operated Instruments (1999).
- EN 1436: 1997 - Road Marking Materials—Road Marking Performance for Road Users (1997).
- ENV 13459-3: 1999 - Road Marking Materials—Quality Control—Part 3: Performance in Use (1999).
- E 2177 - Test Method for Measuring the Coefficient of Retroreflected Luminance (R_L) of Pavement Markings in a Standard Condition of Wetness (2001).
- E 2176 - Measuring the Coefficient of Retroreflected Luminance (R_L) of Pavement Markings in a Standard Condition of Continuous Wetting (2001).

DOT Guidance for Pavement Markings

According to a report, most DOTs typically adhere to the national MUTCD when it comes to temporary pavement markings in work zones. [41] However, some states have developed their own MUTCD supplements, while others have adopted their own MUTCD. The state manuals and supplements usually align with the national MUTCD, but there are instances where they provide additional or revised guidelines. [41] listed some of the guidelines mentioned in their report, which include:

- California uses 4-in. by 24-in. lines or raised markers as temporary lane lines and center lines. [53]
- Delaware limits the use of temporary markings to 30 days. [54]
- Idaho requires temporary edge lines and channelizing lines for interstate highways and expressways, but not for other roadways. [55]
- Minnesota allows the use of signs instead of pavement markings for up to 14 days on roads with ADT of less than 400 vpd, with appropriate signage provided. [56]
- New Hampshire requires all temporary markings to be offset 1 ft from the final striping location. [57]
- West Virginia permits signs instead of markings to indicate no-passing zones for durations of three or fewer calendar days. [58]
- Illinois provides guidance for short-term markings with abbreviated patterns that are necessary at the end of each day. [59]

- Washington requires that temporary markings meet the requirements for permanent markings outlined in Chapters 3A and 3B of the national MUTCD. [60,61]

DOT Specifications for Temporary Pavement Markings

Temporary pavement markings are subject to various DOT specifications that cover a range of requirements, including materials and construction, time considerations, method of measurement and basis for payment, and inspection and monitoring. Brown and Edara (2021) provide a comprehensive overview of these requirements, which are discussed in the following sections.

Materials and Construction Requirements

Temporary pavement markings for road work are subject to different requirements and specifications set by various state Departments of Transportation (DOTs). These regulations include geometric layouts, allowable marking types, material specifications, and application instructions. For instance, California's DOT prescribes a minimum lane line/centerline delineation using Temporary Raised Pavement Markers (TRPMs) every 24 ft, while edge line markings may be 6-in. wide tape, cones, delineators, channelizers placed at 100-ft maximum intervals, or TRPMs at 6-ft intervals for the left edge line. [53] Hawaii requires TRPMs every 20 ft for solid lines, with 5-ft sections spaced 20 ft on center. [62]

The types of markings allowed also vary. Arkansas requires retroreflective tape or Type 4 retroreflective pliant-polymer preformed tape for concrete pavements, while South Dakota permits temporary paint, TRPMs, temporary flexible vertical markers (tabs), and temporary tape. [18,63] In Alaska, only TRPMs are allowed for interim markings on seal coat and surface treatment pavements, while South Carolina mandates the use of thermoplastic markings for asphalt pavements and epoxy markings for concrete pavements when the work zone duration is 4 to 6 months or greater. [64,65] Material requirements and installation instructions are also specified by DOTs. For example, Maryland prescribes specific requirements for temporary paint, including viscosity, pigment for yellow paint, and color and appearance, while Idaho requires temporary paint markings to meet the same material specifications as permanent paint markings. The tape must also be installed in accordance with the manufacturer's recommendations.

Various state DOTs have specific requirements for the application of temporary pavement markings. Kentucky requires 24.8 gal/mi for 6-in. paint, 16.5 gal/mi for 4-in. paint, and 6 lb/gal for glass beads. [66] Alabama requires application rates of 10 gal/mi and 18 gal/mi for paint on rough surfaces. [66] New Jersey mandates a paint thickness of 5 to 7 mils with glass beads applied at a rate of 12 lb/gal, and the paint must be applied when the air temperature is above 45°F and the pavement temperature is below 140°F. [67] Louisiana prohibits applying thermoplastic markings within 12 hours of rain, to wet surfaces, or when temperatures are below 50°F. South Carolina does not allow installing thermoplastic, epoxy, or tape within 24 hours after rainfall. [65]

Time Considerations

Temporary pavement markings in work zones are subject to various time-related specifications under DOT regulations. These include classification based on duration, deadlines for installation or removal, and material requirements based on duration or time of year. For instance, Ohio categorizes work zone markings as Class I, Class II, and Class

III, depending on the exposure to traffic and the timing of final markings installation. (68) Louisiana's specifications feature a table of temporary pavement-marking patterns for short-term and long-term markings, distinguished by their duration. (69) DOTs often impose strict timelines for the installation or removal of temporary pavement markings. For example, North Dakota and Rhode Island require that such markings be installed by the end of the workday. (70,71) In Idaho, temporary markings must be applied as soon as possible on newly placed pavement.[34] South Carolina mandates that TPMs be placed within 7 days of applying for an asphalt pavement course, unless another course is scheduled within 30 days. (65) Pennsylvania allows the use of "No Pavement Markings" signs at 0.5-mile intervals instead of temporary pavement markings for up to 14 days on seal coats and surface treatments and up to 7 days on other types of pavement operations. (72)

Different state DOTs have set limits on how long temporary pavement markings can remain in place. For instance, Arkansas mandates the replacement of interim markings within three days for high-volume roads or 14 days for low-volume roads with permanent or construction markings or covered with another pavement layer. (18) In Colorado, full compliance markings must be installed within two weeks of final surfacing, or within one week for seal coat projects, or when pavement work is suspended for at least two weeks. (73) New York State DOT requires contractors to place the next pavement course or apply remaining temporary pavement markings, such as edge lines, stop bars, and crosswalks, within 14 days of placing temporary pavement markings. (74) Delaware limits the use of temporary pavement markings to 30 days, while Oregon allows 28 days for the installation of permanent markings after the placement of temporary markings. (75) Massachusetts has set the maximum duration for temporary pavement markings at 90 days. (76)

Method of Measurement and Basis for Payment

The payment for temporary pavement markings varies among different states in the US, as outlined in the following state-specific guidelines. The standard units for striping are linear feet, and each for TRPMs and symbol markings. However, Texas and South Dakota use plan quantities for both temporary pavement markings and pavement marking removal. (77) South Dakota also measures only one centerline for all temporary pavement markings, while Montana measures by linear mile. (63) Colorado uses gallons as a unit of measurement for paint, epoxy, and methyl methacrylate, whereas linear feet is used for thermoplastic, preformed markings, and tape. (73) In Wyoming, temporary pavement markings are included in the cost of TTC, and any additional striping or tape not included in the contract is paid for by length as Category IV Traffic Control Device (TCD) Units. (78)

Monitoring and Inspection

Temporary pavement markings require monitoring and inspection according to DOT specifications, which may involve personnel requirements, mandatory inspections, and adherence to standards. The ATSSA's guidelines are a commonly used standard for monitoring and inspecting TTC devices. (79) For instance, New Hampshire mandates that all TTC devices meet the acceptable criteria outlined in the ATSSA guidelines and that any unacceptable TTC devices must be replaced. (57) Similarly, North Dakota stipulates that the engineer will rate short-term pavement markings in accordance with the ATSSA guidelines, and any markings rated as unacceptable must be replaced within 24 hours. (70) Various other DOT practices for monitoring and inspecting temporary pavement markings exist. For example, the Mississippi requirement that the contractor is responsible for maintaining temporary pavement markings. (80) Delaware and New Hampshire require that the contractor maintain TTC devices, including temporary pavement markings, according to the Delaware MUTCD and national MUTCD. (57) Ohio's approach of evaluating markings according to performance parameters, whereby markings receiving unsatisfactory numerical ratings must be replaced immediately. (68) New Mexico's daily inspections of TTC devices and the contractor's obligation to appoint at least one traffic control supervisor with ATSSA or other certification in charge of maintaining and replacing TTC devices. (81) Kentucky requires that the contractor replace missing or damaged TRPMs within 3 days and missing or damaged stripes or tape within 24 hours. (66) Maryland requires that the contractor monitor and replace tape for 180 days and paint for 60 days. (18)

Pavement Marking for Autonomous Vehicle (AV)

Autonomous vehicles are becoming increasingly prevalent on our roads, and technologies such as lane departure warning (LDW) and lane keeping assistance (LKA) are designed to enhance safety by providing warnings or actively steering a vehicle back into its lane when it deviates from the intended path. LDW and LKA typically use machine vision (MV) technology, such as cameras, to detect longitudinal pavement markings, as demonstrated in Figure 8. However, the current standards and policies on pavement marking design and maintenance have been developed with the human driver in mind, specifically the human vision system. With the increasing number of AVs on the road, it is crucial to examine the impact of these technologies on pavement marking design and maintenance standards. LDW and LKA technologies are important components of autonomous driving systems, and their effectiveness is heavily reliant on the quality and visibility of pavement markings. Therefore, it is essential to explore the current specifications and requirements for road markings and stripes paints for AV operation and their suitability for LDW and LKA technologies. This literature review aims to analyze the current standards and identify the gaps and challenges in the specifications and suggest potential areas for future research and development to ensure safe and efficient operation of AVs.

Figure 8. Lane tracking algorithm showing the estimated lane boundary against shadows, obstacles, and misleading markings [82]

Current Status of Pavement Marking Requirements and Standards for AV in the US

To date, there are no established pavement marking requirements or standards for automated vehicles in the United States, although ongoing research and discussions have been conducted to modify infrastructure to better accommodate AVs. The U.S. Department of Transportation has developed guidelines and best practices for AVs that suggest infrastructure modifications, including pavement markings, to support automated vehicle technologies.

Federal Highway Administration (FHWA)

In January 2018, the FHWA issued a Request for Information (RFI) seeking feedback from the automotive and road infrastructure industries on infrastructure requirements and standards necessary for enabling safe and efficient operations of Automated Driving Systems (ADS). To facilitate further discussions on ADS infrastructure needs and impacts, FHWA conducted six workshops across the United States on topics such as infrastructure planning/policy, digital infrastructure/data, infrastructure design and safety, operations, and freight. Respondents consistently believed that greater uniformity and quality in road markings and traffic control devices would enable automation. In October 2018, FHWA announced its intention to release a 2020 update to the MUTCD that would consider new ADS technologies. This announcement coincided with the release of the U.S. Department of Transportation's policy statement on automated vehicle technologies, Automated Vehicles 3.0 (AV 3.0). The FHWA has summarized its findings from both the RFI and workshops in a number of presentations. The latest policy statement, Automated Vehicles 4.0 (AV 4.0), builds upon AV 3.0 and expands the scope to 38 relevant United States Government components that have direct or tangential equities in the safe development and integration of AV technologies. AV 4.0 is structured around three key areas: USG AV Principles, Administration Efforts Supporting AV Technology Growth and Leadership, and USG Activities and Opportunities for Collaboration.

American Traffic Safety Services Association (ATSSA)
ATSSA supported the following proposals specifically related to road markings and Driving Automation System (DAS) technologies: (83)The next edition of the MUTCD should include the following policy changes regarding the use of pavement markings in support of ADAS:

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

Lane Detection (LD) Challenges
LD systems can be categorized into three functional components: hardware, software, and infrastructure. (84) The hardware component pertains to the sensing equipment used in the LD system, such as monocular and stereo vision cameras. Hardware components may vary in terms of the sensor type, lens type (wide angle, fisheye), lens properties (field of view, focal length), and camera specifications (pixel size, megapixels, resolution, frame rate). On the other hand, the software component encompasses the algorithms employed by the LD system to detect lanes and aid in vehicle navigation. Generally, vision-based LD systems are composed of three main subprocesses: image preprocessing, LD, and lane tracking.

Lastly, the infrastructure component relates to the lane markings and pavement surfaces that machine vision systems utilize to sense lanes. Lane markings can differ in color, geometry (continuous/intermittent lanes, width, length), and lane marking performance characteristics (luminance, retroreflectivity, color), among other pavement variables (asphalt, concrete). When detecting road lane markings, image-processing algorithms can be affected by factors such as:

- viewing geometry that determines the distance to the target area,
- viewing angle with respect to horizontal positioning to the target area (sun location),
- lighting conditions (directness of illumination [clear vs. overcast vs. foggy]),

- physical properties of the feature in the target area (intrinsic visual properties of the white/yellow stripe, such as width, contrast, etc., as described before),
- environmental conditions (amount, rate, and type of precipitation).

While this list does not cover all the factors, it highlights the significance of developing and evaluating algorithms while considering other criteria. Nonetheless, regardless of their robustness, algorithms depend on the data received from cameras.

Lane Detection Performance Evaluation

Test

In the testing regiment proposed for verification and validation of LDW, ISO 17361:2007 does not explicitly state the types of road markings that the system has to detect. [85] However, the system has to be able to pass a series of performance tests. These are performed in a test location where the "lane markings are in good condition in accordance with the nationally defined visible lane markings." There are no requirements regarding the environmental conditions that the system must be capable of operating under. However, the performance testing must be carried out where the visibility range is greater than 1 km. [86] A similar approach can also be found in the National Highway Traffic Safety Administration (NHSTA) LDW test procedure document, requiring high-contrast and uniform pavement; lane marking specifications adhering to the Manual on Uniform Traffic Control Devices (e.g., standard marking widths of 4–6 inches and considered in good condition; and avoidance of tests in inclement weather, including rain, fog, snow, hail, smoke, or ash. [87,88] Additionally, the National Institute of Standards and Technology has developed guidance on the proper documentation of factors when collecting and analyzing data to evaluate intelligent vehicle systems. [89] A report for the Federal Motor Carrier Safety Administration (FMCSA) outlined several proposed requirements for LDW systems in commercial vehicles [90], such as performance of a self-test; detection of vehicle position relative to various lane marker types and levels of wear; tracking at speeds in excess of 37 mph and in various lighting conditions; use of a variety of warning thresholds; accuracy within 4 inches; and ability to track 95 percent of the time in ideal conditions, issue warnings under various curve scenarios, not issue warnings when the driver uses the turn signal, and function properly when windshield wipers are used. Beyond scenarios where LDWs must issue warnings, LDWs may do the following: issue warnings related to direction of drift, widen the warning thresholds on curves, provide warnings based on time to lane crossing, use differential warnings based on type of lane marking, warn about the road edge in absence of lane markings, report system faults where conflicting boundaries exist, and issue warnings when turn signals are left on.

Performance Metrics

The quality of LDW systems is commonly evaluated using various performance measures in the existing literature. Among these measures, the rate/frequency of false alarms and efficacy rate (the ratio of alarms to actual encroachments) are frequently utilized. [26,27] However, false alarms are generally associated with less effective systems, as stated in studies by Navarro et al. (2016). Objective test procedures outlined in a U.S. Department of Transportation report also use false alarms (termed false positives) and false negative rates (encroachment without alarm) as performance metrics [91], which were previously outlined in the field. [92] Availability, which refers to the percentage of time that the system is able to track the lane delineators, has also been utilized in various studies. (93,94) At a more microscopic level, the algorithm's performance can be evaluated by considering the error distribution of the rate of change of lane position, which reflects the accuracy of the lane model.

In addition to identifying proper performance metrics, establishing a threshold for satisfactory performance is also a task confronting researchers and policymakers. Therefore, evaluating LDW systems requires a comprehensive approach that includes identifying appropriate performance metrics and establishing a threshold for satisfactory performance.

Pavement Marking Characteristics for AV Operation

After reviewing the literature, it can be concluded that several factors affect the proper functioning of LSS, including the visibility of road markings during both daytime and nighttime, which is considered one of their most crucial properties. (96)

According to Wilson et al. (2007), LSS systems only work properly 36% of the time when road markings are unclear. (29) Hadi et al.(2017) highlighted that the performance of lane departure warning systems improves with the increase of line $R_{L.}$ (26) Gordon et al. (2010) found that these systems can achieve 90% capacity during the daytime, but only 20% during the nighttime due to poor lighting conditions. (97) After adjusting for various factors, the overall effectiveness was estimated to be between 13% and 31%. A Swedish study highlighted the importance of visibility in road markings, suggesting a luminance coefficient of at least 5 mcd/lx/m^2 higher than the road surface and a minimum of 85 mcd/lx/m^2. (98) Hadi and Sinha (2011) suggested adequate R_L of road markings is needed for all vision-based MV systems for proper nighttime guidance. (26,27)

Potters Industry and Mobileye (2016) found that machine-vision systems can detect markings within a range of 6-18 m in front of the vehicle and that retroreflectivity affects reading quality, with higher retroreflectivity resulting in increased reading levels and confidence. (99) Carlson and Poorsartep (2017) also found that machine-vision detection of lane markings increased with the increase of retroreflection and contrast ratio. However, these systems can only detect markings with a minimal retroreflectivity of 100 mcd/lx/m^2 and do not necessarily provide the strongest detection in all cases.

Marr et al. (2020) conducted an extensive study in Australia to determine the implications of road markings for machine vision. The study involved several vehicles equipped with a Mobileye camera to test marking detection in various scenarios, including different road marking characteristics such as luminance coefficient, contrast ratio, retroreflectivity, marking width, and complex situations like road curvature and non-marked edge lines. Based on the analysis, it was concluded that lane detection during daytime was generally less effective than at nighttime due to the complexity of visual clutter and the fact that the retroreflective properties of well-maintained lane markings provide greater contrast during nighttime. The study also highlighted that the contrast ratio between lane markings and the surrounding substrate should be between 5-to-1 and 10-to-1 during nighttime and 3-to-1 during daytime.

In 2018, Mobileye, the global camera sensor market leader, produced a summary of road marking challenges with accompanying recommendations. [99] They request a better-maintained and more uniform marking system. Ideally, they prefer to see markings that are 12-15 cm wide and nothing over 25 cm wide (some European markings are up to 30 cm wide). They also asked for standardized lane line lengths, with a preference of 5 m (in the US the most common lane line is 10 ft (about 3 m). Other road marking preferences include:

- Lane lines are being fully marked and starting at the split point (gore point).
- Higher retroreflectivity levels in wet conditions.
- Removal of old markings.
- More uniformity in the shape and use of arrows.
- More uniformity on the width of Stop bars (35 to 50 cm).
- More uniformity on speed bump markings.
- Clearer distinction between vehicle, bike, and pedestrian areas (shared and/or exclusive).

MUTCD chapter 5 provides guidance for selecting and maintaining traffic control devices to support both human drivers and automated vehicles (AVs), emphasizing uniformity, consistency,

Pavement marking materials improve highway traffic safety and mobility. Supply chain difficulties may affect certain commodities' availability, quality, and pricing. Pavement marking material supply chain issues include the lack of coordination between manufacturers, suppliers, contractors, and government agencies. Inefficiencies, delays, and cost overruns may emerge from these materials' manufacture and supply. The pavement marking supply chain lacks standards, quality control, and stakeholder participation. Resins and pigments for pavement marking items are scarce. This may affect material costs and quality by disrupting the supply chain. Due to raw material price volatility, the pavement marking industry, which uses petroleum-based solutions, is struggling. Transportation and logistics may bottleneck pavement marking material supply chains. Heavy, difficult-to-handle goods can increase transportation costs and delivery times. US highways and roads. Pavement marking supply chain logistics are limited by carrier capacity, lead times, and stakeholder cooperation. Sustainability and the environment are also important in the pavement marking supply chain. Traditional solvent-based products can pollute the environment and harm public health. Pavement marking materials that are healthier and more environmentally friendly are becoming more significant. In a nutshell, the US supply chain for pavement marking materials is complex and requires a coordinated and cooperative approach. The associated agencies must address coordination, raw material supply, transit and logistics, and sustainability to increase traffic safety and mobility on US roads and highways.

The recent Coronavirus 2019 (COVID-19) outbreak has posed significant hazards and difficulties for global supply chain management (GSCM). To survive the crisis, it is essential to reevaluate the proper configuration of global supply chains and reform numerous associated operational strategies. Researchers across the globe have endeavored to reform the GSCM from both the supply and demand perspectives, considering the various pandemic stages (i.e., pre-, during-, and post-pandemic). Some previous studies researched real-world case studies to investigate the pandemic's effects on global supply chains and its specific challenges. For instance, Xu et al. (2023) obtained insights by reviewing public records search and reporting the actual practices of GSCM under COVID-19 in nine of the world's leading corporations. To accomplish responsiveness, resiliency, and restoration (3Rs), they proposed the "GREAT-3Rs" framework, which illustrates the critical issues and reform measures for GSCM during the three pandemic stages. Specifically, the "GREAT" portion of the framework consists of five critical domains, namely "government proactive policies and measures," "redesigning global supply chains," "economic and financing strategies under risk," "adjustment of operations," and "technology adoption," to assist global enterprises in surviving the pandemic; "3Rs" are the outcomes that can be achieved by implementing the "GREAT" strategies during the three pandemic stages. The authors further proposed a future research agenda based on five factors. [(100)]

Shortages of the supply of pavement markings have been observed in many states after the pandemic. Iowa State recorded a shortage in marking supplies, and they narrowed the marking width to accommodate it. Another option they chose was to start prioritizing critical areas like interstates, high-traffic areas, and center lines. [(101)] The state of Missouri encountered a two-month delay in the supply of paint. The pandemic and natural events created a price surge of 27% in paints, increasing the per-gallon price from $9.0 to $11.5. The higher price of the ingredients decreased the purchase of paint marks. The state usually tries to capitalize on the summer temperature to avoid drying time issues, having summer temperature (90°F) decreasing the drying time as half as the other season (60°F). The state policy to address these issues was to purchase the paints in bulk and avoid multiple purchases over the summer. This way, the temperature of summer is not wasted, and the drying time issue is solved. [(102)] The price of any paint ingredient can increase the price of the paint. Since paint is usually finalized with a huge number of ingredients, any supply deficit could delay paint manufacturing. With the increased delay, there has been a backlog of all kinds of paints in the United States. [(103)]

For transportation logistics, the risks are from the demand and supply side. The demand side risk included closing locations, adjusting operations, and suspending the "money-back guarantee". In contrast, the supply side risk included monitoring transportation networks, developing contingency plans, partnering with governments worldwide, and shifting bargaining power. [(100)] Choi (2020) analyzes the innovative "bring-service-near-your-home" model under COVID-19 in the context of a real-world case from Hong Kong. The author examines how logistics (offering services on a vehicle) and technologies can support this new business model to combat the pandemic-caused operational challenges. Specifically, the author suggests that the government could implement various subsidy programs to improve supply chain performance if technologies such as blockchain are known to be advantageous, but companies lack the necessary resources. i) Most previous studies have focused on supply chain resilience during the "pandemic" phase. [(105)] They disregard the other phases. (ii) The findings of previous evaluations are primarily focused on the healthcare industry and disregard other industries. Analytical, computational, and simulation research methods are utilized more frequently than other approaches. Moreover, from a different angle, our review results reveal the critical dimensions (with associated organizational behaviors) that can assist researchers in developing empirical hypotheses for future studies to enhance the 3Rs in global supply chains.

Supply Chain (SC) Managers could plan the response to supply chain issues by making short-, medium-, and long-term decisions, connecting diverse SC areas such as human resources, finance, and maintenance, and evaluating the response using indicators of the SC and each of its processes. Second, the study identified various options for responding to a stimulus, emphasizing the need for SC managers to examine all alternatives based on information that facilitates the detection and comprehension of the stimulus. This study provides valuable insight into how businesses in Santiago de Cali responded to the stimuli that impacted their SC during COVID-19. Researchers, professionals, and consultants interested in evaluating and enhancing SC responses to stimuli can use these insights as a guide. [106]

Summary of Relevant Studies

Table 14 provides a summary of the key findings from relevant studies related to pavement markings, including the current state of practice and art, as well as lessons learned.

Table 14 - Summary of key findings of relevant studies

Study and Year[Ref.]	**Aim/ Objective**	**Key Findings/ Summary**
(Ellis, 2003)[107]	Develop methods to remove pavement markings without damage.	• Sand seal successfully covers temporary pavement markings. • Seal costs less than grinding or blasting methods. • Covering tapes also successfully mask pavement markings.
(Finley et al., 2005)[108]	Assess pavement marking's potential to improve driver safety.	• Type I orange RRPMs are rarely mistaken as red. • Removable paint has potential for easy application/removal. • Durability of white removable paint at field was not optimal.

Study and Year[Ref.]	**Aim/ Objective**	**Key Findings/ Summary**
(3M Company, 2008)[109]	Assess the all-weather pavement marking system for work zones.	• Shorter work zone durability allows low-cost alternative. • All-weather markings improve safety in demanding work zones.
(Miles et al., 2008)[76]	Evaluate drivers' comprehension of red RRPMs on different roads.	• Red RRPMs on one-way divided roads help drivers realize wrong direction. • Replacing RRPMs with arrows improves rates of correct responses for all road configurations.
(Ullman et al., 2008)[43]	Develop guidelines to improve traffic control in urban freeway interchanges and select proper pavement marking materials in work zones.	• Diagrammatic signing and pavement marking symbols in work zones improve drivers' ability to choose lanes and navigate interchanges. • The generated matrices can recommend marking materials based on phase duration and AADT. • The generated matrices enable flexible selection of marking materials by adjusting input assumptions.
(Bham et al., 2010)[111]	Evaluate markings on VMAs in work zones.	• Red and white checkerboard pattern was most effective.
(Ellis et al., 2010)[112]	Investigate seal coating to obscure temporary pavement markings.	• Modified sand-seal coat effectively covers temporary pavement paint markings with good friction, coverage, and durability. • It is a cost-effective alternative to removable tape or mechanical line removal methods.

Study and Year[Ref.]	Aim/ Objective	Key Findings/ Summary
(Cho et al., 2011)[45]	Find suitable techniques and protocols for removing temporary markings from concrete and asphalt pavements with efficiency.	• Chemical removal of markings proved to be a cost-effective, efficient, and successful approach in contrast to other methods. • It was safe for both the environment and the people using the road.
(Songchitruksa et al., 2011)[113]	Develop a cost-effective approach for selecting pavement marking materials meeting work zone requirements.	• Buttons work better on concrete with moderate traffic and shorter phase durations. • Thermoplastics are cheap for moderate asphalt projects, but not for concrete. • Paint works for short projects on all surfaces and traffic levels.
(Hawkins et al., 2012)[114]	Assess pavement markings for daytime visibility, reflectivity, and removal effectiveness.	• With the exception of rough surfaces like rumble strips and potential tearing due to vehicle maneuvering, temporary pavement marking tapes exhibited satisfactory performance over a 56-day period.
(Cho et al., 2013)[115]	Find methods that work well for removing temporary markings on pavements within construction zones on roadways.	• Image-processing technology was utilized to create a new method for inspecting the pavement's visual damage during removal. • The non-MeCl chemical stripping method performed best in terms of quality among the tested removal methods.

Study and Year(Ref.)	Aim/ Objective	Key Findings/ Summary
(Cunningham et al., 2013)(22)	Assess the safety of AWP versus standard pavement markings on actual roads based on reflectivity, speed, lane encroachments, and displacement.	• AWP showed better retroreflectivity than regular pavement markings. • Most drivers speed up after work zone lane shifts, regardless of marking type, with no clear AWP advantage. • AWP lanes tended to promote safer driver lane placement more frequently.
(Pike and Miles, 2013)(46)	Identify optimal procedures for safely, affordably, and eco-friendly removal of pavement markings with minimal damage to the pavement.	• Grinding is a popular and cost-effective method for removing pavement markings despite leaving visible scars. • Grinding and water blasting are the only methods used for extensive marking removal due to their speed. • Fog or slurry seals blend color changes, scars, or surface texture of pavement only for asphalt surfaces.
(ATSSA, 2014)(44)	Create a manual that provides instructions on how to utilize temporary pavement markings in work zones.	• Short-term work zones can use buttons, paint, or raised markers; long-term zones can use thermoplastic or epoxy. • Durability of markings can be affected by weather, material quality, practitioner experience, and pavement temperature. • Common removal methods include grinding (fast but leaves scarring), water blasting (slow but less scarring, good for concrete), and shot blasting.

Study and Year(Ref.)	Aim/ Objective	Key Findings/ Summary
(Shaw et al., 2017)(11)	Examine the global methods and techniques used for utilizing special-colored pavement markings in work zones	• Policy difference: some places use new special-color markings over old, others use special-color temporary marking and remove old lines. • Recent special-color marking demos in Australia, Canada, New Zealand, and the US are on freeways, but Europe suggests using them on urban streets too.
(Shaw et al., 2018)(116)	Evaluate the use of orange pavement markings in work zones, including conducting a literature review, field observations, surveys, and interviews to gather data on driver behavior, public acceptance, and agency satisfaction.	• Analysis of data on vehicle positioning and speed showed that the behavior of drivers using the standard color and the orange color was very comparable. • Surveys and interviews conducted with drivers and field engineers demonstrated that orange is preferred for lateral lane shifts. • The most practical approach is to use orange as an accent color for work zone locations that involve challenging driving maneuvers.
(Higgins et al., 2009)(117)	Examine how visible three prototype work zone markings are in the nighttime during dry, wet-recovery, and rainy conditions.	• Prototypes and wet-reflective tape remain visible in wet recovery and rain, sustaining 50-80% of dry detection distance. • Conventional glass beads-on-paint drops to 17-28% of dry detection distance in wet recovery and rain. • Participants couldn't see the conventional system in rain, while prototypes were still visible.

Study and Year(Ref.)	Aim/ Objective	Key Findings/ Summary
(Brown and Edara, 2021)[41]	Examine and record the procedures and regulations implemented by state DOTs for positioning, upkeep, and elimination of road markings in work zones.	• State DOTs consider marking duration, experience, and safety when selecting temporary markings. • Temporary marking type depends on various factors such as duration, weather, pavement type, and traffic. • Provisions for CAVs are seldom considered when choosing temporary pavement markings by 80% of DOTs.
Jo et. Al., 2021)[118]	Develop and test pavement marking materials, assess properties, and evaluate durability in different conditions	• Smooth surface or reinforced tapes had higher peel strength with modular peel fixture. • Commercial TPM tapes were more likely to peel than tear during removal. • PPM had better adhesion with higher asphalt surface temperature.
(Lammers et al., 2021)[119]	Assess the safety benefits of using orange pavement striping in work zones.	• Orange pavement markings led to increased crashes, but less severe ones. • Public survey indicated openness to the use of orange pavement markings in future work zones.
(Xu et al., 2021)[120]	Evaluate advanced pavement marking technologies, their environmental impact and cost-effectiveness.	• Waterborne paints have environmental, cost-saving, and health benefits compared to other pavement marking materials. • Nanocomposite paints and photo-luminescent coatings have the potential to improve traffic safety, but their application must be carefully evaluated.

Study and Year(Ref.)	Aim/ Objective	Key Findings/ Summary
(Jiang et al., 2022)[121]	Develop a new pavement marking material that is durable, healable, easy to remove, and suitable for both permanent and temporary use.	• The developed PMM - has a longer life than epoxy systems. - can be easily removed without expensive and polluting techniques. - last longer and don't fail before construction concludes compared to other options.
(Katzorke et al., 2022)[122]	Explore techniques and materials for flexible changing of road marking patterns that are effective and efficient.	• Type I temporary road marking tape is more efficient and sustainable for automotive proving grounds. • White type II temporary markings have higher retroreflectivity compared to permanent adhesion markings.
(Pike and Speidel, 2022)[123]	Examine methods for the temporary application and removal of pavement markings on airfields.	• UHP water blasting is effective in removing temporary markings from both concrete and asphalt surfaces, with minimal scarring on concrete and a likely removal scar on asphalt. • Shot blasting can remove temporary markings from ungrooved surfaces.
(Sidhu, 2022)[124]	Evaluate orange striping's success and challenges in installation, exposure, and removal.	• To establish orange striping as an industry standard in heavy civil construction, uniform specifications, visibility for color-blind individuals, efficient cleaning methods, waterproof tape, retro-reflectivity, and compatibility with AVs must be considered.
(Kluge and Johnson, 1995)[93]	Automate characterization of intrinsic visual properties of white painted lane markings	• Lane detection system reliability affected by intrinsic marking properties, lighting and weather conditions, and viewing geometry.

Study and Year(Ref.)	Aim/ Objective	Key Findings/ Summary
(Kobayashi S, 1998)[125]	Evaluate lane marking detection with machine vision under poor visibility	• A next generation lane marking detection system formulated using gas-discharge headlamps, high-luminance type lane markings and a near infra-red CCD camera can by-and-large meet the standards established for lane marking detection on dry or wet roads. • The image sensor should be sufficiently sensitive for use with the lane marking luminance of 1 cd/m, and the lane marking-to-road contrast of 0.2.
(McCall and Trivedi, 2005)[95]	Examine the performance of lane position tracking in driver assistance systems	• System actually performs better at night. • Complex shadows hamper the system's ability. • Roads that are marked with solid line markings had better results than areas marked only with circular reflectors.
(Wilson et al. 2007)[61]	To evaluate the performance, driver acceptance, and safety benefits of the Road Departure Crash Warning system.	• Lane Departure Warning systems only work properly 36% of the time when road markings are unclear. • Inaccuracies in some measures led to alerting inconsistencies.
(Hadi et al., 2007)[26]	Investigate the effects of environmental conditions on LDWS performance with typical lane-marking installations on limited-access facilities.	• The ER (Effectiveness Rate) of the LDWS (Lane Departure Warning System) under dry and light rain conditions is 100%. • Under heavy-rain night conditions, most observed ER values were between 0% and 30%. • The ER associated with night rain conditions appears to increase with increased lane-marking retroreflectivity.

Study and Year[Ref.]	Aim/ Objective	Key Findings/ Summary
		• Dusk conditions were found to drop the ER of LDWS by 15% to 18%. • LDWS had difficulty detecting yellow lane markings near the end of their service lives or on concrete pavements due to the low level of contrast between the yellow markings and the pavement.
(Gordon et al., 2010)[97]	Estimating safety benefits of LDW	• LSS systems can achieve 90% capacity during the daytime, but only 20% during the nighttime due to poor lighting conditions
(Sinha, 2011)[27]	Examines the effects of the marking's retroreflectivity on the performance of LDWS	• Adequate R_L of road markings is needed for all vision-based MV systems for proper night time guidance. • Thermoplastic and paints improve the performance of LDWS for rain conditions at night.
(Bar Hillel et al., 2014)[126]	Survey the approaches and algorithmic techniques used for road or lane perception in advanced driver assistance systems	• Review of road and lane detection by MV.
(Lundkvist and Fors, 2010)[94]	Investigate the interaction between the Volvo Lane Departure Warning System (LDW) and the road markings.	• LDW requires a minimum retroreflectivity of 70 or 20 mcd/m^2/lx in dry and wet conditions, respectively to work in headlight illumination. • In daylight, the luminance coefficient must have at least 5 mcd/m^2/lx higher value than the road surface for LDW to work
(Mathibela et al., 2015)[127]	Addresses the problem of automatically reading	• Review of issues encountered with interpretation of various road markings by MV algorithms.

Study and Year(Ref.)	Aim/ Objective	Key Findings/ Summary
	the rules encoded in road markings.	
(Matowicki et al., 2016)[128]	Analysis of possibility of utilizing road marking for the needs of AVs	• Malfunction of MV equipment during a field test at a road with markings having R_L of only 50 mcd/m²/lx.
(Potters Industry and Mobileye, 2016)[99]	Investigate how pavement marking affect the performance of machine vision	• Machine-vision systems can detect markings within a range of 6-18 m in front of the vehicle and retroreflectivity affects reading quality, with higher retroreflectivity resulting in increased reading levels and confidence
(Davies, 2017)[32]	Investigate the effects of pavement marking characteristics on the performance of machine vision systems	• Results of laboratory testing of MV with various road markings. • Their detection depended on (1) line width (broader lines gave better results, even at lower RL), (2) R_L(higher R_L was easier to detect), and (3) color (yellow was more difficult to recognize than white). • Poor results obtained during laboratory-induced rain.
(Carlson and Poorsartep, 2017)[96]	Enhancing the roadway physical infrastructure for advanced vehicle technologies	• Numerous deficiencies noted during a field experiment in North America. • Emphasized critical role of marking width, R_L, and contrast ratio (recognition was reduced by glare).
(Narote et al., 2018)[129]	Provides an overview of current LDW system, describing in particular pre-processing, lane models, lane detection techniques and departure warning system.	• Review of advances in pattern recognition; noted the critical role of contrast ratio for proper road marking recognition.

Study and Year(Ref.)	Aim/ Objective	Key Findings/ Summary
(Pike et al., 2019)[130]	Investigate of the effects of levels of wet retroreflectivity of pavement markings on factors that determine robust feature detection in machine vision and light detection and ranging (LiDAR) systems in continuously wet road conditions.	• Common pavement marking constructions based on exposed beaded optics that might be completely immersed by a rainstorm or puddling, incorporation of high index (n-2.4) wet retroreflective beaded optics is likely to be advantageous to both visible machine vision systems and LiDAR for detection of those retroreflective markings in both night and day.
(Burghardt et al., 2020)[131]	Horizontal road markings for human and machine vision	• Durable horizontal road markings have the potential of being one of the solutions to lower accident occurrences in poorly developed countries.
(Cafiso and Pappalardo, 2020)[132]	Safety, effectiveness and performance of lane support systems for driving assistance	• Inadequate retroreflectivity of road markings correlated with failures of the lane support system; erroneous performance was measured at about 2% of the analyzed road stretches. • The role of R_L under the test conditions (only daylight, dry) was limited.
(Marr et al., 2020)[133]	Provide a literature review	• The contrast ratio between lane markings and the surrounding substrate should be between 5-to-1 and 10-to-1 during nighttime and 3-to-1 during daytime.
(Nayak et al., 2020)[134]	To develop a reference lane detection system that will provide a benchmark for evaluating different lane markings and perception algorithms.	• A systems approach is presented by correlating the algorithm performance data to the environmental factors, lane marking types, color, material, and the retroreflectivity of pavement markings.

Study and Year(Ref.)	Aim/ Objective	Key Findings/ Summary
(Sauter et al., 2021)[135]	Investigate high-performance pavement markings on camera and lidar detection	• High-performance markings help to increase the level of detection by both camera and LiDAR sensors. • The AWE marking was detected from significantly longer distances, especially in wet and rainy conditions. • In combination with common camera based LKA and LDW systems, the LiDAR sensors can increase the overall detection rate of pavement markings.
(Calvert et al., 2021)[136]	Identify gaps in the control of automated vehicles on roads	• A recommendation is made to consider automated vehicle control from the perspective of MHC to aid a closed control system that is reasonable and humanly acceptable and achievable.
(Babic et al., 2022)[137]	Investigate the impact of road marking retroreflectivity on machine vision in dry conditions	• The minimal value of retroreflection for a minimum level 2 detection should be above 55 mcd/lx/m^2 and 88 mcd/lx/m^2 for the best detection quality (level 3).
(Burghardt et al., 2021)[138]	Investigate the visibility of various road markings for machine vision	• The highest MV intensities were measured with a structured cold plastic reflectorized with ‘premium’ glass beads (refractive index 1.6–1.7) and with white road marking tape. Orange paint under dry conditions furnished LiDAR recognition disproportionally high to its retroreflectivity.
(Nayak et al., 2022)[84]	Reference test system for machine vision used for ADAS functions	• Validate the effectiveness of lane markings’ material characteristics as well as the vision algorithms through a systematic testing of lane detection algorithms in a robust test/vehicle environment.

Study and Year[Ref.]	Aim/ Objective	Key Findings/ Summary
(Wang et al., 2022)[139]	A survey of transportation infrastructure needs in the automated vehicles industry	• The most important roadway characteristics that have the potential to benefit the automated driving system (ADS) are (1) digital mapping and signage; (2) lane markings; (3) work zone and incident information; (4) Vehicle-to-Everything (V2X) communications; (5) actual traffic signals; (6) general signage; and (7) lighting.
(Pappalardo et al., 2022)[140]	Assess the operational design of lane support system for automated vehicles in different weather and road conditions	• Wet pavement doesn't affect the LSS performance when compared to the dry condition. • Rain was critical even with very good road characteristics.
(Lu et al., 2019)[141]	Explore potential infrastructure requirements for automated driving SAE Level 4.	• Clear and harmonized road signs and lane markings are key requirements
(Germanchev et al., 2019)[142]	Assessment of readiness of Australian and New Zealand freeways and highways for active safety systems and automated driving.	• The presence of left and right lane line markings is critical for lane positioning and there are significant proportions of the road network without edge lines. • Increasing the use of edge lines and dividing lines (lane lines and center lines) will provide a clear immediate benefit for both automated driving and human drivers.
(Iparraguirre et al., 2022)[143]	Evaluate detection of road markings damage using computer vision techniques	• It is crucial to pay attention to road infrastructure, because without it, intelligent vehicles will not be able to operate reliably.

CHAPTER 2: CONDUCT STRUCTURED INTERVIEWS WITH PUBLIC AND PRIVATE AGENCIES AND STAKEHOLDERS

Introduction

The project team incorporated feedback from relevant stakeholders and finalized the structured interview and web-based survey questionnaires designed for multiple target groups, including the NJDOT, pavement marking material manufacturers, and AV industry representatives. Following the approval from the Institutional Review Board (IRB), the finalized web-based survey was deployed through the Qualtrics platform. Subsequently, the survey link was shared with NJDOT for distribution to the appropriate agency personnel.

- Web-based survey Questionnaires for agencies included questions on using various pavement marking materials and their performance, protocols/requirements/inspection testing, supply chain issues and alternative specifications, etc.
- Interview Questionnaires for agencies included using various pavement marking materials and their performance, protocols/requirements/inspection testing, supply chain issues and alternative specifications, etc.
- Interview Questionnaires for Pavement Marking Material Manufacturers included questions on the types of materials manufactured, the performance evaluation, durability, and supply chain issues faced in pavement marking manufacturing.
- Interview Questionnaires for AV industries included questions on guidance on specifications and requirements for AVs.

Reaching Out to Potential Interviewees

The research team has gathered the list of potential interviewees from various DOT and government agencies for surveys and interviewees from the NCHRP report on temporary pavement marking and the ATSSA report. The team has sent formal invitation emails to each person on the potential interviewees list. Almost one-third of the DOT personnel responded positively and were available for the interview. On the other hand, the positive response rate was low for the manufacturers and AV industries. One respondent from each manufacturer and AV industry has consented to participate in the interview. Table 15 illustrates the list of the agencies, manufacturers, and AV industries reached and the total interviewees.

Table 15 - Frequency of Invitation Emails and the Interviews Conducted

#No	Type of interview	Total invitation emails sent	Total number of interviews conducted
1	Agency Interview	25	9
2	Pavement Marking Materials Manufacturer	8	2
3	AV Industry	13	1

At the end of each interview, the respondents were requested to refer to contacts they knew who would be interested in taking the same interview with the research team. The research team has formally emailed the contacts from the reference of the interviewed personnel and managed to get the consent and interviews from the agencies and industries. Table 16 lists the conducted interviewee list for various agencies, pavement marking manufacturers, and the AV industry.

Table 16 - List of Interviewees Conducted from Agencies

#No	Type of Interview	Agency
1	DOT	Arizona DOT
2	DOT	Illinois DOT
3	DOT	Arkansas DOT
4	DOT	Iowa DOT
5	DOT	Minnesota DOT
6	DOT	Wisconsin DOT
7	DOT	Kansas DOT
8	DOT	Missouri DOT
9	DOT	New Hampshire DOT

Summary of Agency Interview

After conducting the interviews, the research team prepared a summary of the findings to learn about the existing practices for implementing hardened pavement markings in their states. The summary consists of various sections like the use of various materials, the experience of using various materials, the impact of the environment, the experience of using temporary pavement markings, pavement marking management systems, existing field evaluations, past research on the topic, and supply chain issues. A summary of each of the sections is provided as follows:

Approved Materials and Service Life

The respondents were asked about the various pavement marking materials their state approved for using and the expected service life for each of them. According to the respondents, most states have used thermoplastic, Epoxy, and paint pavement marking materials. Apart from those, some have also used tapes for pavement marking. The service life of thermoplastic materials varied from 2 to 6 years, with most states experiencing a service life of 3 to 4 years. Epoxy had a comparatively short service life, with most states experiencing a 2 years' service from the Epoxy. Paint pavement materials had the least service life, with most states experiencing one year of service from the paint materials. Tapes have a higher lifespan (5-8 years) than the other materials. However, few of the interviewed states use them for pavement marking.

Contributing Factors to the Service Life of Materials

The respondents from various agencies were asked about their perception of various factors contributing to the service life of the materials they have used in their states. Based on the responses, it is observed that most of the respondents consider AADT or traffic volume as the most important factor in the service life of materials. More traffic volume means more interaction of the markings with the tires, eventually shortening the material's service life. Roadway classification is also important for service life as the roads with a higher proportion of heavy vehicle access have more impact on the markings; hence, the service life is shortened. The surface type also plays a role in the service life of materials, as concrete surfaces tend to have more service life for pavement markings than asphalt. Finally, the region plays a big role in the service life of the materials, especially the region with heavy snowfall that necessitates continual snow plowing throughout the heavy winter months, which eventually deteriorates the durability of the pavement markings on the road.

Cost of Material

The respondents were asked about the pavement marking materials their state approved for using and how the cost varies with line width. According to the respondents, the cost per linear foot of 6-inch thermoplastic paint varied from $0.30 to $0.70 based on the pavement surface material it is placed on. For Epoxy, per linear foot of six-inch thickness marking costs around $0.50. There are two types of paint marking materials: white and yellow. Per linear foot for 6-inch white paint marking material costs $0.33, while yellow paint costs $0.26. Tapes are higher in cost than other materials. Per linear foot cost for six-inch tape is $3 to $5.

Use of Thermoplastic Materials

Seven of the nine state DOTs interviewed reported using thermoplastic materials. Most of the states use Type I, Type III, and Type IV thermoplastic materials as per the AASHTO M247 guidelines. When asked about the performance of the thermoplastic materials, the ratings varied from 4 to 8 on a scale of 1 to 10, 10 being the best. Most of the states stated reasons like imperfect workmanship (putting beads too fast or too slow affects bindings), improper cleaning of the surface, and improper bead drop rates leading to failure to achieve the minimum required retro-reflectivity, etc., for the low rating of thermoplastic. The states have experienced that bead type III works better than other types because of the cost, better performance in snowplows, and ease of upgradations.

Use of Epoxy

Epoxy materials were used by all the state DOTs interviewed. The states use the Type III and Type IV epoxy materials as per the AASHTO M247 guidelines. When asked about the performance of epoxy materials, the ratings varied from 5 to 10 on a scale of 1 to 10, 10 being the best. Most states stated reasons like good visibility for the good rating of Epoxy. The states have experienced that bead type III works better than other types.

Use of Paint Materials

Seven out of nine interviewed state DOTs use paint pavement marking materials. Most of the paints used were waterborne, while the two states also used solvent-based paints. The states use solvent-based paints and use those 2% of the time, while they use waterborne paints most of the time. Most states use Type I, Type II, and Type III paint materials per the AASHTO M247 guidelines. When asked about the performance of the paint materials, the ratings varied from 4 to 8 on a scale of 1 to 10, 10 being the best.

Most states stated issues with glass bead installations, the requirement of higher mils for using bigger beads, and low service life for the low rating of paint materials. In contrast, the positive ratings were associated with consistent retroreflectivity and cost-effectiveness. The states have experienced that blend beads work better than other types because of the higher retro-reflectivity values.

Use of Recessed Markings
Few of the interviewed state agencies use recessed pavement markings. While using the recessed pavement markings, the states usually put the groove depth the same as the pavement markings. The major advantage of using the recessed marking is an increase in lifespan, not affected by snowplow or traffic, and consistent presence and retroreflectivity, as stated by the interviewees.

Quality Control Practices
Most of the agencies interviewed have stated that they have quality control practices like measuring retroreflectivity or thickness of pavement marking materials. Almost all states interviewed have shown that they have standard guidelines to have the equipment necessary for quality control practices.

Climate and Environmental Factors
A majority of agencies interviewed have a uniform climate throughout the state, especially the states known as snow states. Hence, specific requirements for the climate or weather do not apply to those states. However, few respondents stated that they have some guidelines to have the equipment necessary for inclement weather quality control practices. Some states have very hot summer conditions, requiring special guidelines for when to put the asphalt. Most states are satisfied with the performance of marking materials in resisting fading due to UV exposure, although some states do not feel they are exposed to UV during the summer. The rating for the materials' performance in resisting color fading ranged from 7 to 9. Most agencies have stated that they follow the standard color spaces defined by the AASHTO guidelines.

Temporary Pavement Marking Standards
Seven out of the nine state DOTs interviewed stated that they had designed standard pavement marking material installation and removal guidelines. Those standards contain the type of material used in specific scenarios and site-specific procedures that need to be followed while removing a temporary marking

Frequency of Applying Temporary Marking Materials
The respondents were further asked about the frequency of using various materials with the following rankings (5= Always, 4= Almost always, 3= Sometimes, 2= Rarely, 1= Never).

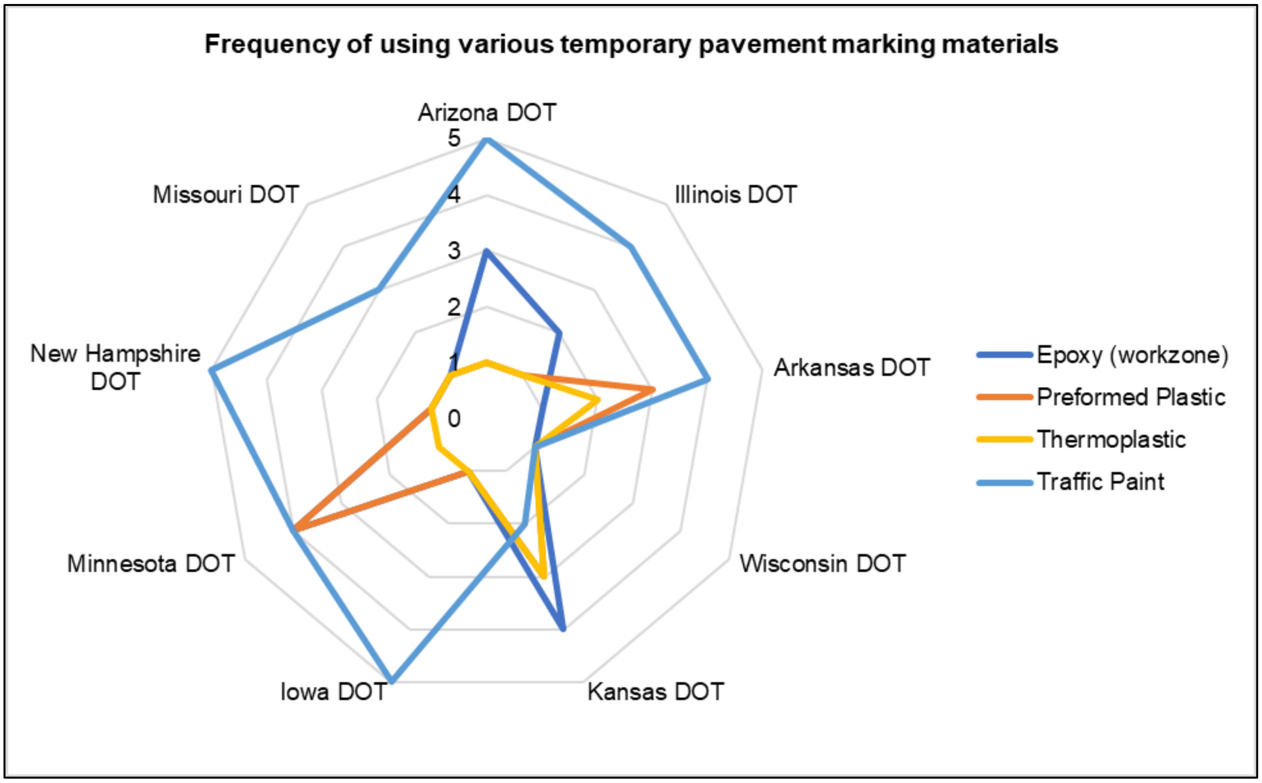


Figure 9. Frequency of using Epoxy, thermoplastic, traffic paints, and preformed plastic

According to the respondents, most DOTs prefer traffic paint over Epoxy, preformed plastic, and thermoplastic for temporary pavement marking. The radar chart clearly shows that traffic paint has a wider coverage area. Arizona DOT rates traffic paints the highest with a rating of 5, while Wisconsin DOT rates the lowest with a rating of 1. Epoxy is the second most frequently used temporary pavement marking, following traffic paint. Preformed plastic and thermoplastic are the least commonly used materials (Figure 9).

Apart from these materials, temporary tape, buttons, and tabs are also used by the state DOTs, but to a lesser extent. As seen in Figure 10, Temporary tape is the most chosen material for temporary pavement marking (among Buttons, Tabs, and temporary tape) by most DOTs. This is clear from the larger coverage area shown in the radar chart. Arizona DOT and Iowa DOT give temporary tape the highest rating of 5, while Wisconsin DOT rates it the lowest with a rating of 1. Following temporary Tape, Tabs are the second most frequently used material for temporary pavement marking. Buttons are the least utilized material for this purpose.

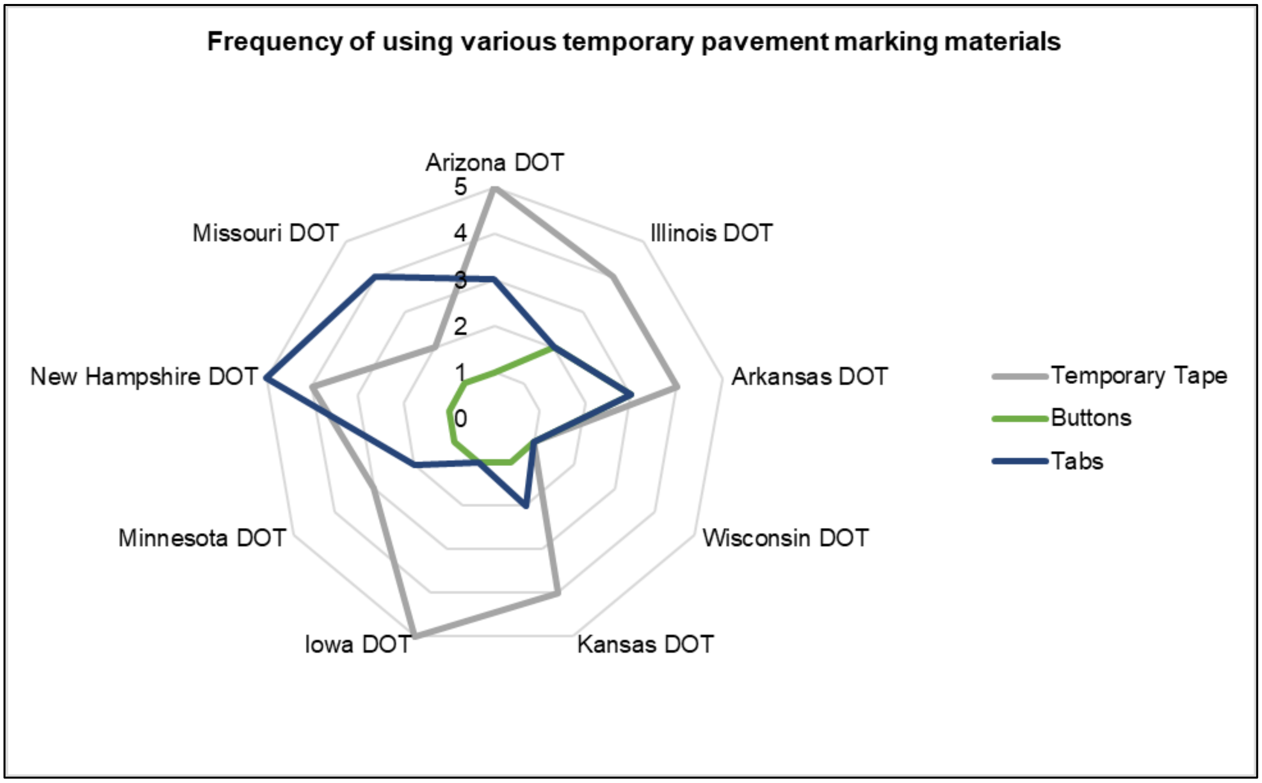


Figure 10. Frequency of using temporary tapes, buttons, and tabs

Various Types of Temporary Pavement Marking Removal Techniques

The respondents were further asked about the various removal methods applied for the temporary pavement markings. As per the responses, grinding is a commonly employed technique for removing temporary pavement markings, as the radar chart shows. Among the 9 DOT agencies, excluding Iowa and Wisconsin DOT, none of them rated it below 5. Following grinding, water blasting is the second most popular method for temporary marking removal. The least preferred methods for removing marking material are sandblasting and shot blasting, in that order.

Apart from those methods, milling, black tapes, and slurry seals are also used as temporary pavement marking removal techniques by various state DOTs. Milling is a commonly employed technique for removing temporary pavement markings compared to Black tape and Slurry Seal, as shown by the radar chart. Following Milling, Black tape is the second most popular method for temporary marking removal. The least preferred method for removing marking material is a slurry seal in that order.

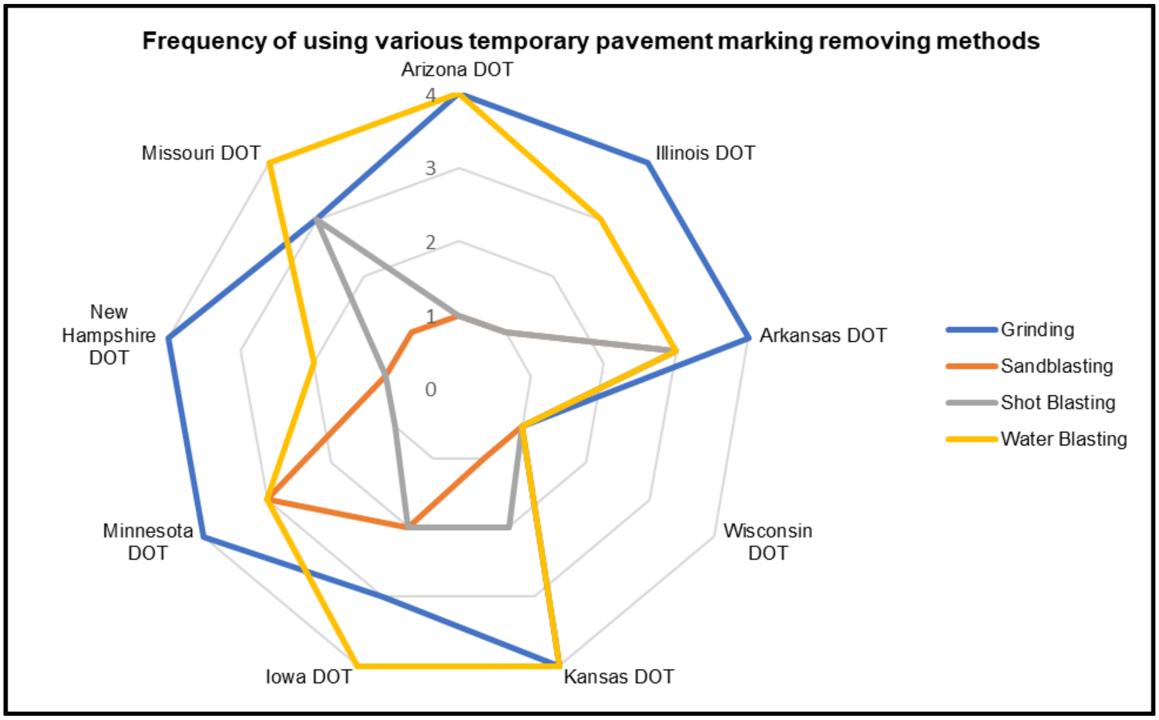


Figure 11. Frequency of using various temporary pavement marking removal methods (grinding, sandblasting, shot blasting, water blasting)

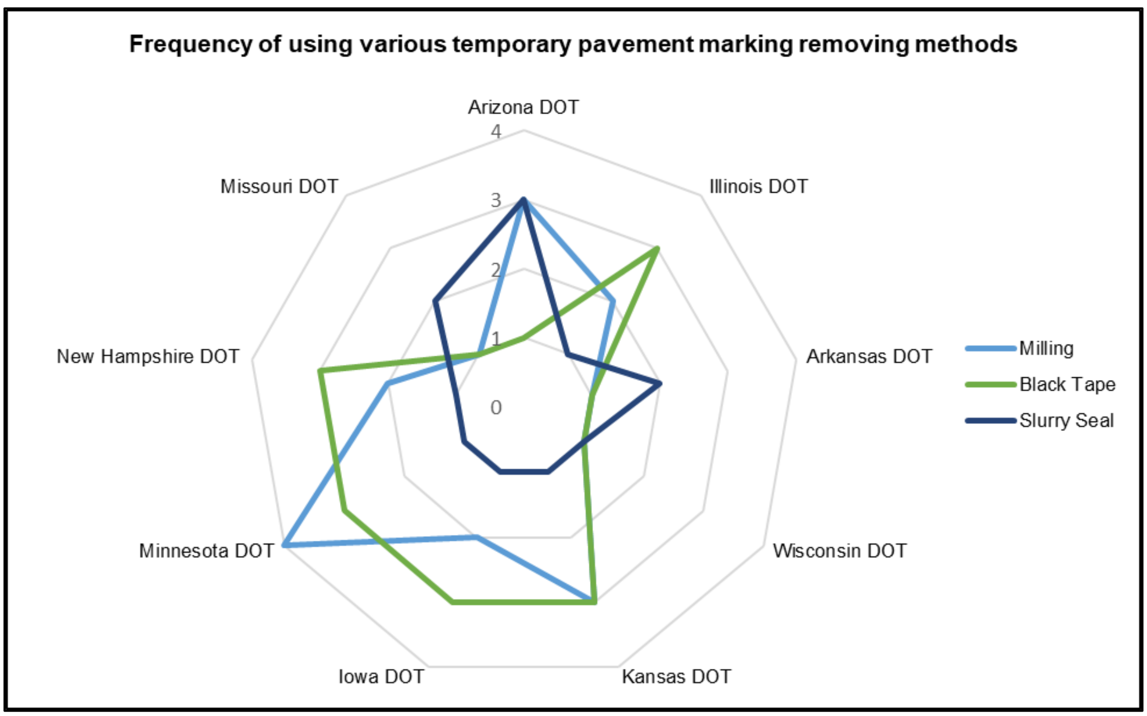


Figure 12. Frequency of using various temporary pavement marking removal methods (Milling, Black Tape, Slurry Seal)

Performance Rating of Various Temporary Pavement Marking Materials
The respondents were further asked to rate their experience with the performance of various pavement marking materials. The performance rating criteria were visibility, durability, and cost.

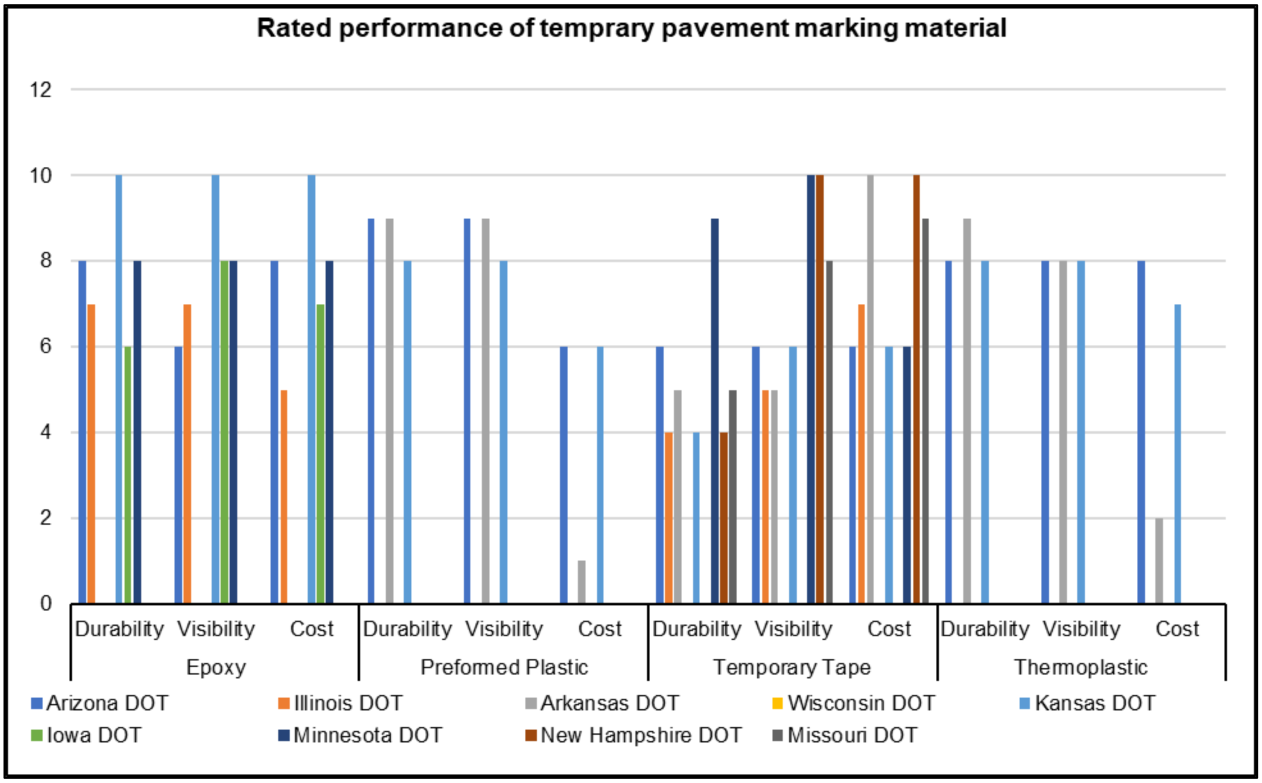


Figure 13. Rated performance of temporary pavement marking material

Figures 13 and 14 give an overview of ratings from different DOTs for various marking materials used for temporary pavement marking. In the case of “Epoxy” as a temporary pavement marking material, Arizona and Kansas DOT rated Epoxy highly for durability (8 and 10, respectively) and visibility (6 and 10, respectively), but there are differences in cost perceptions. The “Performed Plastic” section shows that it is generally seen as durable (Arizona DOT: 9, Kansas DOT: 8) and visible (Arizona DOT: 9, Arkansas DOT: 9), with varying cost ratings. “Temporary Tape” receives mixed ratings across DOTs, with variations in durability, visibility, and cost assessment. “Thermoplastic” demonstrates high durability ratings (Arizona DOT: 8, Arkansas DOT: 9, Kansas DOT: 8) and good visibility (Arizona DOT: 8, Arkansas DOT: 8, Kansas DOT: 8), but there are differences in cost perceptions. Lastly, the “Traffic Paint” section shows diverse ratings for durability (Arizona DOT: 8, Illinois DOT: 6, Arkansas DOT: 8) and visibility (Arizona DOT: 6, Illinois DOT: 6, Arkansas DOT: 8), with varying cost assessments. The “Button” and “Tabs” sections provide information on the durability, visibility, and cost of these materials, with Arkansas DOT rating buttons positively and tabs showing diverse ratings. Overall, the table provides valuable information for decision-making in selecting materials for transportation projects, taking into account their performance and cost across different states.

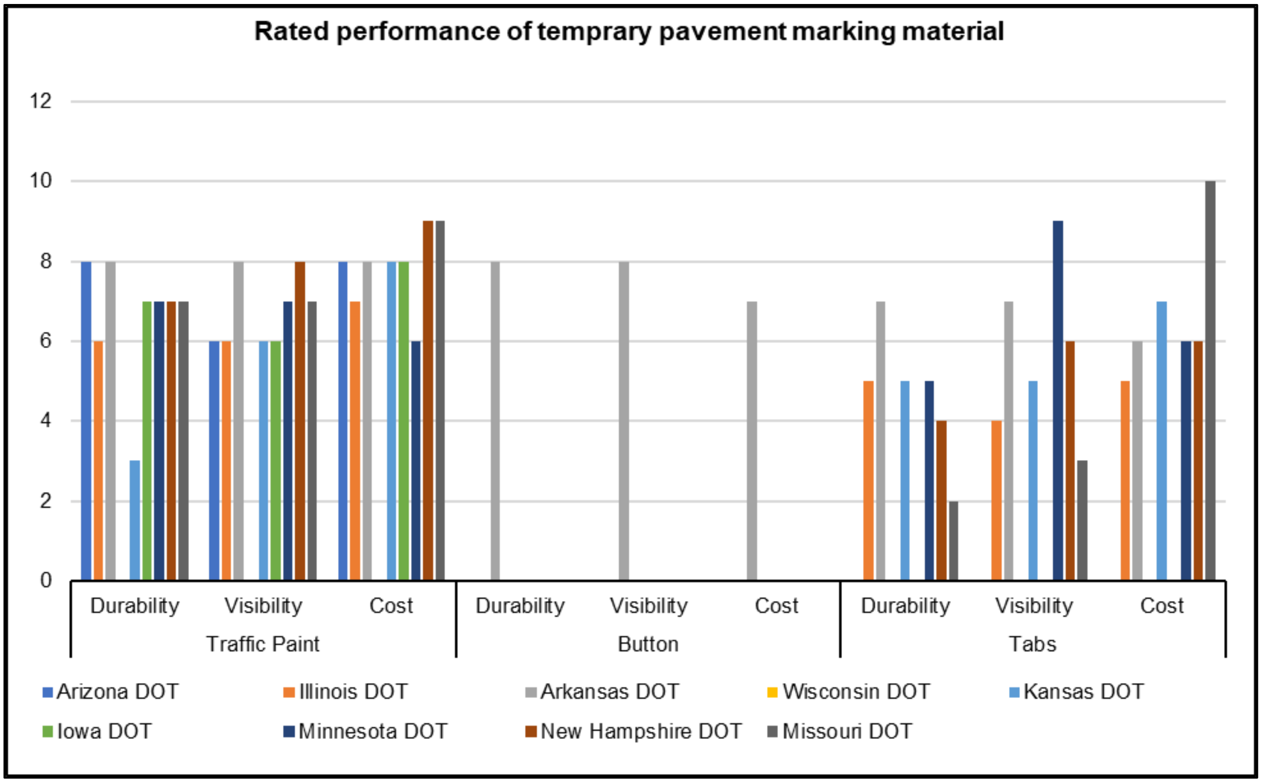


Figure 14. Rated performance of temporary pavement marking material

Performance Rating of Various Temporary Pavement Marking Removal Techniques
The respondents were asked to rate their experience on the performance of the various removal methods applied for the temporary pavement markings. For the use of these techniques, the performance ratings were taken on three surface types: asphalt (intermediate), asphalt (surface), and concrete.

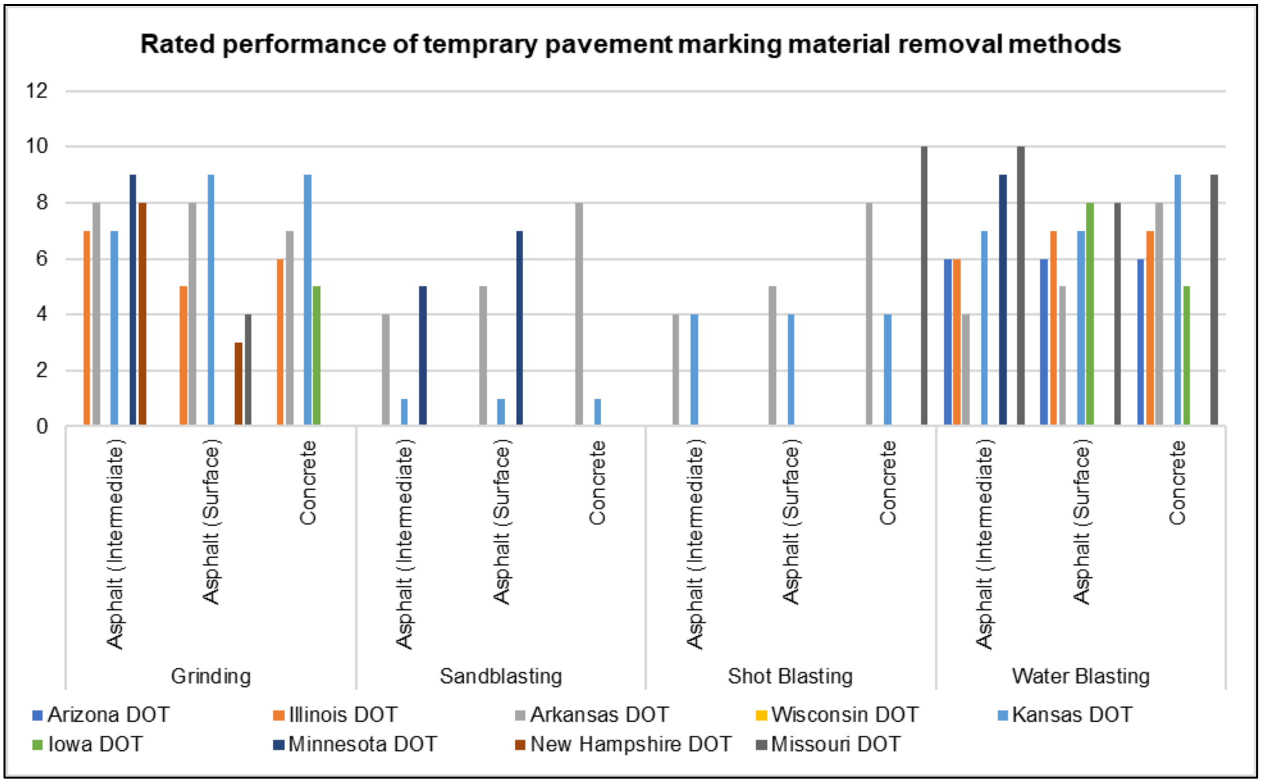


Figure 15. Rated performance of temporary pavement marking removal methods

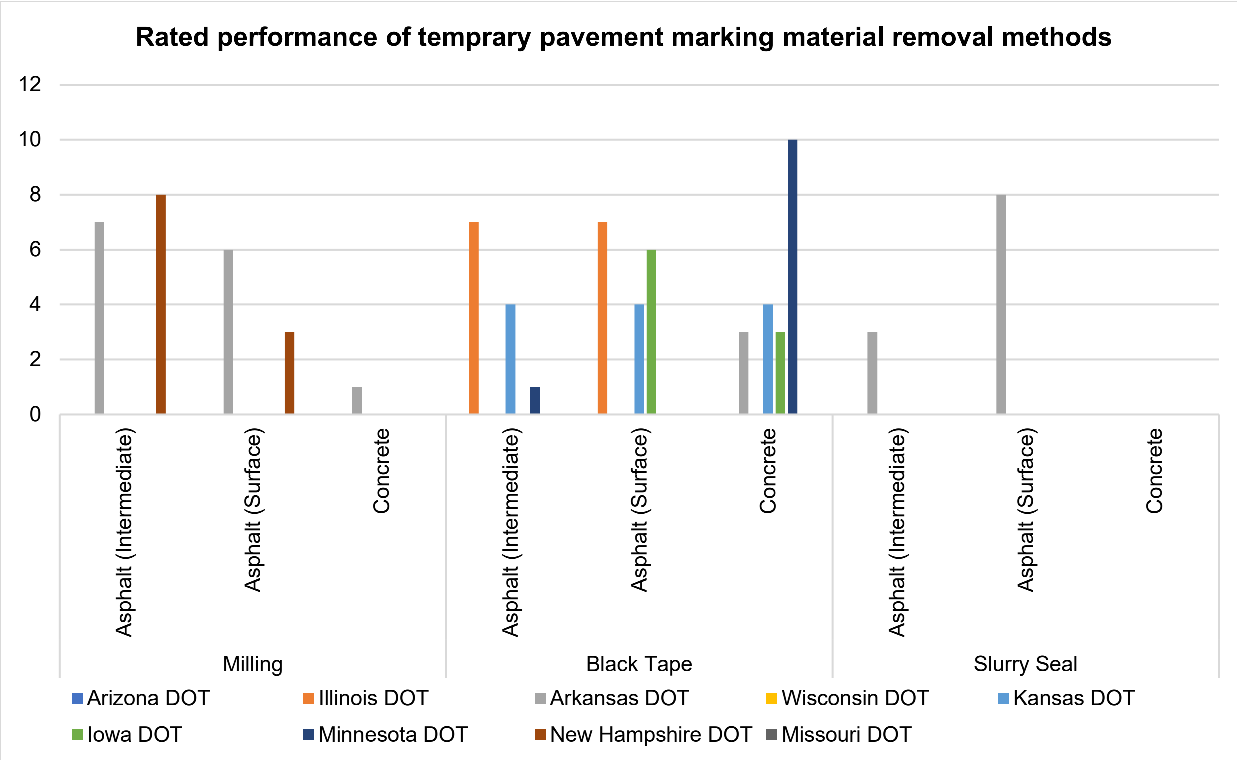


Figure 16. Rated performance of temporary pavement marking removal methods

Figures 15 and 16 display ratings from the DOTs for the removal of various pavement marking material methods on different types of pavement surfaces., Illinois DOT has rated grinding as 7, 5, and 6 for asphalt (intermediate), asphalt (surface), and concrete pavement surface, respectively. Arkansas DOT, on the other hand, rated grinding as 8, 8, and 7 for the type of pavement surface. The “sandblasting” section reveals noticeable differences, with Arkansas DOT having higher ratings in asphalt (intermediate) and concrete pavement surfaces. For the “water blasting” method, Missouri DOT stands out with consistently high ratings across all types of pavement surfaces. The “black tape” marking removal method indicates variations, with the Illinois dot having notable ratings in asphalt (intermediate) and the Minnesota dot having a prominent 10 in concrete. Lastly, the “slurry seal” removing method shows diversity, with Arkansas DOT having a high rating in asphalt (surface).

Factors Considered for the Selection of the Type of Temporary Marking

The respondents were asked to the extent to which they consider factors that contribute to selecting the type of temporary pavement markings for a given project. These factors include cost, durability, ease of placement, durability, ease of removal, material quality, experience, etc. The frequency of considering those factors was scaled from 1 to 5 (5=Always, 4=Almost always, 3=Sometimes, 2=Rarely, 1=Never).

Table 17: Frequency of Factors Considered for the Selection of the Type of Pavement Markings

Factor	Arizona DOT	Illinois DOT	Arkansas DOT	Wisconsin DOT	Kansas DOT	Iowa DOT	Minnesota DOT	New Hampshire DOT	Missouri DOT
Cost	5	5	4	4	5	5	4	5	2
Durability	5	5	3	3	5	3	5	4	5
Duration for Marking Remain in Place	5	5	3	3	5	3	5	5	4
Ease of Placement	1	4	3	3	4	4	4	3	4
Ease of Removal	1	4	3	4	4	4	3	3	4
Material Quality	1	3	4	4	4	2	4	4	4
Past Experience	1	3	1	2	4	3	5	3	5
Pavement Type	1	4	3	3	4	3	5	4	2
Retroreflectivity	5	3	3	3	4	4	4	5	4
Safety	5	5	4	4	3	5	5	3	5
Temperature at Time of Placement	1	3	4	4	4	5	5	1	3
Traffic Counts	5	2	4	3	3	3	4	3	2
Weather Effects	1	3	3	5	2	5	3	1	2
Wet Retroreflectivity	1	3	3	2	2	3	5	1	1
Connected and Autonomous Vehicles	1	2	3	1	2	1	3	1	1

Table 17 provides a detailed overview of DOTs ratings for different factors affecting the choice of temporary pavement marking material in multiple states. Cost, durability, and how long the marking stays in place are considered the most important factors, receiving a rating of 5 from states like Arizona and Illinois. Interestingly, factors like ease of placement, ease of removal, material quality, experience, pavement type, temperature, weather effects, wet retroreflectivity, and considerations for connected and AVs all receive a low rating of 1 from Arizona DOT, which strongly focuses on these factors. On the other hand, Illinois DOT shows a more varied response, with ratings ranging from 2 to 4 for some factors. Retroreflectivity and safety are common priorities across states, consistently receiving a high rating of 5. It is worth noting that Arizona DOT gives a top rating of 5 to traffic counts, highlighting its significant importance in their decision-making process. This comprehensive analysis demonstrates the diverse considerations made by different DOTs when evaluating factors for selecting temporary pavement marking materials.

Pavement Marking Management

Five of the nine state DOTs interviewed stated they maintain a pavement marking management program. There are specific criteria for the states to determine the end of service life of various materials. For example, some states consider minimum retro reflectance as the end of service life for materials. Some states maintain a threshold for the minimum retro reflectance, like 100 mcd for white and 150 for yellow markings. Some states just consider relatively low retroreflectivity as the end of the service life of materials. However, most states consider the presence test to be the criterion for determining the service life of materials. Materials with mid or low presence are considered reaching the end of their service life in some states, while some states only consider low presence to be the end of service life. Some other states only consider the presence test for specific materials like thermoplastic, while they have a threshold of 1-2 years for waterborne materials. The presence test is not always based on the percentage remaining; few states do that based on visual inspection.

Performance-based Specifications for Pavement Markings
Out of the nine, six DOTs interviewed have stated that they maintain a performance-based pavement marking specification. Most of those are the 180-day retroreflectance test, and they do it with the handheld retro reflectometer. When asked about the data collection on pavement marking performance, only two states interviewed had experience of collecting that data.

Warranty Period
The agencies interviewed were asked about their specific warranty period for the various materials used in pavement marking. Few of the states have specific warranty periods for some materials. Like, tape materials have a warranty of 5-6 years. As mentioned by Kansas DOT, under ideal installation practices, the DOT expects to have the following warranty period for the materials: Epoxy (3-4 years), Multi-component: 4+ year, Thermoplastic: 3+ year, Preformed Thermoplastic: 3+ year, MMA: 4+ year, Pattern Cold Plastic: 4+ year.

Pavement Marking Guide
Seven out of nine DOTs have the pavement marking guide, but two of them stated that their guide is outdated. DOTs typically consider material cost and AADT when selecting marking material, and some also consider durability and safety. However, none of the DOTs mentioned included considerations for climatic conditions in their marking guide.

Performance Evaluation
The respondents were asked about the performance evaluation practices of the pavement markings across their state roadways. Six out of the nine states conduct the dry performance retro-reflectivity, while only one state does the wet retro-reflectivity evaluation. The states performing dry retro-reflectivity tests have stated that they do the test during the night. Only one of the states does the luminous contrast ratio test. As far as the bed retention test is concerned, four of the states perform it. However, one of the states does the retention test based on visual inspection, while another two states do the bead retention by pocket microscope test. The durability test is performed by four of the nine states, with one state doing it through the percentage remaining during the winter season. Finally, only two of the states perform the color test. As additional information, one of the states informed us that they do the epoxy yellow line performance test. While most states do retro-reflectivity tests themselves, one of them mentioned that their 3rd party contractor conducts retro readings each spring.

Retro-reflectivity Measurement

The respondents were asked about the frequency of retro-reflectivity measurement. Immediately after placing the new markings, all the states have retro-reflectivity measurements. The measurement time varies from 4-7 days for one state, while other states do so within 15-45 days after all the markings are placed on a particular batch or schedule. Two of the states also do the long-term retro-reflectivity test. One state only measures retroreflectivity on newly applied pavement marking during the first 30 days of application followed by 60 and 90 days. While one state has a periodic annual retro-reflectivity test, while every year, another state (KDOT) has a 3rd party contractor collect after the winter retros on the entire state highway system and provides the state a dashboard to view and access the reflectivity across the state to plan in-house striping as well as using FHWA HSIP (Highway Safety Improvement Program) funds solely for pavement markings. The states using retro-reflectivity use the handheld retroreflectometer, and most of the states hold one to four handheld retroreflectometers. The retroreflectometer models are LTL 2000, Delta TLT- X, Zehntner ZRM 6010 R_L, and StripeMaster 2 Touch.

Past Research on Pavement Markings and Observed Safety Benefits

When asked about conducting research on pavement marking materials, four out of nine states said they did some research on them over the past five years. The pavement marking research focused on contrast marking, human factors, and the utilization of AV in pavement markings. Although studies were done from various perspectives, none of the interviewed state agencies have documented any safety benefits (decrease in crash frequency or crash severity) because of the pavement marking materials' better quality, durability, or retro-reflectivity.

Significant Challenges or Issues Faced

The respondents were asked to share the most significant problem or challenge they faced in implementing hardened pavement markings. Different factors were mentioned in the interviews in response to this question. The durability of the markings was the most important challenge for all the states. Some states have mentioned that completing the work within the allocated budget was the most challenging part of the pavement marking. The other notable challenges include recessed pavement marking, deterioration on the edge of grooving, adapting materials at low temperatures, marking inside the rumble strips, long life of markings, finding the best application, finding the best striping material type for each surface type, and supply chain issues.

Response to Post-COVID Supply Chain Issues

The respondents were asked to share their experiences with the supply chain issues due to COVID. The respondents had mixed opinions about the supply chain issues. One of the states had not faced any supply chain issues during the COVID pandemic since they had an internal in-house manufacturer. However, the rest of the states had experienced some difficulty coping with supply chain issues. While some states have faced the issue during COVID or early post-COVID, other states are still facing it. The majority of the states stated that the production of beads was affected due to COVID. A few states have also faced the issue of waterborne paints. Two of the states faced raw material shortages issue. To cope up with the beads issue, some states have used alternative beads or high-build waterborne as a solution, some states have only painted edge lines to utilize existing materials. The states have faced supply chain issues and come up with alternative materials or cost-effective material implementation to solve the issue.

Response to New MUTCD Guidelines

The respondents were asked to share their experiences with the new MUTCD Guidelines to update the marking widths of six inches. The respondents had mixed opinions about the new guidelines by MUTCD. Two states already had six inches running before the MUTCD guidelines came into effect; hence, they had no experience with this. However, the rest of the states experienced some difficulty in coping with the changes. Most of the states faced financial challenges (increased cost, budget adjustment, etc.) to meet this guideline, while some states had additional challenges like local issues and additional paperwork to be done to implement the 6" marking widths. Hence, the new guidelines have put some extra financial and challenge on the states who had to shift from thinner widths to 6".

Summary of Manufacturer Interview

A summary of the findings from the interview with the manufacturers is needed to learn about the existing practices of the manufacturers on the production of hardened pavement markings in their states. The summary consists of various sections like the list of various materials, the standards for yellow and white markings, field tests, factors contributing to improved pavement marking material, recent changes in the cost of materials, supply chain issues, recommendations for improved durability and visibility, and recommendations for better quality of the products. A summary of each of the sections is provided as follows:

List of Materials

The interviewee from manufacturers implied that they use four variations of epoxy pavement marking and two different types of polyurea marking. The improved materials now have a quicker setting time of 4-5 minutes. Regarding NJ, LS50 or LS90 are the big contractors in Northern Jersey, and Southern Jersey supplies those materials. It is noteworthy that some companies do not manufacture any thermoplastic. On the other hand, other manufacturers produce all types of horizontal pavement markings like water and solvent-based traffic paint, preformed thermoplastic, and Polyurea. In terms of thermoplastic, they produce hydrocarbon (Alkene) thermoplastic, thermodrop thermoplastic. They also produce LER, resin epoxy, and slow and fast-drying epoxy.

Standards for Yellow and White Pavement Markings

As a certified ISO9001 company, some manufacturers must pass four internal and two external audits, highlighting its commitment to excellence. Their in-house labs manufacture all resins, demonstrating a hands-on approach to quality. Rigorous testing includes seven assessments for each lot, covering compressive tests, FTI analysis, and even fingerprint examinations. They mentioned that they maintain a wide range of specifications likewise Federal, State, AASHTO, NETPEP, and FAA specifications while they produce yellow and white pavement marking paints.

Field Tests
Regarding field tests, manufacturers do not have a regular schedule for testing the retroreflectivity or durability test. However, if the agency reports any problem, they check the retro-reflectivity using the handheld retro reflectometer. Some of them, usually do their field test in the internal lab, test deck, with state partnership, or using NETPEP. They mostly do their color measurement during the daytime they also test the opacity and retroreflectivity.

Factors Contributing to Improved Pavement Marking Material
The manufacturers were asked about the factors that would need to be ensured for better performance of pavement marking materials. The major ways to do so were i) to install the marking thicker, ii) to use a more durable quality, and finally, iii) to use a higher quality marking- the orders of mentioning representing the order of the importance of the factors.

Recent Change in Cost of Materials and Supply Chain Issues
The manufacturers were asked about the recent supply chain issues after COVID. While one of the interviewees mentioned, the company did not face any major difficulties with supply chain issues, as they had a strong team to manage those issues of production and raw material management. While according to another interviewee, their company faced power loss issues in the post-COVID period. The interviewee mentioned that the workforce was absent from the workspace even though those who were present were reluctant to work in the group. However, the industry has faced a surge in the price of raw materials and the overall production cost after the pandemic. As stated by both interviewees, the cost has increased by a minimum of 25% to a maximum of 50% for various pavement marking materials.

Recommendations for Optics or Installation Practices
The manufacturers were asked about the recommendations for the optics or installation practices to enhance the visibility of pavement markings. As per one of the manufacturers, B package or Actual glass optics are important as they change color. AASTHO Type IV from M247 with a Type I double drop is best to enhance the visibility of the markings. While others mentioned about larger beds like Type III can improve the visibility if a better ratio (50% to 60%), adequate binder, and standard installation practice can be maintained.

Recommendations for Improved Drying Time of Marking
The manufacturers were asked about the recommendations for improved drying time. According to the manufacturers, the drying time is fast in summer, while in fall and spring, it is slow and might need road closure. The problem with going too fast is the lack of time to get a good binding with the road surface.

Recommendations for Improved Durability
The manufacturers were asked about the recommendations for the improved durability of pavement markings. According to the manufacturer, the only way to improve durability is by improving the retro-reflectivity of the markings, which the industry is extensively working on while taking the interview.

Recommendations for Better Product

The manufacturers were asked about the recommendations for better products in pavement markings. The major point of improvement was the durability of the epoxy materials, as per the interviewee.

Summary of AV Industry Interview

A summary of the findings from the interview with the manufacturer is needed to learn about the existing practices of the manufacturers on the production of hardened pavement markings in their states. The summary consists of various sections like the reliance of AV on pavement marking, pavement marking improvements to improve AV, maintaining safety during AV transition, improvement of pavement marking during AV malfunction, and normal operation of AV. A summary of each of the sections is provided as follows:

Reliance of AV on Pavement Marking

The AV industry interviewee was asked about the perception of the reliance of AV on pavement marking in the present and the future. According to the interviewee, the existing AV technology heavily depends on pavement marking for Level 1 assistants like Lane Keep Assist and Lane Departure Warning. Apart from pavement markings, the built-in maps made using satellites or probe vehicles can work as a supporting means to assist the AV technology. However, soon, the reliance on pavement marking is unlikely to change, as the interviewee mentioned.

Improvements to Pavement Markings Helping AV Development and Reliability

The AV industry interviewee was asked about the improvements to pavement markings that can help AV development and reliability. According to the interviewee, the existing AV technology can benefit from improving pavement markings on multiple factors, including high contrast, broader –oreo, black border, tiger tail –black line white line, reduced escape way range, and higher retroreflectivity—at night.

Role of Pavement Marking in Maintaining and Improving Safety During the Period of AV Transition

The AV industry interviewee was asked about the role that pavement marking could play in maintaining and improving safety during the transition period of AV introduction. According to the interviewee, the existing AV technology can benefit from pavement markings improvement; more research needs to be done. As per the interviewee, the FHWA and USDOT do not have enough research until the point of the interview. So, more research should be done to find out that. However, the actual safety benefits of maintaining good quality pavement markings would especially help AVs in scenarios like off-ramp, on-ramp, and turning vehicle maneuvers.

Role of Pavement Marking during AV Malfunction and Normal Operation

The AV industry interviewee was asked how pavement marking can handle AV malfunctions and mishaps as well as the normal operations of AVs. According to the interviewee, improvements like higher quality and durability of pavement markings could help AV to avoid any mishaps during malfunctions. If high-definition maps have issues, then the high-quality pavement marking will help; hence, more weight should be given to vision rather than maps for the better functioning of AV during normal operations and critical situations.

Role of Pavement Markings in Limiting AV Impacts on Traffic Flow

The AV industry interviewee was asked about the role pavement marking could play in limiting potential AV impacts on traffic flow, average speeds, etc. According to the interviewee, Marking does not play any role in impacting traffic flow. If your marking is good, both the human eye and the machine can recognize it, which is good for safety. AV's interaction with pavement marking is all about lateral control, not with traffic flow and speed (which is more vertical).

Improvements Needed for Various Factors for a Better AV System

The AV industry interviewee was asked about the improvements needed for several factors to improve the performance of the AV system. According to the interviewee, marking width is not important in perfect weather conditions. However, in bad lighting and inclement weather, it is the most important as it assures the visibility of marking in all conditions to both humans and the machine. Patterns between lanes are also crucial as they improve longitudinal movement and visibility of human eyes and AV. Brightness at night improves the quality of visibility by helping detect the edge of the marking, especially if snow plows. Visibility in wet night conditions could be improved by ensuring better retroreflectivity, which could be evaluated using a wet retroreflectivity test. Contrast during the day is also important, as the sun's glare and reflection could impair visibility. Because of this reason, high contrast works better at night than in the day. Another important factor is the choice of materials, which depends on the environmental conditions. For instance, thermoplastics are better than paint when it comes to the performance of AV.

Requirements of Pavement Marking Components for Various Levels of AV

The AV industry interviewee was asked about the role or importance of the various components of pavement markings for various levels of AV, i.e., Level 2, Level 2+, and Level 4. According to the interviewee, all the features like marking width, pattern between the lines, brightness at night, visibility at night, and contrast during the day are highly important for Level 2 AV. The reason behind that is the high dependence of Level 2 AV on the pavement marking because that is all that it has gotten. Moving into Level 2+, the importance of pavement marking components like marking width, patterns between lines, brightness, and contrast play a moderate role. However, in Level 4, AV is expected to rely less on pavement markings. The only factor would be the width of the marking, which would have little importance. However, for an advanced system like Level 4 AV, the pattern between lines, contrast, and wet night visibility must not be perfect. This implies that pavement marking would play a vital role in the transition from Level 2 to Level 4.

Table 18 - Requirement of Pavement Marking Components for Various Levels of AV

Feature	Level 2	Level 2+	Level 4
marking width	High	Moderate	Least
pattern between lanes	High	Moderate	No Need
brightness at night	High	Moderate	No Need
visibility in wet night conditions	High	Moderate	No Need
contrast during the day	High	Moderate	No Need

Handling Marking Obscured by Snow

The AV industry interviewee was asked how their system handles markings obscured by snow. According to the interviewee, the snow is handled very poorly and could impact the lateral control system. As a supporting role, those inclement weather scenarios could only be tackled with a high-definition map and accurate positioning of the vehicles.

Improvements to Pavement Markings in Helping LiDAR Technology

The AV industry interviewee was asked about the improvements that could be made to the markings to make them more compatible with LiDAR. According to the interviewee, the intensity value given LiDAR, 1550 devices is not enough range, do not think it is a practical solution.

Role of Transportation Agencies for Better AV Experience

The AV industry interviewee was asked about what transportation agencies should be doing now to their pavement markings to assist AV development. According to the interviewee, the transportation agencies and DOTs could do the following to improve their pavement markings for a better AV experience: i) examine this subject closely ii) prioritize marking, iii) play a prominent role in the AV system.

CHAPTER 3: CREATE INVENTORY OF REQUIRED DATA SUCH AS PAVEMENT AND MARKINGS

Introduction

To achieve the goals of this task, the project team prepared a list of data inventory, listed down important information available, and prepared a list of information/data needed with the help of DOT, including performance measures, protocols, etc. Some examples of the inventory are as follows:

Inventory of Pavement Marking Paints and Strips

To get information on pavement marking materials, inventory on material characteristics, installation, construction cost, material manufacturer, image and videos, methods, and pavement marking index need to be performed. Table 19 archives the list of the information needed and the sources of that information.

Table 19 - Pavement Marking Materials and Their Sources

#	Performance Measure	Source
1	Color	-
2	Drying time	-
3	Durability	-
4	Retroreflectivity	-
5	Marking Age/Installation date	-
6	Marking line type	-
7	Material type	-
8	Installation (Location, Crew, Date, Method)	-
9	Material/Bid Cost	-
10	Manufacturers	-
11	Surface Image/Video	SLD Data Browser

Inventory of Pavement Surfaces

To get information on pavement surfaces, inventory on both the pavement surface type and geometric highway characteristics needs to be performed. Table 20 archives the list of the information needed and the sources of that information.

Table 20 - Inventory of Pavement Surface

#	Performance Measure	Source
1	Surface Type	-
2	Climatic Region	-
3	Pavement Width	-
4	Raised Pavement Marker	-
5	Skid Resistance	-
6	Surface Distress	-
7	Last Overlay Thickness	-
8	Year of Last Construction	-
9	Year of Last Improvement	-

Inventory of Roadway Data

Inventory on geometric highway characteristics data like curve classification, lane width, etc., are gathered from sources like the SLD browser of NJDOT and NJDOT Shapefiles.[81] Table 21 archives the list of the information needed and the sources of that information.

Table 21 - Roadway Inventory Data and Sources

#	Performance Measure	Source
1	Curve Classification	-
2	Grade Classification	-
3	Lane Width	SLD Data Browser
4	Large Truck Access	SLD Data Browser
5	Rumble Strip	SLD Data Browser
6	Functional Classification	SLD Data Browser
7	AADT	NJDOT Shape File
8	Peak Hourly Volume	NJDOT Shape File
9	Vehicle Regulatory Speed Limit	SLD Data Browser

List of NJDOT Contractors

The research team has prepared an initial list of contractors and vendors to reach out to get information on the existing materials used and the manufacturers providing the paints in the existing pavement marking project throughout the state. The list in Table 22 contains vendors/contractors for standard pavement markings, while Table 23 contains the list of the long-life pavement marking vendors/contractors in New Jersey. This list was obtained from NJDOT's website [145]

Table 22 - NJDOT Approved Vendors/Contractors for Standard Pavement Paint Markings

#	Contractor Specialty (Class Code)	Contractor Name
1	Standard Pavement Markings (17)	Benchmark Site Development, LLC.
2		Denville Line Painting, INC.
3		Iannella General Contracting, INC.
4		Zone Striping, INC.
5		Traffic Lines, INC.
6		Straight Edge Striping, LLC.
7		Penhall Company
8		L & L Property Enterprises, LLC.
9		James J. Anderson Construction Co., INC.
10		Benchmark Site Development, LLC.
11		Denville Line Painting, INC.

Table 23 - NJDOT Approved Vendors/Contractors for Long-Term Pavement Paint Markings

#	Contractor Specialty (Class Code)	Source
1	Long Life Pavement Markings (18)	Denville Line Painting, INC.
2		Iannella General Contracting, INC.
3		L & L Property Enterprises, LLC.
4		Traffic Lines, INC.
5		Straight Edge Striping, LLC.
6		Penhall Company
7		Zone Striping, INC.
8		Denville Line Painting, INC.
9		Iannella General Contracting, INC.
10		L & L Property Enterprises, LLC.
11		Traffic Lines, INC.

Table 24 contains the information on the existing routes provided by the pavement marking consultant, Traffic Lines. The list contains the name of the route, the start and end Mile Post, the county, municipality, PE no, CE no, DP no, funding info, and the work type. The study team further expanded the inventory with the length of the section, the intersections present in the section, and the number of lanes in the section. etc. Google Street and Google Maps were explored to ascertain the information on those route sections.

Table 24 - Potential Field Locations from Sub-Contractors

Main Contractor	**Schifano Construction**	**Earle Asphalt**	**Earle Asphalt**
Our Contact	Traffic Lines	Traffic Lines	Traffic Lines
Construction date	last 6 months (9/28/2023)	last 6 months (9/28/2023)	last 6 months (9/28/2023)
Route Segment	NJ 33 in Monmouth County and Various Locations	Route 72, Old South Broadway to Marsha Drive	Route 37, Thomas Street to Fischer Boulevard
City/Township	Multiple	Stafford Township	Toms River Township
County	Mercer, Monmouth, and Ocean	Ocean	Ocean
Work Type	Maintenance Roadway	Pavement Preservation	Resurfacing
Funding Info	100% State Funded	Federal Project No. NHP-0072(311)	100% State Funded
PE No.	2622600	2207030	1507510
UPC No.	N/A	223350	N/A

Main Contractor	Schifano Construction	Earle Asphalt	Earle Asphalt
CE No.	2622863	1519508	1507512
DP No.	23406	22144	21124
Start MP	30.04	23	6.8
End MP	42.03	26	10.9
No Lane	2, 4	2	3
Length	11.99	2.6	4.1
Intersections	Yes	Yes	Yes

Similar to Table 24, Tables 25, 26, and 27 provide information on similar parameters. However, the research team has gathered data by extensively exploring the bid website for the existing contractors with pavement marking projects. Based on the data available, there were still important parameters that needed to be known, like the contractor for the pavement marking in the project, as well as the date of construction of the project.

Table 25 - Potential Field Locations from DOT Bid Website

Main Contractor	Arawak Paving Co., Inc.	Berto Construction, Inc.	Green Construction, Inc
Pavement Marking Contractor	Data Required	Data Required	Data Required
Construction Date	Data Required	Data Required	Data Required
Route Segment	NJ 7, Mill Street (CR 672) to Park Avenue (646)	NJ 53, Pondview Road to Hall Avenue	NJ 46, Route 80 to Walnut Road
City/Township	Belleville and Nutley Township	Townships of Parsippany-Troy Hills and Denville	Township of Knowlton
County	Essex County	Morris County	Warren County
Work Type	Pavement Resurfacing and Reconstruction	Pavement Restoration	Pavement Reconstruction
Funding Info	Federal Project No: 0007-334	Federal Project No: NHP-0053(302)	Federal Project No: 0046(999)
PE No.	706500	1411504	2107519
UPC No.	158100	124240	148100
CE No.	706502	1411507	2107522
DP No.	23122	23112	23113
Start MP	6.48	1.9	0.1

Main Contractor	Arawak Paving Co., Inc.	Berto Construction, Inc.	Green Construction, Inc
End MP	8.68	4.5	1.2
No Lane	2,4	2	2
Length	2.2	2.6	1.1
Intersections	Yes	Yes	No

Table 26 - Potential Field Locations from DOT Bid Website

Main Contractor	Arawak Paving Co., Inc.	Della Pello Paving, Inc.	Della Pello Paving, Inc
Pavement Marking Contractor	Data Required	Data Required	Data Required
Construction Date	Data Required	Data Required	Data Required
Route Segment	Route 9, Wrights Lane to Harbor Road	Route 130, Westfield Avenue to Main Street	Route 23 Alexander Road to Maple Lake Road
City/Township	Upper Township	East Windsor Township, Borough of Hightstown	Township of Pequannock, Boroughs of Riverdale, Kinnelon, and Butler
County	Cape May County	Mercer County	Morris County
Work Type	Resurfacing	Reconstruction and Resurfacing	Resurfacing
Funding Info	Federal Project No: NHP-0009(335)	Federal Project No. 0130(332)	Federal Project No: NHP-0023(329)
PE No.	504509	1123505	N/A
UPC No.	154000	113090	114240
CE No.	504513	1123510	N/A
DP No.	23108	23114	22153
Start MP	19.5	68	0.9
End MP	27.4	70.4	17.8
No Lane	1,2	2	1,2,3,4
Length	7.9	2.4	16.9
Intersections	Yes	Yes	Yes

Table 27 - Potential Field Locations from DOT Bid Website

Main Contractor	Asphalt Paving Systems, Inc.	Della Pello Paving, Inc.	Asphalt Paving Systems, Inc.
Pavement Marking Contractor	Data Required	Data Required	Data Required
Construction Date	Data Required	Data Required	Data Required
Route Segment	US 22 Eastbound, Dickens Lane to Fairway Drive	I 80 Westbound, South Beverwyck Road (CR 637) to Riverview Drive (CR 640)	US 322, Boro Commons Drive to CR 536 (Main Street)/CR 654
City/Township	Union Township, Springfield Township, Borough of Kenilworth, and Borough of Mountainside	Parsippany-Troy Hills Township, Montville Township, Fairfield Township, Totowa Borough, Wayne Township	Hamilton Township & City of Absecon
County	Union	Morris, Essex, Passaic	Atlantic
Work Type	Pavement Preservation	Pavement Preservation	Pavement Preservation
Funding Info	Federal Project No: NHP-0022(354)	Federal Project No: NHP-0080(336)	Federal Project No: NHP-0322(330)
PE No.	2207030	2207030	2202262
UPC No.	223430	223690,	213030
CE No.	2003563	1414524	826513
DP No.	23107	23110	22138
Start MP	52.18	45.6	18.25
End MP	54.72	56.29	24.09
No Lane	3	3	2
Length	2.54	10.69	5.84
Intersections	Yes	No	Yes

Roadway Data

Roadway data, including geometric roadway features and other traffic volume data, has been gathered from sources like the SLD browser of NJDOT and NJDOT Shapefiles. Table 28 through Table 31 list the roadway data achieved for the aforementioned road segments with ongoing pavement marking works from NJDOT projects.

Table 28 - Inventory of Roadway Data for Field Locations from Pavement Marking Contractors

#	Performance Measure	NJ 33	NJ 72	NJ 37
1	Lane Width	48	26	36
2	Large Truck Access	Access	Access	Access
3	Presence of Rumble Strip (Rows)	Yes (2)	No	No
4	Functional Classification	Principal Arterial	Principal Arterial	Principal Arterial
5	AADT	27,355	30,791	31,348
6	Vehicle Regulatory Speed Limit	55	55	50

Table 29 - Inventory of Roadway Data for Field Locations from NJDOT Bid Website

#	Performance Measure	NJ 7	NJ 53	NJ 46
1	Lane Width	60	40	24
2	Large Truck Access	Access	Prohibited	Access
3	Presence of Rumble Strip (Rows)	No	No	No
4	Functional Classification	Principal Arterial	Principal Arterial	Principal Arterial
5	AADT	10,342	18,561	7,975
6	Vehicle Regulatory Speed Limit	35	40	50

Table 30 - Inventory of Roadway Data for Field Locations from NJDOT Bid Website

#	Performance Measure	US 9	US 130	NJ 23
1	Lane Width	36	24	60
2	Large Truck Access	Access	Access	Access
3	Presence of Rumble Strip (Rows)	No	No	No

#	Performance Measure	US 9	US 130	NJ 23
4	Functional Classification	Principal Arterial	Principal Arterial	Principal Arterial
5	AADT	11,493	31,352	71,798
6	Vehicle Regulatory Speed Limit	50	50	55

Table 31 - Inventory of Roadway Data for Field Locations from NJDOT Bid Website

#	Performance Measure	US 22	I 80	US 322
1	Lane Width	36	48	60
2	Large Truck Access	Access	Network	Access
3	Presence of Rumble Strip (Rows)	No	Yes (2)	No
4	Functional Classification	Principal Arterial	Interstate	Principal Arterial
5	AADT	75,444	184,226	11,519
6	Vehicle Regulatory Speed Limit	45	65	45

CHAPTER 4: FIELD DATA COLLECTION

Introduction

The research team completed the final set of data collection in NJ. Data were collected in December 2023, September 2024, and April 2025. All data collected were downloaded, cleaned, and organized for analysis. Notes on each data collection trip for each roadway evaluated were summarized to provide additional information on each test section. The data collection team noted things they observed and took on-road images of many of the test areas where it was safe.

The data collected for this study utilized previously installed and planned installations of markings across the NJDOT system. Two test areas on NJTPA roadways were also included. Inspections and evaluations of existing and planned-to-be-striped markings were conducted. The research team gathered information on a wide variety of marking ages across a range of conditions (location within New Jersey, pavement surface, traffic volume, line type, etc.). Evaluations included new markings that NJDOT applied before the project began and did not restripe during the project and markings applied in previous years that were restriped during the project. Specific sites were selected based on available marking data information: marking type (materials, color, line type, etc.), installation date, roadway characteristics, and geographic location. The research team attempted to collect data at enough sites to cover all factors of interest. Each test area was at least a mile long and included most markings on the test area's roads. Some markings were not evaluated if they were short or had many breaks due to access points.

Site Identification

Initially the research team identified a series of NJDOT pavement marking contracts for 2023. Upon discussion with the contractors some of these contracts had been striped whereas others had yet to start striping. The newly striped sections were used to provide initial data on new markings that were monitored throughout the project. The research team had hoped to evaluate the sites that had not been striped to provide data on in-service markings that may be near the end of their service life. The research team was unable to read these sections before they could be restriped. The research team identified additional sites by reviewing google satellite and street view imagery. The goal with the imagery review was to find newly installed markings, markings that appear to have some level of wear but not at end of service life, and markings that appear to be near their end of service life. This review was based purely off the daytime visibility of the markings and on how recent Streetview images were. The goal was to select data collection sites across a range of pavement marking conditions. The locations around the state and different pavement surface conditions were also of interest. Table 32 lists the test sites and provides additional site information. Figure 17 shows the location of the data collection.

Table 32 - List of Data Collection Sites.

Roadway	Limits of Data Collection	Location within State	Roadway Surface	Markings Evaluated	Pavement Marking Material Type
US 206	I 80 to Bartley Chester Rd	North	Asphalt	White Edge, Yellow Center	Epoxy
SH 15	Mirror Lake Rd to SH 181	North	Asphalt	White Edge, White Skip, Yellow Center	Epoxy
SH 53	I 80 to Adams Ave	North	Asphalt	White Edge, Yellow Center	Epoxy
I 80	Exit 48 to Exit 54	North	Asphalt	White Skips, Yellow Edge	Thermoplastic
US 130	Brick Yard Rd to Westfield Ln	Central	Asphalt	White Edge, White Skip, Yellow Center	Epoxy
SH 33	GSP to Wakefield Rd	Central	Asphalt	White Skip, Yellow Edge	Epoxy
GSP	Driscoll Bridge Area	Central	Asphalt on ends, PCC in middle on bridge	White Skip, Yellow Edge	Thermoplastic on asphalt, tape on PCC
SH 37	Washington St to Thomas Mathis Bridge	South	Asphalt	White Skips, Yellow Edge	Epoxy
GSP	MM60 to MM81	South	Asphalt	White Skip, Yellow Edge	Thermoplastic
SH 72	US 9 to Marsha Dr	South	Asphalt	White Skip, Yellow Edge	Epoxy
SH 50	US 322 to Atlantic City Expressway	South	Asphalt	White Edge, Yellow Center	Epoxy
US 40	Millville Ave to Beacon Ave	South	Asphalt	White Edge, Yellow Center	Epoxy
SH 73	SH 54 to Lenore Ct	South	Asphalt	White Edge, Yellow Center	Epoxy
SH 54	SH 73 to Pagano Dr	South	Asphalt	White Edge, Yellow Center	Epoxy
US 322	SH 47 to Fries Mill Rd	South	Asphalt	White Edge, Yellow Center	Epoxy

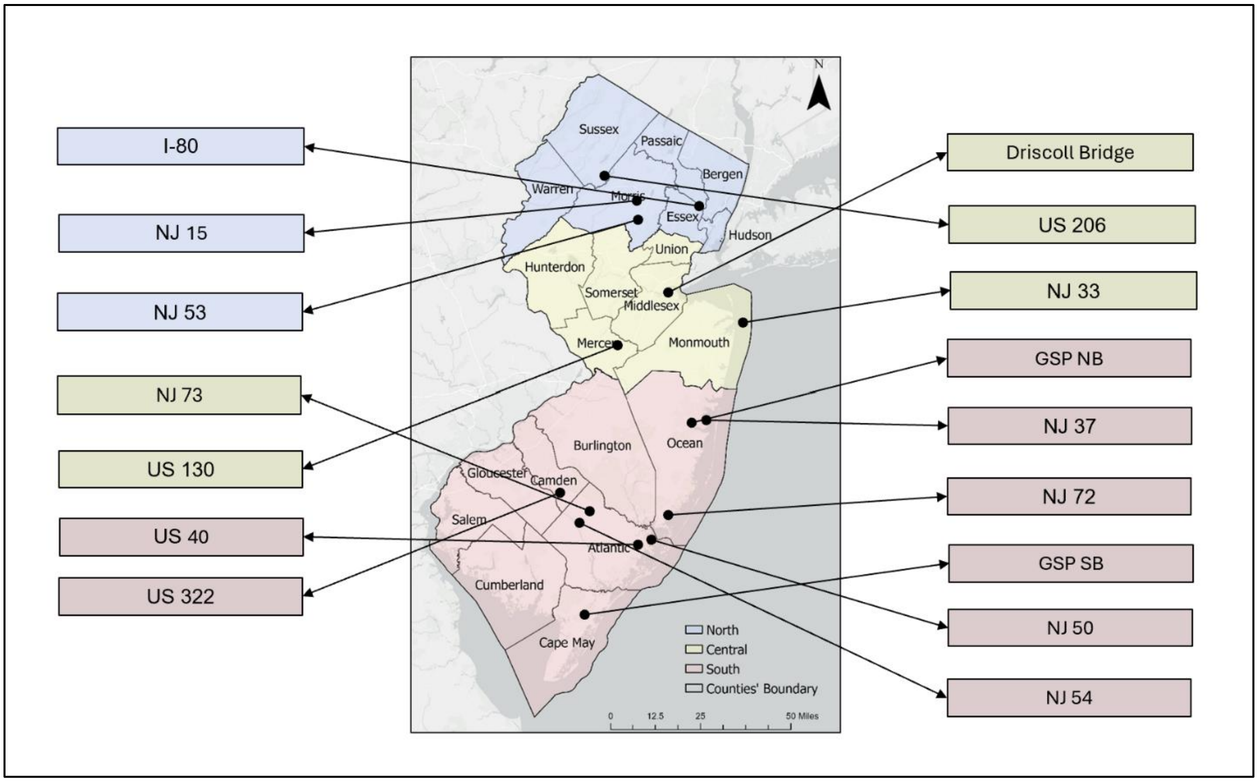


Figure 17. Data Collection Locations

Data Collection Timeframe

Data collection occurred three times over the course of the project. The initial data collection took place in December 2023. The second set of data collection took place in September 2024. The final data collection took place in April 2025. During each data collection time frame, all the sites were evaluated. The one exception was the Driscoll Bridge location which was not evaluated during the initial data collection. After the data were collected, the data were downloaded, organized, summarized, and analyzed.

Pavement Marking Performance Data Collection

The research team focused the data collection effort on documenting the retroreflectivity (R_L – coefficient of retroreflected luminance) and presence of the markings evaluated. Both sets of data were collected from a moving vehicle and did not require lane closures. A mobile retroreflectometer was used to collect the retroreflectivity of each pavement marking in each test area. Multiple passes were made through each test area to measure each of the markings in each direction of travel. The mobile retroreflectometer measures the markings at the standard 30-meter geometry. The mobile retroreflectivity data were continually collected the entire length of the test area. The research team collected handheld retroreflectivity measurements at select locations where there were low traffic volumes. These measurements required the research team to be on the road with the instrument. The handheld readings were only taken along a short stretch of each marking.

The handheld readings were taken to verify the accuracy of the mobile retroreflectometer. Figure 18 provides an image of the data collection vehicle with the mobile retroreflectometer mounted on the left side. Figure 19 provides an image of handheld data collection. The mobile and handheld retroreflectometers were calibrated multiples times per day to ensure accurate measurement. The front of mobile retroreflectometer was frequently cleaned to maintain a clear window for the data collection.

Figure 18. Mobile Pavement Marking Retroreflectometer and Camera System.

Figure 19. Handheld Pavement Marking Retroreflectivity Data Collection.

The research team utilized two camera systems to capture video of the pavement markings. These cameras were operating while collecting the mobile retroreflectivity data. One camera system was mounted on the side of the vehicle and looked downward toward the pavement markings. This camera was focused only on collecting pavement marking presence. Figure 18 provides an image of the camera system mounted near the front wheel of the vehicle. A forward-facing camera was mounted near the rearview mirror and was linked with the mobile retroreflectometer data collection system. This forward-facing camera captured the forward view including the pavement markings. The data from the mobile retroreflectometer overlaid on the video feed. Figure 20 shows a screenshot of the forward-facing video being collected on Interstate 80. Figure 21 provides a screenshot of the forward-facing video while collecting data on US 40.

In addition to the video data collection, the research team also collected general images of the test areas. The images were used to verify the general roadway conditions and appearance. Figure 22 provides two images of markings in good condition. Figure 23 provides two images of markings with some damage. The white marking in Figure 23 is experiencing bead loss and the yellow marking is experiencing a loss of material in the milled rumble strip area. The research team also took notes on the visual appearance of the markings in each test area. These notes will include information pertaining to daytime visibility (if observed during the day), nighttime visibility (if observed during the night), and the general appearance/quality of the markings. Most of the data collection occurred during the day.

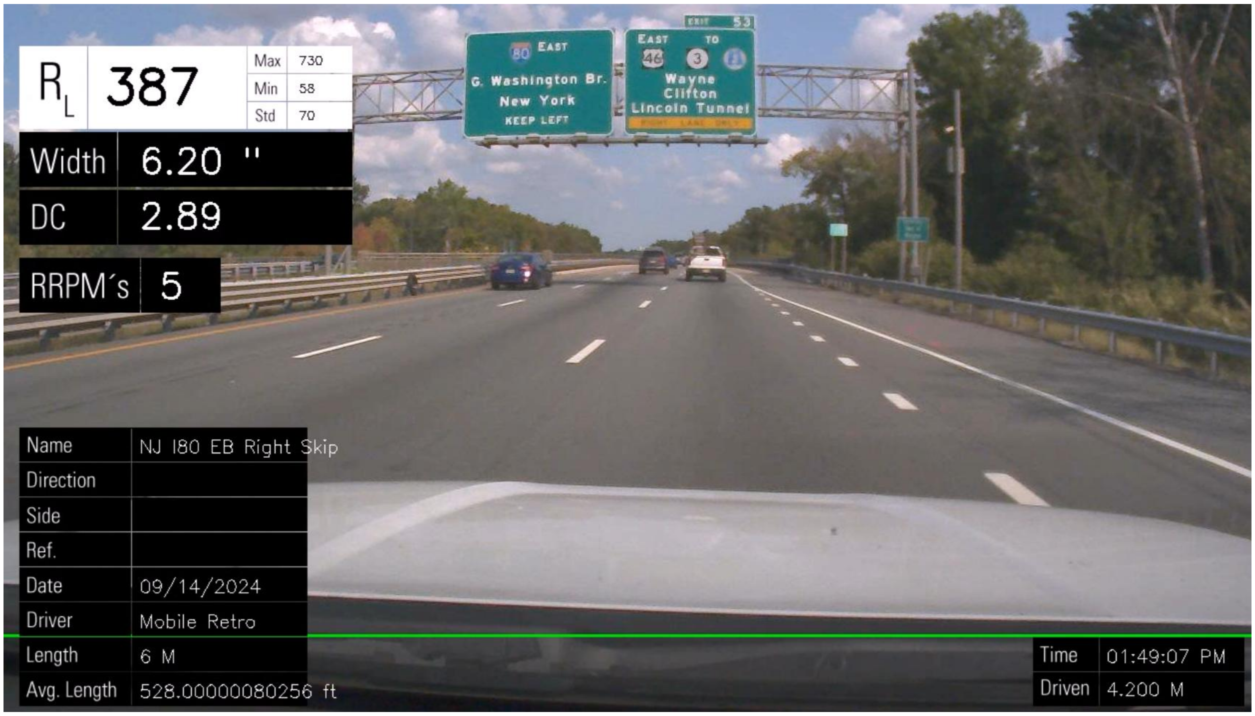


Figure 20. Screenshot from I-80 Data Collection Video with Data Overlay.

Figure 21. Screenshot from US-40 Data Collection Video with Data Overlay.

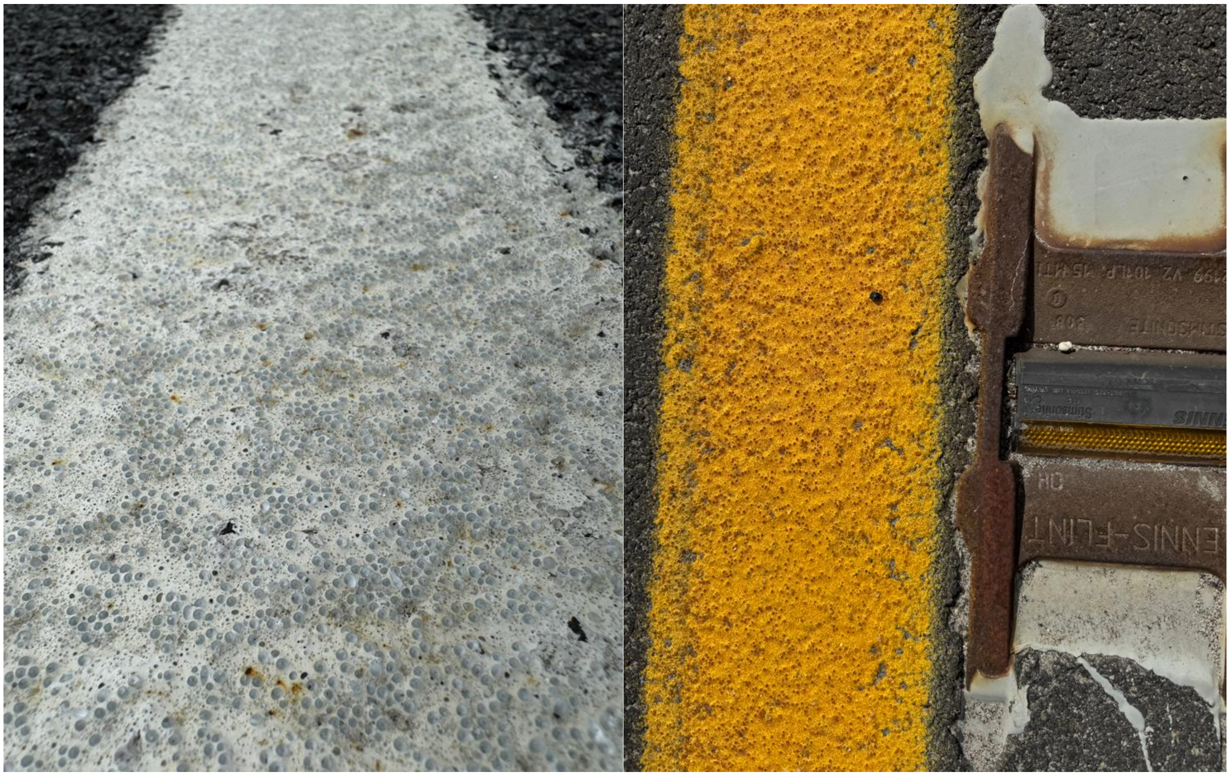


Figure 22. Images of Markings in Good Condition.

Figure 23. Images of Markings with Damage.

CHAPTER 5: EVALUATION OF MARKING VISIBILITY

Introduction

To rigorously evaluate the quality and effectiveness of pavement markings, this study employed a comprehensive analytical approach. First, pavement marking quality was assessed through advanced image processing techniques, utilizing data extracted from the NJDOT Straight Line Diagram (SLD) database. This enabled an objective examination of the visual condition and continuity of road markings across the network. Second, retroreflectivity (R_L), the capacity of pavement markings to return light from vehicle headlights to drivers, a crucial safety factor at night, was quantitatively measured through on-site data collected in three systematic phases. These field measurements and their comparative analysis provided direct insight into the real-world visibility and durability of the markings over time. Third, the assessment process was further enhanced by applying computer vision methodologies to the R_L video datasets gathered in each of the three collection phases. The marking visibility analysis aimed to develop a model that can detect pavement quality, identify the road location in an image, and classify the pavement marking as "Good", "Moderate", or "Poor", where "Good" refers to R_L values more than 150 mcd/m^2/lx, "Moderate" refers to R_L values 70 – 150 mcd/m^2/lx, and "Poor" refers to less than 70 mcd/m^2/lx. Utilizing automated pattern recognition and analysis, this approach offered an additional layer of accuracy and consistency, allowing for the evaluation of pavement marking performance. This study follows a three-phase approach to assessing pavement marking R_L (see Figure 24).

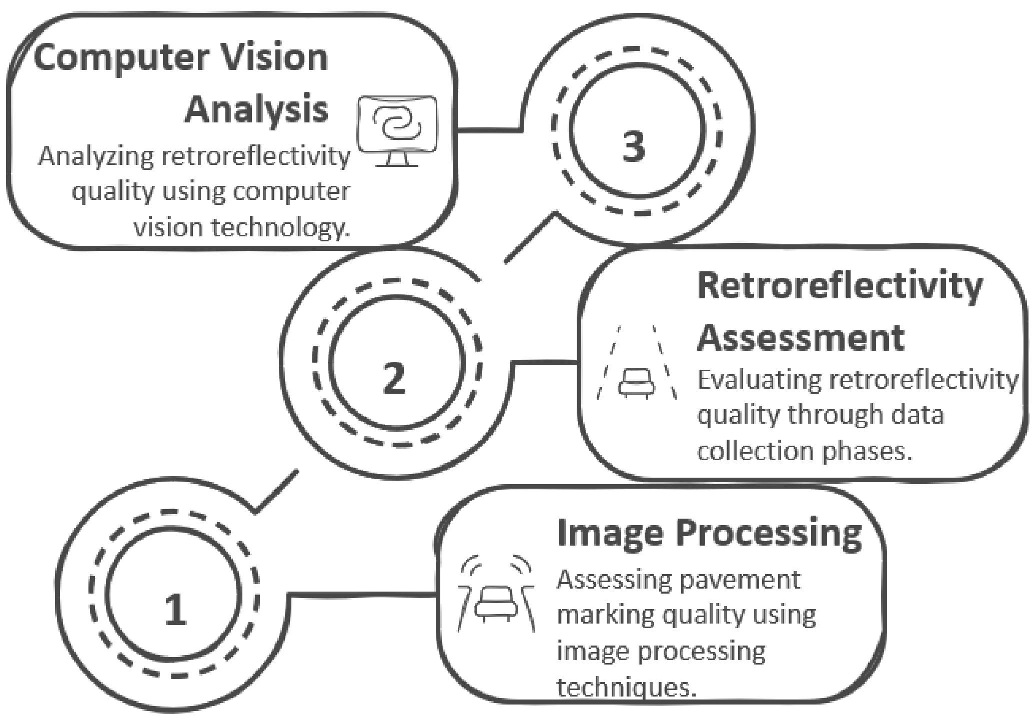


Figure 24. Data Analysis Framework

NJDOT Straight Line Diagram (SLD)

Data Extraction

The first set of image data was collected from NJDOT Web SLD Data Browser (website: https://njsld.org/NJDOT/SLD/DataBrowser/). This tool provides access to roadway inventory data organized by Standard Route Identifiers (SRIs), which are unique codes assigned to specific highway segments. For this project, a total of nine SRIs (00000007, 00000009, 00000023, 00000033, 00000037, 00000046, 00000053, 00000072, 00000130) were selected, representing approximately 83 miles of roadway. The selection of these segments allowed for a manageable yet diverse sample of the state's road network. Each SRI provided access to a detailed photobook, which includes time-stamped, georeferenced roadway images captured from multiple camera angles (e.g., front, rear, side). Through the photobook interface, two types of data were collected: image data and roadway feature data. The image data consisted of high-resolution roadway photos extracted directly from the photobook, which helped document physical roadway features and conditions. Simultaneously, roadway attribute data, such as lane configuration, signage, and surface characteristics, were manually extracted based on visual inspection of these images. This step resulted in a compiled database of 15,536 images, covering the selected roadway segments with accompanying visual and descriptive information suitable for further analysis. The steps are illustrated in Figure 25.

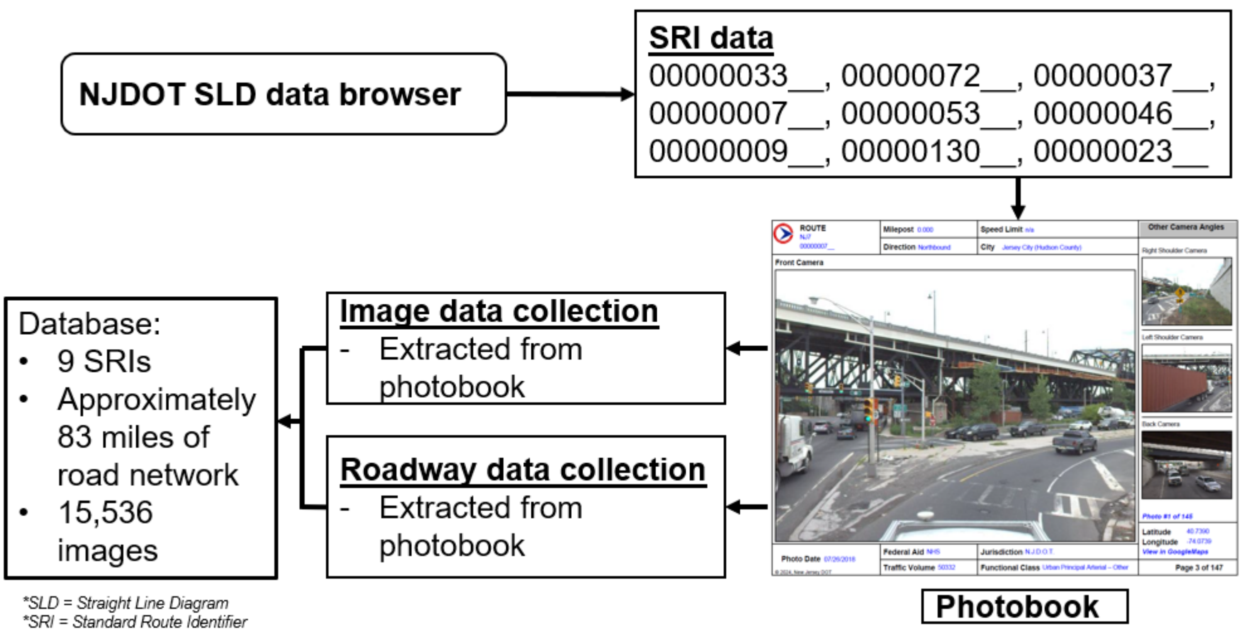


Figure 25. Data collection process from photobook

In the next step of the data collection process (see Figure 26), images were systematically extracted from the photobooks using a custom R script. The script was designed to automatically crop the front-facing camera images from each photobook page, focusing on the most relevant view for analyzing roadway features. This automation helped streamline the extraction process, reducing the need for manual intervention and ensuring consistency across all images. Once cropped, the images were sorted and organized by location. Specifically, images from 154 distinct roadway sites were stored in separate folders, each representing a unique site along the selected SRIs. This directory structure allowed for efficient management of the large image dataset and supported organized downstream analysis. In total, the process yielded 15,536 images, each labeled and filed in its corresponding site-specific folder for easy reference during future annotation or feature extraction tasks.

Figure 26. Automated cropping and sorting of images

As part of the data collection workflow, the same automated process used to crop images from the NJDOT photobooks was extended to extract associated roadway information for each image (see Figure 27). This metadata, which includes variables such as route number, milepost, city, direction, speed limit, traffic volume, and functional class, was parsed from each photobook entry and stored in tabular format. Each roadway segment's information was saved in a separate Excel file, corresponding to its folder of images. As a result, 154 Excel files were generated, collectively containing 15,536 rows, one for each photo. Each row in the dataset represents a unique image, paired with its corresponding location and roadway characteristics. This structured format ensures easy access to both visual and tabular data for further annotation or modeling.

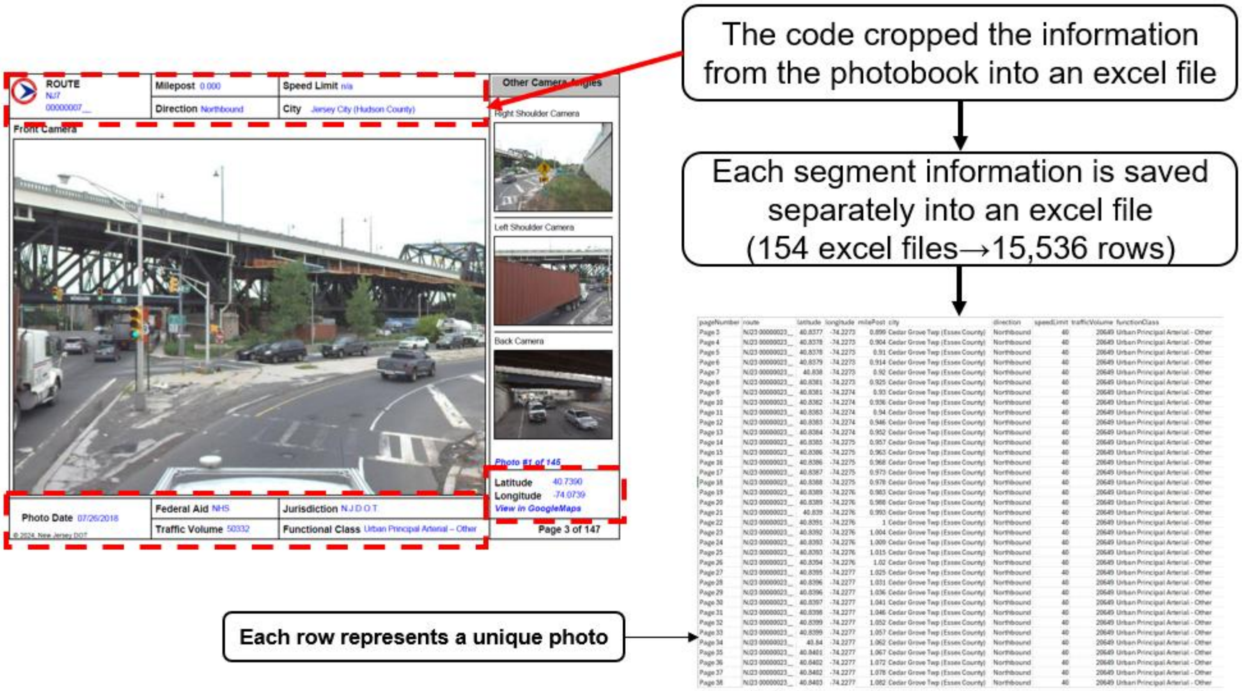


Figure 27. Extraction of roadway metadata

In the final stage of the data collection and preparation process, manual annotation was performed to enhance the dataset with visual roadway condition attributes (see Figure 28). The research team matched each image's filename with the corresponding metadata and roadway information previously extracted from the photobook. This alignment ensured that every observation was tied to the correct roadway segment and visual scene. Manual data collection focused on key roadway features related to traffic control and visibility. For each image, researchers recorded details such as the presence of intersection or offset flags, the color, visibility, and condition of centerlines, and the characteristics of right-side edge lines and lane separation markings. These qualitative attributes were coded consistently across all images. A total of 865 rows were completed in this phase, each representing a detailed observation of visual road features based on the extracted images.

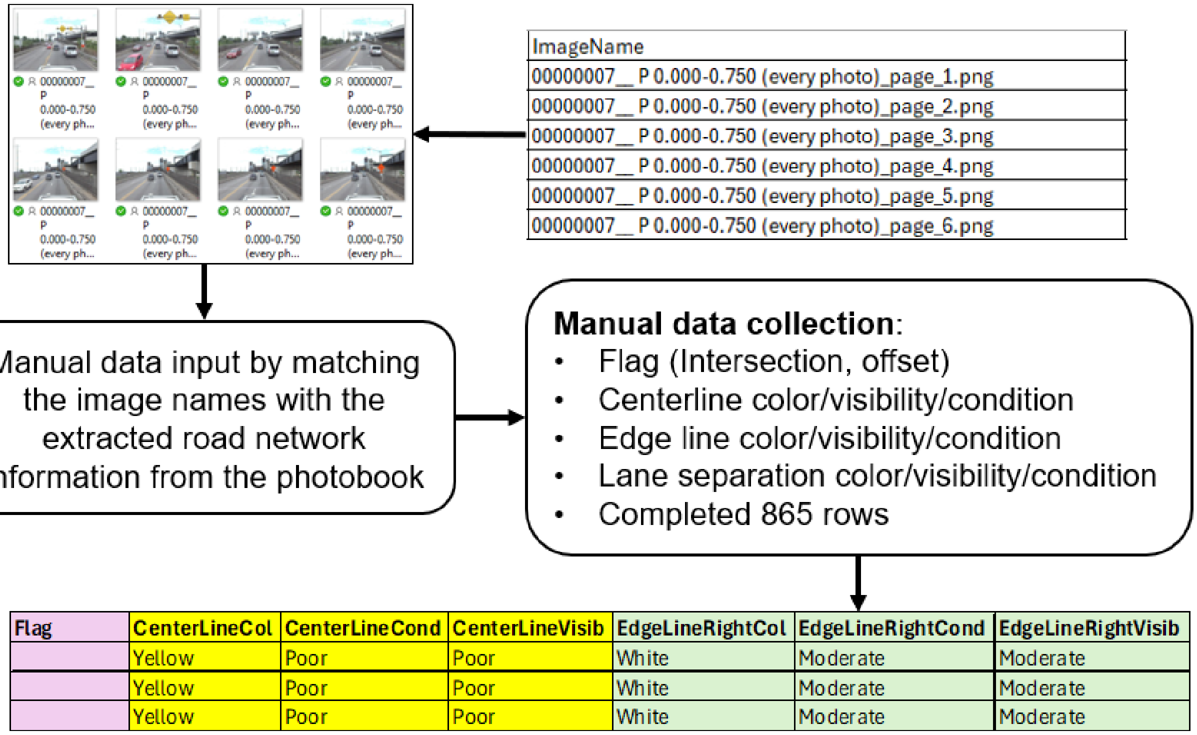


Figure 28. Manual annotation process of the collected images

The overall analysis framework is shown in Figure 29, which offers a detailed explanation of the methodology, highlighting each phase (stage 1 and stage 2) involved in the assessment of road marking quality. It involves manual data annotation, model optimization, and hyperparameter tuning to achieve precise and reliable detection outcomes. The analysis employs the You Only Look Once, version 8 (YOLOv8) object detection framework (144). YOLO is a state-of-the-art, real-time object detection algorithm widely used in computer vision tasks. Version 8 represents a refined release in the YOLO series, offering improved accuracy, faster inference speed, and better support for custom training compared to earlier versions. This makes it well-suited for identifying subtle variations in pavement marking conditions across thousands of roadway images. As depicted in the methodology diagram, the YOLOv8 framework guides the sequential steps from data preparation to model evaluation, ensuring the interpretability and robustness of the results. This dataset comprises 15,536 raw road images, meticulously chosen to represent the quality of pavement markings (e.g., good, moderate or poor).

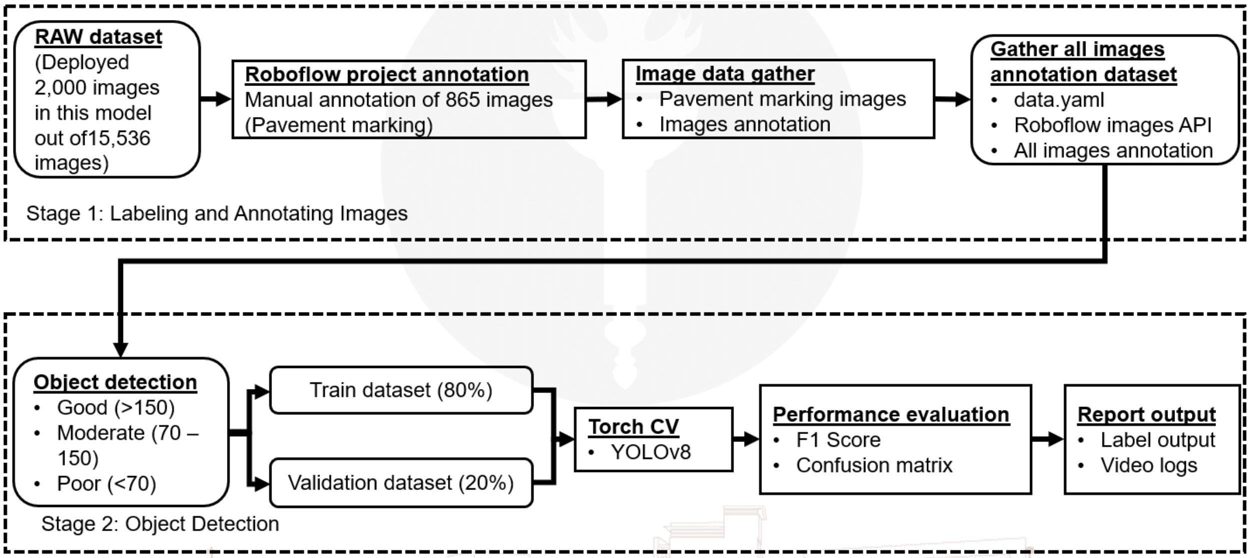


Figure 29. Experimental flow for SLD data analysis.

Model Deployment and Evaluation

In evaluating the performance of YOLOv8 for the detection of retroreflective road markings, the dataset (865 images) is strategically split into an 80% training set (692 images) and a 20% validation set (173 images) (see Figure 30). This division ensures that the model is trained on a substantial portion of the data while reserving a separate subset for testing its generalization capabilities and preventing overfitting. The primary metric used to evaluate the model’s performance is the mean Average Precision (mAP) over a range of Intersection over Union (IoU) thresholds from 0.50 to 0.95 (mAP50-95). This metric provides a comprehensive view of the model's accuracy at various levels of IoU, offering insights into how well the predicted bounding boxes align with the ground truth across different degrees of precision. A higher mAP score across these thresholds indicates better model performance in detecting and delineating road markings accurately. During training, the model’s performance is validated at the end of each epoch using the validation set. This involves calculating the mAP50-95 for the predictions made by the model on the validation images. By monitoring this metric over successive epochs, it is possible to observe trends in the model’s learning progress, such as improvements in detection accuracy or potential signs of overfitting if the validation performance begins to decline while training performance continues to increase.

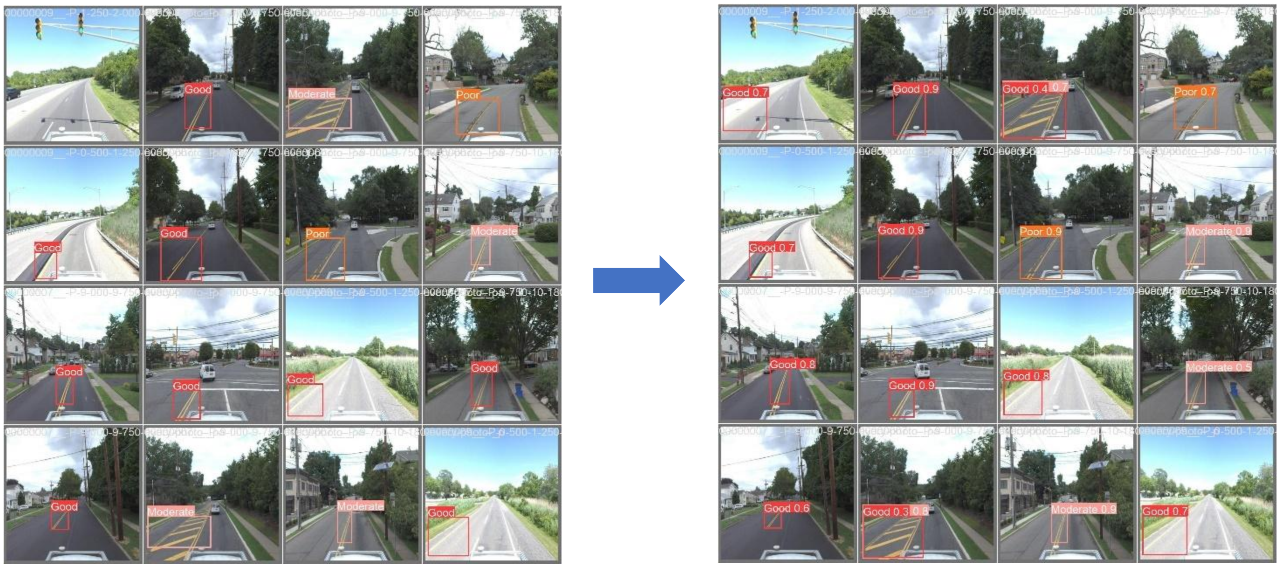


Figure 30. Batch data example for training and validation

Object Detection Result and Performance Metrics

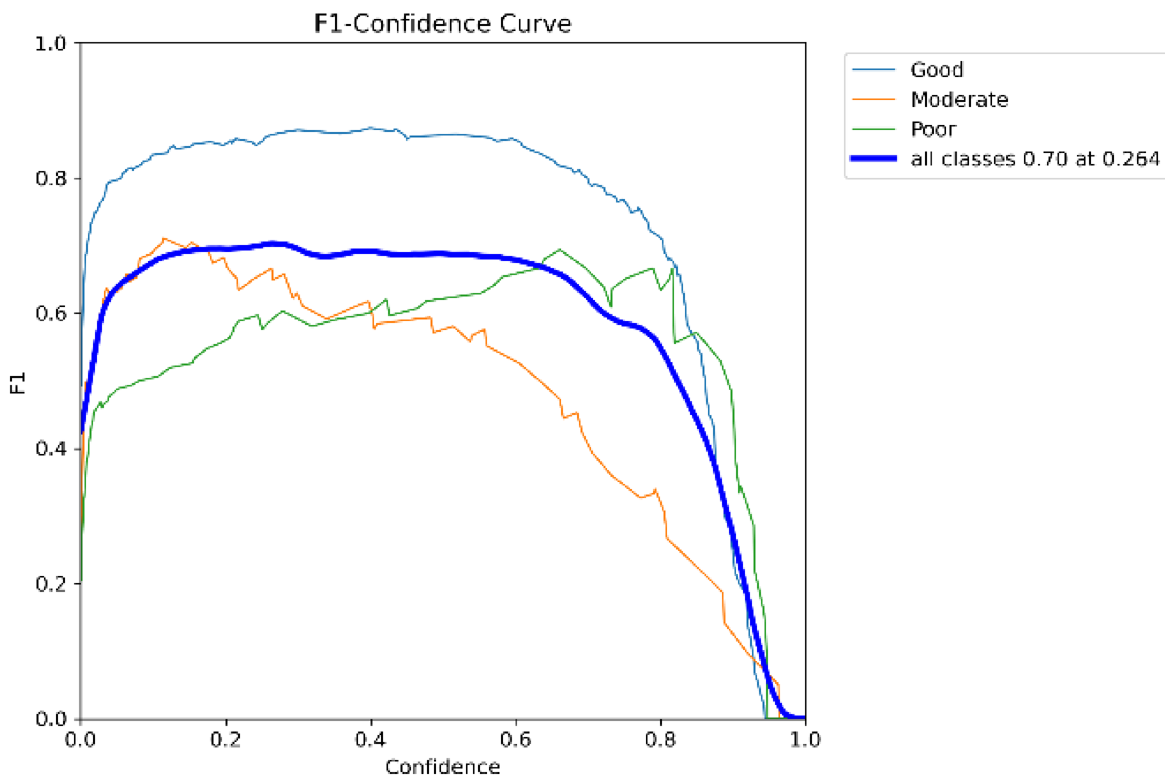
Upon deployment, the YOLOv8 model continuously processes images of road markings, automatically classifying the quality of each marking as either good, moderate, or poor based on their retroreflectivity. As the system identifies and evaluates each instance of road markings, it not only generates the classification labels but also logs these assessments. Each detected marking, along with its classified quality, is systematically recorded in an Excel file, as shown in Table 33. This output file serves as a comprehensive database, documenting the condition of road markings across the assessed areas, facilitating easy access and analysis of the data for maintenance and safety evaluations. The blank cells in the detection report refer to the road segments where there is no retroreflective pavement marking present.

Table 33 - Report on image object detection

image name	label
00000007_P_0.000-0.750 (every photo) page_1.png	Poor
00000007_P_0.000-0.750 (every photo) page_2.png	Moderate
00000007_P_0.000-0.750 (every photo) page_3.png	Good
00000007_P_0.000-0.750 (every photo) page_4.png	Moderate
00000007_P_0.000-0.750 (every photo) page_5.png	Good
00000007_P_0.000-0.750 (every photo) page_6.png	Good
00000007_P_0.000-0.750 (every photo) page_7.png	Good
00000007_P_0.000-0.750 (every photo) page_8.png	Moderate
00000007_P_0.000-0.750 (every photo) page_9.png	Moderate
00000007_P_0.000-0.750 (every photo) page_10.png	Moderate
00000007_P_0.000-0.750 (every photo) page_11.png	Good
00000007_P_0.000-0.750 (every photo) page_12.png	Moderate
00000007_P_0.000-0.750 (every photo) page_13.png	Good

image name	label
00000007_P_0.000-0.750 (every photo) page_14.png	Good
00000007_P_0.000-0.750 (every photo) page_15.png	Good
00000007_P_0.000-0.750 (every photo) page_16.png	Good
00000007_P_0.000-0.750 (every photo) page_17.png	Good
00000007_P_0.000-0.750 (every photo) page_18.png	Good
00000007_P_0.000-0.750 (every photo) page_19.png	Moderate
00000007_P_0.000-0.750 (every photo) page_20.png	Moderate
00000007_P_0.000-0.750 (every photo) page_21.png	Moderate

The performance metrics, such as F1-confidence and precision curve, provide insights into the model outcome (see Figure 31). The model is highly effective for detecting the 'Good' visibility of the center line, but has more difficulty with the 'Moderate' and 'Poor' classes. At extremely high confidence levels, the model's performance typically drops, as only a few predictions meet such a high threshold.



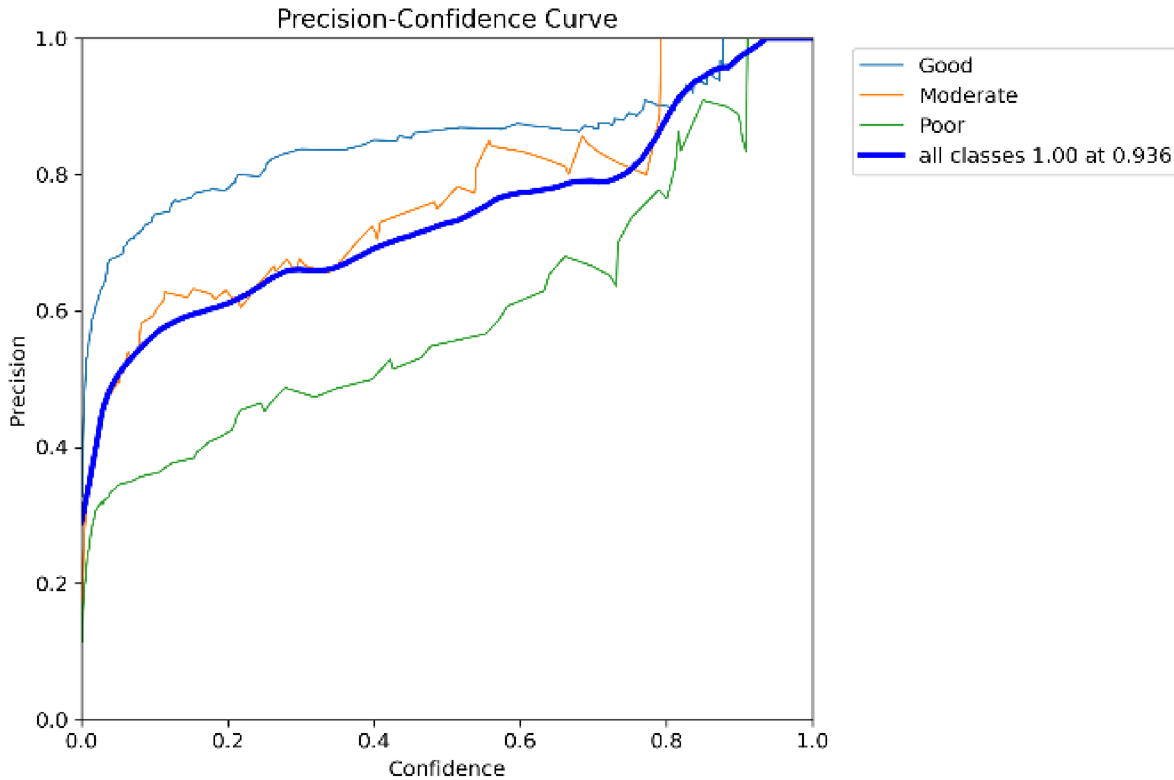


Figure 31. Evaluation performance of YOLOv8

In Figure 32, the confusion matrix depicts the performance of a classification model across four classes: Good, Moderate, Poor, and Background. It shows that the model predicts 'Good' correctly 93% of the time, but misclassifies it as 'Moderate,' 'Poor,' or 'Background' 7% of the time. 'Moderate' predictions are correct 44% of the time, with notable misclassifications to 'Good,' 'Poor,' and 'Background.' The model accurately predicts 'Poor' 71% of the time, but also shows some misclassification. Predictions for 'Background' are less accurate, with significant misclassification across other classes. The matrix highlights high accuracy for 'Good' and 'Poor' predictions, but indicates areas for improvement in 'Moderate' and 'Background' classifications, suggesting the need for more distinct features or additional training data to improve classification. The misclassification of pavement as 'background' suggests that some pavement marking visibility condition features may not be learned well, or that the 'background' contains elements similar to pavement marking. The framework and code developed for this analysis are publicly available at: https://github.com/Xatta-Trone/njdot-image-metadata-extraction.

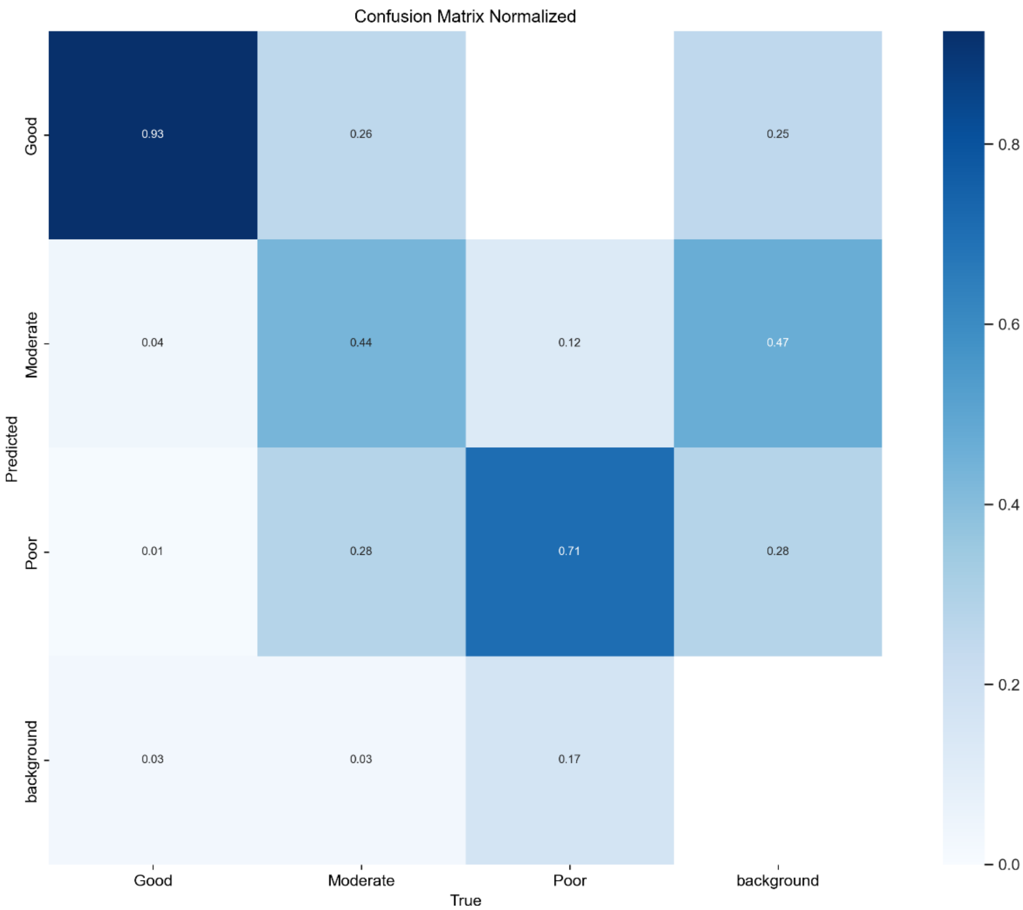


Figure 32. Confusion matrix

Field Data Analysis

The research team conducted a comprehensive collection of field data across three distinct time periods to evaluate pavement marking performance and monitor changes in R^L over time. These three data collection efforts are referred to as Phase I, Phase II, and Phase III, and took place in December 2023, September 2024, and April 2025, respectively. The main objective of this phased approach was to capture both the short-term and long-term durability of pavement markings under real-world conditions, including weather exposure, traffic wear, and other environmental influences. During each phase, R_L measurements were collected systematically across multiple states and U.S. routes throughout New Jersey. These measurements served as key indicators of the visibility and effectiveness of pavement markings, especially for nighttime driving. By comparing R_L values across the three phases, the research team aimed to identify performance trends, such as improvements following maintenance or deterioration over time. This repeated assessment allowed for a more accurate understanding of how different marking materials, conditions, and installation practices impacted long-term visibility and safety.

Summary of the Collected Data

Phase I (December 2023)

In Phase I, the R_L level varied significantly across routes, with higher mean values observed on routes like US 130 (388.33) and SH 72 (367.99), indicating better pavement visibility. The lowest R_Ls were recorded on SH 50 and SH 73, especially for older markings, such as SH 73, with a mean R_L of 131.32. The width of markings was generally around 4.5 to 5.9 inches, with I-80 and GSP having the highest width at 5.96 inches.

Table 34 - Information of the marking by Route ID (Phase I)

Route	Condition	RL	Width	RRPM	Driven Miles
GSP	Good	268.27 (256.05, 280.49)	5.96 (5.93, 5.99)	4.14 (3.93, 4.35)	10.45 (9.96, 10.94)
I 80	Good	298.11 (286.54, 309.68)	5.96 (5.73, 6.19)	5.71 (5.57, 5.86)	2.92 (2.77, 3.07)
SH 15	Older	133.59 (128.25, 138.92)	4.88 (4.51, 5.26)	1.45 (1.23, 1.67)	2.39 (2.19, 2.59)
SH 33	Good	247.43 (239.18, 255.69)	4.66 (4.54, 4.79)	6.23 (5.84, 6.63)	1.10 (0.98, 1.23)
SH 37	Good	323.70 (307.37, 340.02)	4.73 (4.13, 5.33)	5.99 (5.81, 6.16)	1.09 (1.00, 1.19)
SH 50	Good	126.78 (121.46, 132.10)	5.29 (4.41, 6.18)	3.02 (2.46, 3.59)	1.08 (0.96, 1.19)
SH 53	Good	191.15 (183.02, 199.28)	5.62 (4.52, 6.72)	8.73 (8.06, 9.40)	1.80 (1.59, 2.01)
SH 54	Good	190.10 (181.75, 198.44)	5.09 (4.85, 5.33)	2.55 (1.96, 3.13)	0.77 (0.67, 0.87)
SH 72	Good	367.99 (351.19, 384.78)	4.43 (4.32, 4.54)	6.14 (5.90, 6.38)	0.93 (0.82, 1.03)
SH 73	Older	132.41 (123.22, 141.59)	5.86 (4.78, 6.94)	1.19 (0.85, 1.53)	1.26 (1.14, 1.39)
US 130	Mixed	388.33 (361.97, 414.70)	5.53 (4.68, 6.37)	3.79 (3.38, 4.20)	1.12 (1.02, 1.21)
US 206	Good	341.61 (327.07, 356.14)	4.47 (4.41, 4.54)	4.54 (3.90, 5.18)	2.16 (2.00, 2.32)
US 322	Good	312.67 (292.75, 332.60)	4.51 (4.44, 4.59)	5.69 (5.48, 5.91)	1.17 (1.05, 1.28)
US 40	Good	303.91 (290.47, 317.35)	4.82 (4.78, 4.86)	2.57 (2.16, 2.99)	1.54 (1.40, 1.67)

Note: RRPM = Raised retroreflective pavement marker

Phase II (September 2024)

Phase II showed an overall increase in R_L values, with SH 53 having the highest R_L of 447.37, and SH 50 and SH 54 also exceeding 400, reflecting improved or newer markings. Widths across routes were generally consistent with Phase I but showed slightly more variability, such as 6.17 inches on I 80 and 4.73 inches on SH 15.

Table 35 - Information of the marking by Route ID (Phase II)

Route	Condition	RL	Width	RRPM	Driven
GSP Bridge	Good	257.15 (243.61, 270.69)	6.01 (5.98, 6.04)	4.51 (4.33, 4.69)	69.00 (66.47, 71.52)

Route	Condition	RL	Width	RRPM	Driven
I 80	Good	423.76 (414.97, 432.54)	6.17 (6.14, 6.19)	5.98 (5.86, 6.11)	2.88 (2.73, 3.03)
SH 15	Older	360.59 (346.35, 374.83)	4.73 (4.63, 4.82)	3.93 (3.53, 4.33)	1.23 (1.13, 1.33)
SH 33	Good	182.96 (176.70, 189.23)	4.40 (4.35, 4.45)	6.06 (5.76, 6.35)	1.26 (1.14, 1.39)
SH 37	Good	392.22 (379.87, 404.57)	4.59 (4.56, 4.63)	6.21 (6.01, 6.41)	1.04 (0.95, 1.14)
SH 50	Good	411.09 (395.24, 426.94)	4.72 (4.68, 4.76)	3.92 (3.27, 4.57)	1.06 (0.95, 1.18)
SH 53	Good	428.66 (409.95, 447.37)	4.46 (4.41, 4.51)	4.47 (3.78, 5.15)	1.79 (1.64, 1.93)
SH 54	Good	400.94 (384.42, 417.47)	4.59 (4.52, 4.66)	2.51 (1.92, 3.09)	0.91 (0.81, 1.02)
SH 72	Good	298.19 (287.67, 308.72)	5.13 (3.98, 6.28)	6.32 (6.05, 6.59)	0.85 (0.75, 0.95)
SH 73	Older	162.19 (150.43, 173.96)	4.82 (4.71, 4.94)	1.50 (1.13, 1.86)	1.35 (1.22, 1.48)
US 130	Mixed	246.70 (233.95, 259.45)	4.66 (4.56, 4.75)	3.18 (2.84, 3.52)	1.24 (1.14, 1.34)
US 206	Good	131.06 (127.54, 134.58)	4.46 (4.41, 4.50)	4.10 (3.56, 4.64)	2.22 (2.06, 2.38)
US 322	Good	258.11 (243.14, 273.08)	4.53 (4.47, 4.59)	6.27 (5.69, 6.84)	1.22 (1.08, 1.36)
US 40	Good	248.15 (237.45, 258.84)	4.74 (4.69, 4.80)	3.33 (2.88, 3.79)	1.46 (1.33, 1.60)

Phase III (April 2025)

Phase III data reflected a mixture of improved and degraded conditions. The R_L was the highest mean on SH 50 (353.77) and SH 54 (328.99), both marked in good condition. Conversely, US 206 had a significantly low mean R_L of 94.50 despite being in good condition, suggesting degradation. Marking widths were highest on GSP Bridge (6.40) and I 80 (6.35), indicating consistent application. Driven distances were comparable to earlier phases, with GSP again having the longest (10.35 miles) and most others around 1–2 miles.

Table 36 - Information of the marking by Route ID (Phase III)

Route	Condition	R_L	Width	RRPM	Driven
GSP	Good	201.50 (193.09, 209.91)	6.03 (5.98, 6.07)	3.92 (3.77, 4.08)	10.40 (9.91, 10.89)
GSP Bridge	Good	291.16 (255.16, 327.16)	6.40 (6.29, 6.52)	1.23 (0.93, 1.53)	1.28 (1.15, 1.40)
I 80	Good	277.17 (272.78, 281.55)	6.35 (6.32, 6.39)	5.65 (5.53, 5.77)	2.73 (2.59, 2.88)
SH 15	Older	138.16 (133.09, 143.23)	4.73 (4.66, 4.79)	3.92 (3.52, 4.32)	1.27 (1.16, 1.37)
SH 33	Good	166.07 (159.98, 172.16)	4.53 (4.48, 4.58)	5.74 (5.27, 6.20)	1.25 (1.13, 1.37)
SH 37	Good	277.59 (271.26, 283.92)	4.83 (4.79, 4.86)	5.98 (5.77, 6.19)	1.13 (1.04, 1.23)

Route	Condition	R_L	Width	RRPM	Driven
SH 50	Good	353.77 (339.12, 368.41)	4.87 (4.84, 4.90)	3.68 (2.99, 4.37)	1.08 (0.96, 1.19)
SH 53	Good	261.32 (250.49, 272.15)	4.60 (4.57, 4.64)	4.67 (3.95, 5.40)	1.80 (1.66, 1.94)
SH 54	Good	328.99 (316.85, 341.12)	4.99 (4.93, 5.05)	4.51 (3.48, 5.55)	0.90 (0.80, 1.00)
SH 72	Good	279.87 (269.19, 290.55)	4.54 (4.41, 4.68)	6.40 (6.13, 6.67)	0.89 (0.78, 0.99)
SH 73	Older	168.26 (157.42, 179.11)	5.35 (4.66, 6.04)	1.53 (1.17, 1.89)	1.40 (1.27, 1.53)
US 130	Mixed	194.44 (183.48, 205.41)	5.09 (4.51, 5.66)	3.01 (2.65, 3.38)	1.20 (1.10, 1.29)
US 206	Good	94.50 (91.55, 97.44)	4.63 (4.59, 4.66)	3.70 (3.21, 4.20)	3.36 (3.08, 3.64)
US 322	Good	179.85 (169.26, 190.43)	4.63 (4.58, 4.69)	5.35 (5.02, 5.68)	1.28 (1.15, 1.40)
US 40	Good	291.59 (278.57, 304.61)	5.30 (4.70, 5.89)	2.96 (2.52, 3.41)	1.65 (1.51, 1.79)

The following subsections include the comparison of R_L values based on several selection or evaluating criteria, such as analysis by route, marking condition, marking type, pavement material type, and phases. The analysis assisted in getting an overall understanding of how the R_L values changed or impacted throughout all three data collection phases.

Analysis by Phase

The violin plot in Figure 33 illustrates the distribution of R_L values across three data collection phases. In Phase I, the mean RL is 265.36, indicating moderately high visibility of pavement markings during the initial assessment. Phase II shows an improvement, with the mean R_L increasing to 302.44, likely due to recent maintenance or application of newer markings. However, a notable decline is observed in Phase III, where the mean R_L drops to 224.75, suggesting deterioration over time due to environmental exposure and traffic wear. The spread of R_L values in each phase also provides key insights. Phase II exhibits the widest distribution with more high-end outliers, reflecting variability in marking quality and possibly new applications in certain locations. In contrast, Phase III displays a denser concentration of lower R_L values, indicating a general reduction in reflectivity across the network. These results emphasize the importance of timely reapplication and consistent maintenance of pavement markings to ensure long-term visibility and safety.

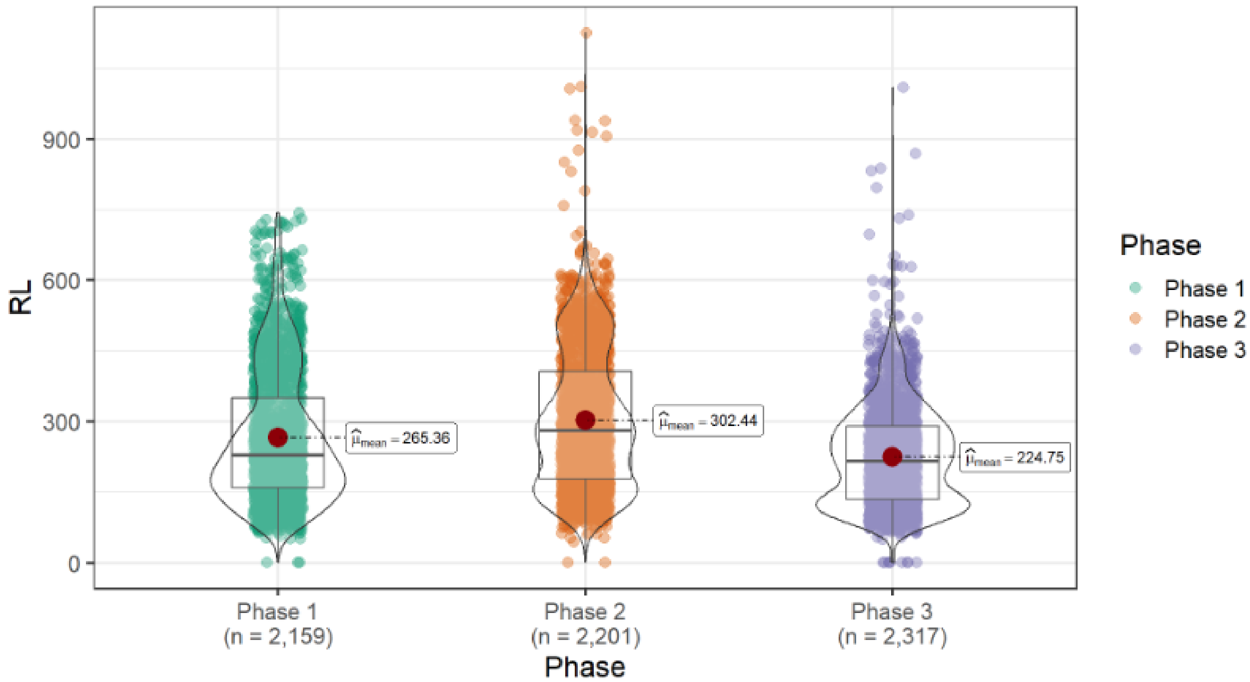


Figure 33. Distribution of R_L measures by phase

Analysis by Marking Condition

Good

The violin plot in Figure 34 shows the distribution of R_L values for pavement markings classified as being in Good condition across the three phases of data collection. In Phase I, the mean R_L is 281.22, suggesting strong visibility among recently applied or well-maintained markings. Phase II demonstrates a further improvement, with the mean R_L increasing to 311.32, reflecting enhanced performance due to newer applications or environmental conditions favorable to reflectivity. However, by Phase III, the mean R_L drops to 237.56, indicating a decline in marking performance over time despite the markings being visually assessed as “good”. This drop underscored that visual classification alone may not fully capture functional degradation in visibility, especially under nighttime conditions. The distribution in Phase I is also slightly more compressed and skewed toward lower R_L values, highlighting emerging inconsistencies in performance. The findings emphasized the importance of supplementing visual assessments with objective R_L measurements to better inform maintenance schedules and uphold safety standards.

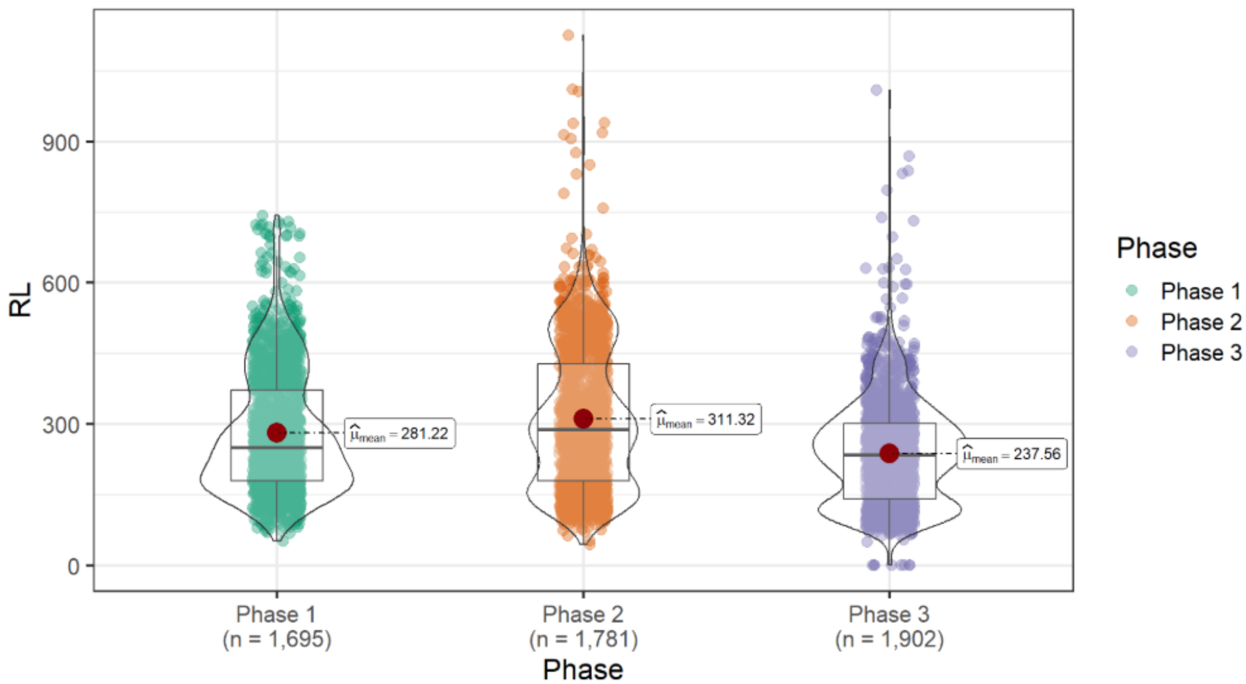


Figure 34. Distribution of R_L measures by marking condition (Good)

Mixed

Figure 35 presents the R_L distribution for pavement markings classified under the Mixed condition across three phases. In Phase I, the mean R_L is 388.33, reflecting strong visibility for many of the markings, despite their classification as mixed, potentially due to sections with recently refreshed markings alongside deteriorating ones. In Phase II, the mean R_L drops significantly to 246.70, suggesting a general decline in performance, possibly due to aging materials or exposure to harsh conditions. This downward trend continues into Phase III, where the mean R_L further decreases to 194.44, indicating continued deterioration or insufficient maintenance for markings in this category. The violin shapes also show a clear tightening and downward shift in distribution from Phase I to Phase III, highlighting a loss of higher-R_L observations over time.

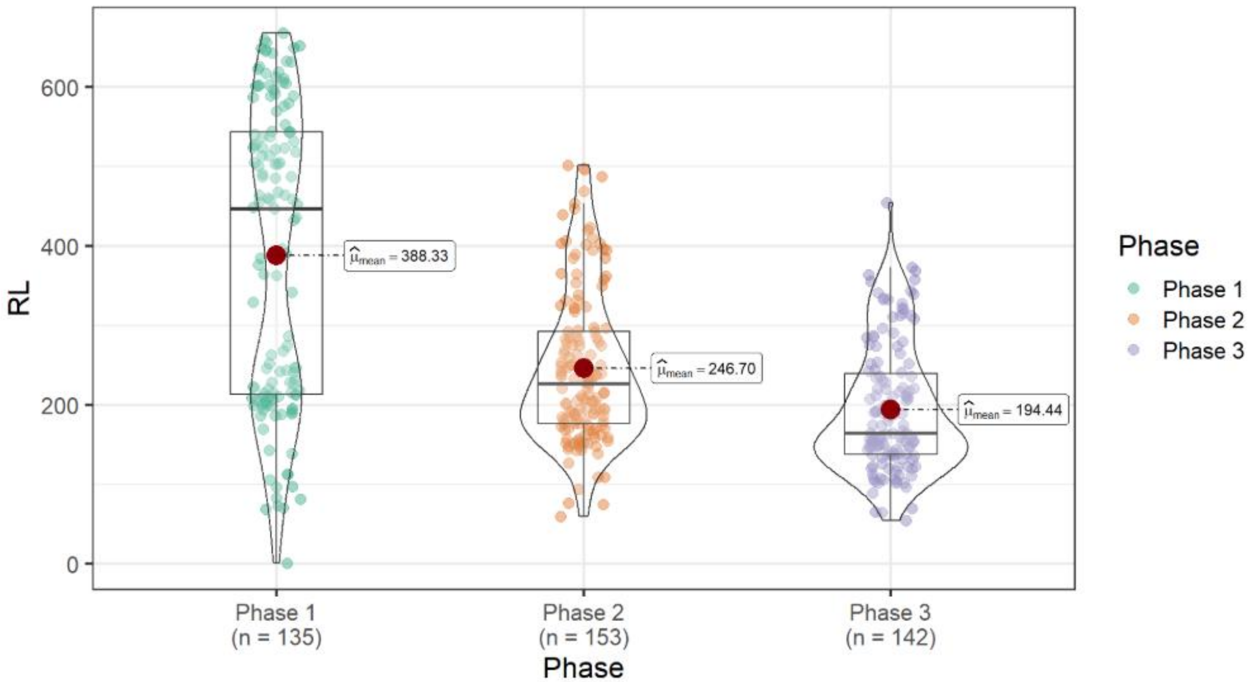


Figure 35. Distribution of R_L measures by marking condition (Mixed)

Older

The violin plot in Figure 36 illustrates the R_L distribution for pavement markings classified as Older across three data collection phases. In Phase I, the mean R_L is 133.21, indicating generally poor visibility for these aged markings. Interestingly, a sharp improvement is observed in Phase II, where the mean R_L rises to 275.13, suggesting possible reapplication or maintenance efforts aimed at restoring visibility to these older segments. However, in Phase III, the mean R_L drops again to 151.28, reflecting a decline in performance, possibly due to further aging or lack of consistent upkeep following the temporary improvement seen in Phase I. The plots reveal that Phase II had the widest range and highest concentration of mid-to-high R_L values, whereas Phases I and III exhibit more compressed distributions skewed toward the lower end of the R_L scale. These findings underscored the need for sustained maintenance planning for older pavement markings, as short-term improvements may not ensure lasting performance.

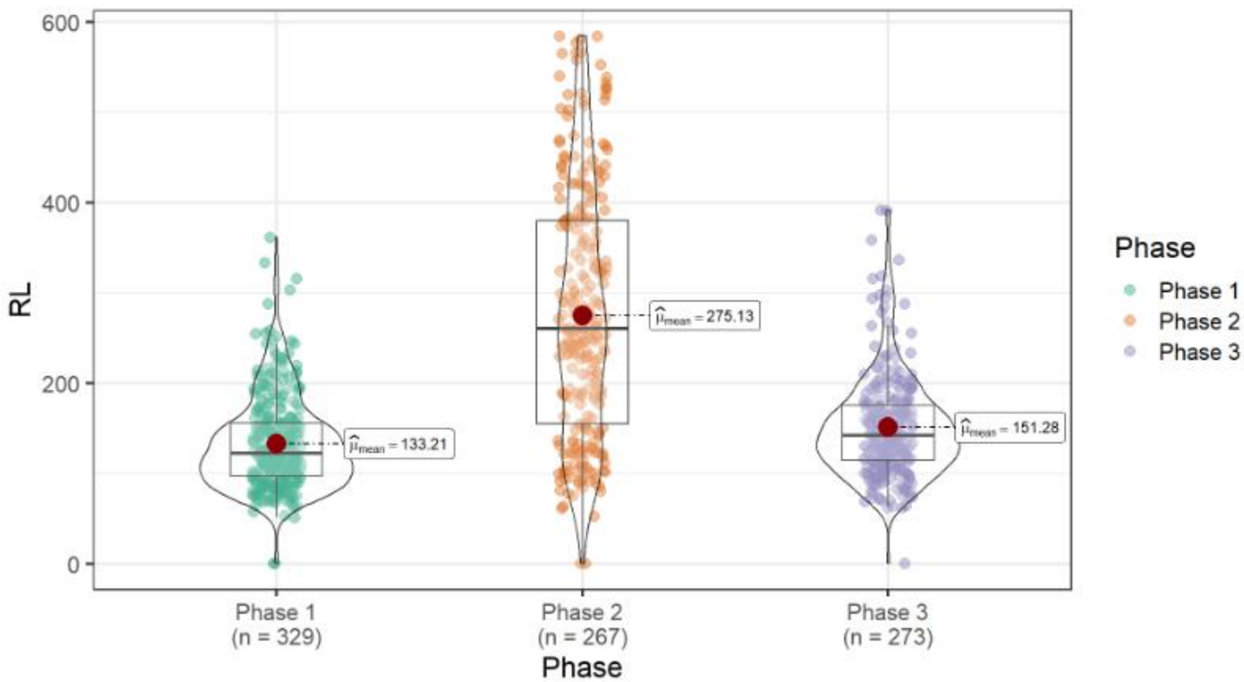


Figure 36. Distribution of R_L measures by marking condition (Older)

Analysis by Marking Type

The plot in Figure 37 displays the distribution of R_L values across five different pavement marking types. The 6in marking type exhibits the highest mean R_L at 333.99, indicating that wider markings tend to provide superior visibility, especially under nighttime conditions. Some milled rumble markings also show high performance with a mean R_L of 313.94, reinforcing the benefit of textured markings in enhancing reflectivity. In contrast, Milled Rumble and Different Types have lower mean R_L values at 243.18 and 237.21, respectively, suggesting potential variability in their application or wear performance. The Unknown category yields a moderate mean R_L of 260.30, indicating mixed performance likely due to inconsistent or undocumented marking characteristics. The spread of data varies considerably across types. “Different Types” shows a broad range with multiple outliers, while "Markings 6in" and "Some milled rumble" show tighter, more concentrated distributions, reflecting more consistent performance. These findings support the effectiveness of wider and specially textured markings in maintaining higher RL, and they highlight the need for clearer documentation and uniform standards across other marking types.

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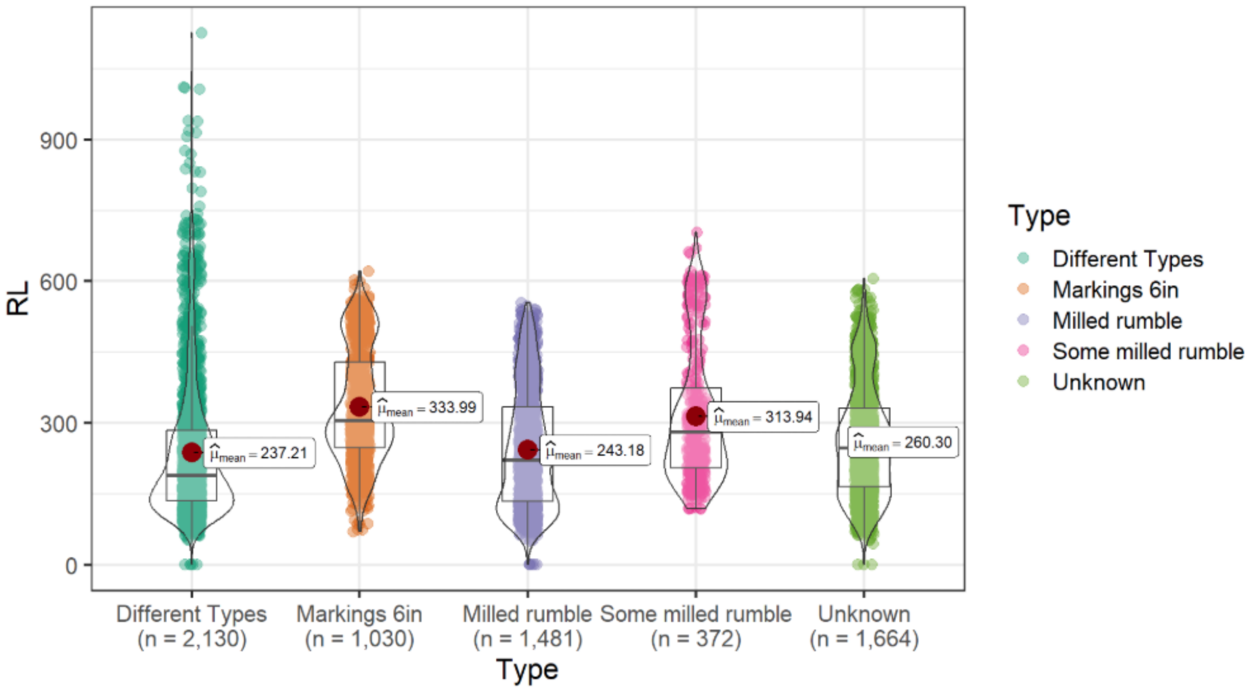

Figure 37. Distribution of R_L measures by marking type

Analysis by Material Type

Figure 38 compares the R_L performance across three pavement marking material types: Epoxy, Thermoplastic, and Thermoplastic tape. Among these, Thermoplastic demonstrates the highest mean R_L at 289.79, suggesting it offers superior visibility and reflectivity over time compared to the other materials. Thermoplastic (on asphalt) and tape (on PCC) follow with a mean R_L of 263.80, indicating relatively good performance, though with slightly greater variability. Epoxy, while being the most widely used material in the dataset (n = 4,287), has the lowest mean R_L at 252.06, highlighting potential limitations in maintaining long-term visibility under certain conditions. The spread in R_L values is broadest for thermoplastic, with a dense concentration of higher R_L values, reflecting strong and consistent visibility. Epoxy shows a more compressed distribution, suggesting more uniform but lower reflectivity performance. These results underscore thermoplastic's suitability for applications where enhanced nighttime visibility is a priority and highlight the need to re-evaluate maintenance strategies for epoxy-based markings.
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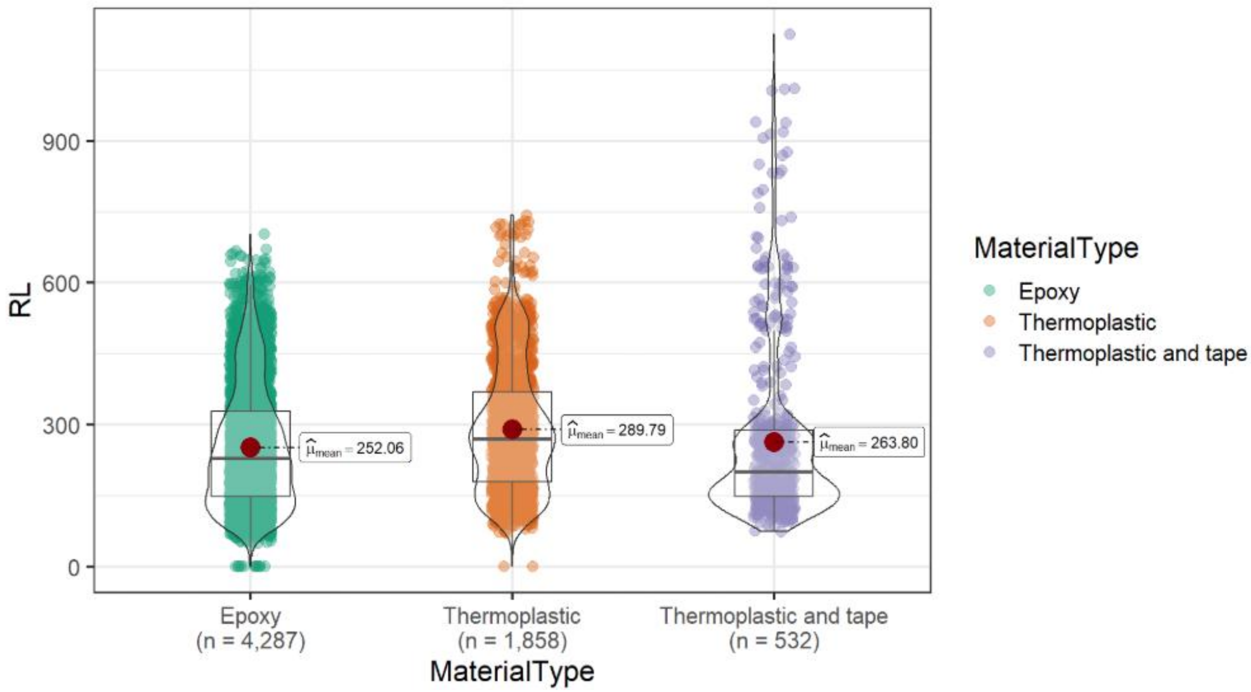


Figure 38. Distribution of R_L measures by material type

Analysis by Route

This section represents an overview of the exploratory analysis of the R_L values by routes. In this section, I 80, SH-15, and US-130 have been illustrated. The results from the analysis for all other routes are included in the appendix (see Figure 67-Figure 78).

Route I 80

The violin plot in Figure 39 shows the distribution of R_L values for pavement markings on I-80 across three phases of data collection. In Phase I, the mean RL value is 298.65, which increases to 423.76 in Phase II, indicating a strong improvement in pavement marking visibility during that period. However, by Phase III, the mean R_L value drops to 277.17, suggesting a reduction in R_L over time. The plot also shows changes in the shape and spread of the data. Phase II has a broader and taller distribution, with many R_L values in the higher range (above 400), while Phase III shows a tighter cluster of values with fewer high readings. Phase I has a moderate spread with R_L values mainly between 200 and 400. These patterns suggest that markings were likely refreshed or performed best during Phase II, but experienced wear and decline in brightness by Phase III.

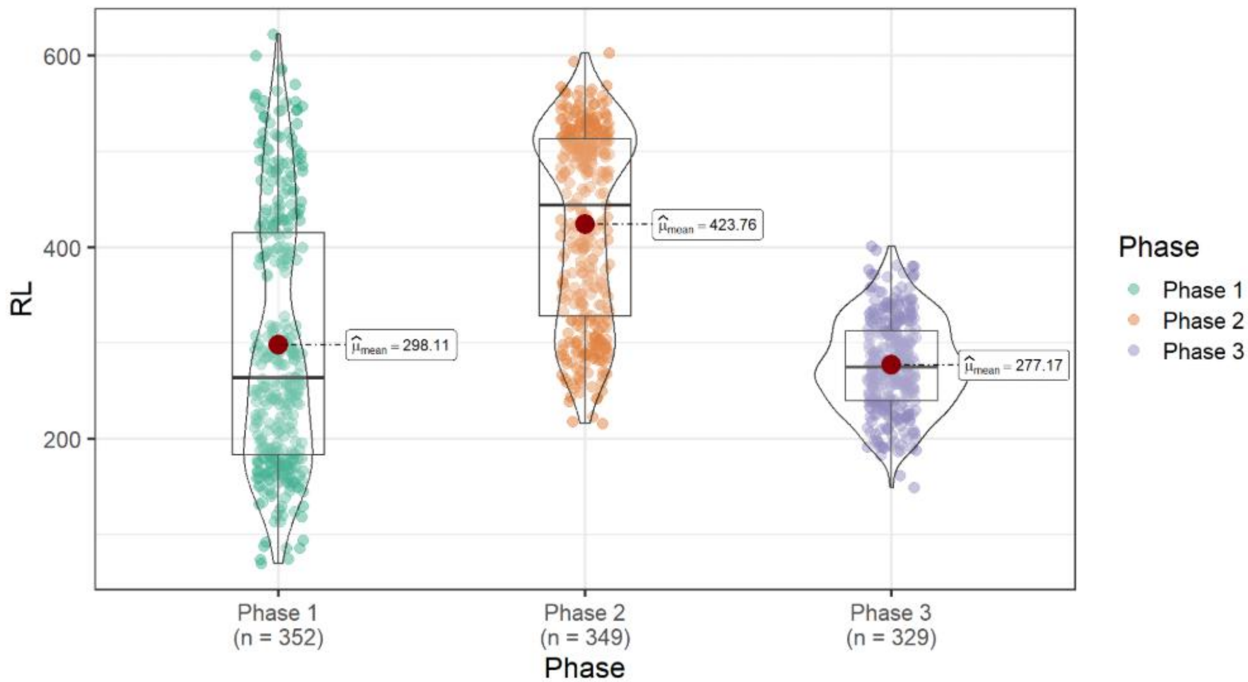


Figure 39. Distribution of R_L measures by route in all phases (I-80)

Route SH 15

Figure 40 shows the distribution of R_L values for pavement markings on SH 15 across three data collection phases. In Phase I, the mean R_L value is 133.59, indicating relatively low pavement marking visibility. In Phase II, the mean increases sharply to 360.59, reflecting a major improvement in R_L, likely due to new or recently refreshed markings. However, in Phase III, the mean R_L value drops back down to 138.16, nearly matching the value from Phase I. This pattern suggests that the pavement markings on SH 15 were either newly applied or significantly improved before Phase II but then experienced a noticeable decline by Phase III, possibly due to wear, traffic, or environmental exposure. The distribution in Phase II is wider and skewed toward higher values, while Phases I and III have tighter clusters around lower R_L values.

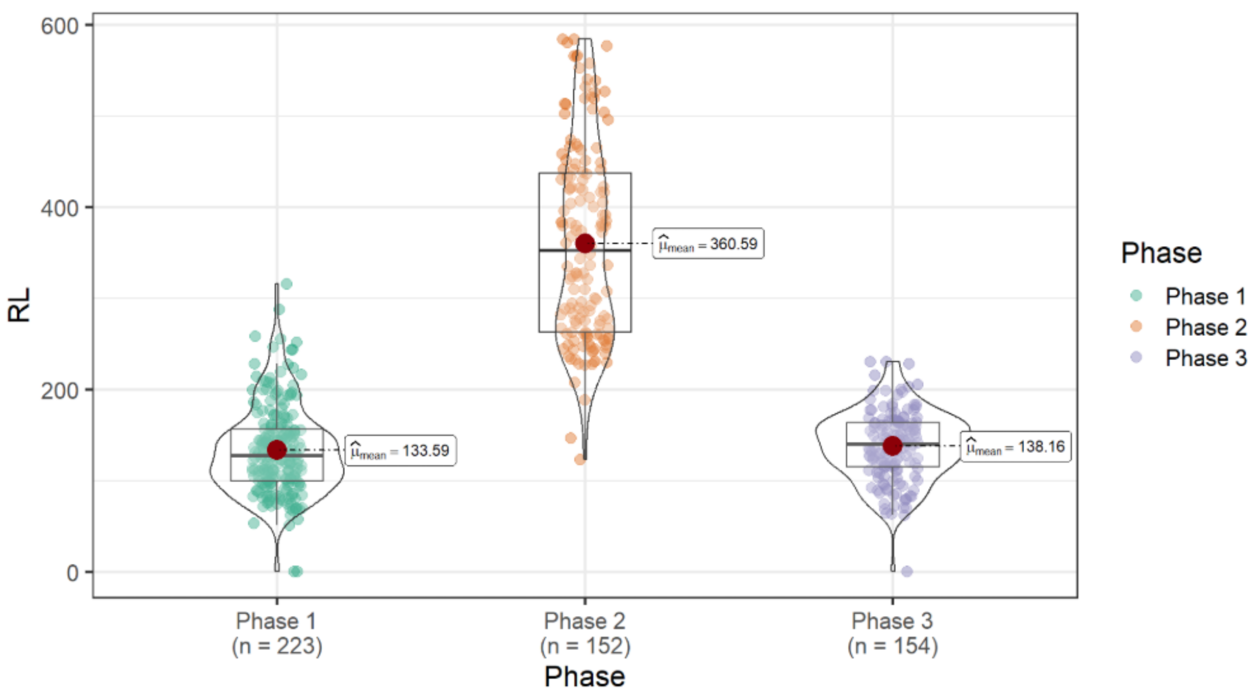


Figure 40. Distribution of R_L measures by route in all phases (SH 15)

Route US 130

The violin plot in Figure 41 for US 130 illustrates notable changes in pavement marking RL. In Phase I, the mean R_L is 388.33, indicating strong pavement marking visibility, with a wide distribution skewed toward higher reflectivity values (many measurements between 300 and 600). However, there is a significant decline in Phase II, with the mean dropping to 246.70. The distribution also shifts downward, suggesting that many pavement markings deteriorated or were not refreshed during this period. In Phase III, the mean R_L further declines to 194.44, and the distribution narrows, clustering more tightly around low R_L values. This suggests a continued degradation of marking visibility, potentially raising safety concerns for nighttime or low-visibility driving.

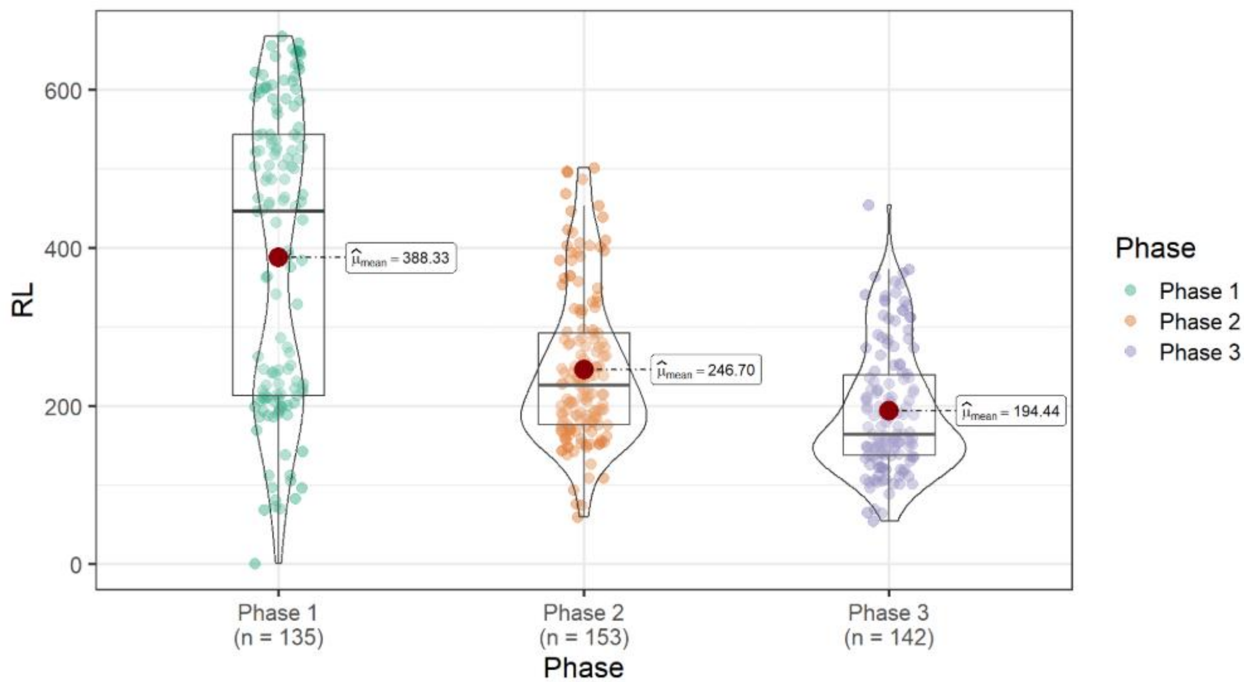


Figure 41. Distribution of R_L measures by route in all phases (US 130)

Analysis by Marking Color

Yellow

The violin plot in Figure 42 illustrates the R_L distribution for yellow pavement markings across the three data collection phases. In Phase I, the mean R_L is 222.83, reflecting a moderate level of visibility. Phase II shows a slight improvement, with the mean increasing to 233.50, possibly due to newer applications or recent maintenance activities during that period. However, in Phase III, the mean R_L declines to 193.71, suggesting that yellow markings are experiencing degradation in reflectivity over time. This reduction could be attributed to environmental wear, fading pigments, or material breakdown. The violin plot shape in Phase III also shows a more compressed distribution concentrated at lower R_L values, indicating a widespread reduction in visibility performance.

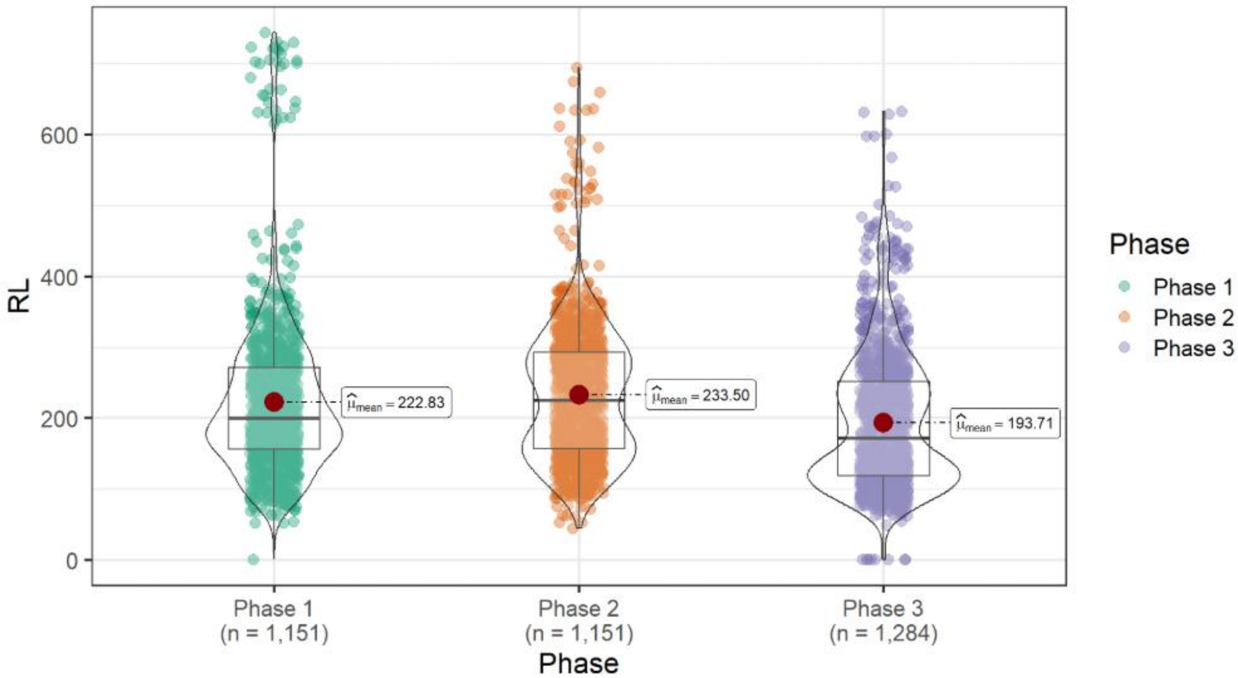


Figure 42. Distribution of R_L measures by marking color in all phases (Yellow)

White

The distribution of R_L values for white pavement markings across three data collection phases is illustrated in Figure 43. In Phase I, the mean R_L is 313.94, indicating strong visibility and performance. This visibility further improves in Phase II, where the mean R_L increases to 378.01, suggesting that many white markings were recently applied or had undergone maintenance during this phase. By Phase III, however, the mean R_L drops to 263.33, pointing to a decline in reflectivity likely caused by environmental wear, dirt accumulation, or degradation of marking materials. Despite the decrease, the Phase III mean remains above the critical visibility threshold, although the violin shape shows a wider spread, suggesting more variability in performance.

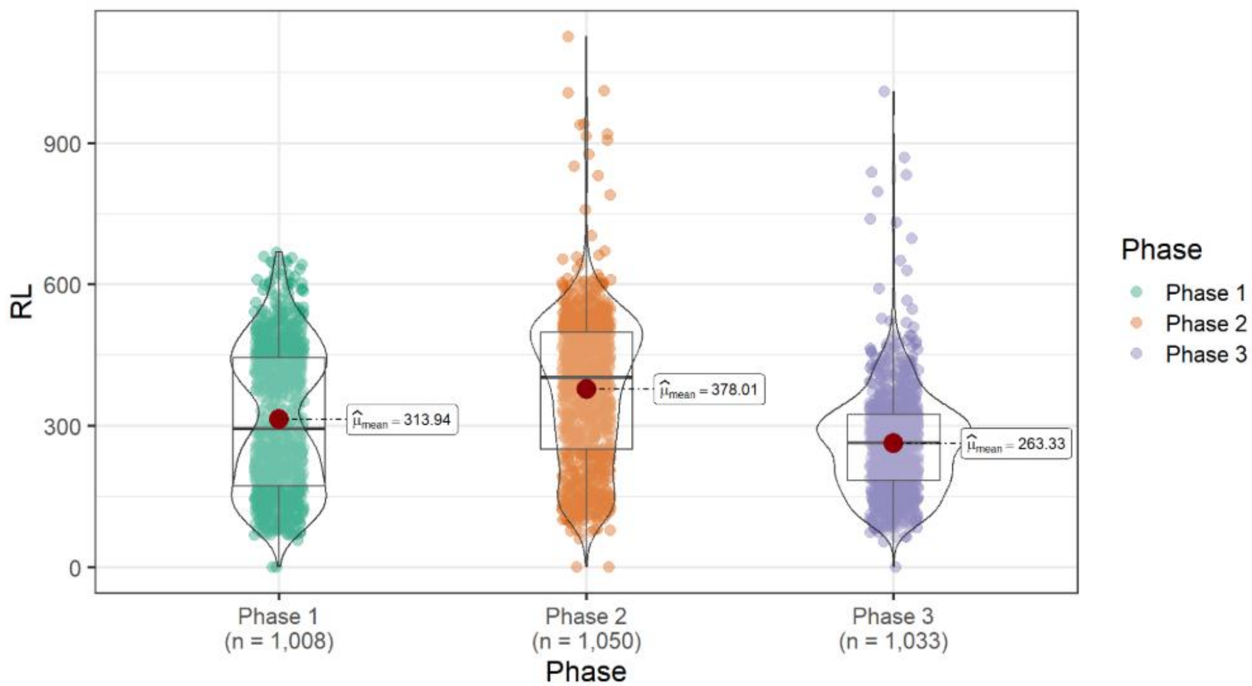


Figure 43. Distribution of R_L measures by marking color in all phases (White)

Analysis by Line Type

Edge

The plot in Figure 44 displays the distribution of R_L values for edge lines across all three phases. In Phase I, the mean R_L is 242.14, representing a moderate level of edge line visibility at the start of the study period. In Phase II, the mean R_L increases to 283.27, indicating improved performance, likely due to recent applications or better material conditions during that phase. However, Phase III shows a decline in mean R_L to 226.93, pointing to a deterioration in reflectivity over time. While still above the minimum visibility thresholds in many contexts, the downward trend suggests that edge lines are susceptible to wear and environmental degradation, emphasizing the importance of periodic maintenance. The plot across all phases reveals considerable spread, indicating variability in performance across locations. This variability reinforced the need for location-specific assessments rather than relying solely on phase-wide averages. These findings highlight that although edge lines initially perform well, proactive management is essential to ensure long-term visibility and safety, particularly for nighttime and low-contrast driving environments.

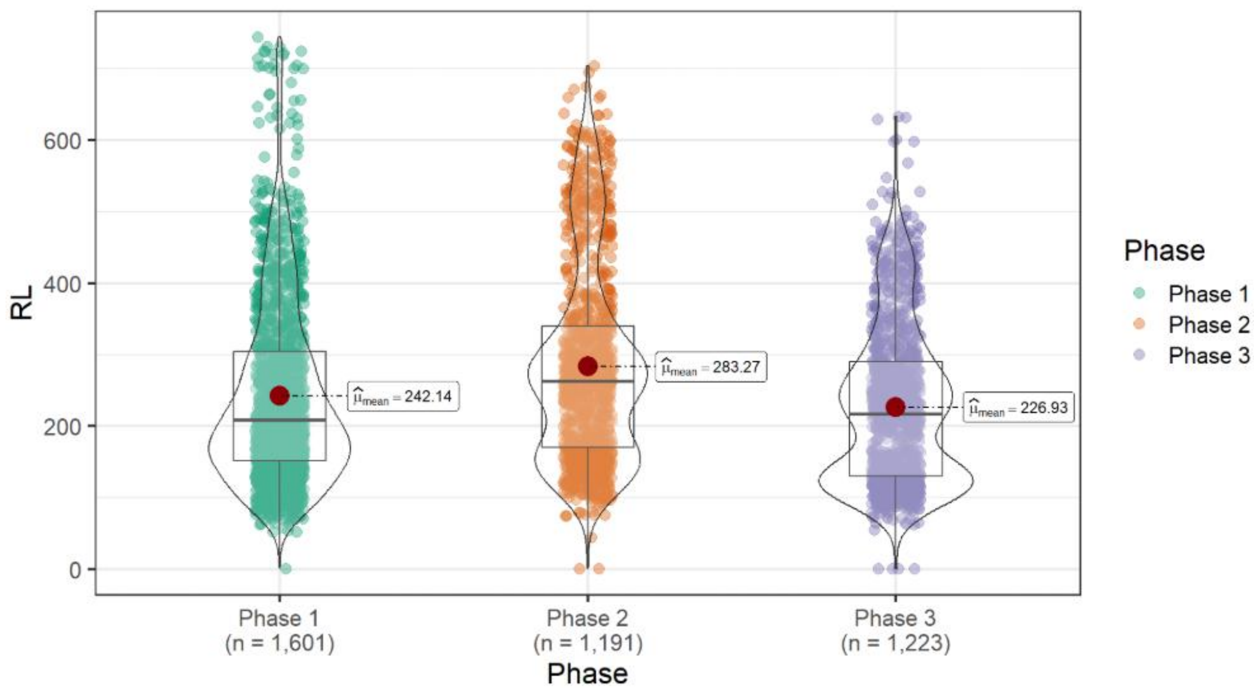


Figure 44. Distribution of R_L measures by line type in all phases (Edge)

Center

The plot in Figure 45 presents the R_L distribution for centerline markings across the three data collection phases. In Phase I, the mean R_L is 202.56, suggesting a modest baseline visibility for center markings. Phase II shows a slight improvement with a mean R_L of 214.67, which may reflect resurfacing or temporary enhancements in certain locations. However, in Phase III, the mean R_L declines to 173.85, indicating noticeable degradation in reflectivity. This decrease in R_L values may be due to material wear, environmental exposure, or lack of recent maintenance. The Phase III violin plot also shows a compressed and lower-shifted distribution, highlighting a broad reduction in visibility for centerline markings. The findings suggest that centerlines exhibit lower R_L levels compared to edge lines, and their reflectivity appears to decline more consistently over time. This underscored the need for closer attention to centerline maintenance, as these markings play a critical role in guiding vehicle positioning and ensuring roadway safety, particularly under low-light or nighttime conditions.

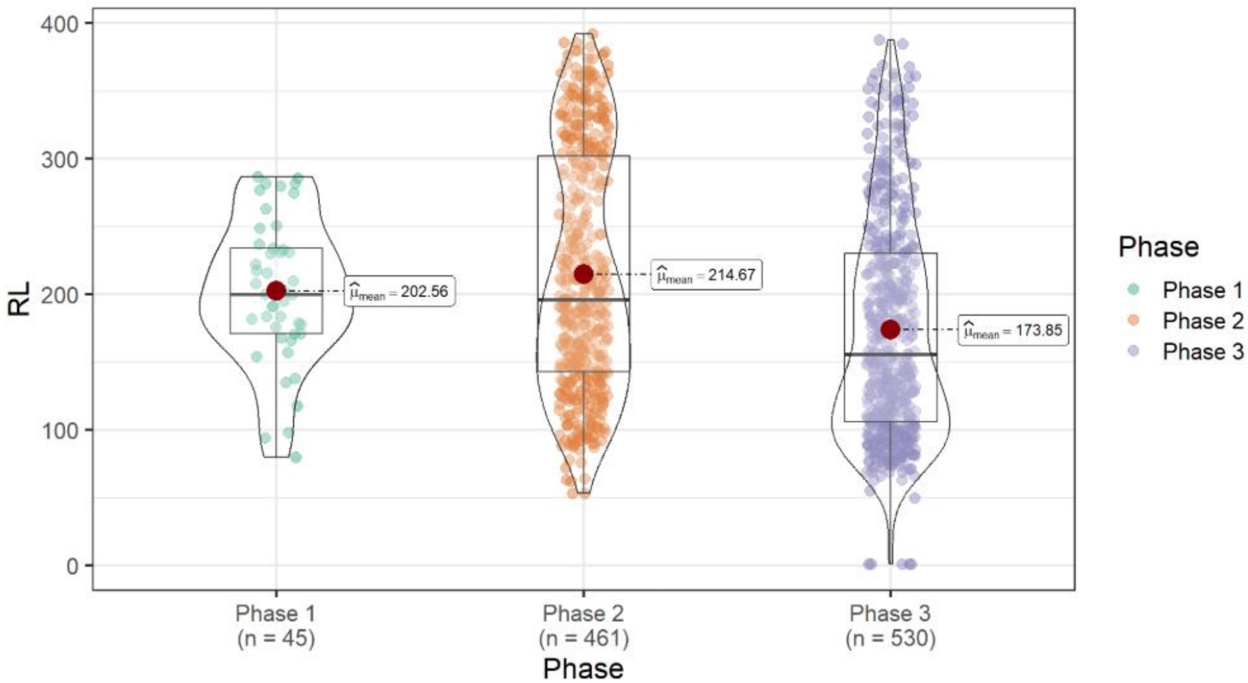


Figure 45. Distribution of R_L measures by line type in all phases (Center)

Skip

Figure 46 illustrates the R_L distribution for skip lines across the three study phases. In Phase I, the mean R_L is 343.36, indicating a relatively high level of visibility for these lane markings. Phase II shows an even more substantial improvement, with the mean R_L rising to 417.73, which may be attributed to recent installations or enhanced material performance during that timeframe. In Phase III, however, the mean R_L drops to 267.85, suggesting a significant decline in reflectivity. Despite the drop, skip lines still maintained higher reflectivity on average than edge and centerlines during this phase. The violin plot in Phase III shows a tighter distribution with fewer high outliers, pointing to a uniform but reduced performance. These results suggest that skip lines, which are often used for lane division and guiding traffic flow, initially perform well but may require periodic restriping to sustain high visibility.

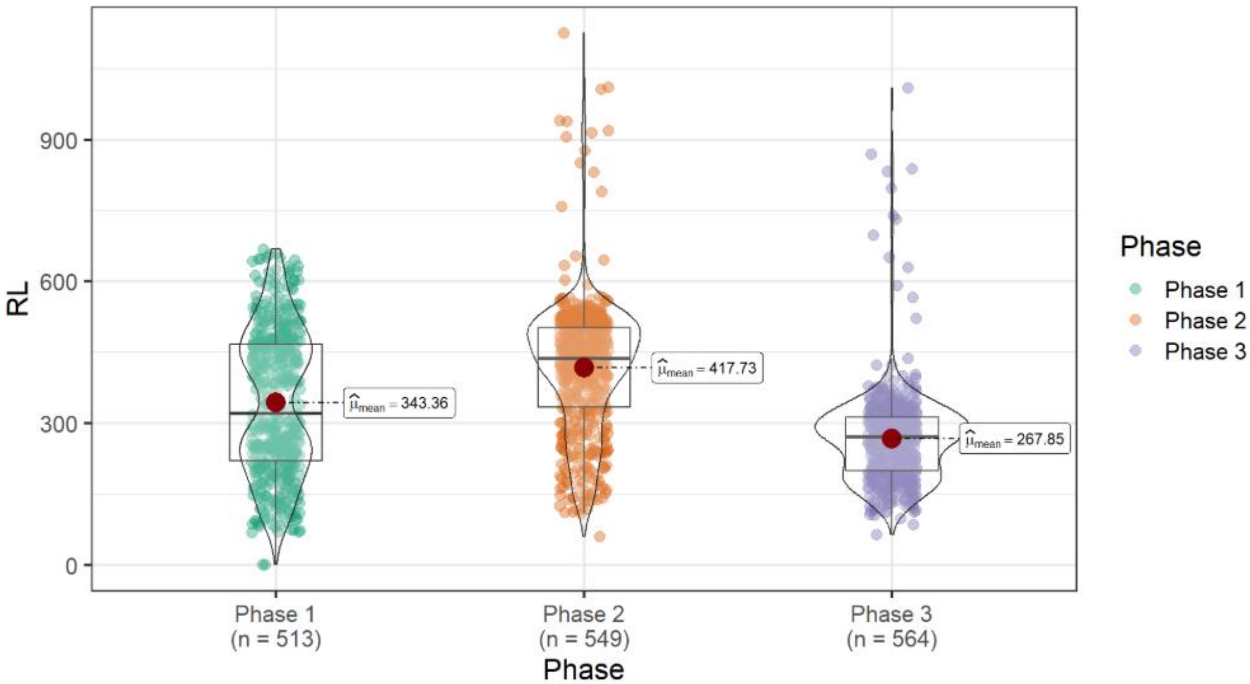


Figure 46. Distribution of R_L measures by line type in all phases (Skip)

***R_L* Value Trends by Driven Distance and Phase**

The changes in R_L across different road segments based on the distance driven is highlighted in Figure 47. Each small chart represents a specific route with direction, with the x-axis showing the miles driven and the y-axis showing the R_L values. The three colored lines represent the different data collection phases: red for Phase I, yellow for Phase II, and blue for Phase III. The shaded areas around each line show how much the R_L values varied at each point, giving a sense of consistency or fluctuation in marking performance. In many routes, R_L values were highest in Phase II, shown by the yellow lines. This suggests that the markings were either newer or better maintained during that time. In contrast, R_L values in Phase I and Phase III were generally lower, indicating older or more worn-out markings. This pattern can be seen clearly in routes like SH 54, I-80, and SH 37. In some cases, the decline from Phase II to Phase III is steep, pointing to rapid deterioration within a short time frame. Some routes show sudden increases or drop in R_L values at certain mile points. These changes may be caused by differences in marking material, resurfacing activities, or changes in pavement conditions. For example, the GSP Bridge and GSP segments have sharp shifts in R_L, especially over longer distances. On the other hand, routes like SH 72 EB and SH 72 WB show more stable R_L values across all three phases, which may indicate uniform application and consistent material quality. There are also differences in performance between travel directions for the same route. For instance, US 206 NB and SB show different patterns, with the southbound direction in Phase III having much lower R_L than the northbound. This suggests that direction-specific wear, maintenance schedules, or traffic volume could influence marking conditions. In several charts, especially for SH 15 and SH 50, the shaded areas are quite wide, showing a lot of variation in R_L across different mile points. This may point to uneven wear or inconsistent marking quality along those routes. This analysis gives a more detailed picture of how pavement markings hold up over time and distance. It highlights which routes have consistently good performance and which ones may need more attention. By looking at these patterns, it becomes easier to plan maintenance more effectively and ensure that markings stay visible and safe throughout their service life.

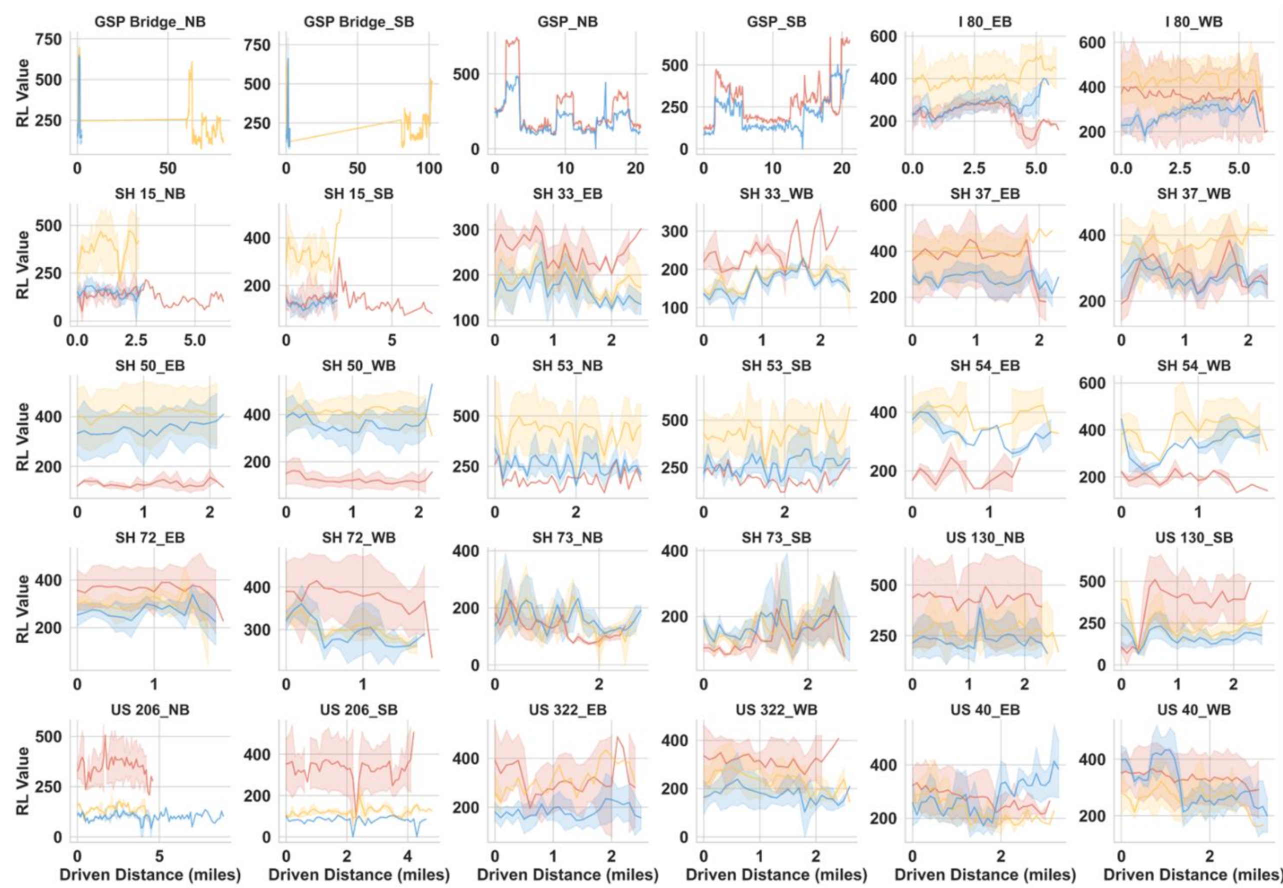


Figure 47. Line plot of R_L values by driven distance and phase

R_L Value Trends by Marking Color

The distribution of R_L values separately for yellow and white pavement markings across various roadway segments are shown in Figure 48. Each chart compares the R_L values between the two-color types using density plots, where the yellow lines represent yellow markings and the blue lines represent white markings. The x-axis shows the R_L values, while the y-axis indicates how densely those values appear in the dataset. White markings tend to have a wider spread and sometimes higher R_L values than yellow markings. This can be seen in routes like SH 54 EB, SH 50 WB, and US 322 EB, where the blue curve stretches farther to the right than the yellow curve, indicating a higher number of white markings with strong RL. In contrast, the yellow markings are often more tightly clustered and skewed toward lower R_L values, which may suggest faster degradation or less frequent maintenance. In some routes, such as SH 15 NB and GSP_SB, the yellow and white lines follow a similar shape but peak at different values, pointing to consistent differences in reflectivity between the two colors. In other cases, such as SH 33 WB or US 40 WB, the distributions are more spread out, which may reflect a mix of marking conditions across the segment. Notably, some white lines show multiple peaks, especially in places like SH 54 WB and US 130 NB, suggesting varying performance levels or different application times across the route. These patterns can help identify where markings may need improvement. For instance, consistently lower R_L values for yellow markings may highlight a need for more frequent maintenance or use of longer-lasting materials. The wider distribution for white markings may also indicate differences in how markings were applied or the traffic conditions that affect their wear. Overall, this analysis gives a clearer view of how pavement marking colors perform across the network.

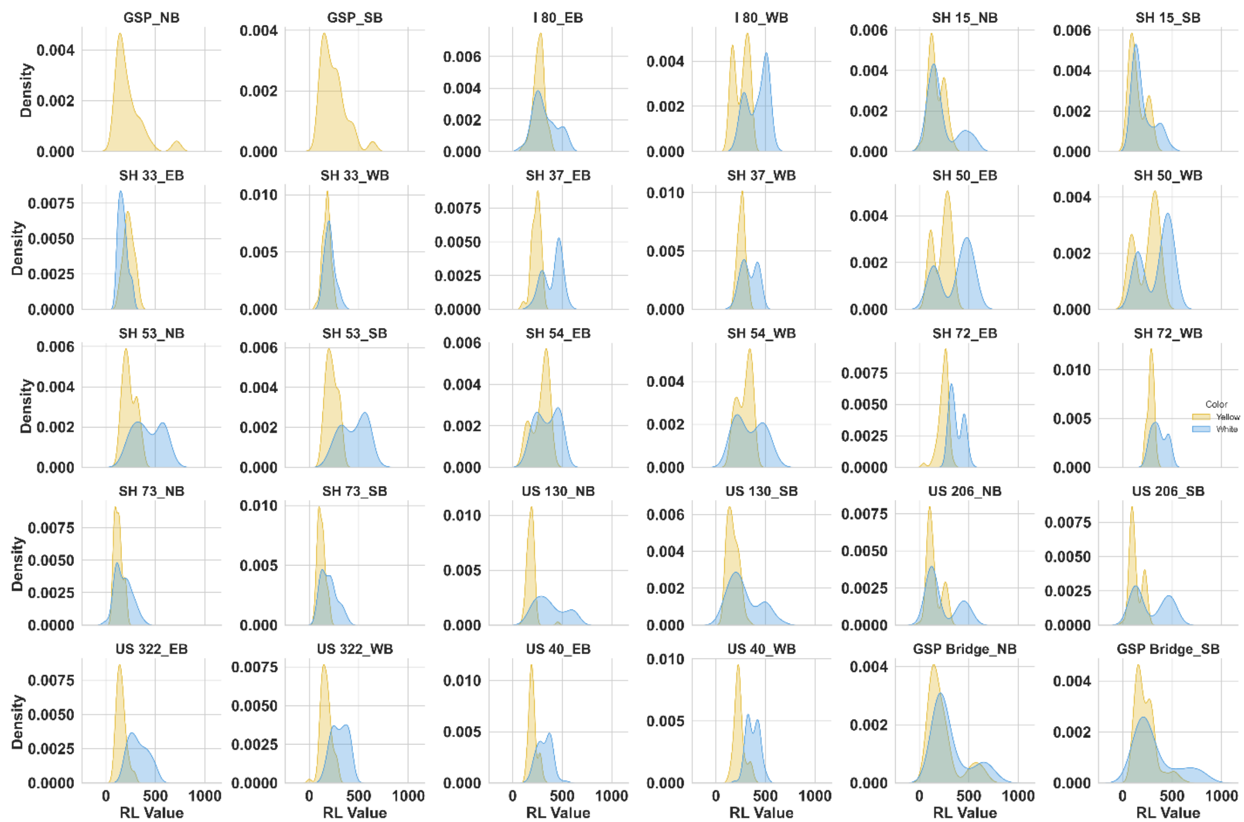


Figure 48. Density plot of R_L values across all routes by marking color

R_L Value Trends by Line Type

The changes in R_L values change with driven distance across various road segments, categorized by line type is shown in Figure 49. Each small plot represents a specific road segment and direction, while the three colored lines correspond to different line types: centerline, edge line, and skip line. The shaded regions around each line show the range or variability in the R_L values for that line type. In many of the segments, such as I 80_EB and US 130_SB, centerlines tend to have higher R_L values compared to skip or edge lines. This is evident from the consistently higher curves in those plots. In contrast, skip lines and edge lines often show lower R_L values, as seen in routes like SH 15_NB and US

322_WB. This suggests that some line types are wearing out faster or were initially applied with lower retroreflective quality.

For some routes, like GSP_NB and GSP_SB, the R_L values for all line types show significant fluctuation over the distance, possibly reflecting changes in pavement surface, environmental exposure, or variation in application quality. In a few roadways such as SH 33_EB or US 40_WB, all three-line types remain relatively close together in value, indicating more uniform marking conditions. This also highlights different line types of age and perform differently across road segments. Edge lines and skip lines often show lower R_L values and higher variability, which may require more frequent maintenance to ensure visibility, especially under nighttime or wet conditions.

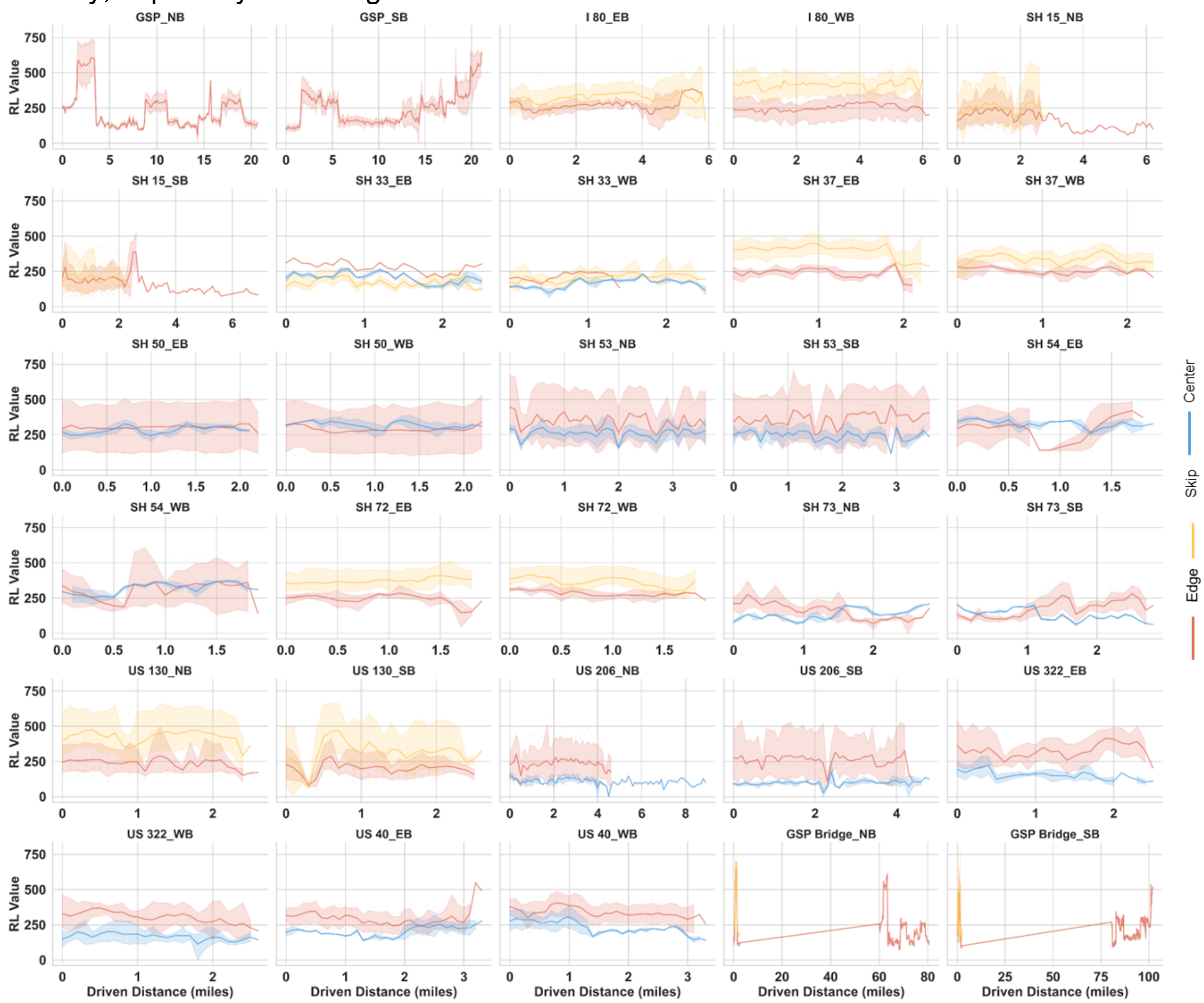


Figure 49. Line plot of R_L values by driven distance and line type

Retroreflective Quality Assessment

Video Data Processing

The video data used in this study was collected across fourteen distinct roadway routes as part of a systematic data acquisition effort conducted in December 2023 to April 2025 in three phases. Each video captured detailed pavement-related information, including retroreflectivity levels (R_L, Max, Min, Std), marking width, daylight contrast (DC), presence of raised retroreflective pavement markers (RRPM), temporal details (Date, Time), and roadway metadata such as route name, direction, phase, and condition. These attributes were encoded within the video frames and later extracted using optical character recognition (OCR), supporting automated assessment of pavement marking conditions through vehicle-mounted camera systems.

Video recordings were standardized with a resolution of 1280×720 and encoded using the MPEG4 codec. For each video, frames were extracted at one-second intervals, ensuring consistent sampling of the pavement surface while maintaining computational feasibility. This approach provided a representative visual subset of each roadway segment, capturing relevant features such as marking wear, gaps, and brightness levels.

Automated frame extraction was conducted using Python-based video processing scripts. The resulting images were organized into structured directories based on their respective phases and routes. This organization allowed for seamless integration with additional metadata extracted using OCR and laid the foundation for image-level classification tasks in the subsequent modeling phase. By covering all available routes and phases, the frame extraction process ensured comprehensive spatial and temporal representation of pavement conditions across the study area. Table 37 through Table 38 provide a phase-wise summary of the video metadata, including route names, durations, frame counts, and the number of extracted images for Phases I, II, and III respectively.

Table 37 - Phase I – Video Metadata Summary

Route Name	Duration (seconds)	Width (px)	Height (px)	Frames	Framerate	Total Images
Gsp Nb	1083.12	1280	720	27078	25	1083
Gsp Nb	1083.12	1280	720	27078	25	1083
Gsp Sb	1098.52	1280	720	27463	25	1099
Gsp Sb	1098.52	1280	720	27463	25	1099
I 80 Eb	339.48	1280	720	8487	25	339
I 80 Eb	339.48	1280	720	8487	25	339
I 80 Eb	370.76	1280	720	9269	25	371
I 80 Eb	370.76	1280	720	9269	25	371
I 80 Eb	275.52	1280	720	6888	25	276
I 80 Eb	275.52	1280	720	6888	25	276
I 80 Wb	326.2	1280	720	8155	25	326
I 80 Wb	326.2	1280	720	8155	25	326
I 80 Wb	350.76	1280	720	8769	25	351
I 80 Wb	350.76	1280	720	8769	25	351
I 80 Wb	332.92	1280	720	8323	25	333
I 80 Wb	332.92	1280	720	8323	25	333
Sh 15 Nb	629.28	1280	720	15732	25	629

Route Name	Duration (seconds)	Width (px)	Height (px)	Frames	Framerate	Total Images
Sh 15 Nb	629.28	1280	720	15732	25	629
Sh 15 Nb	187.96	1280	720	4699	25	188
Sh 15 Nb	187.96	1280	720	4699	25	188
Sh 15 Nb	184.32	1280	720	4608	25	184
Sh 15 Nb	184.32	1280	720	4608	25	184
Sh 15 Sb	711	1280	720	17775	25	711
Sh 15 Sb	711	1280	720	17775	25	711
Sh 15 Sb	176.84	1280	720	4421	25	177
Sh 15 Sb	176.84	1280	720	4421	25	177
Sh 15 Sb	206.28	1280	720	5157	25	206
Sh 15 Sb	206.28	1280	720	5157	25	206
Sh 33 Eb	308.16	1280	720	7704	25	308
Sh 33 Eb	308.16	1280	720	7704	25	308
Sh 33 Eb	329.08	1280	720	8227	25	329
Sh 33 Eb	329.08	1280	720	8227	25	329
Sh 33 Wb	336.44	1280	720	8411	25	336
Sh 33 Wb	336.44	1280	720	8411	25	336
Sh 33 Wb	233.12	1280	720	5828	25	233
Sh 33 Wb	233.12	1280	720	5828	25	233
Sh 37 Eb	166.68	1280	720	4167	25	167
Sh 37 Eb	166.68	1280	720	4167	25	167
Sh 37 Eb	213.72	1280	720	5343	25	214
Sh 37 Eb	213.72	1280	720	5343	25	214
Sh 37 Eb	160.64	1280	720	4016	25	161
Sh 37 Eb	160.64	1280	720	4016	25	161
Sh 37 Wb	188	1280	720	4700	25	188
Sh 37 Wb	188	1280	720	4700	25	188
Sh 37 Wb	266.88	1280	720	6672	25	267
Sh 37 Wb	266.88	1280	720	6672	25	267
Sh 37 Wb	169.24	1280	720	4231	25	169
Sh 37 Wb	169.24	1280	720	4231	25	169
Sh 50 Eb	158.16	1280	720	3954	25	158
Sh 50 Eb	158.16	1280	720	3954	25	158
Sh 50 Eb	150.04	1280	720	3751	25	150
Sh 50 Eb	150.04	1280	720	3751	25	150
Sh 50 Wb	167.88	1280	720	4197	25	168
Sh 50 Wb	167.88	1280	720	4197	25	168
Sh 50 Wb	153.04	1280	720	3826	25	153
Sh 50 Wb	153.04	1280	720	3826	25	153

Route Name	Duration (seconds)	Width (px)	Height (px)	Frames	Framerate	Total Images
Sh 53 Nb	396.16	1280	720	9904	25	396
Sh 53 Nb	396.16	1280	720	9904	25	396
Sh 53 Sb	413.12	1280	720	10328	25	413
Sh 53 Sb	413.12	1280	720	10328	25	413
Sh 54 Eb	106.88	1280	720	2672	25	107
Sh 54 Eb	106.88	1280	720	2672	25	107
Sh 54 Eb	93	1280	720	2325	25	93
Sh 54 Eb	93	1280	720	2325	25	93
Sh 54 Wb	143.08	1280	720	3577	25	143
Sh 54 Wb	143.08	1280	720	3577	25	143
Sh 54 Wb	100.2	1280	720	2505	25	100
Sh 54 Wb	100.2	1280	720	2505	25	100
Sh 72 Eb	144.52	1280	720	3613	25	145
Sh 72 Eb	144.52	1280	720	3613	25	145
Sh 72 Wb	143	1280	720	3575	25	143
Sh 72 Wb	143	1280	720	3575	25	143
Sh 72 Eb	176.68	1280	720	4417	25	177
Sh 72 Eb	176.68	1280	720	4417	25	177
Sh 72 Wb	183.92	1280	720	4598	25	184
Sh 72 Wb	183.92	1280	720	4598	25	184
Sh 73 Nb	217.92	1280	720	5448	25	218
Sh 73 Nb	217.92	1280	720	5448	25	218
Sh 73 Nb	237.56	1280	720	5939	25	238
Sh 73 Nb	237.56	1280	720	5939	25	238
Sh 73 Sb	222.6	1280	720	5565	25	223
Sh 73 Sb	222.6	1280	720	5565	25	223
Sh 73 Sb	239.8	1280	720	5995	25	240
Sh 73 Sb	239.8	1280	720	5995	25	240
Us 130 Nb	265.08	1280	720	6627	25	265
Us 130 Nb	265.08	1280	720	6627	25	265
Us 130 Nb	312	1280	720	7800	25	312
Us 130 Nb	312	1280	720	7800	25	312
Us 130 Nb	356.12	1280	720	8903	25	356
Us 130 Nb	356.12	1280	720	8903	25	356
Us 130 Sb	285.68	1280	720	7142	25	286
Us 130 Sb	285.68	1280	720	7142	25	286
Us 130 Sb	314.44	1280	720	7861	25	314
Us 130 Sb	314.44	1280	720	7861	25	314
Us 130 Sb	359.4	1280	720	8985	25	359

Route Name	Duration (seconds)	Width (px)	Height (px)	Frames	Framerate	Total Images
Us 130 Sb	359.96	1280	720	8999	25	360
Us 206 Nb	462.44	1280	720	11561	25	462
Us 206 Nb	462.44	1280	720	11561	25	462
Us 206 Nb	431.56	1280	720	10789	25	432
Us 206 Nb	431.56	1280	720	10789	25	432
Us 206 Sb	374.88	1280	720	9372	25	375
Us 206 Sb	374.88	1280	720	9372	25	375
Us 206 Sb	341.64	1280	720	8541	25	342
Us 206 Sb	341.64	1280	720	8541	25	342
Us 322 Eb	225.4	1280	720	5635	25	225
Us 322 Eb	225.4	1280	720	5635	25	225
Us 322 Eb	201.16	1280	720	5029	25	201
Us 322 Eb	201.16	1280	720	5029	25	201
Us 322 Wb	200.8	1280	720	5020	25	201
Us 322 Wb	200.8	1280	720	5020	25	201
Us 322 Wb	164.76	1280	720	4119	25	165
Us 322 Wb	164.76	1280	720	4119	25	165
Us 40 Eb	221.76	1280	720	5544	25	222
Us 40 Eb	221.76	1280	720	5544	25	222
Us 40 Eb	217.32	1280	720	5433	25	217
Us 40 Eb	217.32	1280	720	5433	25	217
Us 40 Wb	226.48	1280	720	5662	25	226
Us 40 Wb	226.48	1280	720	5662	25	226
Us 40 Wb	229.32	1280	720	5733	25	229
Us 40 Wb	229.32	1280	720	5733	25	229

Table 38 - Phase II – Video Metadata Summary

Route Name	Duration (seconds)	Width (px)	Height (px)	Frames	Framerate	Total Images
NJ GSP	1116.88	1280	720	27922	25	1117
NJ GSP	1116.88	1280	720	27922	25	1117
NJ GSP	1150.48	1280	720	28762	25	1150
NJ GSP	1151.84	1280	720	28796	25	1152
NJ I80	288.48	1280	720	7212	25	288
NJ I80	288.48	1280	720	7212	25	288
NJ I80	331.2	1280	720	8280	25	331
NJ I80	331.2	1280	720	8280	25	331
NJ I80	314.4	1280	720	7860	25	314

Route Name	Duration (seconds)	Width (px)	Height (px)	Frames	Framerate	Total Images
NJ I80	314.4	1280	720	7860	25	314
NJ I80	321.2	1280	720	8030	25	321
NJ I80	321.2	1280	720	8030	25	321
NJ I80	323.92	1280	720	8098	25	324
NJ I80	323.92	1280	720	8098	25	324
NJ I80	327.6	1280	720	8190	25	328
NJ I80	327.6	1280	720	8190	25	328
NJ15 NB	203.08	1280	720	5077	25	203
NJ15 NB	203.08	1280	720	5077	25	203
NJ15 NB	209.08	1280	720	5227	25	209
NJ15 NB	209.08	1280	720	5227	25	209
NJ15 NB	258.64	1280	720	6466	25	259
NJ15 NB	258.64	1280	720	6466	25	259
NJ15 SB	184.4	1280	720	4610	25	184
NJ15 SB	184.4	1280	720	4610	25	184
NJ15 SB	232.4	1280	720	5810	25	232
NJ15 SB	232.4	1280	720	5810	25	232
NJ15 SB	164.84	1280	720	4121	25	165
NJ15 SB	164.84	1280	720	4121	25	165
NJ33 EB	282.4	1280	720	7060	25	282
NJ33 EB	282.4	1280	720	7060	25	282
NJ33 EB	378.08	1280	720	9452	25	378
NJ33 EB	378.08	1280	720	9452	25	378
NJ33 WB	401.4	1280	720	10035	25	401
NJ33 WB	401.4	1280	720	10035	25	401
NJ33 WB	379.32	1280	720	9483	25	379
NJ33 WB	379.32	1280	720	9483	25	379
NJ37 EB	192.36	1280	720	4809	25	192
NJ37 EB	192.36	1280	720	4809	25	192
NJ37 EB	244.84	1280	720	6121	25	245
NJ37 EB	244.84	1280	720	6121	25	245
NJ37 EB	163.32	1280	720	4083	25	163
NJ37 EB	163.32	1280	720	4083	25	163
NJ37 WB	197.16	1280	720	4929	25	197
NJ37 WB	197.16	1280	720	4929	25	197
NJ37 WB	209.44	1280	720	5236	25	209
NJ37 WB	209.44	1280	720	5236	25	209
NJ37 WB	196.56	1280	720	4914	25	197
NJ37 WB	196.56	1280	720	4914	25	197

Route Name	Duration (seconds)	Width (px)	Height (px)	Frames	Framerate	Total Images
NJ50 EB	147.16	1280	720	3679	25	147
NJ50 EB	147.16	1280	720	3679	25	147
NJ50 EB	159.4	1280	720	3985	25	159
NJ50 EB	159.4	1280	720	3985	25	159
NJ50 WB	154.12	1280	720	3853	25	154
NJ50 WB	154.12	1280	720	3853	25	154
NJ50 WB	165.56	1280	720	4139	25	166
NJ50 WB	165.56	1280	720	4139	25	166
NJ53 NB	426.64	1280	720	10666	25	427
NJ53 NB	426.64	1280	720	10666	25	427
NJ53 NB	424.08	1280	720	10602	25	424
NJ53 NB	424.08	1280	720	10602	25	424
NJ53 SB	403.8	1280	720	10095	25	404
NJ53 SB	403.8	1280	720	10095	25	404
NJ53 SB	373.12	1280	720	9328	25	373
NJ53 SB	373.12	1280	720	9328	25	373
NJ54 EB	117.44	1280	720	2936	25	117
NJ54 EB	117.44	1280	720	2936	25	117
NJ54 EB	139.12	1280	720	3478	25	139
NJ54 EB	139.12	1280	720	3478	25	139
NJ54 WB	125.04	1280	720	3126	25	125
NJ54 WB	125.04	1280	720	3126	25	125
NJ54 WB	123.36	1280	720	3084	25	123
NJ54 WB	123.36	1280	720	3084	25	123
NJ72 EB	132.32	1280	720	3308	25	132
NJ72 EB	132.32	1280	720	3308	25	132
NJ72 EB	154.84	1280	720	3871	25	155
NJ72 EB	154.84	1280	720	3871	25	155
NJ72 WB	151.76	1280	720	3794	25	152
NJ72 WB	151.76	1280	720	3794	25	152
NJ72 WB	156.84	1280	720	3921	25	157
NJ72 WB	156.84	1280	720	3921	25	157
NJ73 NB	237.8	1280	720	5945	25	238
NJ73 NB	237.8	1280	720	5945	25	238
NJ73 NB	236.56	1280	720	5914	25	237
NJ73 NB	236.56	1280	720	5914	25	237
NJ73 SB	239.52	1280	720	5988	25	240
NJ73 SB	239.52	1280	720	5988	25	240
NJ73 SB	238.52	1280	720	5963	25	239

Route Name	Duration (seconds)	Width (px)	Height (px)	Frames	Framerate	Total Images
NJ73 SB	238.52	1280	720	5963	25	239
NJ US130	302.12	1280	720	7553	25	302
NJ US130	302.12	1280	720	7553	25	302
NJ US130	275.96	1280	720	6899	25	276
NJ US130	275.96	1280	720	6899	25	276
NJ US130	269.12	1280	720	6728	25	269
NJ US130	269.12	1280	720	6728	25	269
NJ US130	345.44	1280	720	8636	25	345
NJ US130	345.44	1280	720	8636	25	345
NJ US130	249.16	1280	720	6229	25	249
NJ US130	249.16	1280	720	6229	25	249
NJ US130	310.88	1280	720	7772	25	311
NJ US130	310.88	1280	720	7772	25	311
NJ US206	426.28	1280	720	10657	25	426
NJ US206	426.28	1280	720	10657	25	426
NJ US206	644.56	1280	720	16114	25	645
NJ US206	644.56	1280	720	16114	25	645
NJ US322	210.2	1280	720	5255	25	210
NJ US322	210.2	1280	720	5255	25	210
NJ US322	216.52	1280	720	5413	25	217
NJ US322	226.24	1280	720	5656	25	226
NJ US322	221.16	1280	720	5529	25	221
NJ US322	221.16	1280	720	5529	25	221
NJ US322	231.36	1280	720	5784	25	231
NJ US322	231.36	1280	720	5784	25	231
NJ US40	180.48	1280	720	4512	25	180
NJ US40	180.48	1280	720	4512	25	180
NJ US40	272.44	1280	720	6811	25	272
NJ US40	272.88	1280	720	6822	25	273
NJ US40	186.04	1280	720	4651	25	186
NJ US40	186.04	1280	720	4651	25	186
NJ US40	221.52	1280	720	5538	25	222
NJ US40	221.52	1280	720	5538	25	222

Table 39 - Phase III – Video Metadata Summary

Route Name	Duration (seconds)	Width (px)	Height (px)	Frames	Framerate	Total Images
GSP NB	1032.28	1280	720	25807	25	1032

Route Name	Duration (seconds)	Widt h (px)	Heigh t (px)	Frame s	Framerat e	Total Images
GSP SB	1017	1280	720	25425	25	1017
GSP BRIDGE NB	136.16	1280	720	3404	25	136
GSP BRIDGE NB	139.04	1280	720	3476	25	139
GSP BRIDGE SB	149.92	1280	720	3748	25	150
GSP BRIDGE SB	144.12	1280	720	3603	25	144
I 80 EB	295.4	1280	720	7385	25	295
I 80 EB	356.68	1280	720	8917	25	357
I 80 EB	248.48	1280	720	6212	25	248
I 80 WB	310.04	1280	720	7751	25	310
I 80 WB	348.68	1280	720	8717	25	349
I 80 WB	261.28	1280	720	6532	25	261
SH 15 NB	228.84	1280	720	5721	25	229
SH 15 NB	184.28	1280	720	4607	25	184
SH 15 NB	180.08	1280	720	4502	25	180
SH 15 SB	220.68	1280	720	5517	25	221
SH 15 SB	200.72	1280	720	5018	25	201
SH 15 SB	186.64	1280	720	4666	25	187
SH 33 EB	278.6	1280	720	6965	25	279
SH 33 EB	300.8	1280	720	7520	25	301
SH 33 WB	312.24	1280	720	7806	25	312
SH 33 WB	335.76	1280	720	8394	25	336
SH 37 EB	268.08	1280	720	6702	25	268
SH 37 EB	221.12	1280	720	5528	25	221
SH 37 EB	232.48	1280	720	5812	25	232
SH 37 WB	175.2	1280	720	4380	25	175
SH 37 WB	193.44	1280	720	4836	25	193
SH 37 WB	174.76	1280	720	4369	25	175
SH 50 EB	150.72	1280	720	3768	25	151
SH 50 EB	178.68	1280	720	4467	25	179
SH 50 WB	158	1280	720	3950	25	158
SH 50 WB	145.96	1280	720	3649	25	146
SH 53 NB	438.68	1280	720	10967	25	439
SH 53 NB	365.92	1280	720	9148	25	366
SH 53 SB	420.76	1280	720	10519	25	421
SH 53 SB	449.88	1280	720	11247	25	450

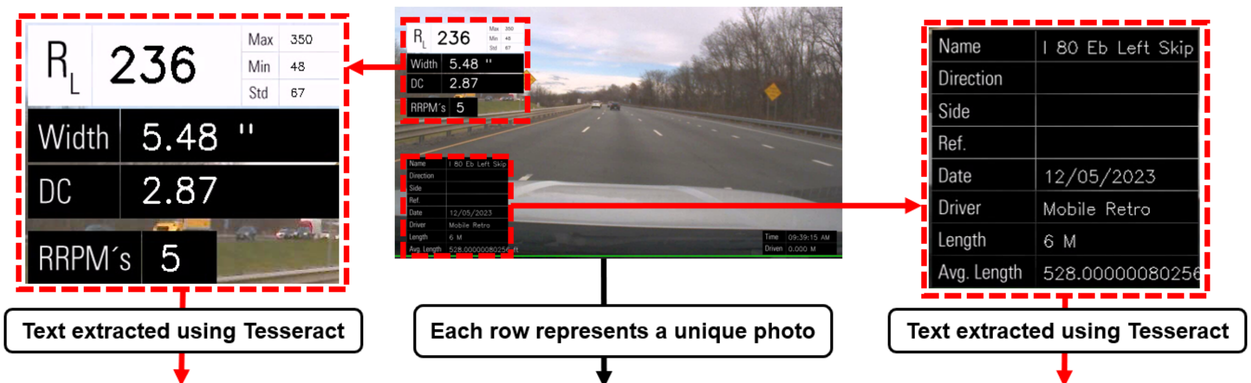
Route Name	Duration (seconds)	Width (px)	Height (px)	Frames	Framerate	Total Images
SH 54 EB	118.68	1280	720	2967	25	119
SH 54 EB	118.2	1280	720	2955	25	118
SH 54 WB	121.12	1280	720	3028	25	121
SH 54 WB	129.12	1280	720	3228	25	129
SH 72 EB	197.2	1280	720	4930	25	197
SH 72 EB	192.52	1280	720	4813	25	193
SH 72 WB	171.96	1280	720	4299	25	172
SH 72 WB	163.36	1280	720	4084	25	163
SH 73 NB	244.52	1280	720	6113	25	245
SH 73 NB	240.44	1280	720	6011	25	240
SH 73 SB	219.04	1280	720	5476	25	219
SH 73 SB	219.52	1280	720	5488	25	220
US 130 NB	293.16	1280	720	7329	25	293
US 130 NB	398.84	1280	720	9971	25	399
US 130 NB	253.76	1280	720	6344	25	254
US 130 SB	342.88	1280	720	8572	25	343
US 130 SB	380.28	1280	720	9507	25	380
US 130 SB	257.24	1280	720	6431	25	257
US 206 NB	675.2	1280	720	16880	25	675
US 206 NB	992.84	1280	720	24821	25	993
US 206 NB	992.84	1280	720	24821	25	993
US 206 SB	511.84	1280	720	12796	25	512
US 322 EB	222.36	1280	720	5559	25	222
US 322 EB	200.72	1280	720	5018	25	201
US 322 WB	212.32	1280	720	5308	25	212
US 322 WB	210.44	1280	720	5261	25	210
US 40 EB	234.88	1280	720	5872	25	235
US 40 EB	235.24	1280	720	5881	25	235
US 40 WB	233.6	1280	720	5840	25	234
US 40 WB	226.08	1280	720	5652	25	226

OCR-Based Image Metadata Extraction

The embedded metadata displayed within each video frame was automatically extracted using Tesseract, an open-source optical character recognition (OCR) engine. The vehicle-mounted recording system superimposed various pieces of information onto the video, such as retroreflectivity (R_L, Max, Min, Std), pavement marking width, daylight contrast (DC), and raised retroreflective pavement markers (RRPM). Additionally, contextual details such as route name, direction, collection date, driver label, and average pavement marking length were visually encoded in the frame overlay.

The OCR process was carefully tuned to ensure reliable text extraction despite varying lighting conditions, font styles, and on-screen distortions. Each frame was preprocessed before OCR to enhance contrast and reduce noise, improving Tesseract's ability to parse text accurately. Once extracted, the textual data was parsed, validated, and structured into a machine-readable tabular format, where each row corresponds to a unique video frame and thus a unique road segment snapshot.

The resulting dataset was saved as a CSV file for each route video files, containing well-labeled columns such as R_L, Max, Min, Std, Width, DC, RRPM, Date, Driver, Length, Avg_Length, Name, and Route. A sample visualization of this extraction workflow is presented in Figure 50, where the structured table at the bottom shows the data derived from OCR, and each text source area within the frame is boxed and labeled.



RL	Max	Min	Std	Width	DC	RRPM	Name	Date	Driver	Length	Avg_Length
236	350	48	67	5.48	2.87	5	I 80 Eb Left Skip _	12/5/2023	Mobile Retro	6M	528
236	350	48	67	5.48	2.87	5	I 80 Eb Left Skip _	12/5/2023	Mobile Retro	6M	528
236	350	48	67	5.48	2.87	5	I 80 Eb Left Skip _	12/5/2023	Mobile Retro	6M	528
236	350	48	67	5.48	2.87	5	I 80 Eb Left Skip _	12/5/2023	Mobile Retro	6M	528
236	350	48	67	5.48	2.87	5	I 80 Eb Left Skip _	12/5/2023	Mobile Retro	6M	528

Figure 50. Flow chart explaining the data extraction process

This tabular data was essential for linking physical roadway conditions with image-based assessments, as it provided quantitative measurements of pavement performance at the time each frame was recorded. Furthermore, it allowed for synchronized use of both metadata and visual inputs in training deep learning models for pavement marking condition classification.

Image Preprocessing

To prepare visual data for model training, a dedicated preprocessing pipeline was implemented to isolate and classify pavement markings. Since the full-frame images captured from the vehicle-mounted camera contained a wide range of visual elements including adjacent lanes, vehicles, background scenery, and signage, only the pavement marking regions were relevant for evaluating marking condition. Therefore, manual cropping was performed for each extracted frame to isolate the pavement markings as the primary region of interest.

This manual process ensured high fidelity in capturing the true condition of the markings while excluding surrounding noise. Each cropped image preserved critical features such as shape, reflectivity, brightness, and surface wear. Figure 51 illustrates this pipeline. beginning with the original frame, the pavement marking is cropped, then subjected to image manipulation such as normalization and resizing to prepare it for classification.

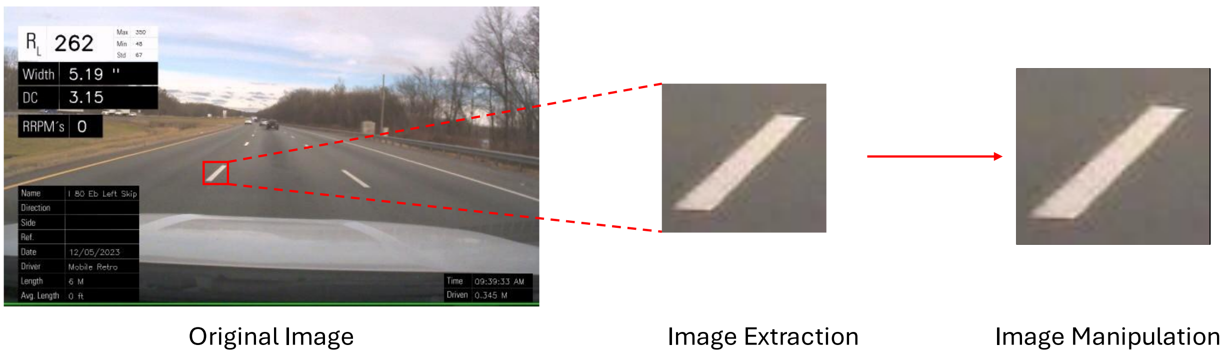
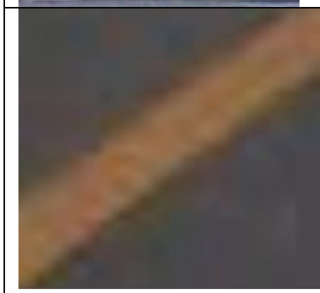
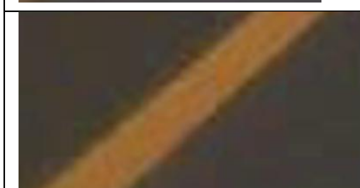
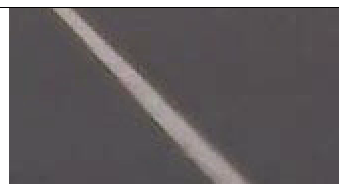
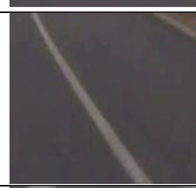
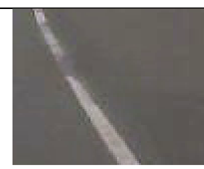
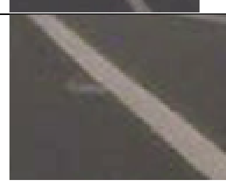
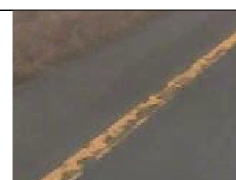
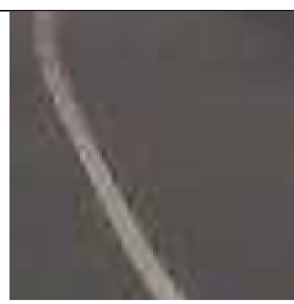
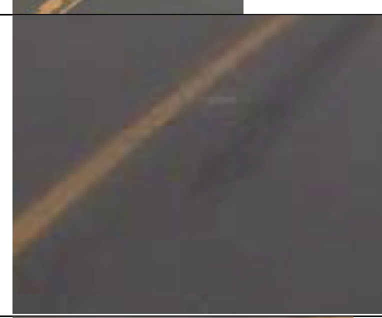
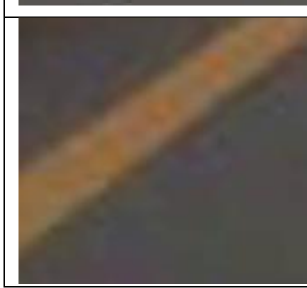


Figure 51. Image extraction and manipulation process

Once the marking regions were cropped, the images were uploaded to Roboflow, a cloud-based platform used for dataset organization, annotation, and preprocessing. Roboflow was used to manage image classification tasks, where each pavement marking was labeled into one of three quality categories based on its visual appearance and corresponding R_L value extracted via OCR:

- Poor – $R_L < 70$, typically representing completely faded or missing markings
- Medium – R_L between 70 and 150, indicating partially worn or degraded visibility
- Good – $R_L > 150$, reflecting clear, bright, and well-maintained markings

These thresholds were selected based on domain-specific guidance and established reflectivity standards in pavement marking evaluation. The labeled dataset was organized into class-specific folders within Roboflow, enabling streamlined exporting, format conversion, and dataset versioning. To illustrate these categories, Figure 52 presents representative samples from each pavement marking class. The examples demonstrate the visual differences in surface clarity, edge definition, and luminance that the deep learning models were trained to distinguish.

Good	Medium	Poor
		
		
		
		
		
		
		

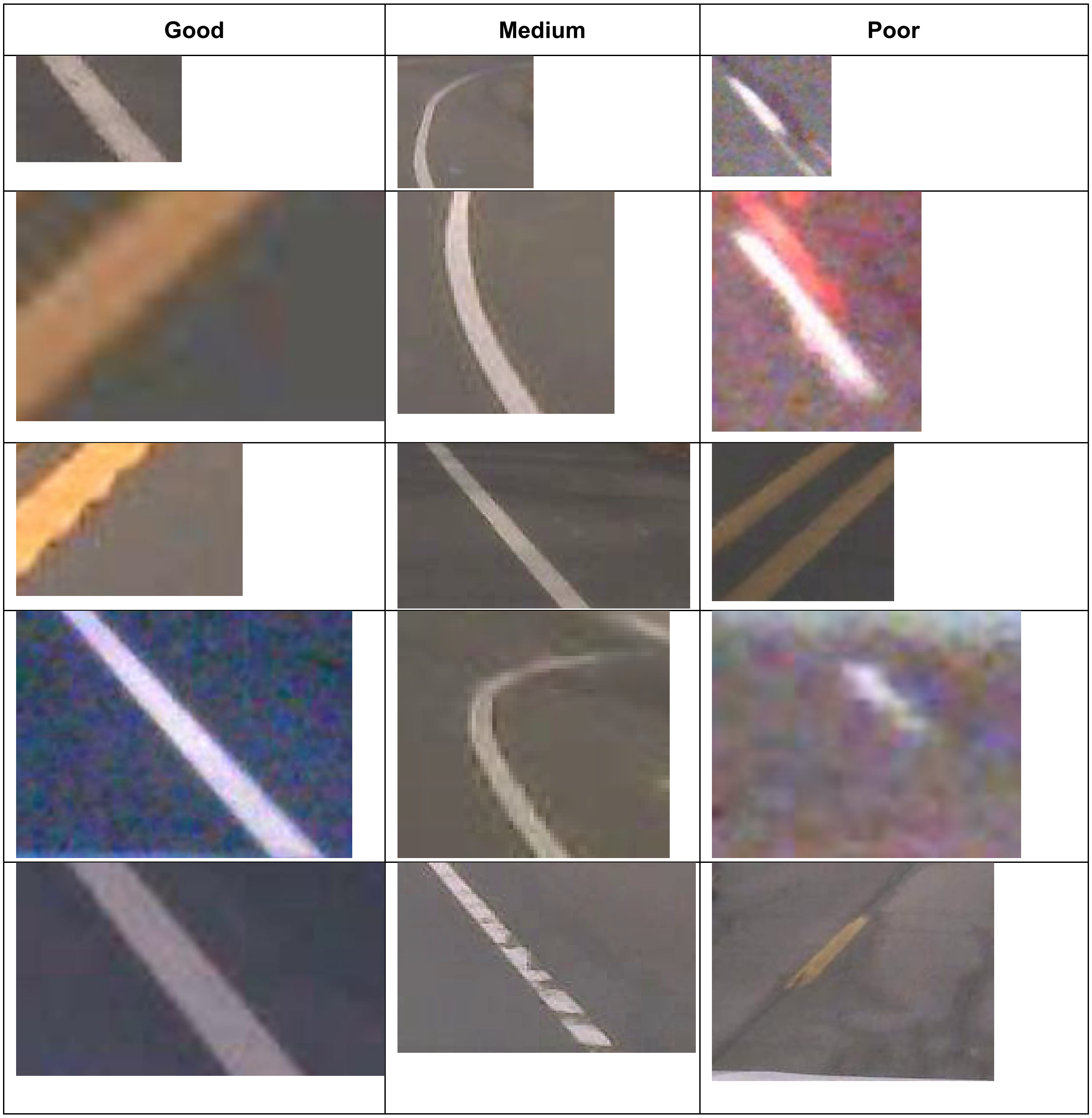


Figure 52. Sample images from each pavement classification

Before the images were incorporated into the dataset for labeling and training, they underwent additional formatting to ensure consistency and compatibility with deep learning workflows. First, all cropped pavement marking images were resized to a uniform dimension to maintain consistent input shape across the entire dataset. This resizing step was crucial to enable batch processing and convolution operations during model training.

Next, the images were normalized in the RGB color space, where pixel intensities were scaled to a fixed range (typically [0, 1]) to reduce the effect of lighting variations and improve model convergence. This step also helped the model generalize better by treating features based on relative color intensity rather than absolute brightness. Care was taken to preserve color integrity, as reflectivity characteristics - such as faded white or bright yellow - were visually distinguishable and relevant for classification.

Dataset Preparation and Modeling Approach

After manual labeling and cropping, the pavement marking images were organized into a structured dataset using Roboflow, a cloud-based platform designed for efficient computer vision dataset management. Roboflow was selected for its support of flexible image uploads, streamlined annotation workflows, and seamless integration with deep learning training pipelines.

The labeled images categorized into Good, Medium, and Poor classes, were uploaded into Roboflow, where each was assigned a single classification label. Since the task was focused on image-level classification (not object detection), bounding boxes were not required. Instead, each cropped pavement marking served as an independent training instance associated with a discrete quality label. Within Roboflow, the dataset was partitioned into training, validation, and testing sets, using stratified sampling to preserve the class distribution across splits. This ensured that each subset contained representative samples of all three categories, which was essential for building a balanced and generalizable model. The typical split used was 70% training, 20% validation, and 10% testing. All uploaded images were then preprocessed uniformly. Roboflow's pipeline resized the images to a fixed dimension (e.g., 640x640 pixels), standardizing the input shape expected by convolutional neural networks. Additionally, the images were normalized within the RGB color space to align pixel intensity values across samples, reduce the influence of lighting variations, and facilitate better convergence during model training.

The complete workflow is illustrated in Figure 53, which shows the full pipeline from processed image cropping to dataset generation. Processed images were uploaded via Python or the Roboflow interface, organized into labeled sets, and exported in a format compatible with machine learning frameworks such as TensorFlow or PyTorch. Each dataset export also included configuration files (e.g., data.yaml) and README documentation, enabling reproducibility and version control across model development iterations.

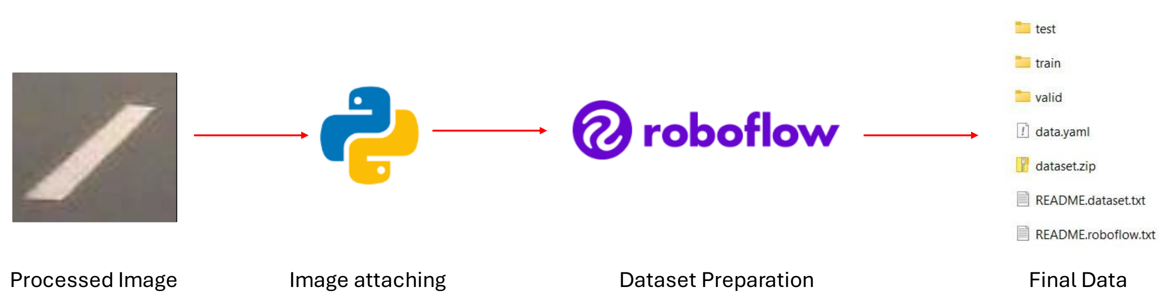


Figure 53. Data preparation process

Figure 54 outlines the modeling technique employed in the pavement marking quality analysis. The input dataset, after undergoing preprocessing, is divided into three distinct subsets using a 70-20-10 split: 70% of the data is allocated for training, 20% for testing, and 10% for validation. This division ensures a clear separation between model learning, evaluation, and generalization assessment. The training subset is used to fit the models, the testing subset evaluates initial performance, and the validation subset serves to fine-tune and select the most robust model based on its ability to generalize to unseen data.

The training process is conducted using six different deep learning architectures, each selected for its unique strengths in image classification:

- Convolutional Neural Network (CNN): A custom architecture that serves as the baseline model, known for its effectiveness in image feature extraction and classification tasks.
- MobileNetV2: A lightweight, mobile-friendly architecture that employs depthwise separable convolutions for efficient and fast image processing, suitable for edge-device deployment.
- EfficientNetB0: An optimized architecture that uses compound scaling to balance depth, width, and resolution, aiming for high performance with reduced computational cost.
- ResNet50: A deep residual network that incorporates skip connections to mitigate vanishing gradient problems, enabling stable training of deep networks.
- DenseNet121: A densely connected convolutional network that facilitates gradient flow and feature reuse, improving performance on complex image patterns.
- InceptionV3: A highly effective architecture that processes input using parallel convolutional layers of varying kernel sizes, enabling multi-scale feature extraction.

Each model is trained and evaluated independently using the same dataset splits to ensure comparability. Performance metrics such as accuracy, precision, recall, and F1-score are recorded during the validation phase. The model that demonstrates the best overall performance on the validation set, particularly in accurately identifying Good, Medium, and Poor pavement marking conditions will be selected as the final model for deployment and quality assessment. This multi-model evaluation framework ensures both robustness and flexibility in the modeling pipeline, leveraging diverse architectural strengths to select the most suitable solution for real-world pavement condition classification.

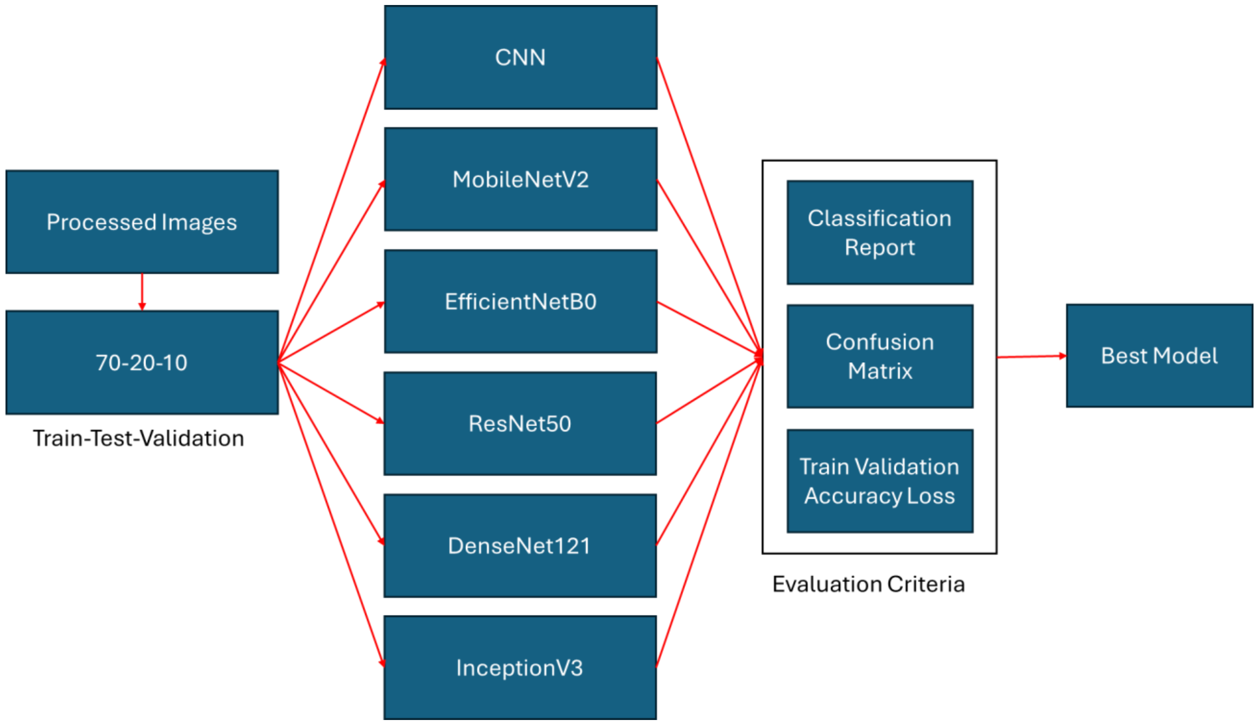


Figure 54. Modeling workflow

Class Imbalance Handling

In any supervised machine learning task, particularly in classification problems, the distribution of classes within the training dataset plays a critical role in shaping the performance and fairness of the model. In the context of this study, which aimed to classify pavement marking conditions into Good, Medium, and Poor, the original dataset exhibited a highly imbalanced class distribution. Specifically, the dataset initially comprised 5,596 images with the following breakdown: Good class contained 5,596 images, Medium had 2,652 images, and Poor contained only 238 images. This imbalance, if left unaddressed, would significantly bias the model toward the majority class and lead to suboptimal detection of degraded or unsafe markings, precisely the cases of most concern for roadway maintenance operations.

The imbalance was expected, as the majority of pavement markings observed during video collection were in satisfactory condition due to recent maintenance or standard upkeep cycles. Poor-quality markings were naturally underrepresented, often occurring in isolated or neglected roadway segments. However, in safety-critical applications such as infrastructure monitoring, the ability to accurately detect minority class instances (e.g., severely worn markings) is often more important than high overall accuracy. Therefore, addressing class imbalance was not just a technical requirement but a domain-specific necessity. To correct this skew and support balanced learning, a two-pronged strategy was adopted: data augmentation and stratified dataset partitioning.

Augmentation of Minority Classes
The first approach involved expanding the minority classes (Medium and Poor) through targeted data augmentation techniques. Augmentation is a widely accepted method in computer vision to synthetically increase dataset diversity without collecting new data. For this study, augmentation focused on generating realistic yet diverse representations of pavement markings by applying the following transformations:

- Rotation (within ±30°) to simulate angled views from vehicle movement or camera tilt
- Brightness and contrast adjustments to mimic different lighting conditions, such as shadows, glare, or dusk settings
- Horizontal flipping where geometrically valid, especially on roadways with symmetric lane structures
- Zooming, cropping, and shifting to account for partial occlusion, off-center alignments, or camera jitter
- Noise addition and slight blurring to emulate degradation from weather, dirt, or motion blur

These augmentation methods were carefully applied to only in the Poor classe to increase its representation in the training set. The transformations were chosen to preserve the semantic meaning of the images (i.e., the condition of the markings) while introducing variability that would help the model generalize better during inference. Augmentation was conducted using Roboflow's automated tools, which offered granular control over transformation parameters and allowed for dataset versioning and reproducibility.

Dataset Rebalancing and Partitioning
After augmentation, the dataset was re-evaluated and structured to ensure a more balanced class distribution. The total number of images in the curated set after preprocessing and augmentation was 4,306, which was then split into training (70%), validation (20%), and testing (10%) subsets. Importantly, stratified sampling was used during this split, ensuring that each partition maintained proportional representation from all three classes. This stratification was critical for fair model evaluation and to prevent data leakage from one phase of model development to another. Although the final dataset was not perfectly balanced across classes, the applied strategies significantly reduced the degree of skew and provided the model with sufficient examples of underrepresented

Model Architecture
To classify pavement marking conditions into three categories: Good, Medium, and Poor, five different deep learning models were developed, trained, and evaluated. These models were selected to explore both custom-built and state-of-the-art pretrained convolutional architectures, allowing for robust comparisons across network complexity, representational power, and generalizability. The section is structured into two parts: (1) a detailed breakdown of model architectures and theoretical foundations, and (2) the training and validation strategy applied uniformly across models. Six models were employed:

- Custom Convolutional Neural Network (CNN)

- MobileNetV2
- EfficientNetB0
- ResNet50
- DenseNet121
- InceptionV3

These models span the design spectrum, from lightweight and efficient networks optimized for mobile deployment to deeper, computationally intensive architectures capable of extracting complex hierarchical features.

Custom Convolutional Neural Network (CNN)
The custom CNN served as a baseline model, built from scratch using the Keras Sequential API. It consisted of two convolutional blocks followed by fully connected layers. Each block contained a 2D convolutional layer with a ReLU activation, followed by max pooling to reduce spatial dimensions:

$$ConvBlock(X) = MaxPool\big(ReLU(W * X + b)\big) \tag{5.1}$$

where $W$is the convolutional kernel, X is the input tensor, and $*$ denotes convolution.
After flattening, two dense layers were applied. Dropout was included to reduce overfitting. The final layer used a softmax activation to output the class probabilities:

$$\widehat{y_i} = \frac{e^{zi}}{\sum_{j=1}^{C} e^{zi}} \; for \; i = 1 \dots\dots C \tag{5.2}$$

where $\widehat{y_i}$ is the predicted probability for class iii, and C=3 for this multiclass classification task. Despite its simplicity, the custom CNN captured low- to mid-level features like line boundaries and reflectivity patches.

MobileNetV2
MobileNetV2 is a highly efficient architecture tailored for edge and mobile applications. It employs depth-wise separable convolutions and inverted residuals with linear bottlenecks, drastically reducing parameters and computation while preserving accuracy. In standard convolutions, the operation involves combining spatial and channel-wise filtering in one step. MobileNetV2 factorizes this into two stages:

- Depth-wise convolution: Applies a single filter per input channel
- Pointwise convolution: Combines output channels with 1×1 convolutions

Mathematically it can be expressed as below:

$$Y = PW\big(DW(X)\big) \tag{5.3}$$

$$DW: R^{HxWxC} \rightarrow R^{HxWxC} \tag{5.4}$$

$$PW: R^{HxWxC} \rightarrow R^{HxWxD} \tag{5.5}$$

MobileNetV2 incorporates linear bottleneck layers, preserving only essential features to reduce loss of spatial information. The base layers were frozen, and a custom classification head was appended using global average pooling and dense layers.

EfficientNetB0

EfficientNetB0 represents a family of models that scale depth, width, and resolution using a principled approach called compound scaling. The model balances model size and accuracy using:

$$depth = \alpha^{\emptyset}, width = \beta^{\emptyset}, resolution = \gamma^{\emptyset} \ subject\ to\ \alpha\beta^2\gamma^2 \approx 2 \tag{5.6}$$

where ϕ is a user-defined compound coefficient. EfficientNetB0 utilizes MBConv blocks (mobile inverted bottlenecks with squeeze-and-excitation modules), enabling the network to adaptively recalibrate channel-wise feature responses. The pretrained base was used with frozen weights, followed by a lightweight dense head. The input image resolution was upscaled to 224×224, matching the base network's configuration. EfficientNetB0 offered a strong trade-off between accuracy and parameter efficiency, making it suitable for moderately constrained environments.

ResNet50

ResNet50 is a deep convolutional neural network that belongs to the Residual Network (ResNet) family, originally proposed to mitigate the degradation problem encountered in very deep networks. The core innovation of ResNet lies in its use of residual connections, or “skip connections,” which allow the model to learn identity mappings by adding the input of a layer to the output of a deeper layer. This enables better gradient flow during backpropagation and facilitates the training of networks with substantially greater depth.

The ResNet50 architecture consists of 50 layers, including a series of convolutional, batch normalization, and ReLU activation layers, structured into bottleneck residual blocks. Each block comprises a 1×1 convolution for dimensionality reduction, a 3×3 convolution for spatial processing, and another 1×1 convolution for restoring dimensions. These layers are followed by global average pooling and a dense layer for classification. This architectural design allows the network to be computationally efficient while still benefiting from the representational power of depth.

In the context of pavement marking classification, ResNet50 serves as a robust feature extractor, particularly effective at capturing subtle differences in texture, brightness, and edge structure. Its pretrained weights on large-scale datasets (e.g., ImageNet) further accelerate convergence and enhance performance through transfer learning. By freezing the initial layers and fine-tuning the deeper layers on the pavement dataset, the model adapts to the domain-specific characteristics while retaining generalizable visual features. ResNet50's depth, stability during training, and proven track record in various vision tasks make it a strong candidate for applications requiring fine-grained visual classification.

DenseNet121

DenseNet121 is built on the concept of dense connectivity, where each layer receives as input the concatenation of feature maps from all previous layers:

$$x_l = H_l([x_0, x_1 \dots \dots x_{l-1}]) \tag{5.7}$$

where H_l is a composite function (BatchNorm → ReLU → Convolution), and $[x_0, x_1 \dots \dots x_{l-1}]$ denotes feature map concatenation.

This architecture encourages feature reuse, mitigates the vanishing gradient problem, and improves flow of information through the network. DenseNet121 was employed as a feature extractor, with a global average pooling layer and dense layers appended on top. Its ability to capture fine-grained spatial relationships made it particularly suited for distinguishing subtle differences in marking quality (e.g., between Medium and Poor classes).

InceptionV3

InceptionV3 is a deep CNN known for its multi-scale processing capability through Inception modules, which parallelize convolutions with varying kernel sizes:

$$InceptionOutput = Concat(1x1, 3x3, 5x5, Pooling) \tag{5.8}$$

This enables the model to extract hierarchical features at multiple spatial resolutions. The model also utilizes factorized convolutions (e.g.,3×3→1×3+3×1) to reduce parameters and increase depth.

InceptionV3 required input images of size 299×299, and a classification head was added to adapt the model to the three pavement classes. The pretrained base was frozen to retain general vision features, while the final layers were retrained.
Its expressive power made it effective in learning long-range dependencies and complex visual patterns in real-world road imagery.

Training and Validation

All models were trained using a unified pipeline to ensure comparability. Key training configurations included:

- Loss Function: Categorical Cross-entropy

  $$L = -\sum_{i=1}^{C} y_i \log(\hat{y_i}) \tag{5.9}$$

  where y_i is the ground truth (one-hot encoded) and $\hat{y_i}$ is the predicted probability.

- Optimizer: Adam (adaptive learning rate and momentum)
- Metrics: Accuracy, Precision, Recall, F1-score
- Training Duration: 100 epochs per model
- Batch Size: 32
- Image Resolutions:
  - 128×128 (CNN, MobileNetV2)
  - 224×224 (EfficientNetB0, DenseNet121)
  - 299×299 (InceptionV3)

- Dataset splits:
    - Training: 70%
    - Validation: 20%
    - Testing: 10%

All splits were stratified to preserve class proportions and reduce sampling bias. Training was performed in a CUDA-enabled GPU environment. Learning curves training/validation accuracy and loss were monitored across epochs to track model convergence, detect overfitting, and inform potential early stopping. To assess model performance beyond raw accuracy, class-wise precision, recall, and F1-score were computed from the confusion matrix. These metrics offered insights into model behavior on minority classes, particularly in identifying Poor markings, which carry the greatest practical significance for roadway safety and maintenance planning.

Results

Custom CNN Model

To evaluate the performance of the baseline CNN model for pavement marking classification, several metrics and visualizations were examined. The model was trained for 100 epochs with an Adam optimizer, using a learning rate of 0.001 and categorical cross-entropy as the loss function. As shown in the training curves, the model achieved high training accuracy (~98%) while maintaining stable validation accuracy (~90%) across epochs (see Figure 55). This indicates strong convergence and effective generalization on unseen data.

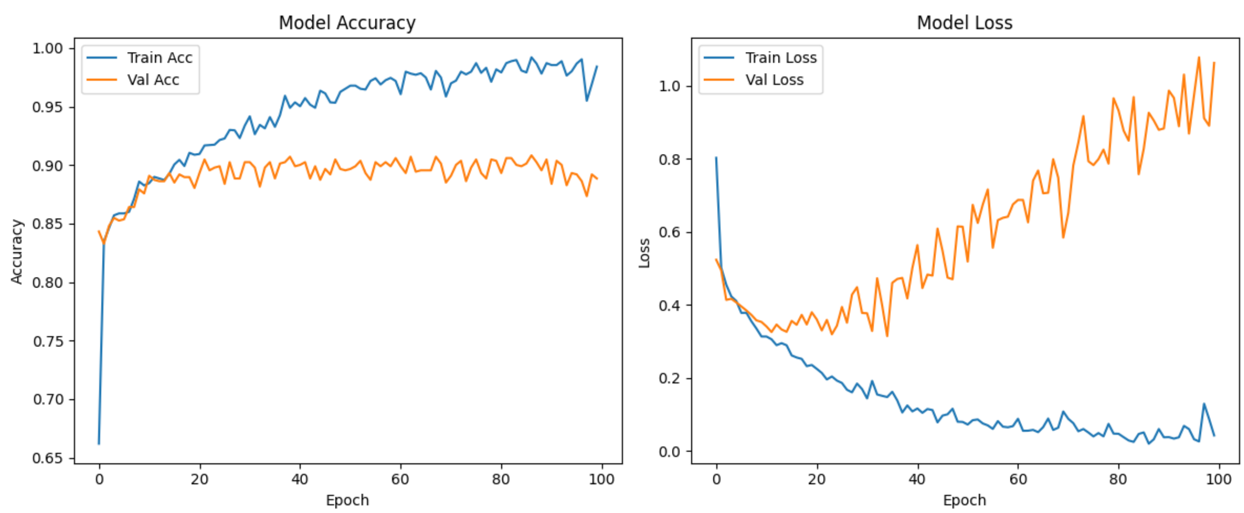


Figure 55. Training and validation accuracy and loss curves of CNN

The confusion matrix (see Figure 56) further validates the model's classification strength across the three categories: Good, Medium, and Poor (see figure below). The matrix reveals that most of the Good and Medium samples were accurately predicted, with 148 and 168 correct predictions respectively. The model also demonstrated robust performance in identifying Poor markings, with only a few misclassifications.

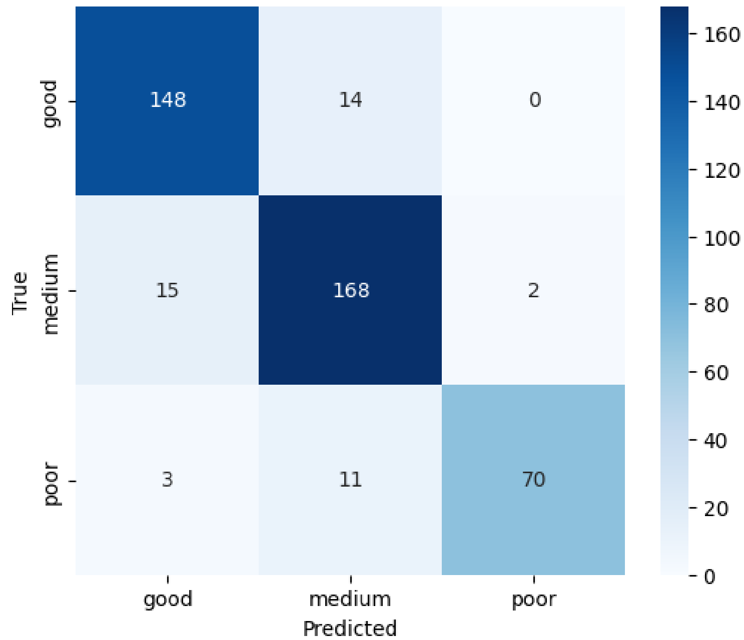


Figure 56. Confusion matrix of CNN

In addition to these visual assessments, the detailed classification report is summarized in Table 40. The model achieved an overall accuracy of 90% on the test set (431 samples). The precision and recall scores were particularly high for the Poor class (0.97 and 0.83, respectively), indicating the model's sensitivity to identifying degraded markings, which is crucial in real-world road maintenance applications.

Table 40 - CNN Model Classification Report

Class	Precision	Recall	F1-Score	Support
Good	0.89	0.91	0.90	162
Medium	0.87	0.91	0.89	185
Poor	0.97	0.83	0.90	84
Accuracy			0.90	431
Macro Avg	0.91	0.89	0.90	431
Weighted Avg	0.90	0.90	0.90	431

The macro average F1-score of 0.90 and the consistent weighted averages across all metrics suggest balanced model performance across all classes despite initial class imbalance in the dataset. This confirms the effectiveness of preprocessing, class balancing, and augmentation strategies adopted during dataset preparation.

MobileNetV2

MobileNetV2, a lightweight convolutional neural network architecture optimized for mobile and embedded vision applications, was deployed as one of the key transfer learning models for pavement marking quality classification. It is structured with inverted residuals and linear bottlenecks, significantly reducing computation while maintaining high representational power. The model's depthwise separable convolutions allow it to extract spatial features efficiently, making it particularly suited for large-scale image classification tasks under constrained computational resources.

To evaluate performance, MobileNetV2 was fine-tuned on the prepared dataset consisting of 4,306 images, split into training (70%), validation (20%), and testing (10%) subsets. The model was trained for 100 epochs using the Adam optimizer with a learning rate of 0.001, and categorical cross-entropy was employed as the loss function.

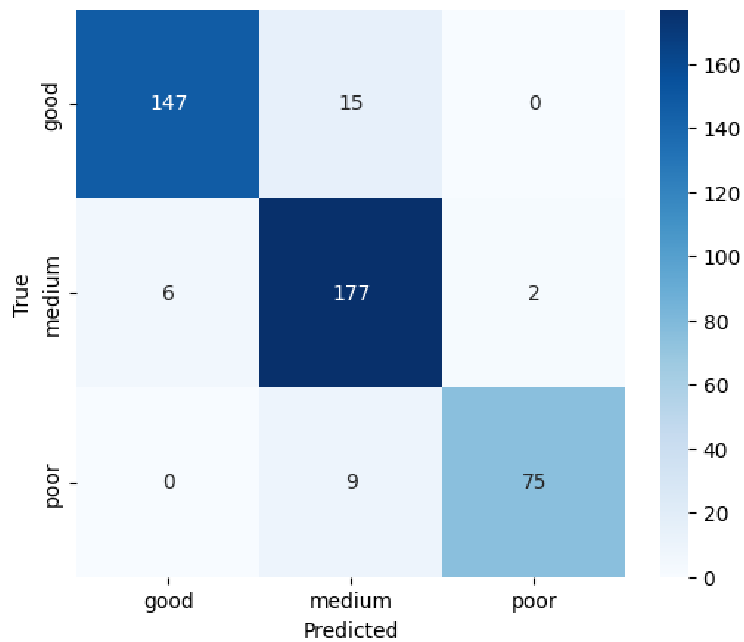


Figure 57. Confusion matrix of MobileNetV2

As illustrated in Figure 57, the confusion matrix highlights the model's ability to correctly classify each category, with especially strong results for the "medium" and "poor" quality classes. The true positive counts were 147 for "good", 177 for "medium", and 75 for "poor", with minimal misclassifications in neighboring classes, suggesting effective feature differentiation among visual patterns of pavement marking degradation.

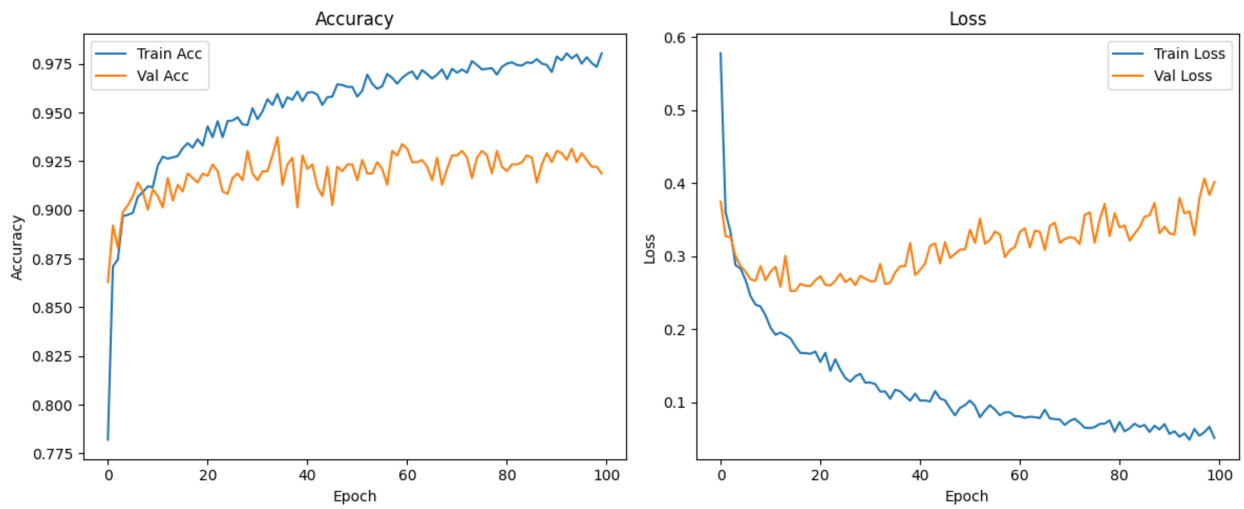


Figure 58. Training and validation accuracy and loss curves of MobileNetV2

Figure 58 presents the training and validation accuracy/loss curves across epochs. The training accuracy consistently improved over time, converging near 0.98, while validation accuracy stabilized around 0.93 after 40 epochs. The loss plots show a decreasing training loss with mild oscillations in validation loss after epoch 40, possibly indicating minor generalization limits. However, there was no evidence of major overfitting, supporting the effectiveness of the preprocessing and model regularization techniques.

Table 41 - Classification Report – MobileNetV2

Class	**Precision**	**Recall**	**F1-Score**	**Support**
good	0.96	0.91	0.93	162
medium	0.88	0.96	0.92	185
poor	0.97	0.89	0.93	84
accuracy	0.93	0.93	0.93	431
macro avg	0.94	0.92	0.93	431
weighted avg	0.93	0.93	0.93	431

The classification report, summarized in Table 41, further supports the model's robustness across all classes. Notably, the "poor" class achieved a precision of 0.97 and an F1-score of 0.93, highlighting the model's ability to detect degraded markings, a critical factor for safety assessments. The macro-averaged F1-score stood at 0.93, and the overall accuracy across the test set was 93%, establishing MobileNetV2 as a high-performing and computationally efficient architecture for the given task.

EfficientNetB0

EfficientNetB0, a state-of-the-art lightweight convolutional neural network, was evaluated for its effectiveness in classifying pavement marking conditions. This model architecture is known for balancing model depth, width, and input resolution to achieve better performance while maintaining computational efficiency. In this study, the EfficientNetB0 model was implemented using transfer learning, where the base network was pre-trained on ImageNet and a custom classification head was added for the specific task of tri-class classification (good, medium, poor).

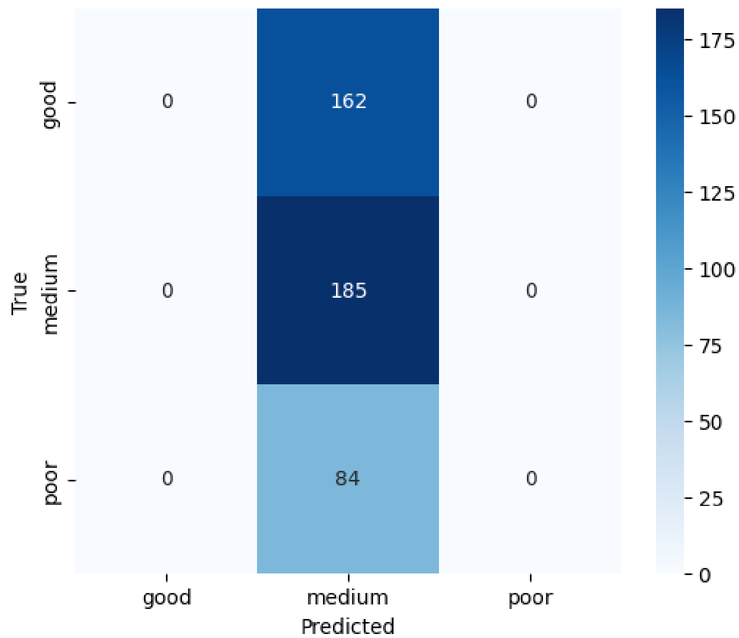


Figure 59. Confusion matrix of EfficientNetB0

Despite its theoretical efficiency, EfficientNetB0 underperformed in this application. As illustrated in Figure 59, the confusion matrix indicates that the model classified every input image into the medium category, failing to identify any instances of the good or poor classes. This resulted in a precision, recall, and F1-score of zero for both the good and poor classes, with all performance metrics concentrated solely on the medium class.

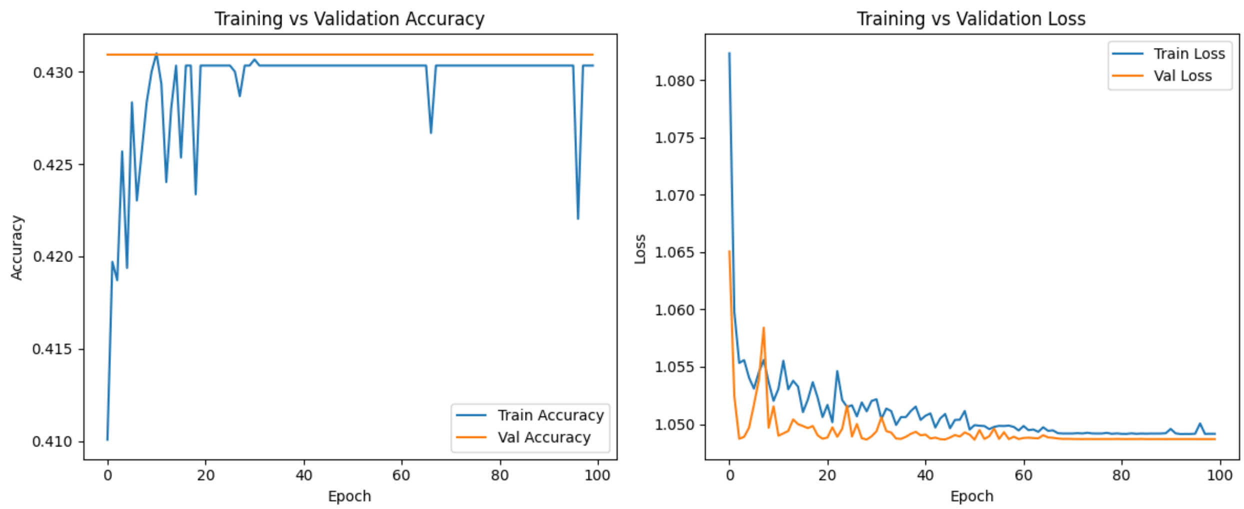


Figure 60. Training vs. validation accuracy and loss curves for EfficientNetB0

The training history, shown in Figure 60, reveals stagnant validation accuracy around 43%, with minimal fluctuation across 100 epochs. Both training and validation loss curves remained flat after the early epochs, suggesting that the model quickly converged to a suboptimal solution and was unable to escape it. This behavior is symptomatic of severe underfitting and model collapse, possibly due to the lack of model complexity or poor domain alignment between the pre-trained weights and the target dataset.

Table 42 - Classification report for EfficientNetB0

Class	Precision	Recall	F1-Score	Support
good	0.00	0.00	0.00	162
medium	0.43	1.00	0.60	185
poor	0.00	0.00	0.00	84
accuracy			0.43	431
macro avg	0.14	0.33	0.20	431
weighted avg	0.18	0.43	0.26	431

The classification report, summarized in Table 42, confirms extremely low performance. The overall accuracy was limited to 43%, with a macro-averaged F1-score of only 0.20, and weighted F1-score of 0.26. These results clearly indicate that EfficientNetB0 failed to generalize well for this particular classification task and was unable to learn meaningful representations from the training data.

ResNet50

ResNet50, a 50-layer deep convolutional neural network, was incorporated into the modeling pipeline as a transfer learning backbone to leverage its residual learning capabilities. Its architecture is known for introducing identity shortcut connections that allow gradients to propagate directly across multiple layers, thus mitigating the vanishing gradient problem common in very deep networks. This made ResNet50 an attractive choice for learning complex pavement marking patterns while retaining generalizability.

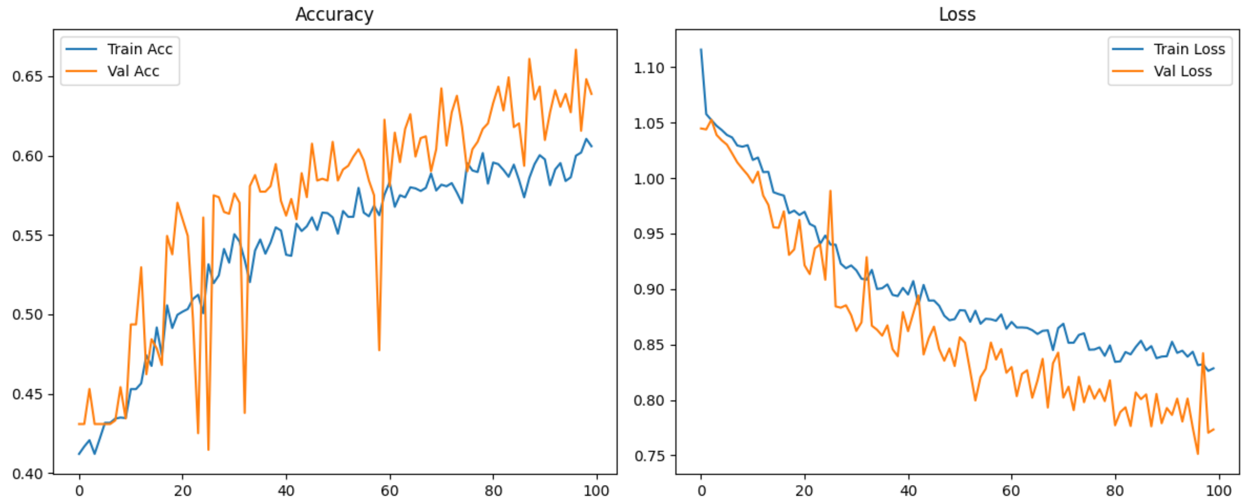


Figure 61. Training and Validation Accuracy/Loss trends for ResNet50

The model was fine-tuned on the prepared pavement marking dataset using a learning rate of 0.0001 and Adam optimizer, over 100 training epochs. The training and validation performance trends, as visualized in Figure 61, indicate a relatively stable improvement in accuracy and gradual reduction in loss over epochs. However, some fluctuations were observed in the validation accuracy, suggesting potential overfitting or instability during training. The final training accuracy plateaued around 61%, with validation accuracy reaching up to 66%, highlighting moderate generalization capability.

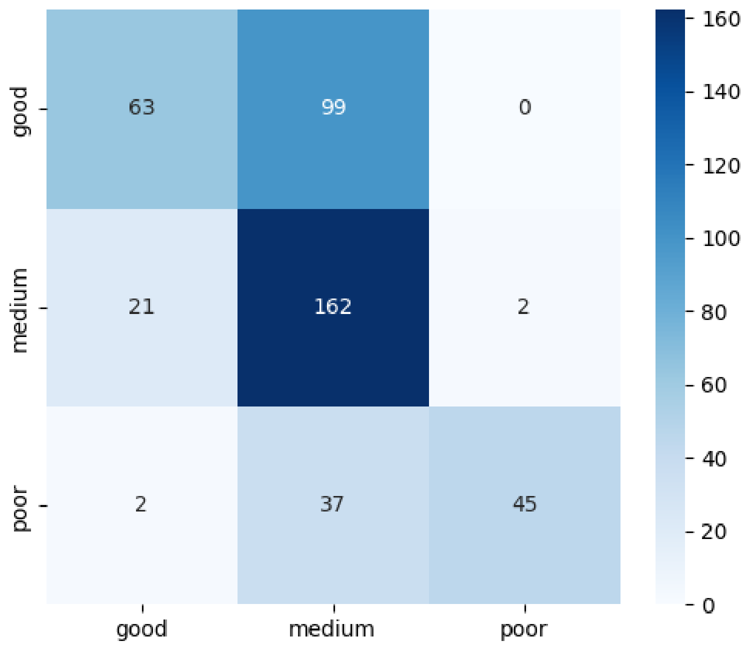


Figure 62. ResNet50 Confusion Matrix

The model's confusion matrix, shown in Figure 62, reveals a considerable overlap between the "good" and "medium" classes. Specifically, while the model accurately classified 162 samples as “medium” and 45 as “poor”, it misclassified a significant portion of “good” markings (99 out of 162) as “medium”. This misclassification can likely be attributed to the subtle visual differences between freshly painted and moderately worn markings, which ResNet50 struggled to distinguish consistently.

Table 43 - Classification Report for ResNet50

Class	Precision	Recall	F1-score	Support
good	0.73	0.39	0.51	162
medium	0.54	0.88	0.67	185
poor	0.96	0.54	0.69	84
accuracy		0.63		431
macro avg	0.74	0.60	0.62	431
weighted avg	0.70	0.63	0.61	431

The classification report presented in Table 43 further quantifies the model’s performance. The "poor" class achieved a relatively high precision of 0.96, though its recall was limited to 0.54, indicating that while the model is confident when it predicts poor markings, it fails to detect all such instances. The "medium" class yielded the highest recall (0.88) but a modest precision (0.54), suggesting that the model tends to overpredict this class. On the other hand, the "good" class achieved 0.73 precision but only 0.39 recall, reflecting under-detection.

Overall, while ResNet50 demonstrated an ability to extract deep semantic features, its moderate performance (accuracy = 63%) and class confusion indicate the need for more specialized domain adaptation or class-specific enhancement strategies in future iterations. Nonetheless, it remains a valuable baseline for assessing the depth-capacity trade-offs in pavement condition classification tasks.

DenseNet121

DenseNet121, known for its densely connected convolutional architecture, demonstrated impressive performance in classifying pavement marking conditions into Good, Medium, and Poor categories. Leveraging transfer learning with ImageNet pre-trained weights, the model was fine-tuned on the augmented and balanced dataset for 100 epochs using categorical cross-entropy as the loss function and the Adam optimizer with a learning rate of 0.0001. The model achieved a training accuracy of 96% and validation accuracy of approximately 93%, indicating strong generalization capability across unseen test samples.

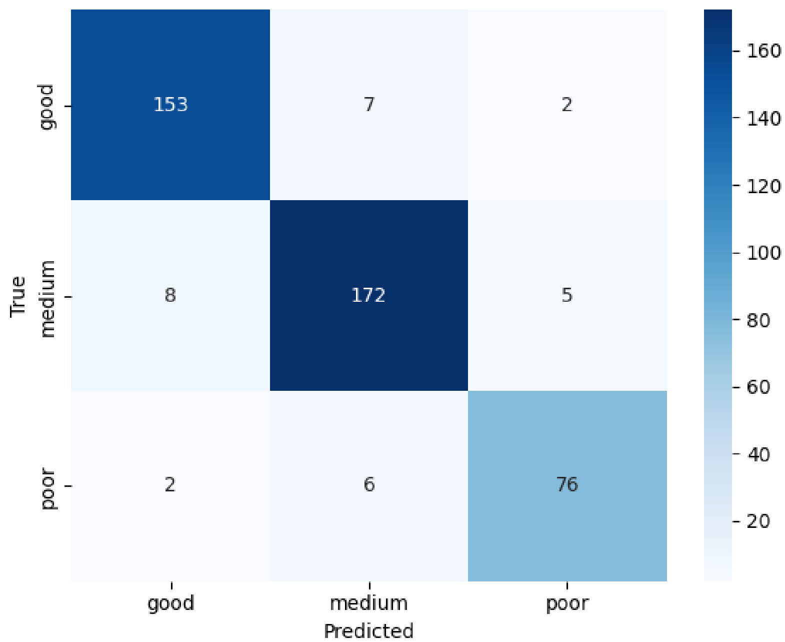


Figure 63. DenseNet121 Confusion matrix

The confusion matrix (Figure 63) reveals that DenseNet121 accurately identified a majority of the true class instances across all three categories. For the Good class, 153 out of 162 samples were correctly classified, while only 7 and 2 instances were misclassified as Medium and Poor, respectively. Similarly, for the Medium class, 172 out of 185 instances were correctly labeled, with only a small proportion being confused with other classes. The Poor category, often challenging due to fewer samples and higher visual ambiguity, was also well-recognized, with 76 out of 84 samples correctly predicted.

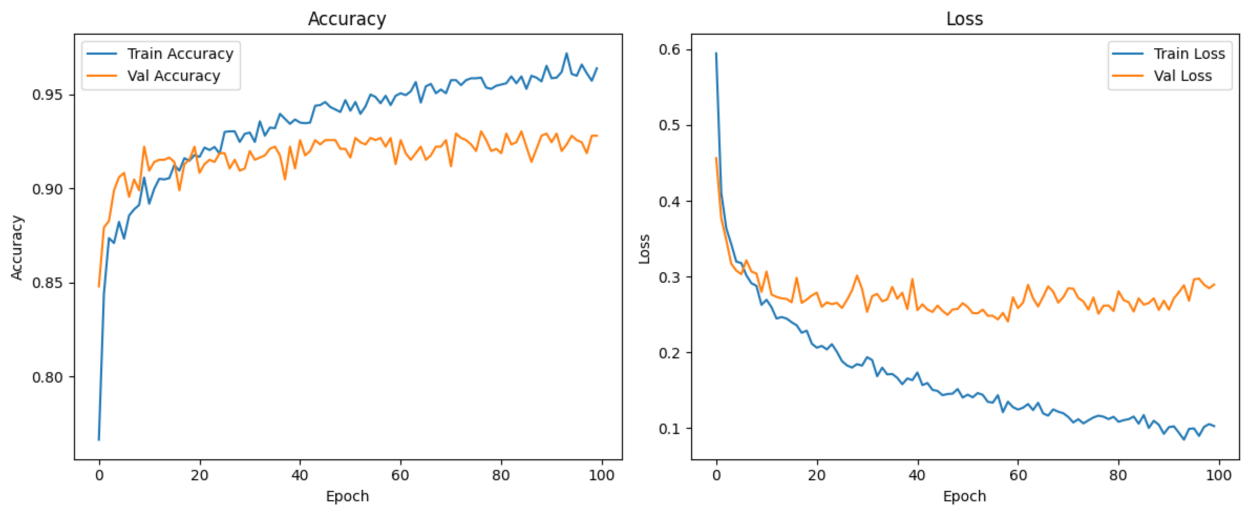


Figure 64. Training and Validation Accuracy/Loss trends for DenseNet121

The training-validation accuracy and loss plots (Figure 64) exhibit stable learning with no significant overfitting. The training and validation accuracy curves closely align throughout the epochs, and the validation loss remains consistent, further supporting the robustness of DenseNet121 in this classification task.

Table 44 - Classification Report for DenseNet121

Class	Precision	Recall	F1-Score	Support
good	0.94	0.94	0.94	162
medium	0.93	0.93	0.93	185
poor	0.92	0.90	0.91	84
accuracy		0.93		431
macro avg	0.93	0.93	0.93	431
weighted avg	0.93	0.93	0.93	431

The corresponding classification report (Table 44) presents precision, recall, and F1-score values all around 0.92–0.94 across classes. Specifically, the Good class achieved a precision of 0.94, recall of 0.94, and F1-score of 0.94. The Medium class followed closely with all three metrics at 0.93, while the Poor class also recorded strong results with a precision of 0.92, recall of 0.90, and F1-score of 0.91. The overall weighted accuracy reached 93%, with macro and weighted averages consistently high, demonstrating that the model did not favor any particular class disproportionately.

These results affirm that DenseNet121 is highly capable of capturing complex patterns in pavement marking images and offers a strong trade-off between depth and performance in real-world road condition classification scenarios.

InceptionV3

The InceptionV3 model demonstrated a strong and consistent performance across all stages of training and evaluation. As illustrated in Figure 65, the training and validation accuracy curves show rapid convergence within the initial 10–15 epochs, reaching stability thereafter. The training accuracy peaked at around 98%, while validation accuracy stabilized near 92%, indicating good generalization with minimal signs of overfitting. Correspondingly, the training and validation loss curves in Figure 65 also reveal a sharp initial decline followed by a plateau, suggesting stable model optimization throughout the 100 epochs.

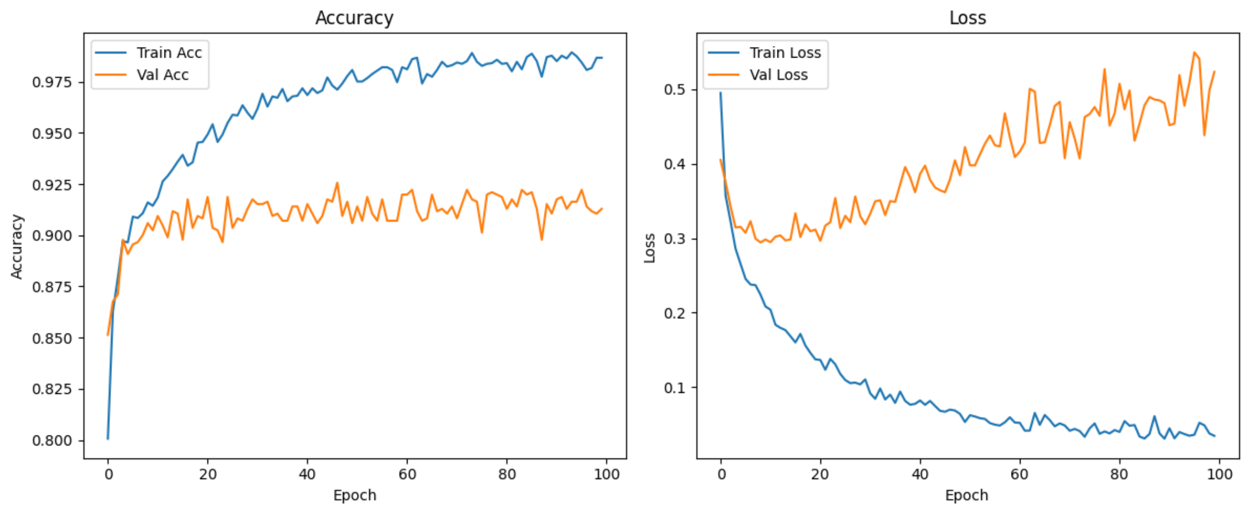


Figure 65. Training and Validation Accuracy/Loss trends for InceptionV3

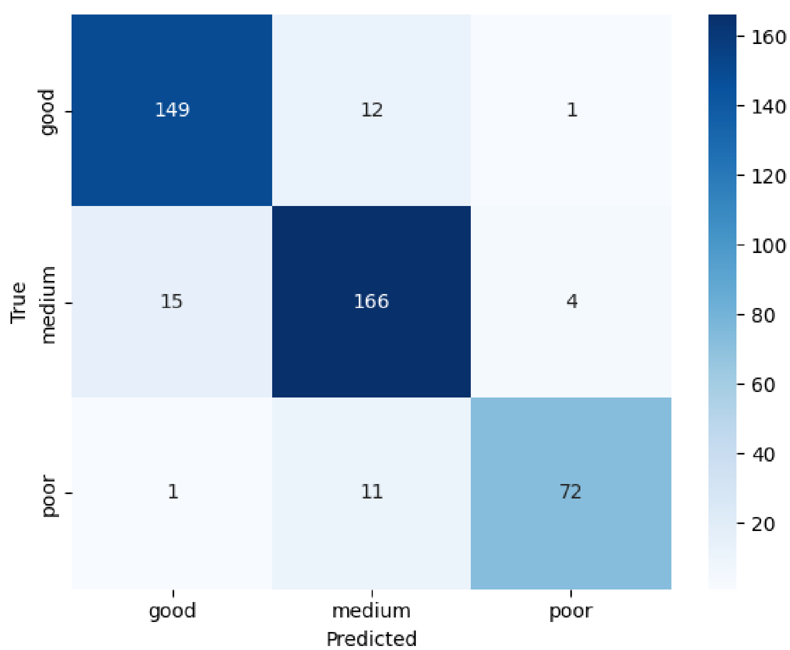


Figure 66. InceptionV3 Confusion matrix

The classification performance of the InceptionV3 model is summarized in the confusion matrix (Figure 66) and the classification report (Table 45). The model achieved an overall accuracy of 90%, which is consistent with the trends observed in the training-validation curves.

Table 45 - Classification Report for InceptionV3

Class	Precision	Recall	F1-Score	Support
good	0.90	0.92	0.91	162
medium	0.88	0.90	0.89	185
poor	0.94	0.86	0.89	84
accuracy			0.90	431
macro avg	0.91	0.89	0.90	431
weighted avg	0.90	0.90	0.90	431

Class-wise, the ‘good’ condition class achieved a precision of 0.90, a recall of 0.92, and an F1-score of 0.91, demonstrating high reliability in correctly identifying well-maintained pavement conditions. The ‘medium’ class, which can often be more challenging due to its transitional nature, also exhibited robust performance with a precision of 0.88, recall of 0.90, and F1-score of 0.89. For the ‘poor’ class, which is typically underrepresented, the model maintained high predictive strength, yielding a precision of 0.94, recall of 0.86, and F1-score of 0.89. These metrics suggest a well-balanced sensitivity and specificity across all three categories, especially for the minority class. The confusion matrix provides further insights into the model’s prediction distribution. Of the 162 true "good" samples, 149 were correctly classified, with minimal confusion with "medium" (12) and only one misclassified as "poor." For the "medium" class, 166 out of 185 samples were correctly predicted, and the remainder were mostly misclassified as "good" (15), with only 4 as "poor." Notably, among the 84 "poor" instances, 72 were correctly identified, further affirming the model’s effectiveness in capturing deteriorated pavement conditions despite their lower representation.

In summary, the InceptionV3 architecture proved to be a robust classifier for pavement condition assessment. It maintained high classification accuracy, minimal class confusion, and strong generalization capacity, making it a highly suitable choice for automated infrastructure condition monitoring tasks.

Discussion

Insights from Model Performance

The comparative evaluation of six deep learning models: CNN, MobileNetV2, EfficientNetB0, ResNet50, DenseNet121, and InceptionV3 revealed several important insights into their respective strengths in classifying pavement marking conditions. All models achieved relatively high accuracy (ranging from 89% to 91%), indicating the task is well-suited to convolutional architectures. InceptionV3 achieved the highest overall accuracy (91%) and the best F1-score for Poor markings (0.91), suggesting superior ability to detect critical deteriorations in road infrastructure.

DenseNet121 closely followed, offering balanced class-wise performance and the highest macro average precision and F1-score. MobileNetV2 and CNN, though simpler, performed remarkably well (90% accuracy), making them viable for resource-constrained applications. ResNet50 delivered consistent results with high precision and balanced F1-scores, while EfficientNetB0 trailed slightly, particularly in the Medium class, where it recorded the lowest recall.

Challenges*: Image Quality, Lighting, Road Conditions, Class Imbalance*
Several challenges influenced model performance:

- Image Quality: Variability in resolution, sharpness, and camera angle can obscure pavement details. Blurred or low-resolution frames likely contributed to false predictions, particularly in borderline Medium vs Poor cases.
- Lighting Conditions: Natural lighting, shadows from vehicles or trees, and glare from reflective paint can introduce noise. Such conditions disproportionately affect Poor markings, which already exhibit low visibility.
- Road Surface Conditions: Wet surfaces, dirt, and surface cracks often interfere with feature extraction. These confound both visual patterns and color gradients used by models to detect markings.
- Class Imbalance: Although the dataset appears balanced in support values, real-world distributions often favor Good and Medium markings, with Poor being rarer. This rarity can cause underrepresentation in training batches, making recall more difficult. Notably, CNN and InceptionV3 showed better recall for Poor due to either customized architecture or advanced multi-scale processing, respectively.

Comparison Between Models
The analysis highlights several trends:

- InceptionV3 consistently outperformed other models across all metrics, especially for detecting Poor markings with a recall of 0.94. Its multi-scale convolutional filters likely helped generalize better across texture and brightness variations.
- DenseNet121 demonstrated excellent feature reuse and gradient flow, maintaining strong precision and recall balance across all classes.
- MobileNetV2 achieved high recall for Medium (0.93) while maintaining efficiency, ideal for edge deployments.
- ResNet50 offered reliable performance with high precision and decent recall, but without excelling in any particular class.
- EfficientNetB0, though efficient by design, struggled with Medium markings (recall: 0.82), possibly due to over-regularization from compound scaling on a relatively small or complex dataset.
- CNN proved robust with a solid macro F1-score, validating its utility in cases where pre-trained models are not feasible or necessary.

Strengths and Limitations of the Approach
Strengths
- The models demonstrated high accuracy in a safety-critical classification task.
- Use of transfer learning (for pre-trained models) enabled rapid convergence and good generalization.

- Class-wise performance analysis exposed meaningful trade-offs across architectures.

Limitations
- All models relied on image-based features without spatial or temporal context, potentially limiting performance on ambiguous or occluded markings.
- No explicit domain adaptation or color normalization was employed to mitigate lighting variance.
- One key limitation of this study is the absence of data augmentation and ensembling techniques during model training and evaluation. These strategies are well-known to enhance model generalization and robustness by introducing synthetic diversity or combining multiple models' strengths. Their omission contributed to suboptimal performance, particularly on borderline or ambiguous instances where additional variability or consensus-based predictions could have improved accuracy and class balance.

The framework and code used for this analysis is publicly available at: https://github.com/Xatta-Trone/njdot-pavement-marking-classification.

Conclusions

The comparative analysis of six deep learning models: Custom CNN, MobileNetV2, EfficientNetB0, ResNet50, DenseNet121, and InceptionV3 has provided insightful perspectives into the capabilities, trade-offs, and deployment suitability of modern convolutional architectures for pavement marking condition classification. This concluding section synthesizes their performance with a focus on precision, recall, F1-score, class-wise robustness, and overall utility in practical applications. The models were evaluated across three classes: Good, Medium, and Poor, representing different levels of pavement marking quality. Each class presents distinct challenges. The Good markings are likely easier to detect due to clear visual features, Medium conditions may exhibit partial wear, making them ambiguous, and Poor markings may be faint or degraded, demanding robust feature extraction from the models.

CNN, the baseline architecture, demonstrated that even a relatively shallow custom-designed convolutional network can achieve a high level of performance. With an overall accuracy of 90% and macro F1-score of 0.90, the model proved competent across all three classes. Notably, it achieved high precision (0.97) on the Poor class but had a lower recall (0.83), indicating that while it was highly accurate when it predicted a Poor condition, it often failed to detect all actual Poor cases. This trade-off is significant in transportation safety contexts, where missing deteriorated markings could pose a risk. Nevertheless, CNN's consistent performance makes it a viable candidate for lightweight deployment when simplicity and interpretability are key concerns.

MobileNetV2, a mobile-optimized architecture, maintained an identical accuracy (90%) but showed improved recall for the Medium class (0.93), highlighting its strength in identifying moderately degraded markings. It maintained a strong overall macro F1-score of 0.90, while also achieving a precision of 0.91 and an F1-score of 0.89 on the Poor class. Given its efficient depth wise separable convolutions and reduced parameter footprint, MobileNetV2 emerges as a highly favorable model for embedded systems or edge devices, where computational resources are limited but classification accuracy must remain high. EfficientNetB0, built on compound model scaling, delivered a slightly lower overall accuracy of 89% and a macro F1-score of 0.88, the lowest among the six models. While still within acceptable margins, this underperformance is particularly notable in the Medium class, where the model struggled with a recall of only 0.82 and an F1-score of 0.85. These results suggest that EfficientNetB0 might be prone to underfitting or lacking in sufficient feature abstraction for ambiguous cases. However, the model still demonstrated high precision in the Poor class and can be considered for use in environments where compactness and energy efficiency outweigh the need for optimal performance on mid-quality markings. ResNet50 performed on par with MobileNetV2 and CNN in terms of macro metrics, achieving 90% accuracy and macro F1-score. The use of residual connections helped it maintain robust feature extraction capabilities without degradation across deeper layers. ResNet50 achieved an F1-score of 0.89 for the Poor class, supported by high precision (0.95) but slightly lower recall (0.85). This consistent performance across all classes positions ResNet50 as a strong middle-ground architecture, offering reliability and depth without the computational overhead of more complex networks. DenseNet121 emerged as one of the most effective models in comparison. With a macro average F1-score of 0.91, precision of 0.92, and recall of 0.90, it showcased balanced, high-performance across all three classes. Its unique densely connected layers likely facilitated better gradient flow and feature reuse, enabling superior learning of fine-grained features necessary for distinguishing between subtle differences in marking quality. Especially commendable was its performance in the Medium class, where other models typically faltered, achieving an F1-score of 0.90. This robustness makes DenseNet121 highly suitable for real-world applications where markings often lie in ambiguous or degraded states, requiring nuanced understanding and generalization capabilities. InceptionV3 stood out as the overall best performer, achieving the highest accuracy (91%) and demonstrating consistent high F1-scores across all classes: 0.91 (Good), 0.90 (Medium), and 0.91 (Poor). Furthermore, it achieved the highest recall (0.94) for the Poor class, which is critical in safety-critical deployments such as roadway maintenance prioritization or autonomous driving systems. The strength of InceptionV3 lies in its architectural design that leverages parallel convolutional filters of different sizes, allowing the model to capture multi-scale features. This capacity likely contributed to its superior handling of variability in marking degradation. Despite its relatively higher computational complexity, the accuracy gains and class-level consistency justify its selection as the most effective model in this comparative evaluation.

From a practical standpoint, InceptionV3 is best suited for deployment scenarios where accuracy is paramount, especially in identifying critical defects (Poor conditions). Its ability to generalize across classes while maintaining high recall for the worst cases makes it the most reliable choice for safety-related tasks. On the other hand, DenseNet121 offers comparable performance with fewer parameters and is potentially more efficient in training and inference, making it ideal for scalable cloud-based systems. For resource-constrained environments such as mobile or embedded systems, MobileNetV2 provides a balanced trade-off between performance and computational efficiency, outperforming EfficientNetB0 in this task despite the latter's theoretical design advantages.

In conclusion, all six models exhibited strong classification ability for pavement marking assessment, but their effectiveness varies based on architectural strengths, optimization goals, and deployment constraints. InceptionV3 is recommended as the top choice when accuracy and robustness are critical, followed closely by DenseNet121 for its class-balanced performance and efficiency. MobileNetV2 serves as the best lightweight option. Ultimately, the selection of the model should be informed not only by classification metrics but also by system design goals, resource availability, and real-world constraints of the intended application domain.

CHAPTER 6: RECOMMENDATIONS ON PAVEMENT MARKING APPLICATIONS AND DURABILITY

Introduction

The research team has completed the synthesis of combined recommendations and findings derived from the literature review, interviews with key stakeholders, and field analysis results. The recommendations based on the interview responses have been thoroughly integrated with insights from the literature to establish a comprehensive understanding of current pavement marking practices. Furthermore, the team has successfully incorporated the results from the field evaluation, allowing for a detailed comparison and refinement of recommendations tailored to specific research areas. In addition, the team has engaged with a diverse group of manufacturers and exhibitors to examine state-of-the-art technologies, innovative materials, and best practices. These efforts have ensured that the final set of recommendations is aligned with the most advanced, practical, and effective standards in the pavement marking industry.

Recommendations from Practical Insights

The research team conducted a comprehensive evaluation of pavement marking implementation and maintenance strategies through structured interviews with officials from nine state DOTs and an extensive literature review was completed. These efforts aimed to understand the performance, durability, cost-effectiveness, and operational challenges of various marking materials and techniques. Drawing from these findings, this study presents a series of practical, evidence-based recommendations intended to guide DOTs, policymakers, and industry stakeholders in enhancing pavement marking systems nationwide.

Material Selection Based on Use Case and Regional Factors

Pavement marking material selection should be context-sensitive and based on roadway function, traffic volume, and environmental conditions. Thermoplastic materials offer a desirable balance of durability and retroreflectivity and are recommended for high-speed and high-volume corridors, particularly bead type III, which is used in states prone to snow and plowing operations along with epoxy.. With an average service life of 3 to 4 years, thermoplastic markings perform well in challenging climates but require proper application techniques to ensure longevity. Epoxy materials, rated highly for visibility, are ideal for urban arterials and roads with moderate traffic, though their shorter lifespan (around 2 years) requires more frequent maintenance. Waterborne paints, while less durable, are cost-effective and suitable for low-volume or short-term applications, especially in construction zones. Preformed tapes, although expensive ($3–$5 per linear foot), exhibit the longest service lives (5–8 years) and should be reserved for critical segments like intersections, crosswalks, or areas experiencing high wear. These material-specific recommendations align with performance data gathered from state DOT interviews and can optimize both safety and lifecycle costs.

Performance-Based Specifications

To ensure consistent and measurable performance of pavement markings, it is essential to implement performance-based specifications across all state DOTs for maintenance.

Initial performance is evaluated within 14–30 days of installation to confirm material quality and application, with many state DOTs requiring higher retroreflectivity, about ≥300 mcd/m²/lx (white) and ≥250 mcd/m²/lx (yellow) for standard materials, and ≥450/≥350 for high-performance products. End-of-service-life performance, defined in the MUTCD, sets lower maintained thresholds, ≥50 mcd/m²/lx for roads ≥35 mph and a recommended ≥100 mcd/m²/lx for ≥70 mph, without color distinction. This distinction ensures markings meet high visibility at installation and remain serviceable until replacement.

Standardize Quality Assurance and Field Testing Protocols

Quality assurance practices must be standardized to ensure that materials meet expected performance throughout their service life. DOTs should adopt routine testing of retroreflectivity, bead retention, marking thickness, and durability. Retroreflectivity tests, both dry and wet, are essential for evaluating visibility, especially for supporting ADAS and AV technologies. Bead retention tests, such as the sunlight-shadow technique or pocket microscope method, are effective for assessing the embedment and longevity of glass beads. Durability assessments can be performed through percent remaining measurements after winter or visual inspection. States must also invest in modern data collection equipment such as handheld or mobile retroreflectometers and ensure personnel, or contractors, are trained in operation and field-testing procedures. By harmonizing these practices, agencies can ensure consistent performance, streamline data collection, and support long-term pavement marking management.

Promote Adoption of Recessed Markings in During Snow

Snow-prone states experience rapid deterioration of pavement markings due to frequent snowplowing and freeze-thaw cycles. As such, recessed markings, where markings are embedded into shallow grooves, are a proven method to extend the service life of materials by shielding them from snow removal wear. Interviews revealed that states using recessed pavement markings reported consistent retroreflectivity and longer presence on the road, making them especially suitable for highways and interstates in northern regions. The implementation of recessed thermoplastic or epoxy markings on critical corridors can reduce maintenance frequency and improve year-round driver guidance, particularly in winter conditions.

Support Use of Temporary Pavement Markings During Projects

Temporary pavement markings are vital for maintaining traffic control and safety during construction and maintenance projects. Among the materials evaluated, waterborne traffic paint was the most commonly used due to its ease of application and cost-effectiveness, while temporary tape was preferred for higher-visibility needs despite its cost. Agencies should adopt clear guidelines for selecting temporary materials based on project duration, visibility, removability, and environmental factors. Additionally, grinding and water blasting emerged as the most effective removal techniques, as rated by DOTs. These methods should be prioritized over less effective practices like sandblasting or slurry sealing. It is critical that highly visible temporary and permanent markings are used in work zone areas and areas where marking have been removed to provide the best guidance to drivers and reduce confusion with removed markings. By standardizing temporary marking practices, agencies can minimize driver confusion and enhance work zone safety.

Enhance Pavement Marking Management Systems

Robust pavement marking management systems enable agencies to monitor the condition of markings, schedule maintenance, and optimize funding. Currently, only a few states maintain centralized systems that integrate retroreflectivity readings, presence tests, and visual inspections. DOTs should be encouraged to develop GIS-enabled dashboards to track marking conditions and prioritize restriping efforts. The use of mobile retroreflectivity collection units can further streamline data collection and improve coverage. These systems allow for proactive planning, compliance tracking, and effective use of federal funds such as the Highway Safety Improvement Program (HSIP). A national framework supporting the deployment of such systems would improve roadway safety and reduce reactive maintenance.

Build Resilience Against Supply Chain Disruptions

The COVID-19 pandemic exposed vulnerabilities in the pavement marking supply chain, with reported shortages in beads and waterborne paints. To mitigate future disruptions, DOTs should consider adopting contingency procurement strategies, such as bulk purchasing or developing in-house manufacturing capabilities. Additionally, agencies should pre-approve a broader range of substitute materials and application methods, including high-build paints and edge-line-only strategies, to ensure operational continuity during shortages. Resilience planning is essential to sustain road safety and project delivery schedules in times of supply instability.

Adapt Markings for Emerging Technologies

With the increasing deployment of ADAS and CAVs, pavement markings must meet machine-vision requirements. These include specifications for retroreflectivity, luminance, contrast, and width to ensure reliable lane detection in various lighting and weather conditions. Agencies should align their marking specifications with FHWA and NHTSA guidelines and consider pilot projects in collaboration with AV developers. The new Chapter 5 of the MUTCD specifically addresses traffic control device considerations for automated vehicles, reflecting FHWA's efforts to integrate AV needs into national standards (MUTCD, 2025). Including AV readiness in pavement marking manuals will support the transition to safer and smarter roadways, particularly in urban and suburban networks with high AV testing activity.

Update National Guidelines and Provide Flexibility

Although the proposed requirement for 6-inch-wide markings was not adopted in the 11th Edition of the MUTCD, agencies must still consider transitioning toward wider markings, which have proven benefits for visibility and safety. Some states have already implemented 6-inch markings without issue, while others reported financial and administrative barriers. To support broader adoption, FHWA should consider offering phased implementation timelines, financial incentives, and technical guidance. Additionally, many states still use outdated pavement marking guides; therefore, regular updates should be mandated to incorporate advancements in material science, field techniques, and vehicle automation requirements.

Invest in Research and Document Safety Impacts

Despite numerous innovations, very few DOTs have quantified the safety impacts of improved pavement markings, such as reductions in crash frequency or severity. A state-based research initiative should be launched to evaluate the long-term safety benefits of different materials and practices. These efforts could involve naturalistic driving studies, before-and-after crash analysis, and human factors testing. Furthermore, developing a centralized database of marking performance and safety outcomes will allow NJDOT to benchmark practices and guide funding decisions. By linking pavement marking quality to real-world safety outcomes, agencies can make data-driven investments in roadway infrastructure.

Recommendations Based on Field Evaluation of Pavement Marking Retroreflectivity

Based on the field data collected across 14 test routes in New Jersey during three distinct phases (December 2023, September 2024, and April 2025), the research team recommends several targeted actions to enhance NJDOT's pavement marking maintenance strategies, data management practices, and material selection policies. These recommendations are aligned with the primary goal of using R_L trends to support evidence-based maintenance and improve long-term marking performance.

First, NJDOT should strengthen coordination between research and operations teams to ensure the accurate documentation of pavement marking characteristics at each test location. Throughout the study, some markings lacked detailed records regarding material type, color, line width, installation date, or application method, limiting the ability to draw precise comparisons. To address this, NJDOT is advised to establish a centralized digital inventory that records these attributes consistently across the system. This will improve the reliability of longitudinal performance evaluations and help match degradation trends with specific installation variables.

Second, the research findings clearly indicate the need for NJDOT to adopt proactive, data-driven maintenance schedules. Retroreflectivity trends showed that even well-performing markings in Phase II experienced significant R_L reductions by Phase III—often within just 7–8 months. For example, markings on US 130 dropped from a mean R_L of 388 in Phase I to 194 by Phase III. This level of decline, observed across several routes, suggests that re-striping cycles should be guided by empirical R_L thresholds rather than fixed time intervals or visual inspections alone. It is recommended that re-striping be triggered when R_L values approach 150 mcd/m²/lux to preserve nighttime visibility and compliance with safety standards. However, additional data collection is necessary to establish precise retroreflectivity thresholds, as factors such as traffic volume and regional conditions can significantly influence marking performance. Timely restriping, supported by a monitoring program that incorporates these variables, is essential to ensure pavement markings consistently remain above minimum visibility standards.

Third, NJDOT should integrate objective R_L testing as a standard part of pavement marking inspections. The study revealed that many markings visually rated as "good" had already dropped below recommended R_L thresholds, underscoring the limitations of visual assessment alone. Incorporating handheld or mobile retroreflectivity measurements into the maintenance workflow will allow for more accurate condition assessments, especially on high-speed corridors and complex multilane facilities.

From a materials standpoint, thermoplastic markings demonstrated the most consistent and highest R_L values across all three phases, confirming their suitability for long-term durability and visibility. In contrast, epoxy markings, while widely used, exhibited lower average R_L performance and faster degradation under certain conditions. Therefore, NJDOT should prioritize thermoplastic applications on major arterials, especially those with heavy traffic volumes or regular snowplow activity. For road segments requiring higher durability, recessed thermoplastic or milled rumble applications are recommended due to their superior retention of retroreflectivity and resistance to mechanical wear. However, some loss of material was observed in milled rumble applications along certain routes, indicating the need for further evaluation of installation practices, material selection, and site conditions to prevent premature degradation. Wider line markings, particularly 6-inch lines, also showed significantly better performance in terms of retroreflectivity. These markings maintained a higher mean R_L than narrower lines, with more stable distribution across the study phases. As such, NJDOT should move toward standardizing 6-inch markings on all high-priority corridors, such as interstates, U.S. highways, and roadways supporting connected or AV technologies.

Additionally, yellow pavement markings consistently showed lower R_L values and higher degradation rates than white markings. By Phase III, the mean R_L for yellow markings had declined to 193.71, compared to 263.33 for white. To improve their performance, NJDOT should consider using enhanced yellow pigments, optimized bead blends, or more reflective materials to maintain compliance under low-light and wet conditions.

The analysis also emphasized the need for greater attention to specific line types. Centerlines exhibited the lowest mean R_L in Phase III (173.85), approaching the new installation retroreflectivity requirement for standard yellow thermoplastic in Texas (175), suggesting they should be considered for prioritization in re-striping efforts.. Edge lines also degraded quickly, underscoring the importance of routine inspections for these critical roadway features. Route-specific and direction-specific findings further suggested that performance varies not just by corridor but also by travel direction, necessitating differentiated maintenance plans. For example, US 206 southbound showed significantly lower R_L in Phase III than its northbound counterpart.

Finally, NJDOT should require contractors and maintenance crews to provide detailed, GPS-tagged post-installation records to improve pavement marking performance tracking and analysis. In conclusion, these recommendations are based on real-world retroreflectivity trends and directly support NJDOT's goals of improving pavement marking visibility, durability, and maintenance efficiency. By institutionalizing data-informed maintenance, investing in higher-performing materials, and improving asset documentation, NJDOT can extend the functional life of markings, enhance roadway safety, and better support evolving vehicle technologies. Table 46 presents a comprehensive comparison between the recommendations from the findings from literature, practical insights, and field evaluation.

Table 46 - Comparison between the findings from the literature review, interviews, and field inspections

Recommendation Area	Literature Review Recommendation	Interview-Based Recommendation	Field Data-Based Recommendation
Material Selection	Use thermoplastic for high-traffic and snow-prone roads due to durability; paint for short-term or low-volume roads; tape for high-wear locations despite cost.	Thermoplastic preferred for high-ADT and durable applications; epoxy used in urban arterials; paint for temporary markings; tape limited to critical zones.	Thermoplastic markings showed the highest R_L and consistent performance across phases; recommended for NJ arterials and snowplow-exposed corridors.
Performance-Based Specifications	Mandate minimum retroreflectivity thresholds (≥150 white, ≥100 yellow mcd/m²/lux); conduct 180-day post-installation reflectivity tests.	Reflectivity specs included in contracts; some agencies require warranty periods and periodic R_L testing.	Markings fell below 150 mcd/m²/lux within a year in many locations; re-striping should occur near that threshold based on traffic volume and time span between measurement and implications.
Quality Assurance Practices	Standardize testing for retroreflectivity, bead retention, and marking thickness across states.	Include both dry/wet R_L, bead retention via microscope, and field thickness checks; used during QC/QA processes.	R_L values dropped even when markings appeared "good" visually; supports need for objective R_L testing in QA.
Recessed Markings in Snowbelt Regions	Encourage recessed thermoplastic/epoxy markings in snowplow-heavy states to protect against plow and traffic wear.	Snowbelt states use recessed thermoplastic; depth equal to marking thickness; helps reduce wear from plowing.	Milled/recessed markings showed R_L>310 mcd/m²/lux; demonstrated resistance to degradation under harsh conditions.

Recommendation Area	Literature Review Recommendation	Interview-Based Recommendation	Field Data-Based Recommendation
Temporary Marking Practices	Prefer traffic paint and temporary tape for short-term markings; grinding and water blasting for removal.	Paint/tape standard in work zones; removal by grinding or water blasting based on surface type.	Temporary markings degraded quickly; recommend paint and removable tape in short-term zones; water blasting preferred for clean removal.
Pavement Marking Management Systems	Establish centralized GIS dashboards to track marking conditions and maintenance schedules.	Some DOTs have condition tracking platforms; a few use mobile R_L tools or visual scoring.	NJ needs integrated asset system; GPS-tagged R_L, material data, and condition tracking are missing for several segments.
Supply Chain Resilience	Use bulk purchasing and approve alternative materials to address supply chain disruptions.	Reported challenges with bead supply; some states bulk buy or rely on multiple vendors to avoid delays.	Bead and paint supply issues noted; suggest bulk purchasing and diversified vendor base.
Readiness for ADAS/AV Technologies	Update marking specs for AV compatibility: width, contrast, luminance, and wet visibility.	Recognize AV compatibility needs; few pilot projects are underway; focus on consistency and lane visibility.	6-inch and high-contrast markings showed better R_L retention, critical for visibility in wet/night AV conditions.
MUTCD Width Standards (6-inch)	Support the adoption of 6-inch markings per MUTCD with phased implementation and funding.	Some states already transitioned to 6-inch; others plan gradual implementation aligned with MUTCD update.	6-inch markings performed best in R_L; should be standard for interstates and major corridors.
Research and Safety Evaluation	Fund studies linking marking performance with crash reduction and AV detection performance.	Limited but growing emphasis on studying safety impacts of markings,	Markings with low R_L linked to higher degradation and potential visibility concerns; supports targeted safety

Recommendation Area	Literature Review Recommendation	Interview-Based Recommendation	Field Data-Based Recommendation
		especially post-installation R_L drop.	evaluations and funding.

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APPENDIX

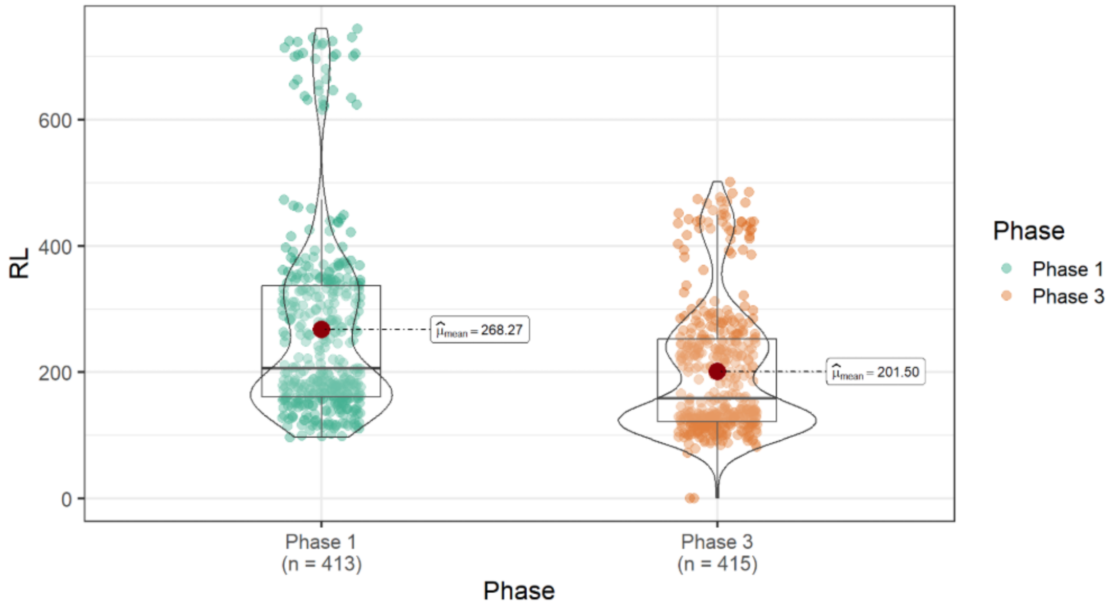

Figure 67. Distribution of R_L measures by route in all phases (GSP)

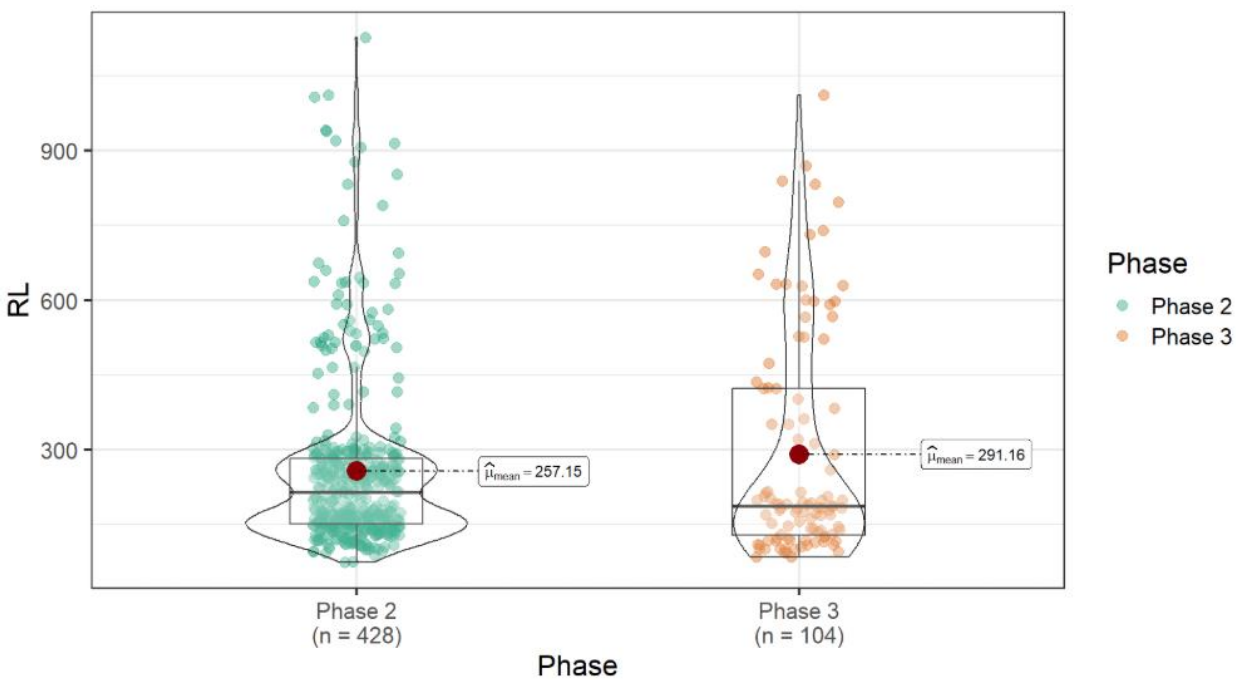

Figure 68. Distribution of R_L measures by route in all phases (GSP Bridge)

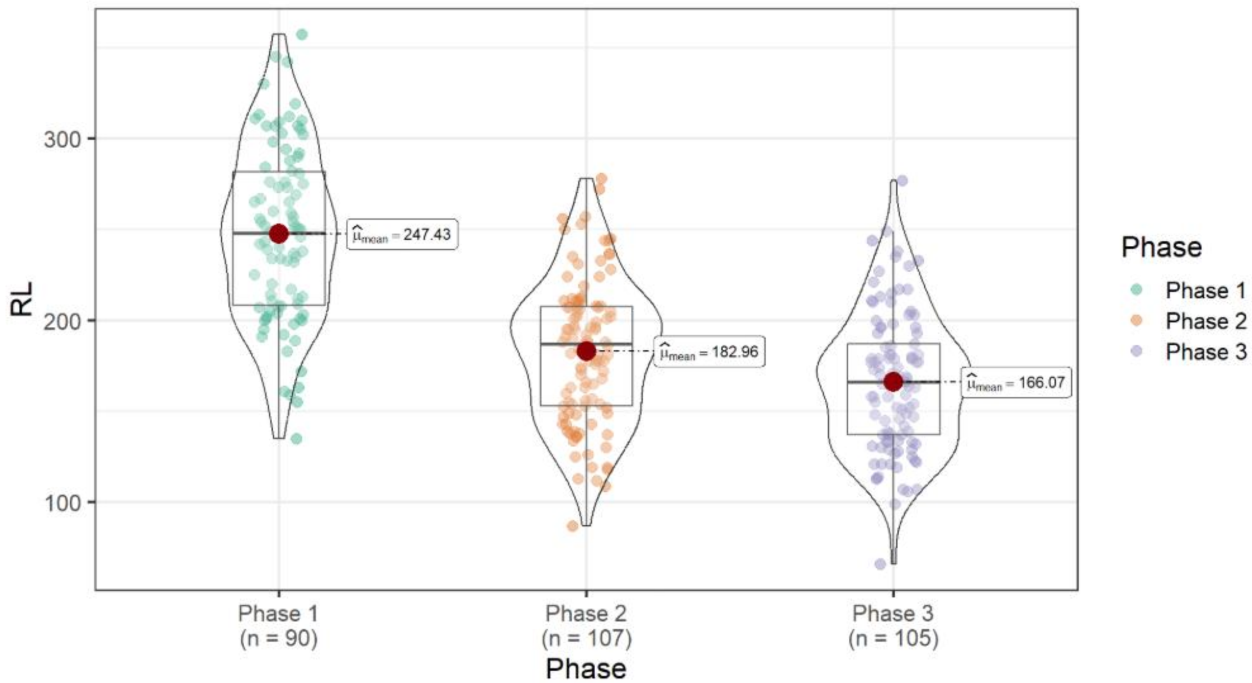

Figure 69. Distribution of R_L measures by route in all phases (SH 33)

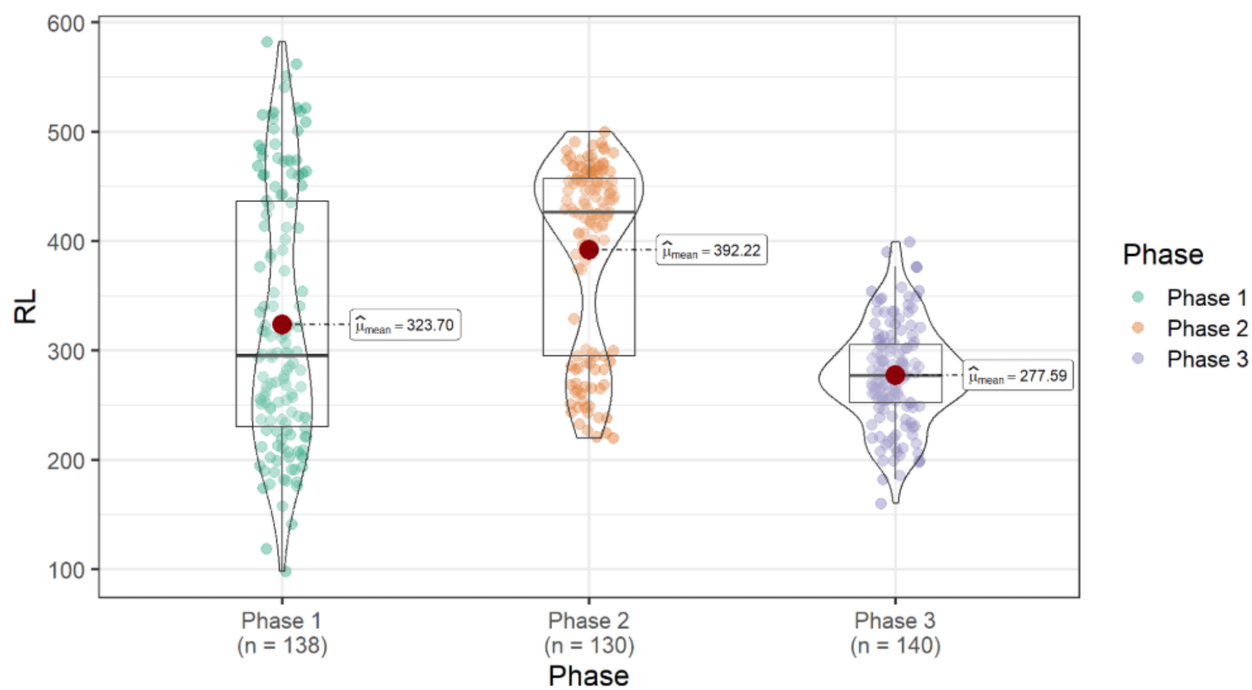

Figure 70. Distribution of R_L measures by route in all phases (SH 37)

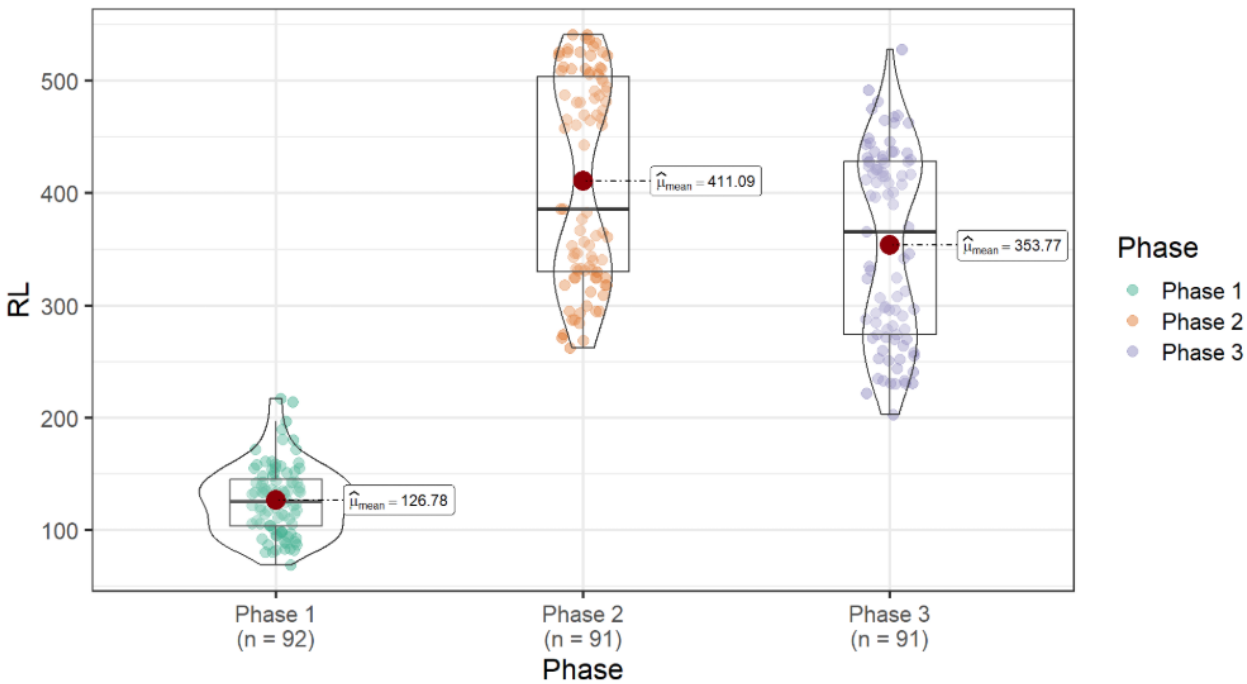

Figure 71. Distribution of R_L measures by route in all phases (SH 50)

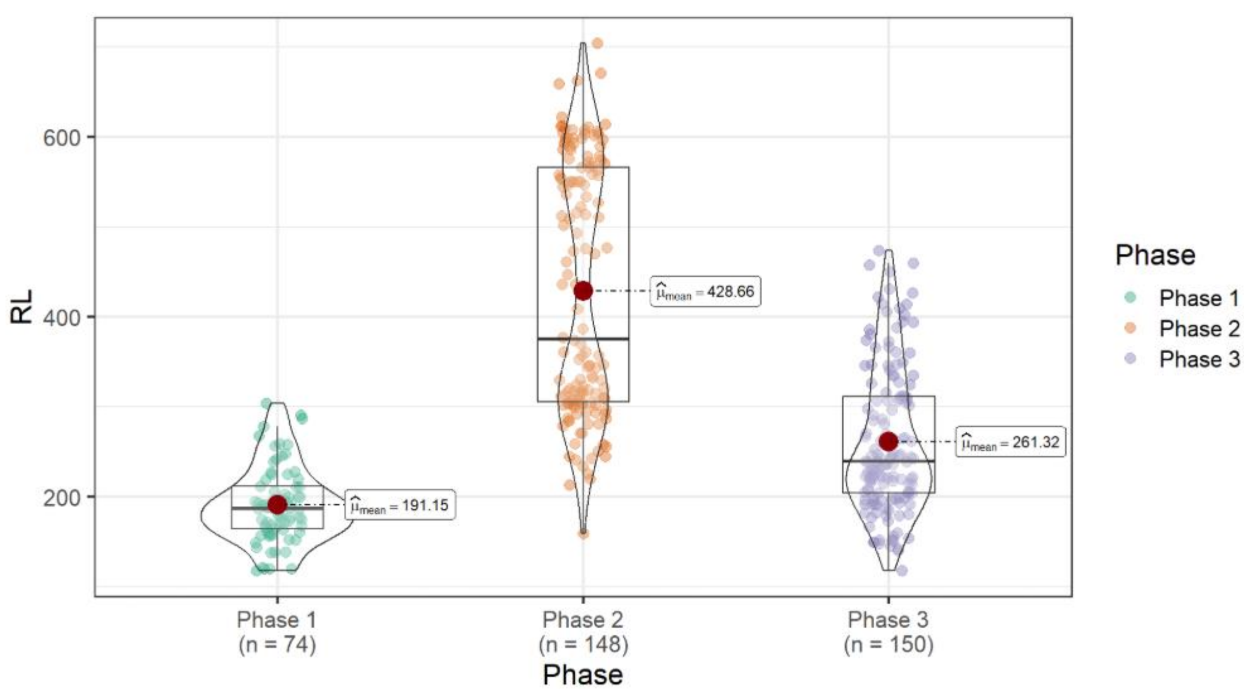

Figure 72. Distribution of R_L measures by route in all phases (SH 53)

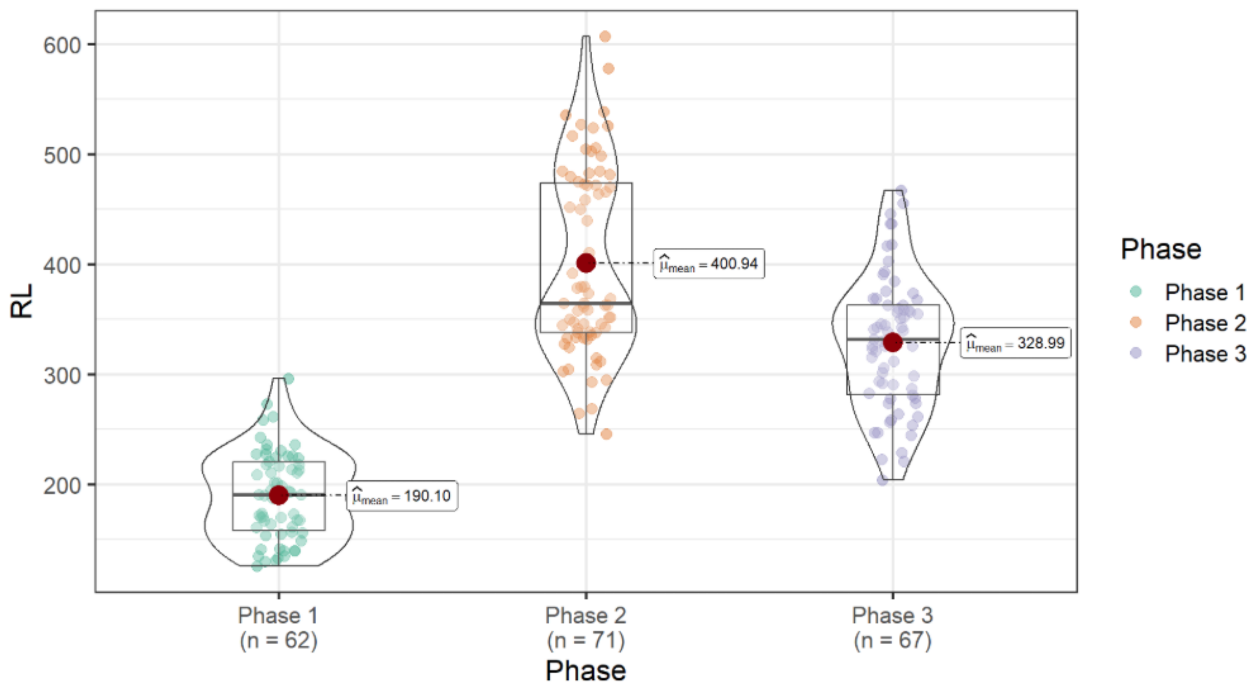

Figure 73. Distribution of R_L measures by route in all phases (SH 54)

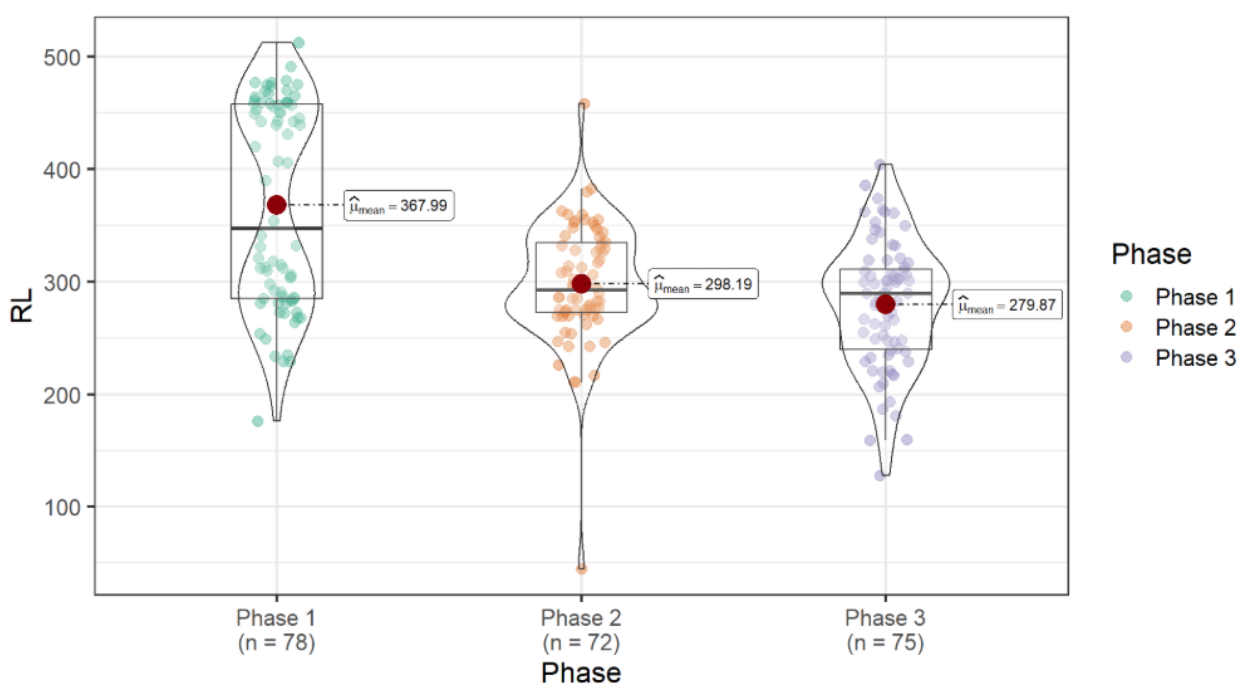

Figure 74. Distribution of R_L measures by route in all phases (SH 72)

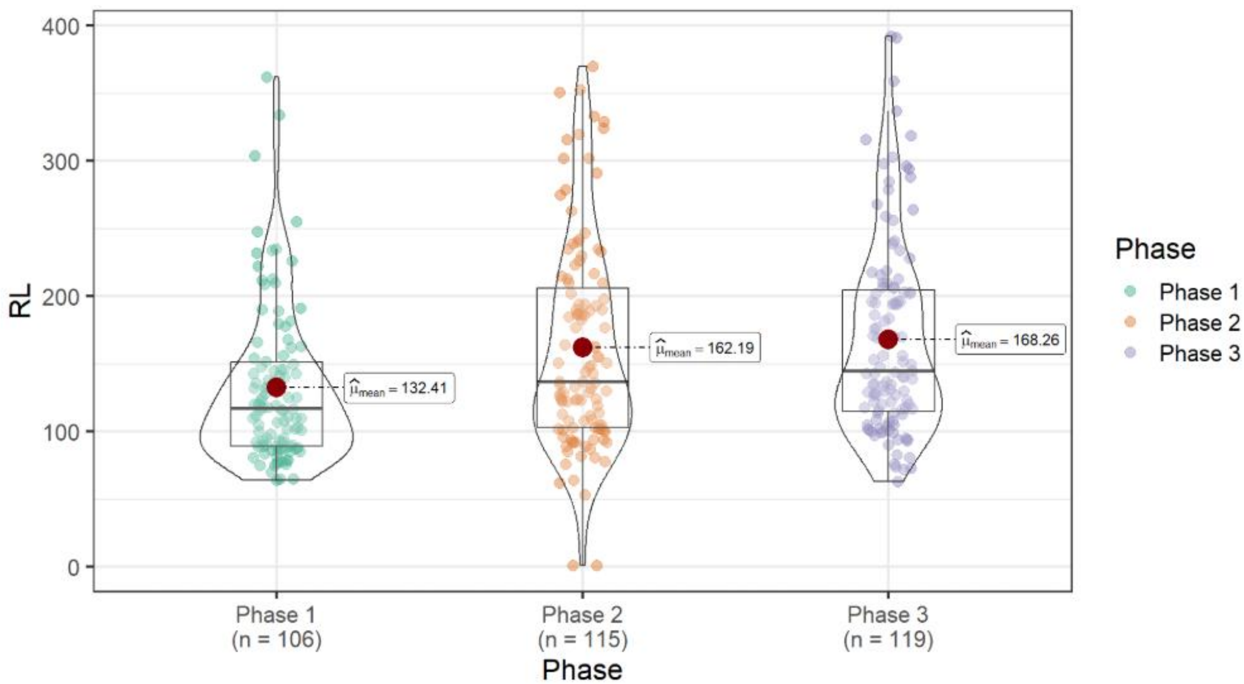

Figure 75. Distribution of R_L measures by route in all phases (SH 73)

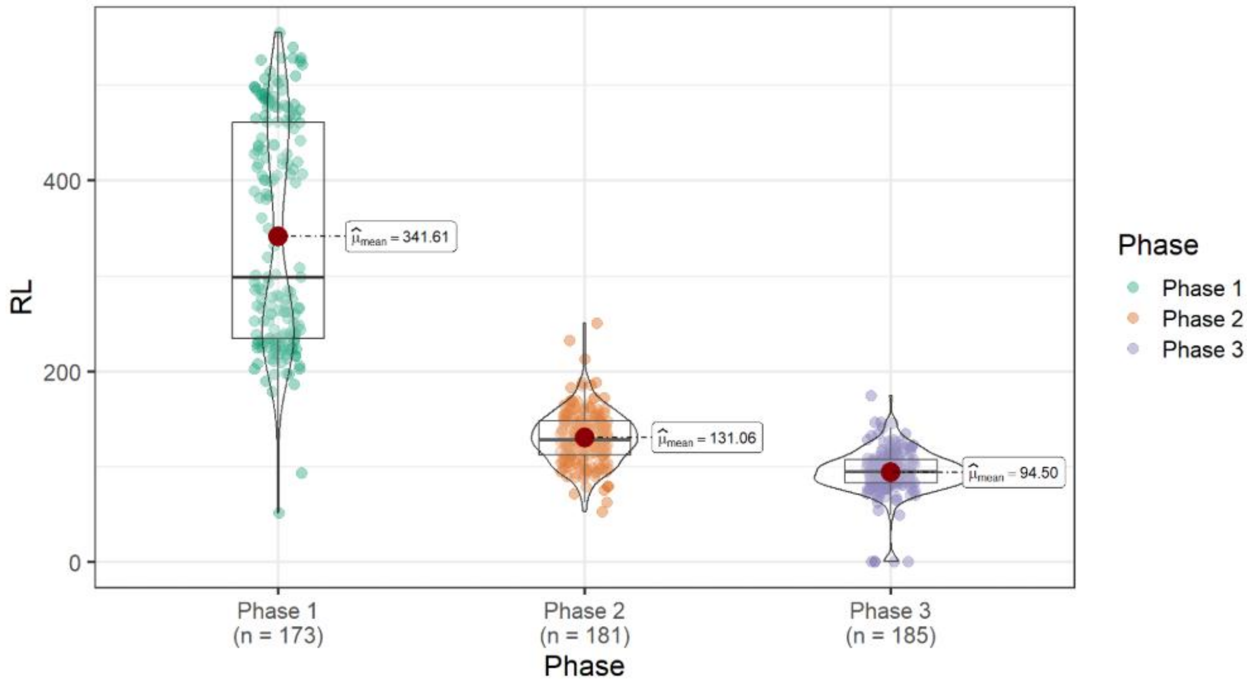

Figure 76. Distribution of R_L measures by route in all phases (US 206)

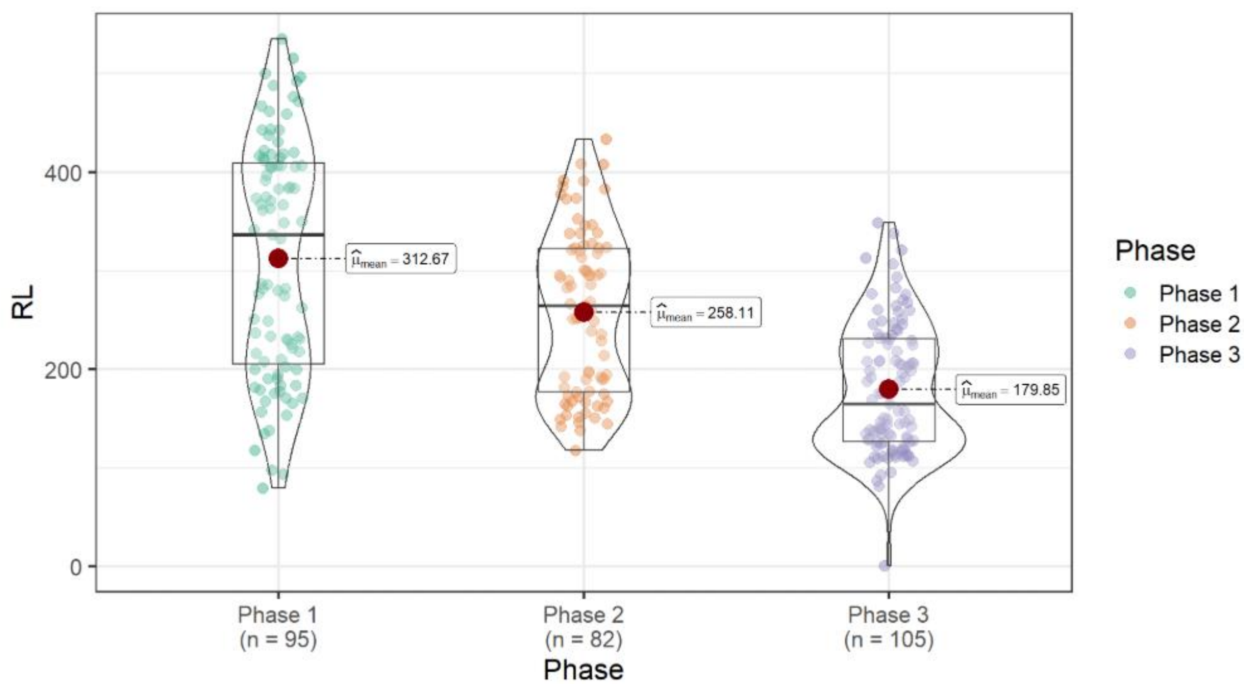

Figure 77. Distribution of R_L measures by route in all phases (US 322)

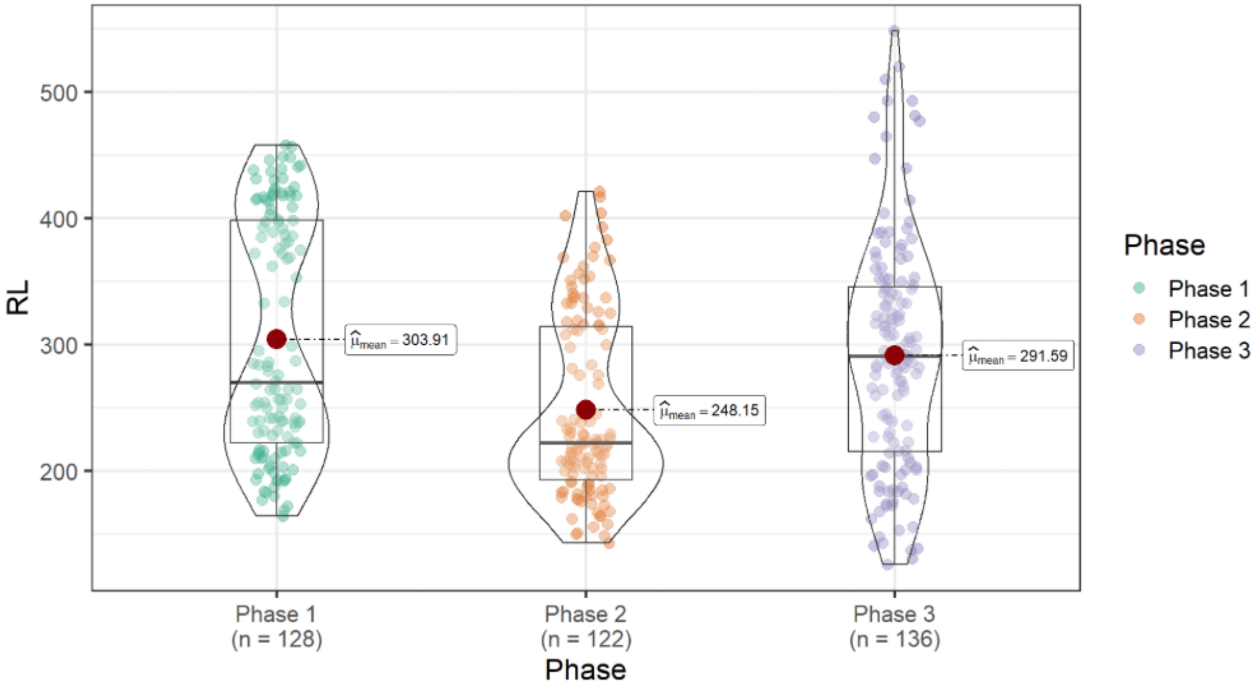

Figure 78. Distribution of R_L measures by route in all phases (US 40)