# FINAL REPORT

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Wyoming Department of Transportation, State of Wyoming

# ENHANCING PAVEMENT MARKING MANAGEMENT PRACTICES IN WYOMING


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16. Abstract:

Pavement markings safeguard road users, and maintaining adequate retroreflectivity is crucial for ensuring road safety. As the Wyoming Department of Transportation (WYDOT) performs routine application of pavement markings, there is a pressing need for a comprehensive management program to ensure their cost-effective management. So, this report focuses on enhancing pavement marking management in Wyoming by investigating factors influencing retroreflectivity, developing predictive models for degradation over time, and establishing a comprehensive Pavement Marking Management Plan (PMMP) template that incorporates the principles of the Transportation Asset Management Plan. Binary Logistic Regression models were developed to determine the contributing factors affecting pavement marking retroreflectivity. The findings of this study indicate that factors, such as the degree of curvature of horizontal curves, location (rural or urban), material type, pavement marking color, and line position significantly affect pavement marking retroreflectivity. The degradation models provide valuable insights into the deterioration process of pavement markings over time and can assist highway agencies in prioritizing maintenance efforts. The proposed PMMP template also integrates Pavement Marking Management Systems of several state DOTs and Transportation Asset Management principles, providing project selection, budgeting, procurement, and contracting strategies.

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Pavement markings; Retroreflectivity; Degradation time; Deterioration rate, Pavement Marking Management System; Pavement Marking Management Plan

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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

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

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oC$ | Celsius | 1.8C+32 | Fahrenheit | $^oF$ |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

**TABLE OF CONTENTS**

## LIST OF FIGURES

## LIST OF TABLES

## LIST OF ACRONYMS/ABBREVIATIONS

| | |
|---|---|
| AADT | Annual Average Daily Traffic |
| AADTT | Annual Average Daily Truck Traffic |
| AASHTO | American Association of State Highway and Transportation Officials |
| ADAS | Advanced Driver Assistance Systems |
| ATSSA | American Traffic Safety Services Association |
| ADT | Average Daily Traffic |
| DOT | Department of Transportation |
| FHWA | Federal Highway Administration |
| I-25 | Interstate 25 |
| I-80 | Interstate 80 |
| LCCA | Life-Cycle Cost Analysis |
| MAP-21 | Moving Ahead for Progress in the 21st Century |
| mcd/m2/lux | milli candela per square meter per Lux |
| MMA | Methyl Methacrylate |
| MP | Mile Post |
| MUTCD | Manual on Uniform Traffic Control Devices |
| NCUTCD | National Committee on Uniform Traffic Control Devices |
| NOAA | National Oceanic and Atmospheric Administration |
| PMMP | Pavement Marking Management Plan |
| PMMS | Pavement Marking Management System |
| RL | Retroreflectivity |
| SAE | Society of Automotive Engineers |
| SAS | Statistical Analysis Software |
| SD | Standard Deviation |
| STIP | State Transportation Improvement Program |
| SRT | Skid Resistance Tester |
| TAMP | Transportation Asset Management Plan |
| USDOT | United States Department of Transportation |
| VOC | Volatile Organic Compound |
| WYDOT | Wyoming Department of Transportation |

# CHAPTER 1: INTRODUCTION

Pavement markings are visual elements strategically placed on the surface of roads, streets, and other transportation infrastructure to provide vital information and guidance to pedestrians and drivers. These pavement markings typically include lines, symbols, words, and colors, forming a visual language that communicates traffic laws, lane boundaries, crosswalks, and other important navigational indications. For pavement markings to be effective, they must be highly visible and durable, as they have been proven to reduce fatalities during nighttime significantly (FHWA 2022; Carlson et al. 2013; Jiang 2008). Moreover, adequate visible pavement marking can also significantly reduce the number of runoff-the-road and cross-centerline collisions by clearly defining roadways when the edges and lanes might otherwise be difficult to recognize. Improved pavement markings and signage might reduce 50 percent of nighttime crashes and about 28 percent of fatalities that happen in the dark (Hussein et al. 2020). In line with this, Wyoming Strategic Highway Safety Plan (SHSP), recognized that around 32 percent of motor vehicle crashes in Wyoming occurred in the dark in 2020, with 78 percent of them happening in dark conditions without lighting, and recommends enhanced pavement marking as an essential treatment for safety improvement.

Pavement markings should be installed with retroreflective properties to ensure adequate visibility during nighttime and unfavorable weather conditions. Retroreflectivity determines how effectively the pavement marking reflects light back to its source, making it visible to road users. Since pavement marking retroreflectivity differs significantly by location, pavement marking type, pavement surface, climate, and traffic (FHWA 2022), an effective pavement marking management plan could save resources and improve driver safety. Therefore, a comprehensive idea of factors affecting retroreflectivity is essential to propose a cost-effective management plan. Considering those facts, this research developed a data collection protocol to collect $R_L$ data from different highways in Wyoming and determined the factors affecting the $R_L$ of pavement marking. In addition, the degradation model of pavement marking retroreflectivity was developed to identify the deterioration trend of $R_L$ with pavement marking age, snowplow activities, material properties, and geometric conditions of the roads. And finally, a framework for a pavement marking management plan template has been developed.

## 1.1 Problem Statement

Retroreflectivity is a measure of pavement marking visibility and is assessed in a standard unit millicandelas per square meter per Lux (mcd/m$^2$/lux). According to the Manual on Uniform Traffic Control Devices (MUTCD 2022), for a speed limit of ≥ 35 mph (56 km/h), the retroreflectivity level of longitudinal pavement marking must be equal to or greater than 50 mcd/m$^2$/lux. If the posted speed limit is ≥ 70 mph (113 km/h), the retroreflectivity level should be at or above 100 mcd/m$^2$/lux. (FHWA 2022). The FHWA's new standard offers agencies a flexible approach to conforming to its requirements, allowing them to adapt and comply in a way that suits their needs and resources due to having varying levels of staffing, equipment, budgets, road systems, and expertise. Therefore, different DOTs (Department of Transportation) still follow their own policies above the MUTCD minimum standard for restriping. Considering the unique geographical features, climate patterns, and traffic conditions in the state of Wyoming, it becomes essential to evaluate pavement markings and develop its own pavement marking management system.

Pavement marking performance may vary across different locations and lines. Some markings may experience significant degradation within a short period of service, and some may be serviceable for a long time. Consequently, there is a clear need to develop a method for evaluating pavement marking at an early age and degradation models over a period, which can aid in selecting suitable pavement marking materials and developing effective restriping schedules.

The Wyoming Department of Transportation (WYDOT) spends around $7 million each year on managing around 25,000 lane miles of pavement markings. Proposed models and recommendations will help WYDOT and other states avoid restriping before reaching the end of the service life. Proper maintenance of pavement markings poses both budgetary and road safety concerns. Replacing pavement markings in advance would incur unnecessary maintenance costs, while delayed replacement could compromise road safety. An efficient pavement marking management plan can save resources and enhance driver safety by ensuring timely and well-informed maintenance decisions.

### 1.2 Research Objectives

The main objectives of this research are to:

- Investigate factors influencing the retroreflectivity of newly applied pavement markings and determine the key factors that impact their performance.
- Develop prediction models to estimate the degradation of pavement marking retroreflectivity over time, considering factors such as road geometry, pavement marking characteristics, traffic attributes, and winter maintenance.
- Develop a Pavement Marking Management System (PMMS) for Wyoming highways through a nationwide survey and integrate other agencies' strategies.
- Develop a comprehensive PMMP template for Wyoming highways that incorporates Transportation Asset Management Plan principles and includes the recommendation of the district engineers of different districts.

The following five research tasks were carried out in this project to accomplish the objectives:

1. Develop data collection protocols by selecting pavement marking test sections across four functional classifications of roads in Wyoming.
2. Organize a comprehensive database for pavement marking in Wyoming by integrating measured pavement marking retroreflectivity data, traffic volumes, weather characteristics, and roadway geometry information.
3. Analyze the factors influencing pavement marking retroreflectivity and determine the impact of significant factors on retroreflectivity through statistical modeling techniques and binary logistic regression model.
4. Develop degradation models for pavement marking retroreflectivity over time for the four functional classifications of highways in Wyoming, using statistical analysis techniques such as Bayesian Ordered Logit Models and Determine the service life of pavement markings.
5. Develop a PMMS for Wyoming highways through a nationwide survey.
6. Establish a template of a comprehensive PMMP for Wyoming, aligned with the principles of the Transportation Asset Management Plan.

### 1.3 Report Organization

This report consists of seven chapters. These chapters are described below.

Chapter 2 of this report presents background information and the relevant literature to build the required body of knowledge and understand the different aspects of this study.

Chapter 3 briefly describes the methodology used for this report.

Chapter 4 shows the methodology and statistical analysis to determine the factors affecting pavement marking retroreflectivity.

Chapter 5 demonstrates the procedure of developing the pavement marking degradation model, provides the result and application of the pavement marking retroreflectivity degradation model, as well as calculation of service life of different marking materials.

Chapter 6 describes the PMMS, integrating with practices and strategies used by transportation agencies based on insights from a nationwide survey.

Chapter 7 introduces the framework for the PMMP, which involves incorporating the PMMP into the overall Transportation Asset Management Plan (TAMP) and integrating it with pavement marking management systems used by different districts of WYDOT from a statewide survey.

Finally, Chapter 8 provides conclusions and recommendations regarding the objectives laid out in this research.

# CHAPTER 2: LITERATURE REVIEW

This chapter serves as a comprehensive literature review by providing the background for pavement marking research. It explores various pavement marking aspects, including pavement marking materials, color, retroreflectivity, data collection protocols, factors influencing pavement marking performance, and pavement marking degradation. Furthermore, relevant studies related to pavement marking management plans are summarized. The chapter also includes statistical tools commonly employed for analyzing pavement markings and an accumulation of previous studies investigating pavement markings.

## 2.1 Details of Pavement Markings

### 2.1.1 Types of Pavement Markings

Pavement markings comprise three types based on the line position or geometrical classification: longitudinal, transverse, and temporary. The characteristics of longitudinal pavement markings, such as color (white or yellow) and pattern (double or single, broken or solid), convey specific meanings.

#### a) Longitudinal Pavement Markings

Longitudinal pavement markings run parallel to the roadway and regulate the vehicle’s lateral positioning. They include various types, such as centerlines, lane lines, edge lines, no-passing lines, channelizing lines, and more.

#### b) Transverse Pavement Markings

Pavement markings installed perpendicular to the traffic flow are known as transverse markings. These markings include shoulder markings, word, and symbol markings, arrows, stop lines, yield lines, crosswalk lines, speed measurement markings, parking space markings, etc. By default, transverse markings are white in color unless specified otherwise in the applicable guidelines or regulations.

#### c) Temporary Pavement Markings

Temporary pavement markings are temporary substitutes for permanent markings and are typically utilized during construction phases in work zones for maintenance or utility projects to guide and direct traffic.

### 2.1.2 Pavement Marking Color

White and yellow are the two main colors used for longitudinal pavement markings. Yellow lines are typically used to divide traffic traveling in opposite directions. For example, centerlines on two-lane roads or the inside edge lines on divided highways are yellow. On the other hand, white longitudinal pavement markings separate traffic flows moving in the same direction. A white pavement marking is used in the pavement's lane line or right edge line. Lane lines are typically broken white lines, while edge lines are solid.

## 2.2 Pavement Marking Components

Five key components are commonly used in pavement marking materials: binder, pigment, filler, dispersion medium, and glass beads (retroreflective material), illustrated in Figure 1 and shown in

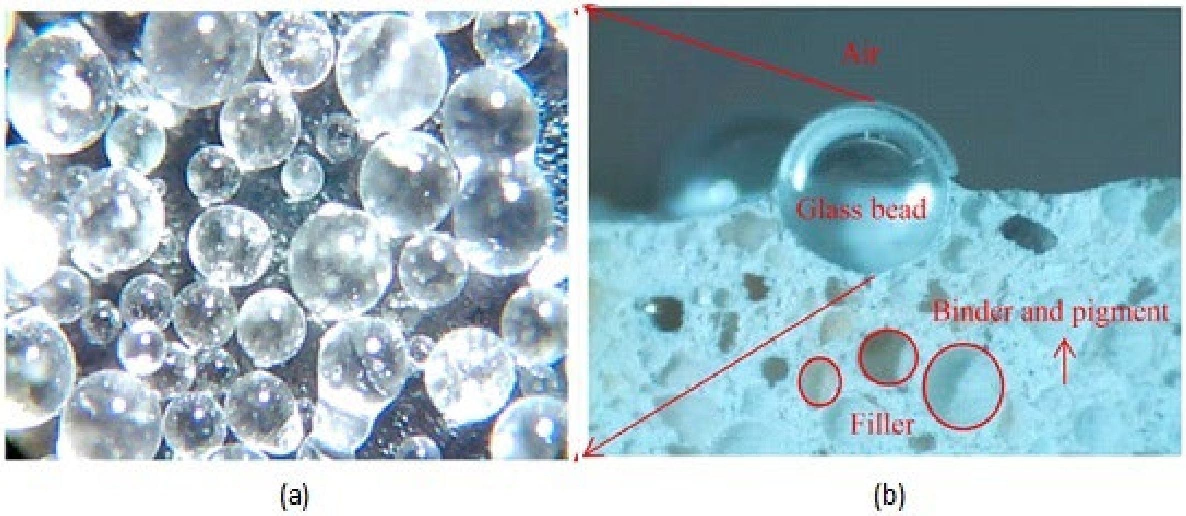



Figure 2. These components work together to form the composition of pavement markings, contributing to their visibility, durability, and reflective properties.

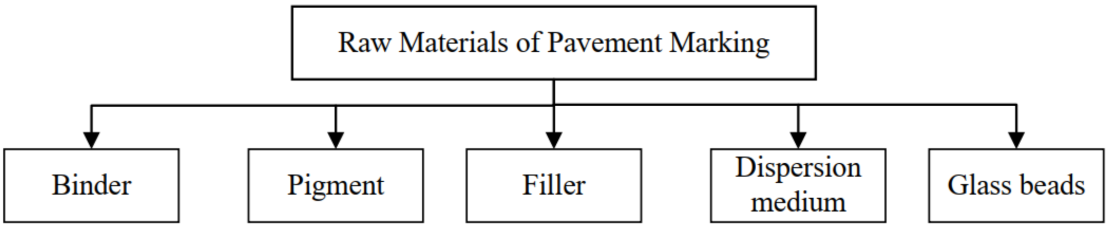



**Figure 1. Chart. Components of Pavement Marking Material.**

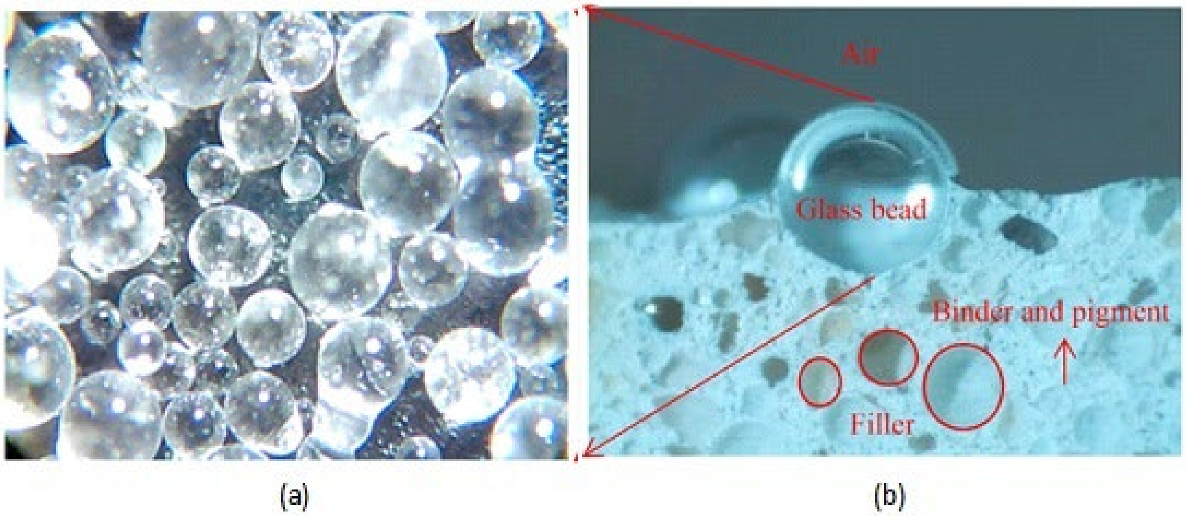



**Figure 2. Illustration. A Microscopic View and Cross-Section of Pavement Marking Materials (Xu et al. 2021).**

### (a) Binder

The binder is responsible for adhering the markings to the pavement surface, enabling it to withstand abrasion caused by traffic and road maintenance activities. In addition, it serves as the binding agent that combines the various marking components, creating a uniform coating or film. Commonly used binders are epoxy, acrylic, alkyd, modified alkyd, petroleum-based compounds, rosin, polyurethane, polyester, and ester resin. Factors such as durability, adhesion, resistance to weathering and traffic, drying time, and application method influence the selection of an appropriate binder for a particular pavement marking project. Therefore, the choice of binder plays a significant role in determining the overall performance, longevity, and quality of the pavement markings on the road surface.

### (b) Pigment

Pigments are used to provide color and visibility to the pavement markings throughout the mix. In longitudinal pavement marking, mainly white and yellow pigments are used. Titanium dioxide ($TiO_2$) is a common and standard pigment for white pavement markings, and lead chromate (PbCrO) is used in yellow markings.

### (c) Filler

Fillers help fill gaps and voids within the pavement marking material, creating a denser and more cohesive mixture and imparting durability to the mix. Fillers also improve moisture sensitivity, abrasion resistance, and temperature stability, preventing sagging. Commonly used fillers in pavement marking materials include calcium carbonate, silica, kaolin clay, mica, and mineral powders.

### (d) Dispersion Medium

The dispersion medium is a volatile liquid that acts as a solvent to dilute or dissolve the film-forming binder. The primary function of the dispersion medium is to ensure the pavement marking's stability and rheology (flow characteristics). Furthermore, it helps maintain a consistent viscosity and prevents the components from separating or settling during application. Additionally, the dispersion medium plays a vital role in the film formation process, assisting in the even distribution and smooth application of the marking material. Finally, by facilitating proper mixing and application, the dispersion medium contributes to the overall quality and longevity of the pavement markings.

### (e) Glass Bead

The retroreflective effect of pavement markings is achieved by including tiny glass beads in the marking material. These beads, called drop-on beads, are incorporated into the liquid pavement marking material during application. The beads stick to the pavement marking surface, creating a coating that improves light reflection. When vehicle headlights or other light sources illuminate the markings, the glass beads refract and redirect the light back toward the source, improving the visibility of the markings, particularly during nighttime or low-light conditions. This retroreflective feature significantly assists drivers in accurately recognizing the pavement markings, ultimately contributing to safer and more effective road navigation.

## 2.3 Classification of Pavement Marking Material

At present, there is no specific classification method for pavement marking materials. Despite the common objective of providing clear visibility on pavements, marking materials exhibit significant differences in composition, durability, and properties. Typically, pavement marking materials can be classified by considering several factors, like durability (non-durable and durable), the form of the markings (solid and liquid), and the type of material used (Sitzabee et al. 2009a). In 2002, Migletz and Graham mentioned 16 types of available pavement marking materials, predominantly durable pavement markings (Migletz and Graham 2002; Sitzabee et al. 2009a). Figure 3 presents a classification of available pavement marking material discussed in the following paragraphs.

### 2.3.1 Non-Durable Pavement Markings

Nondurable pavement markings have a relatively shorter expected lifetime, typically lasting around one year or less, depending on the specific type. The longevity of nondurable markings can be influenced by factors such as traffic volume, weather conditions, and other environmental factors. Nondurable markings are usually composed of solvent and water-based paints that are more environmentally friendly (Craig III et al. 2007; Migletz et al. 2001; Mohamed et al. 2019).

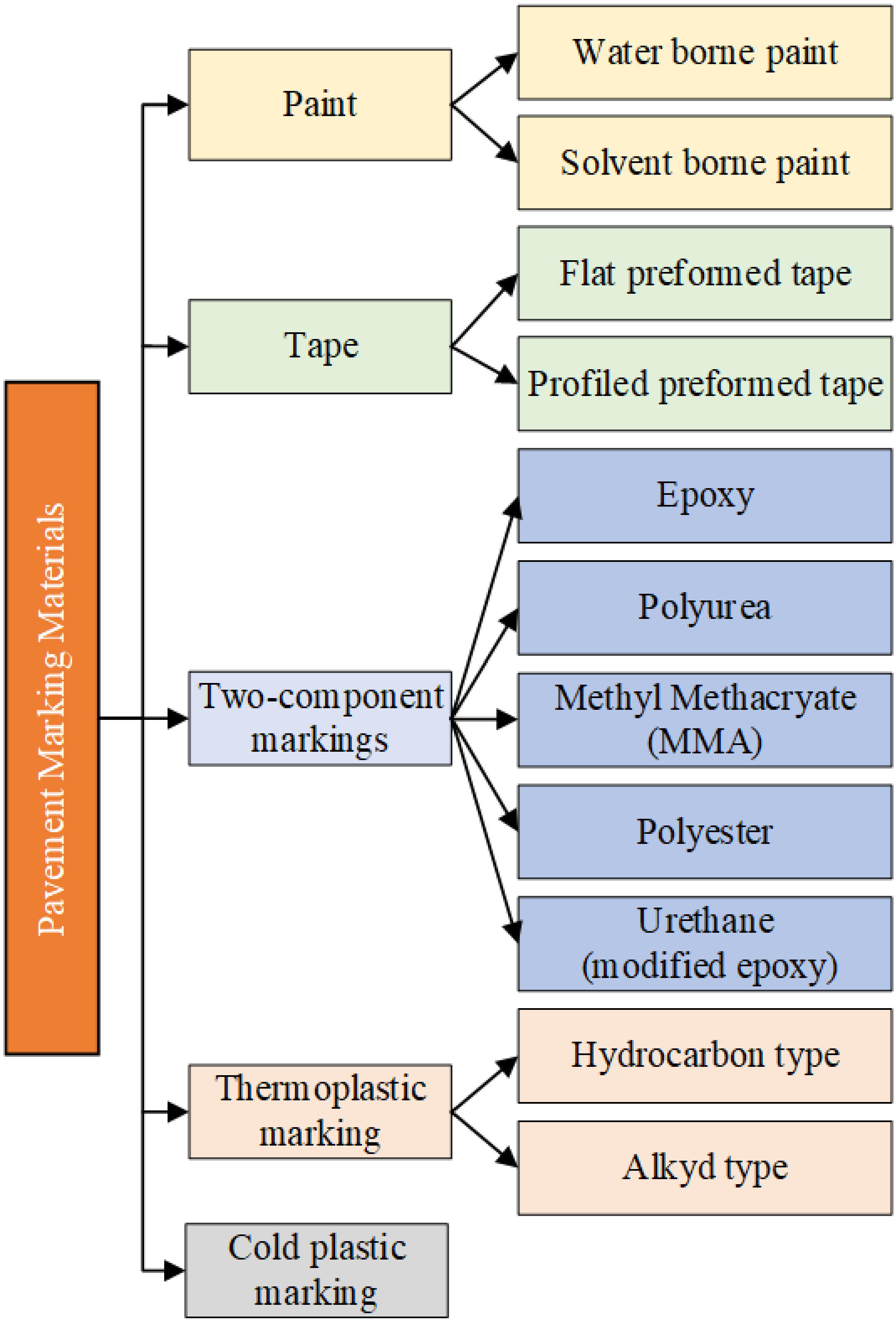



**Figure 3. Flowchart. Classification of Available Pavement Marking Material (Mohamed, 2019; Xu et al., 2021).**

Waterborne paints are widely used marking materials for their eco-friendliness and lower costs. Compared to solvent-based paints containing higher amounts of hazardous volatile organic compounds (VOCs), waterborne material typically has less than 150 g/L (grams per liter) of VOCs, making them a safer alternative for pavement markings from an environmental standpoint (Fatemi et al. 2006). However, these types of markings may not always last as other durable markings when exposed to weather elements and frequent traffic. Therefore, waterborne markings can be best recommended on rural roads for low-volume roads or interim pavement marking materials only. In addition, visibility is greatly improved by adding glass beads into the binder material during application (either via pre-mixing or spraying) (Gates et al. 2003; Jiang 2008). Despite some shortcomings, waterborne paints are still popular for pavement marking materials in the United States of America, accounting for nearly 90 percent of all material types (Xu et al. 2021).

### 2.3.2 Durable Pavement Markings

Durable pavement markings contain chemical compounds. These markings exhibit extended visibility and durability (3 or more years) compared to nondurable markings. However, durable markings can have a more significant environmental impact due to the higher VOC. (Craig III et al. 2007; Migletz et al. 2001; Mohamed et al. 2019). Typical durable markings are described below.

**a) Solvent-borne Paint**

Solvent-borne paints involve organic solvents as a dispersing medium with incorporated glass beads that function efficiently via the premixing, injection, or drop-on methods into wet film painting techniques. However, these paints produce VOC emissions into the atmosphere, averaging around 400-500 g/L (25 percent composition), creating unintended environmental costs. Multiple factors, including air temperature, air movement, and road conditions, influence the performance of paint during the drying process. There are two types of solvent-borne paints depending on construction temperatures- normal type and heating type. Normal types cause health/environmental concerns, prolonging drying times while offering poor wear resistance and limited durability options (Babić et al. 2015). Conversely, heating-based solvents include higher solid content, producing thicker coating films with more durability but less accessible due to cost or restricted usage limits.

**b) Tape**

Marking tapes are considered reliable pavement marking materials due to their durability and ease of application methods. These pre-formed strips or patterns made of reflective materials use an adhesive layer to make it easy to install them onto a primed pavement surface or in specially prepared grooves by sticking them onto a surface. One unique feature that distinguishes this tape from other application methods is its retroreflectivity. Up to 1,000 mcd/m$^2$/lux retroreflectivity can be achieved by adding high-quality glass beads during manufacturing that disperses throughout the matrix and not just on top. However, tapes are not suitable for snow plow operations or old, damaged roads(MacEacheron 2016). High-end marker tapes are relatively expensive, estimated between $1.50-$2.65 per linear foot (Montebello and Schroeder 2000), and offer longer lifespans. Due to easy application removal, low-end marking tapes are preferred for temporary construction site markings (Peng et al. 2013). Two popular varieties available are flat preformed tape and profiled preformed tape. Despite its durability, which lasts up to eight years when installed accurately, retroreflectivity diminishes rapidly over time. Therefore, the recommended service life is limited to up to three years. It is also important to mention that tapes contain no VOCs; however, some VOCs may still be present in their primer or surface preparation adhesives (Jiang 2008).

### 2.3.3 Two-Component Markings

For pavement marking applications where durability is critical, many industry professionals are opting toward using two-component solutions combining binders, pigments, and fillers in Component A with catalysts added to Component B, producing ultimate cross-linking curing. Epoxy, polyurea, methyl methacrylate (MMA), polyester, urethane, and various variations of these materials can be used as common film-forming substances in two-component material. One major difference between this approach versus others is its chemical curing process, while others rely solely on physical methods. Despite being a long-lasting and durable solution for pavement marking, it has some limitations. It might incur issues like discoloration or disintegration when exposed to ultraviolet light over time.

#### a) Epoxy

Epoxy is a durable pavement marking produced by combining two components. Component A is the base material, which includes resin, pigment, extenders, and fillers, and component B is a hardener that works as a catalyst to accelerate setting time. Epoxy suits on asphalt and concrete pavements offer strong adhesion. Glass beads can be mixed or applied on wet stripes in the epoxy material. It has a moderate cost and a service life of up to four years, but one drawback is its color fades with intense ultra violet (UV) exposure. Additionally, Epoxy's long drying time restricts its use in high-traffic areas. However, some transportation agencies use epoxy on high-traffic concrete pavements (Jiang 2008). Epoxy-based systems may also present risks of allergic reactions due to their general human toxicity and the corrosive properties of the polyamine component. Environmental and public health considerations include regulations on using epoxy products in the European Union, but epoxy materials remain widely utilized in the United States (Xu et al. 2021).

### b) Polyurea

Polyurea is a relatively new pavement marking material produced onsite by combining two components. The first component is the base material and comprises a mixture of resins, pigments, and fillers, while the second component acts as a cross-linker. To enhance retroreflectivity, glass beads are applied onto the wet surface. Polyurea has some advantages. It exhibits good color stability when exposed to ultraviolet light and has a short curing time (cures rapidly within 3 to 8 minutes at all temperatures). Polyurea may be applied at low ambient pavement surface temperatures as low as 40 degrees Fahrenheit and unaffected by humidity. It is compatible equally well with asphalt and concrete pavement, especially providing excellent durability on concrete pavement. However, applying polyurea material necessitates specialized equipment and higher cost (Jiang 2008).

### c) Methyl Methacrylate (MMA)

Methyl methacrylate markings are highly durable two-component markings. The first component is pigmented material containing a methyl methacrylate monomer, pigments, fillers, glass beads, and silica, and the second component is a liquid or powder catalyst (Migletz and Graham 2002). It allows spraying or extruding flexibility but typically requires longer no-track times to ensure proper curing and durability (Andrady 1997). Methyl methacrylate (MMA) is suited for cold climates, can be applied at low temperatures, and has resistance to oils. Additionally, it provides strong adhesion to asphalt and concrete surfaces (Gates et al. 2003). MMA-type markings are nonhazardous as they contain negligible VOCs (Mohamed 2019). MMA markings often have an expected service life of more than three years. The 2002 survey revealed that MMA has limited usage in the United States of America, with only Oregon, Alaska, and California implementing them, and these states highly rated the MMA for its superior performance in heavy snowfall areas compared to thermoplastic and paint markings in terms of durability, cost, visibility, and service life (Gates et al. 2003). While MMA pavement markings have seen limited adoption in the United States of America, they are widely utilized in China and Europe (Xu et al. 2021).

### d) Polyester

Polyester pavement marking is similar to epoxy marking in terms of its formation. It is typically created onsite by mixing two components before installation. Glass beads are sprayed on top of the wet striped surface to enhance visibility. Polyester is best suited on asphalt pavements and can be used over existing markings. While it contains a low VOC content, the chemicals involved in their production are classified as hazardous (Bahar et al. 2006; Jiang 2008). The usage of polyester in the United States is less than 1 percent(Mull 2011).

### e) Urethane

Urethane and modified urethane are two-component marking materials with similar performance characteristics to polyurea and epoxy. Limited DOT experience exists for this material, as it has been used experimentally in three surveyed states. Costs for modified urethanes are slightly higher than epoxy but lower than polyurea, and they are marketed as having enhanced durability compared to epoxy. It provides faster cure times (2 minutes) and superior ultraviolet color stability. Standard epoxy equipment can conveniently spray these materials (Gates et al. 2003). Notably, the nationwide usage of modified epoxy or urethanes remains minimal, reflecting their limited adoption (Carlson et al. 2013; Gates et al. 2003; Jiang 2008; Wang 2010).

### f) Thermoplastic Marking

Thermoplastic Pavement Markings represent an established and widely utilized pavement marking solution throughout the United States. Thermoplastics comprise binders, pigments (titanium dioxide), fillers (calcium carbonate), and glass beads. Depending on the binding material employed, they exist in hydrocarbon or alkyd resin variations, of which hydrocarbon resins are renowned for their exceptional heat resistance compared to the alkyd varieties. In preparation for application, these solid materials undergo melting transformation above 400 degrees Fahrenheit (204 degrees celsius) into a liquid state and then are applied via spraying, extrusion, or melting-in-place as preformed thermoplastics (Carlson et al. 2013; Wang 2010; Xu et al. 2021). Though their adherence to asphalt surfaces is generally excellent, bonding difficulties may arise when applied over concrete surfaces, necessitating sealers for adequately establishing the connection (Van Schalkwyk 2010).

Additionally, applying thermoplastic pavement markings to cold regions presents a limitation that manifests via suboptimal bonding at lower temperatures. Nonetheless, these thermoplastic markings has been efficient since their introduction in United States' roadways in 1958 (Mirabedini et al. 2012). Following waterborne paints, it has consistently propelled their popularity, now the second most popularly used pavement marking. Its durability suits it for heavily trafficked roads, including crosswalks and stop bars.

### g) Cold plastic Marking

For pavement markings at pedestrian crossings that can sustain constant passing vehicles over them, selecting cold plastic marking is an ideal choice. Using binders like monomers and oligomers mixed with a peroxide initiator for polymerization on pavement surfaces makes it a durable marking material of preference. However, given the flammable nature of this kind of marker system, careful handling becomes mandatory. It is sensitive to temperature and moisture and requires adding accelerators or retardants (Xu et al. 2021).

## 2.4 Retroreflective Materials

The concept of retroreflectivity was first introduced in the 1942 Manual of Uniform Traffic Control Devices (MUTCD). Over the years, the language in the MUTCD has remained straightforward, stating that markings requiring nighttime visibility should be retroreflective unless there is sufficient ambient illumination. Additionally, it specifies that all markings on Interstate highways must be retroreflective. The retroreflective performance of pavement markings is achieved by the incorporation of reflective media, and the most commonly used reflective medium for marking materials is glass beads.

### a) Glass Beads

Glass beads are small spherical glass balls employed to enhance the retroreflectivity of any pavement marking material. Applying a coating to the surface of glass beads enables them to integrate into the marking material, ensuring consistent retroreflectivity. Glass beads are commonly made by recycling float glass. The glass is mechanically ground to the desired size and placed in special vertical furnaces. In these furnaces, the glass is heated to around 1200 degrees celsius, causing the irregular shards to become mostly round in a matter of milliseconds (Wenzel et al. 2022). Glass beads application on pavement markings can be categorized into two types: surface-sprinkled glass beads and pre-mixed glass beads. Surface-sprinkled glass beads are applied by spreading them on the wet surface of markings using a bead dispenser or paint sprayer. Pre-mixed glass beads are uniformly mixed into the paint before applying the marking material (Xu et al. 2021).
Various key factors related to glass beads affect the newly installed retroreflectivity of pavement markings. These include the material composition of the beads, their refractive index, the amount and dispersion of beads within the marking, the embedment depth, the size type of the beads, their clarity, and their roundness. These factors are briefly described as follows:

### b) Refractive index (RI)

The retroreflective properties of glass beads are determined by their refractive index (RI), which is influenced by the material composition. A higher RI value indicates higher retroreflective capabilities. In pavement markings, glass beads typically have an RI ranging from 1.5 to 2.4. The Standard Specification for Glass Beads in Pavement Markings (AASHTO M 247-13) specifies a required RI between 1.50 and 1.55. To enhance performance in wet conditions, glass beads should ideally have a higher refractive index, around 2.3 or greater (Burns et al. 2008). The chemical and physical properties of the glass material primarily determine the refractive index of the glass beads. Additionally, the glass beads' gradation (diameter) and roundness impact their interaction with the marking binder, influencing the distribution and embedment of the glass beads on the marking surface.

### c) Embedment Depth

Studies have shown that the optimal retroreflection from glass beads occurs when 40 percent of the bead body is visible above the marking surface, while 60 percent is securely embedded beneath it. This embedment level of 60 percent maximizes the retroreflective properties of the beads (Migletz et al. 1999; Rasdorf et al. 2009).

### d) Bead Density

The retroreflectivity of pavement markings is greatly influenced by the density of the installed glass beads. A lower density of glass beads results in reduced retroreflectivity for the markings.

### e) Types of Glass Beads

The American Association of State Highway and Transportation Officials (AASHTO) classifies glass beads used in pavement markings into five types: I, II, III, IV, and V, as outlined in the Standard Specification for Glass Beads Used in Pavement Markings (AASHTO M 247). Type I, known as the standard bead or standard gradation, is the smallest and most used. Types II, III, IV, and V are categorized as modified gradations and have progressively larger bead sizes. Larger beads enhance wet-night visibility as they rise above the water level.

## 2.5 Pavement Marking Performance Evaluation

### 2.5.1 Criteria for Pavement Marking Performance Evaluation

The performance and serviceability of pavement marking materials are evaluated by two criteria: visibility and durability. The brightness defines the visibility of pavement marking, and durability is referred to the resistance against damage (FHWA 2022; Carlson et al. 2013; Jiang 2008). Pavement marking retroreflectivity and contrast ratio serve as widely recognized indicators for assessing the visibility and durability of markings. Besides retroreflectivity, Skid resistance is considered a key indicator for pavement marking as outlined in the European Technical Standard EN 1436 (EN 1998). Although research on skid resistance in pavement markings is limited, its importance has been emphasized in various studies. (Burghardt et al. 2022; Coves-Campos et al. 2018; Markow 2008).

### 2.5.2 Pavement Marking Retroreflectivity

The performance and serviceability of pavement marking materials are evaluated by their retroreflectivity (FHWA 2022) which measures how well the pavement marking is visible to road users. Reduction of nighttime visibility is often the first sign of failure of retroreflectivity performance (Mohamed 2019). Retroreflectivity is a surface property that allows a large portion of the light coming from a point source to be returned directly to a point near its origin. It differs from reflectivity, which involves either specular (mirror-like) light reflection or the scattering of light through matter or diffuse surfaces (MacEacheron 2016) presented in Figure 4.

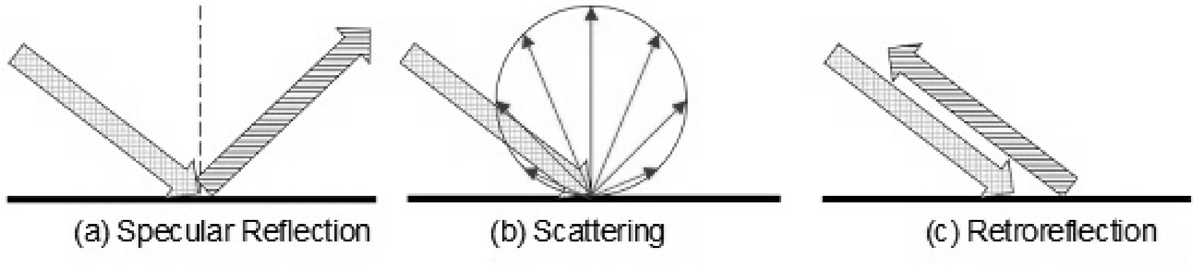



**Figure 4. Illustration. Several Modes of Reflection.**

Small glass beads are applied to binder materials to make the pavement marking retroreflective. Retroreflectors are designed to reflect only a beam of light along the same path as the incoming beam. In the Glass-bead Retroreflection method, the light beam undergoes a bending process when it enters a glass bead, reflects off a mirrored surface positioned behind the bead, and bends once more as it exits the bead, ultimately returning to the light source. More elaborately, on the glass beads embedded in the paint, light from oncoming vehicles' headlights is refracted downward in the beads to a point where it is embedded in the paint. This point is a diffuse reflecting surface that reflects a fraction of the light back toward the vehicle's headlights in the same color as the paint (Austin and Schultz 2002). The principles of retroreflectivity in pavement marking are illustrated in Figure 5.

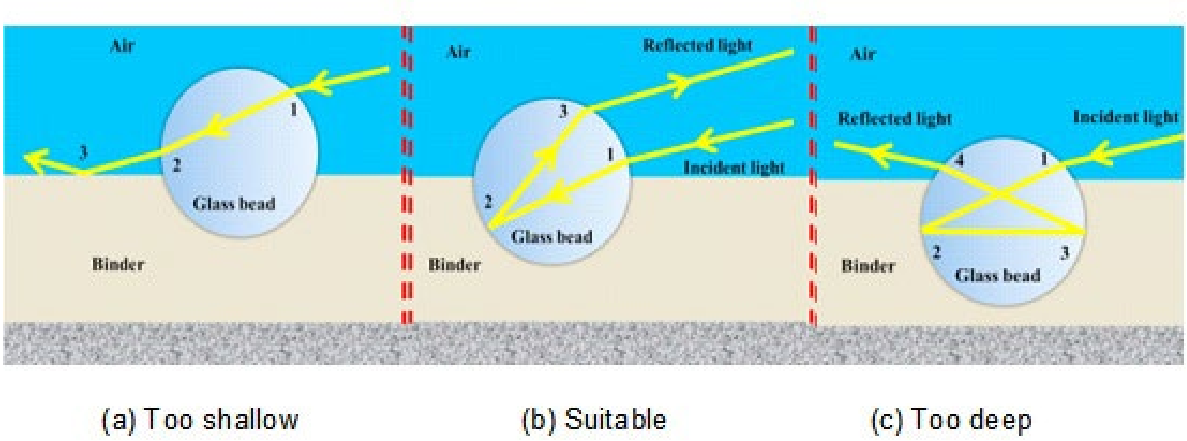



**Figure 5. Illustration. Pavement Marking Retroreflectivity of Glass Beads (Xu et al. 2021).**

Pavement marking retroreflectivity is quantified using the measurement unit- milli candela per square meter per Lux (mcd/m$^2$/lux). Candela is the fundamental International System of unit for luminous intensity, indicating the power emitted by a light source in a specific direction, weighted by the luminosity function. It indicates the brightness or intensity of reflected light. Lux is the SI unit of illuminance which measures the amount of luminous flux (light) falling on a given area. It quantifies the level of brightness or light intensity experienced on a surface. In the case of retroreflectivity measurement, lux indicates the amount of incident light illuminating the pavement marking. Putting it all together, mcd/m²/lux provides a measure of the retroreflectivity of pavement markings by considering the luminous intensity (mcd) of the reflected light per square meter (m²) of the marking relative to the illuminance (Lux) of the incident light falling on the marking.

### 2.5.3 Contrast Ratio

The contrast ratio provides a quantitative value that represents the difference in brightness between the pavement marking and the road surface. Higher contrast ratios indicate better visibility and easier recognition of the pavement marking, especially during nighttime conditions. During the daytime, color contrast is determined by the difference in the roadway surface's colors and the pavement markings. However, during nighttime, the contrast ratio is calculated using the retroreflectivity of the pavement marking and the surrounding road surface, and the nighttime contrast ratio (CR) can be calculated by Equation 1 (Benz et al. 2009):

$$CR = \frac{R_L(Marking) - R_L(Pavement\ Surface)}{R_L(Pavement\ Surface)} \tag{1}$$

### 2.5.4 Durability

Pavement marking durability is defined as its capacity to withstand deterioration over time. There are two commonly employed methods to assess the durability performance of pavement markings. One approach involves visually estimating the proportion of remaining material in a specific pavement surface area. The other method evaluates the cohesion between the marking material and the pavement surface. In the first method, the remaining material on the pavement surface is visually examined and assigned a rating on a scale of 1 to 10. A rating of 1 indicates complete removal of the material, while a rating of 10 indicates that 100 percent of the material is still intact. The durability-rating graphical procedure is illustrated in Figure 6.

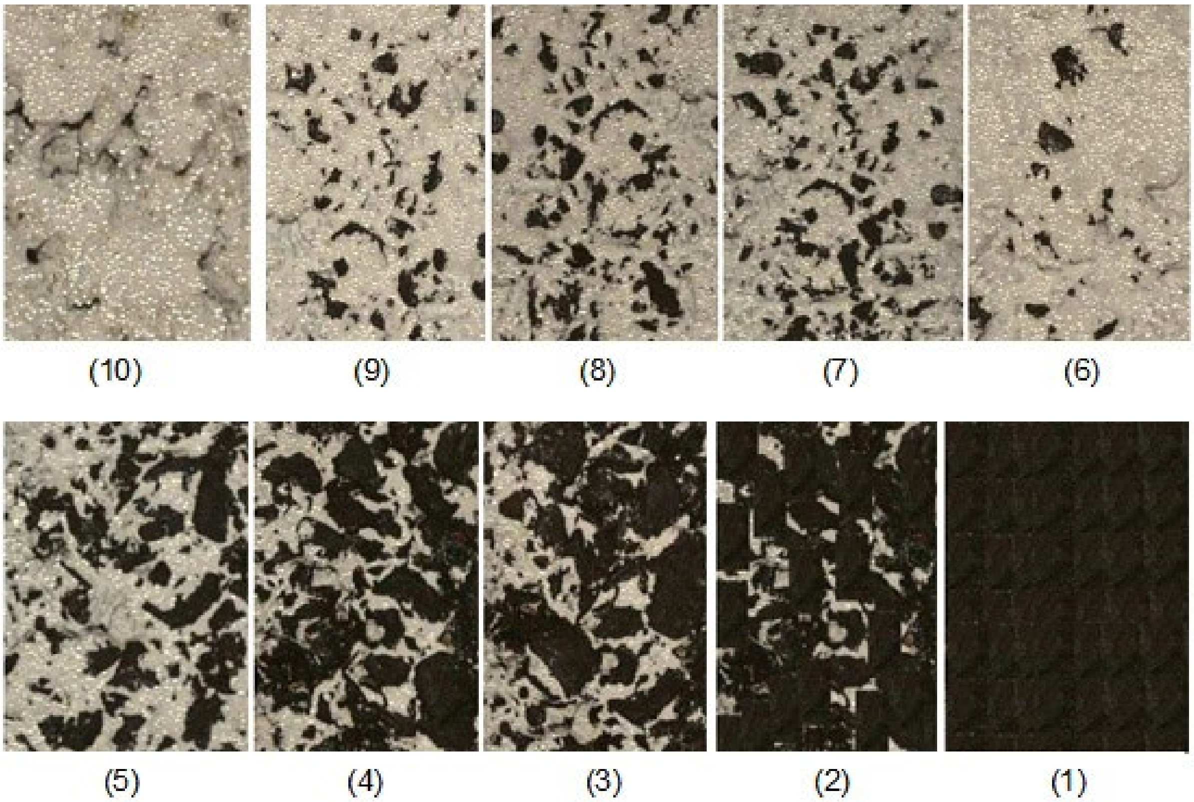



**Figure 6. Illustration. Subjective Durability Rating Procedure (Migletz and Graham 2002; Mohamed 2019).**

### 2.5.5 Skid Resistance of Pavement Marking

Skid resistance is the ability of the marking to provide sufficient grip or friction between the vehicle's tires and the road surface. A pavement marking with good skid resistance helps vehicles to maintain better control, especially during braking or maneuvering. Glass beads in pavement markings improve skid resistance (Xu et al. 2021). Skid resistance is considered a key indicator for pavement marking besides retroreflectivity, as outlined in the European Technical Standard EN 1436 (EN 1998). According to EN 2018 standards, the skid resistance value, expressed in the SRT value measured using the standard British pendulum apparatus, should fall within the range of S1 (≥ 45) to S5 (≥ 65) (EN 2018).

## 2.6 Pavement Marking Performance Evaluation Technique

Pavement marking performance can be assessed by objective and subjective evaluation systems (Sitzabee et al. 2009b). Objective evaluations are conducted using retroreflectometers, either mobile or handheld devices. Subjective evaluations depend on visual inspections performed by trained observers. Both evaluation techniques are considered valid methods for measuring retroreflectivity in the United States (Migletz and Graham 2002). Visual inspections have several advantages, including their simplicity and cost-effectiveness, and they do not require specialized equipment. However, visual inspections are susceptible to human error, and verifying their accuracy can be challenging.

### a) Handheld Retroreflectometers

The handheld retroreflectometers is are portable, lightweight retroreflectometers that are manually placed and moved along a line while collecting retroreflectivity readings. Its small size makes it ideal for laboratory use for having a simple calibration process, affordable to purchase and maintain, and does not require extensive training. However, there are some limitations to consider. Taking measurements with handheld retroreflectometers may require lane closures, particularly for lane lines that can cause inconvenience and potential safety risks for the operator exposed to traffic. Additionally, due to its manual operation, fewer samples can be collected within a given timeframe, and measuring long pavement markings can be time-consuming and costly.

### b) Mobile Retroreflectometers

Mobile retroreflectometers or mobile retroreflectivity units (MRU) is specifically designed to be mounted on a vehicle, typically a specialized measurement vehicle or van, and collect data as the vehicle moves along the road at normal driving speeds. The device is equipped with sensors or detectors that measure retroreflectivity. MRU can collect a large number of measurements at highway speeds without exposing the operator to traffic. They require a two-person team, one operating the instrumented vehicle and the other monitoring the data collection via connected software. Unlike handheld devices, mobile retroreflectometers minimize traffic disruption as lane closures are unnecessary. However, they come with a higher cost, requiring a trained operator and more periodic maintenance (Lopez 2004). Factors such as environmental conditions, measurement geometry, calibration procedures, software operation, and driving precision must be carefully managed for accurate data collection.

### c) Minimum Retroreflectivity Levels

The minimum retroreflectivity level of pavement marking is the acceptable requirement for the amount of light that pavement marking should reflect back to the driver. These levels are established to ensure adequate visibility of road markings, even in low-light conditions. FHWA sponsored several studies after the United States Congress established a minimum requirement for highway pavement markings retroreflectivity in the MUTCD. And finally, on August 5, 2022, the Federal Highway Administration (FHWA) published a final rule incorporating a standard for maintaining minimum retroreflectivity levels for pavement markings into Section 3A.03 of the MUTCD. For a speed limit of ≥ 35 mph (56 km/h), the retroreflectivity level of longitudinal pavement marking must be equal to or greater than 50 mcd/m$^2$/lux. If the posted speed limit is ≥ 70 mph (113 km/h), the retroreflectivity level must be at or above 100 mcd/m$^2$/lux. (FHWA 2022). The FHWA's new standard offers agencies a flexible approach to conforming to its requirements, allowing them to adapt and comply in a way that suits their needs and resources due to having varying levels of staffing, equipment, budgets, road systems, and expertise. Therefore, different DOTs still follow their own policies regarding restriping.

## 2.7 Pavement Markings in Wyoming

The majority of pavement markings in Wyoming are waterborne paint, with small amounts of epoxy-based paint, tape, polyurea, and thermoplastic materials. However, for roads experiencing high traffic volumes, high truck traffic volumes, and frequent snowplow operations, WYDOT has chosen more durable marking materials. The state restripes all highway waterborne pavement markings on an annual fixed schedule instead of waiting for retroreflectivity to fall below a threshold limit. Durable pavement markings are restriped every two years. Pavement striping activities usually start in April and run through October. Factors such as durability, ease of striping, price, and maintenance costs are considered at the decision-making level of pavement marking contracts and material selections.

### 2.7.1 Snow Removal Operations in Wyoming

Wyoming is known for its severe weather, resulting in significant winter snowfall. Wyoming's high elevation and continental climate contribute to frequent snowstorms and prolonged periods of snow cover. Snowfall in Wyoming can vary widely, with some regions receiving heavy snow accumulation while others may have more moderate amounts. To ensure safe and accessible roadways during winter, WYDOT employs an extensive snowplow operation to maintain safe driving conditions. In addition to plowing snow, WYDOT uses various snow management techniques. Before snow events, salt and other chemicals, such as magnesium, are applied to prevent snow from freezing on the roads, especially for low-volume snowfall. Sand or limestone grit is also used to enhance traction on the roadways. If roads have enough snow accumulation, they are plowed using snow plow trucks.

## 2.8 Factors Affecting Marking Performance

Longitudinal pavement markings are provided to assist drivers in recognizing the right road path for accurate vehicle maneuvering and keeping them in safe lateral positions. Several studies have evaluated the factors affecting longitudinal pavement marking performance over the years. Benz et al. (2009) divided the factors affecting marking performance into two categories (Visibility factors and durability factors), which are presented in

Table 1. Visibility factors are associated with the vision capabilities of the driver, and durability factors are related to the material's capability to resist damage due to weather and abrasion influence.

From studies of pavement marking in Texas, Lopez (2004) categorized those factors into two groups: (a) external factors, which include pavement characteristics, traffic conditions, and environmental conditions, and (b) internal factors, which include material properties.

**Table 1. Factors Affecting Pavement Marking Performance (Benz et al. 2009).**

| Visibility Factors | Durability Factors |
|---|---|
| Pavement marking retroreflectivity | Marking material type |
| Color contrast | Marking thickness |
| Pavement color | Pavement type (PCC or ACC) |
| Marking color | Pavement texture (surface roughness, porosity, etc.) |
| Pavement texture | Traffic volume |
| Presence of marking material | Weather condition |
| Marking material type | Maintenance activities (restriping, snow removal, etc.) |
| Marking width | Marking location (edge line, centerline, lane line) |
| Vehicle headlamp type | Roadway geometry (horizontal curves, weaving areas, etc.) |
| Viewing geometry | |
| Ambient lighting conditions | |

Common factors that play a significant role in pavement marking performance are described as follows:

### a) Pavement Marking Material

The performance of all marking materials is not the same on different pavements and locations. Consequently, selecting proper paint types is a challenge for transportation agencies. By studying the service life of thermoplastic, preformed tape, and epoxy material on the highway in Texas, Gates et al. (2003) recommended thermoplastic for short-term application, epoxy for long-term application in most traffic conditions, and preformed tape for long-term with very high traffic conditions. In addition, due to the strong adhesion to the pavement surface, epoxy and thermoplastics are considered more durable than waterborne.

### b) Pavement Marking Color

Numerous studies indicate that white pavement markings generally have notably higher retroreflectivity ($R_L$) readings compared to yellow markings. These findings are supported by Lopez's (Lopez 2004) findings and Clarke and Xuedong (2009), who conducted an extensive study of 121 pavement sites in Tennessee. Bahar et al. (2006) also reached the same conclusions. Although white markings may deteriorate faster than yellow ones, their higher initial retroreflectivity counterbalances this over time. This observed disparity is mostly due to differences in how the two paints' pigments scatter light. White pigments scatter incident light across all wavelengths, giving a brighter effect overall, whereas yellow pigments are prone to absorbing light except for those wavelengths linked to yellow (Bowman and Abboud 2001).

#### c) Traffic Volume

The impact of traffic on pavement markings varies depending on whether they are transverse or longitudinal markings. Transverse markings experience a clear and significant effect due to direct contact with passing tires. However, early longitudinal pavement marking studies did not establish a statistical correlation between traffic volume and retroreflectivity degradation. A study of thermoplastic paints in 50 sites in Michigan reported that the Average Annual Daily Traffic and the speed limit do not affect the service life of pavement marking (Taek et al. 1999). On the other hand, Abboud and Bowman (2002) reported that the service life of thermoplastic paints is 22 months, 7.5 months, and 4.5 months for AADT of <2,500, 2,500-5,000, and >5,000, respectively. Using retroreflectivity data from 150 sites over two years and four months in South Carolina, Thamizharasan et al. (2003) concluded that the lifecycle of pavement marking is affected by the marking color, material, and maintenance practices rather than the traffic volume. Bahar et al. (2006) also found no impact of AADT on pavement marking service life. In contrast, after analyzing the measured retroreflectivity data of epoxy and thermoplastic pavement marking, it was established that higher AADT could reduce the service life of pavement marking (Fitch 2007). However, a study conducted on Tennessee highways in 2009, utilizing retroreflectivity data collected from asphalt highways, revealed that AADT does indeed play a significant role in the degradation of waterborne pavement marking retroreflectivity (Sasidharan et al. 2009). Another study conducted in North Carolina in 2011 supported these findings, concluding that AADT has a small yet significant impact on the deterioration of waterborne markings (Mull, 2011). Recently, Malyuta (2015) reported that higher AADT results in lower service life for both yellow and white pavement marking using the handheld retroreflectometers data measured from 50 sites in Tennessee.

In summary, the degradation of pavement markings is independent of AADT according to several studies (Bahar et al. 2006; Karwa and Donnell 2011; Kopf 2004; Sarasua et al. 2003; Taek et al. 1999; Thamizharasan et al. 2003). Interestingly, among those studies, thermoplastic marking material was common. However, it also has been observed that higher AADT tends to result in shorter service life for both yellow and white pavement markings in other research (Fitch 2007; Fitch and Ahearn 2007; Malyuta 2015; Mull 2011; Mull and Sitzabee 2012; Sitzabee et al. 2009a). The inconsistency in the findings regarding the impact of AADT on pavement marking retroreflectivity can be attributed to factors such as varying sample sizes, different analytical assumptions, data variability, and the presence of other uncontrolled factors influencing retroreflectivity in some studies.

Determining the number of tire crossovers with longitudinal road markings faces significant challenges. Therefore, many researchers combine AADT and age into a single variable named Vehicle Exposure (VE) or cumulative traffic passages (CTPs), defined as the cumulative count of vehicles that have passed the road since introducing the fresh pavement markings. CTP considers the potential number of crossovers within a marking, considering traffic volumes per lane. The CTP would be calculated for edge lines based on the adjacent lane, while for centerlines and lane lines, it would involve the cumulative traffic passages in the two adjacent lanes (Migletz and Graham 2002). Migletz et al. (2001) developed the linear relationships between the retroreflectivity degradation and CTPs for various roadways, regions, materials, and colors using data from 19 states. However, no generalized relationships were developed due to the wide variation in data of different states for the same materials and line types. Migletz's observations might justify the inconsistent conclusion of past studies regarding the effect of AADT on pavement marking degradation. Using 4,815 data from 825 test sites in Alabama, Abboud and Bowman (2002) reported that the service life of thermoplastic paints decreases with VE. It was observed that the service life of pavement marking reduces from 22 months to 4.5 months when AADT increases from 2,500 to >5,000 (Abboud and Bowman 2002). Other studies reported a decreasing relationship between retroreflectivity and CTP (Lindly and Wijesundera 2003; Robertson et al. 2013).

#### a) Lateral Line Location

Pavement marking retroreflectivity varies based on lateral positioning, whether it's an edge line, lane line, or centerline. Natural events like weathering, snowplowing, and movement by passing vehicles result in the deterioration of different lines with time. Research on the impact of lateral location has been conducted extensively. Centerlines and lane lines located in the middle of roads where frequent vehicle passage tend to degrade faster, given the repeated contact with vehicle tires and snowplow activity. One study explored how drivers behaved around 4-inch edge lines when there were no obstacles. Results showed that motorists tended towards roadway centerlines under such circumstances (Sun and Tekell 2005). This behavior is largely impacted by various factors, such as pavement condition, traffic volume from opposite direction lane width, and operating speed (Tsyganov et al. 2005). During normal driving conditions on curved roads or turns when centrifugal force is experienced, drivers often use a curve flattening strategy. This involves positioning themselves closer to the road's centerline during left-hand curves while getting closer to its edge line during right-hand curves (Chrysler et al. 2009).

### b) Winter Maintenance

Winter weather conditions and maintenance activities, particularly snowplowing, significantly impact the degradation of pavement marking retroreflectivity. Snowplow blades and studded tires cause abrasion and lifting of the markings, leading to a rapid decline in retroreflectivity. In addition, the deicing agents, such as salts, can chemically break down the marking material and weaken its bond with the pavement. At the same time, sand acts as an abrasive, degrading the translucent quality of the retroreflective beads (Bowman and Abboud 2001). For example, the retroreflectivity of yellow and white markings on Iowa and Minnesota state highways decreased by 21 percent, 34 percent for waterborne paints, and 24 percent and 23 percent for conventional paints during winter (Migletz et al. 1999).

Furthermore, Mull (2011)found that paint pavement markings degraded by 3.2 mcd/m²/lux during each snowplow event. Several past other studies acknowledged the impact of snowplow or winter maintenance activities on $R_L$ degradation (Bahar et al. 2006; Craig III et al. 2007; Dale 1988; Fitch and Ahearn 2007; Lu and Barter 1998; Mohamed 2019; Mousa et al. 2021; Mull and Sitzabee 2012; Sarasua et al. 2003; Sitzabee et al. 2009a; Wang et al. 2016). However, incorporating snowplows in the degradation models has become challenging due to the lack of snowplow data in a specific road segment and difficulties in measuring retroreflectivity during snow seasons. Therefore, different approaches such as a questionary survey and a small field test in Alaska (Lu and Barter 1998), DOT surveys (Sarasua et al. 2003), and historical snow removal activities (Bahar et al. 2006) were taken to consider the effect of snowplows in retroreflectivity degradation. Past studies (Mohamed et al. 2019; Wang et al. 2016) incorporated snowplow as a categorical variable, meaning that it will yield itself as a qualitative impact coefficient. A retroreflectivity degradation model was proposed by Mull and Sitzabee (2012) using measured snowplowing frequencies and considered cumulative snowplows from 490 miles of roadway in North Carolina. However, Mousa et al. (2021) considered the average monthly snow depth (inch) in the degradation models. Overall, all published literature concluded that snowplowing is a significant factor affecting $R_L$ degradation. Therefore, to create a precise performance prediction model for pavement markings retroreflectivity, it’s crucial to consider snow removal activities, especially in regions like Wyoming that experience severe winters and substantial snowfall.

### c) Environmental Impact

The degradation of pavement markings may be influenced by climate and operating conditions. The surrounding environment plays a crucial role in the performance of pavement markings. The environmental factors can be categorized into two groups: weather conditions during installation and year-round climate. Factors such as temperature, humidity, rain, and wind speed significantly impact the durability of pavement markings. Temperature and moisture levels are particularly important during installation, as they affect drying time and the bond between the marking material and the pavement surface. Additionally, humidity and wind speed can influence curing time and the distribution of glass beads. After application, the long-term performance of pavement markings is directly affected by climatic conditions (Lopez 2004).

#### d) Road Surface Type and Condition

The performance of pavement marking material varies with the pavement surface type (asphalt pavement or concrete pavement). Previous studies have yielded mixed results regarding the degradation rates of pavement markings on asphalt and concrete pavements for different materials. According to Martin et al. (1996) research findings, paint pavement markings exhibit an 80 percentlonger lifespan on Portland cement concrete than asphalt concrete, particularly at low AADT values. However, Bahar et al. (2006) reported no difference in pavement (asphalt and concrete) in the performance of the paint. Furthermore, Sathyanarayanan et al. (2008) found that the degradation rates between markings on asphalt and concrete were negligible for the waterborne material. Thamizharasan et al. (2003) concluded that the epoxy-concrete linear model exhibited a more pronounced decline than the thermoplastic-asphalt models.

In addition, surface treatments, such as seal coat and micro pavement surfacing, negatively affect the bond between the marking and the pavement surface because these types of surfaces have a certain degree of rock loss, contributing to a loss of pavement marking material. Also, the coarse surface condition of the seal coat influences the ability to place the marking material at a sufficient thickness, affecting the marking material performance and glass bead placement (Hawkins and Smadi 2011).

### 2.9 Modeling Pavement Marking Retroreflectivity Deterioration

The current standard for assessing the retroreflectivity performance of pavement marking is wear testing based on the National Transportation Product Evaluation Program (NTPEP) test-deck method. In this procedure, the durability and service life of pavement marking are evaluated by monitoring the degradation for three years on a constructed test deck section (Pike 2007; Pike and Songchitruksa 2015). The degradation trends of retroreflectivity in pavement markings can vary depending on various factors, including the material type, marking color, traffic volume, snowplow activity, and environmental conditions (Clarke and Xuedong 2009; Mohamed 2019; Wang 2010). Numerous studies have been conducted to assess the factors that affect pavement marking retroreflectivity over the years and have yielded different outcomes. A comprehensive summary of related research on the degradation of pavement marking retroreflectivity, highlighting the independent variables incorporated into the model, material, duration, location, used model, and one brief key findings for each study is presented in Table 2. Pavement marking age and road traffic are crucial variables commonly used in determining $R_L$ degradation rate. As a result, some researchers use the cumulated traffic passage (CTP) variable in their models, as it considers both traffic and age. In addition to age/time and traffic volumes, numerous variables have been evaluated in multiple models, including marking material, thickness, color, line position, route locations, speed limit, initial retroreflectivity, maximum retroreflectivity, road surface, winter maintenance, rain, temperature, humidity, lane width, shoulder width, paint manufacturer, and bead type. The explanatory variables utilized in each model are based on the experimental planning and data collection approach. It is visible that there is no unanimity on the most effective explanatory variables to describe the retroreflectivity degradation, implying that various aspects of the experimental planning and road characteristics impact the degradation.

**Table 2. Summary of Retroreflectivity Degradation and Models in the Literature.**

| Reference | Marking Material | Factor considered | Model | Location/Source | Data Collection (Months) | Key findings |
|---|---|---|---|---|---|---|
| Lu and Barter (1998) | Paint, Thermo, Performed tapes, and MMA | Time, Material, and annual snowfall | Exponential model | Alaska, Idaho, Oregon, and Washington | 48 | Substantial Retroreflectivity Reduction in Winter: 62% in White Marking and 21% in Yellow Marking |
| Taek et al. (1999) | Waterborne, Thermo, Polyester, and Tape | Time, Traffic, Speed limit, Snowfall | Linear regression | Michigan | 40 | Snowfall and time strongly affect retroreflectivity degradation, while traffic volumes, commercial traffic, and speed limit have no impact. |
| Migletz et al.(2001) | Waterborne, Thermo, polyurea, epoxy | Initial $R_L$ and CTP | Linear and exponential model | United States (19 states) | 48 | Developed degradation models as a function of time and CTP for various roadways, regions, materials, and colors. Service lives vary due to winter maintenance. |
| Abboud and Bowman (2002) | Thermo and Waterborne paints | ADT and time | Logarithmic | Alabama | 36 | VE had a significant impact on $R_L$ degradation apart from time. |
| Thamizharasan et al. (2003) | White Thermo | Time | Non-linear and linear model | South Carolina | 28 | $R_L$ is affected by the marking color, material, and maintenance practices rather than the traffic volume. |
| Sarasua et al. (2003) | Epoxy, Thermo, and Preformed plastics tape | Color, material, road surface, and AADT | Non-linear and linear model | South Carolina | 12 | Marking color and winter maintenance impacts $R_L$, but AADT and truck percentage have no impact. |
| Lindly and Wijesundera (2003) | Flat and profiled Thermo | Age and CTP | Linear and exponential models | Alabama | 12 | $R_L$ decreases with the increase of CTP. The service life of profiled thermoplastic marking is higher than that of flat thermoplastic. |
| Kopf (2004) | Solvent-borne and waterborne paints | Color, Time, and AADT | Linear, logarithmic, and exponential | Washington | 12 | Due to having significant variability in data, there was no strong correlation between $R_L$ degradation rates and time. |
| Bahar et al. (2006) | Epoxy, MMA, tape, solvent, Thermo, and waterborne paint | Color, material, traffic volume, pavement surface, climatic region, and snow removal | polynomial | NCHRP | | Degradation models were developed considering all of the variables except AADT. |
| Craig III et al. (2007) | Thermo | Lateral location of the marking | ANOVA F Test | North Carolina | 60 | Center lines degrade faster than edge lines |
| Fitch (2007) | Thermo, polyurea, and epoxy | Age, traffic volume, and snow plow | Logarithmic | Vermont | 36 | The retroreflectivity degrades with snow plowing operations and AADT. |
| Fitch and Ahearn (2007) | Thermo, Epoxy paint, and polyurea | Traffic volume, time, and winter maint. | Logarithmic models | Vermont | 36 | Age, AADT, and winter maintenance exhibit the strongest correlation with degradation. |
| Sathyanarayanan et al. 2008) | Waterborne paint | Time, shape, and scale parameters | Weibull analysis method | Pennsylvania | 36 | The wheel path area had higher degradation rates compared to the skip line area. White pavement markings have longer service lives than yellow markings. |
| Sitzabee et al. (2009a) | Thermo and paints | Time, initial $R_L$, AADT, color, and lateral location | Multiple-linear regression | North Carolina | 60 | Degradation of pavement marking depends on the time, initial $R_L$, AADT, color, and lateral location. |

| Reference | Marking Material | Factor considered | Model | Location/Source | Data Collection (Months) | Key findings |
|---|---|---|---|---|---|---|
| Zhang and Wu (2010) | Thermo, tapes, and waterborne paints | Time | Smoothing spline and time series | Mississippi | 24 | $R_L$ prediction methodology was developed, and service life was estimated |
| Hummer et al. (2011) | Solvent-borne paint | Time and color | Linear mixed-effects model (LMEM) | North Carolina | 30 | On average, white and yellow edge pavement markings have an estimated life cycle of 37.5 and 38.9 months. |
| Mull (2011) | Solvent-borne paint | Winter maintenance, AADT, time, and initial $R_L$ | Multiple Linear Regression | North Carolina | 12 | Paint pavement markings degrade by 3.2 mcd/m$^2$/lux during each snowplow event. AADT has a significant impact on pavement marking degradation. |
| Karwa and Donnell (2011) | Thermo | Initial $R_L$, Time, marking type, and color, route location, and traffic flow | Artificial Neural Networks | North Carolina | 36 | Retroreflectivity decay varies among marking types and follows a nonlinear trend, while traffic volume does not significantly affect it. |
| Mull and Sitzabee (2012) | Paint | Time, Initial Retroreflectivity, Traffic and Snowplow | Multiple Linear Regression | North Carolina | 12 | After each snow removal event, paint pavement markings lose over a month of service life, and the degradation is slightly impacted by AADT. |
| Robertson et al. (2013) | Waterborne paint and high-build paint | Initial $R_L$, Time, AADT, CTP, temp., hum., lane width, and shoulder width | Multiple Linear Regression | South Carolina | 36 | CTP was more significant than age or volume alone in $R_L$ degradation, while temperature and humidity did not have a significant impact. |
| Malyuta (2015) | Thermo | Age and AADT | Linear | Tennessee | 24 | Age and traffic have a significant impact on $R_L$ degradation. |
| (Wang et al. 2016) | Preformed tape and MMA | Age, max $R_L$, traffic volume, and Snow load | piecewise multiple linear models | Florida, Pennsylvania, and Minnesota | 36 | Piecewise multiple linear models considering winter weather events performed better than conventional models in retroreflectivity prediction |
| Mohamed et al. (2019) | Waterborne | Age, Snow load, CTP | Logarithmic model | Idaho | 12 | A faster deterioration of $R_L$ with higher ground snow loads, with a logarithmic relationship between $R_L$ and age. |
| Mousa et al. (2021) | Waterborne | Elapsed time, paint manufacturer, surface, color, thickness, bead type, air temp., rain, snow, traffic | Machine Learning | Florida, Pennsylvania, Minnesota, and Mississippi | 36 | Initial retroreflectivity and elapsed time were found to be the most important variables in predicting retroreflectivity. Traffic level and air temperature also significantly contributed to the accuracy of the models. |

Notes: AADT= Annual Average Daily Traffic; $R_L$= Retroreflectivity; CTP= Cumulative Traffic Passages; VE= Vehicle Exposure; ADT = Average Daily Traffic; MMA= Methyl Methacrylate; Thermo= Thermoplastic; Temp.= Temperature; Hum. = Humidity; NA= Not Available

In addition to several variables, various approaches were employed to determine the impact of snowplows. For example, Dale (1988) considered annual snowfall as a category variable; Lu and Barter (1998) conducted a field survey and a small field test in Alaska to highlight the impact of winter weather on $R_L$. Sarasua et al. (2003) surveyed 49 states about snowplowing and winter maintenance in the United States of America. Bahar et al. (2006) considered historical snow removal activities in different climatic regions (None, Low, Medium, and Heavy). Mull and Sitzabee (2012) recorded snowplowing frequencies and considered cumulative snowplows as discrete variables. Wang et al. (2016) proposed a binary variable, whether the marking first winter passed or not. Based on an analysis of a Normalized Ground Snow Load (NGSL) map, Mohamed et al. (2019) divided the analysis region into Higher NGSL and lower NGSL. Mousa et al. (2021) considered the average monthly snow depth (inch) as a continuous variable.

Several models have been developed to analyze $R_L$ degradation, depending on various factors, data trends, and abnormalities, including simple linear regression, exponential, logarithmic, nonlinear, multiple-linear regression, Weibull analysis, smoothing spline and time series, linear mixed-effects model, piecewise multiple linear models, artificial neural networks, and machine learning.

### 2.10 Pavement Marking Service Lives

Service life is defined by the duration for a pavement marking to reach a predetermined minimum retroreflectivity level from the time of application. It is influenced by the relationship between retroreflectivity, marking age, and various factors discussed earlier. Determining when a marking has reached the end of its useful life is based on maintaining a minimum level of retroreflectivity for safe driving. There are two methods for determining service life: the Historical Data Method and the Monitored Markings Method. The Historical Data Method establishes a replacement schedule based on past data. Alternatively, the Monitored Markings Method involves periodically checking the retroreflectivity of a subset of markings to determine when they need to be restriped (FHWA 2022).

Literature review and agency surveys have shown that pavement marking service life varies across the United States, emphasizing the need for using local historical data to determine accurate expectations. The range of values for pavement marking types presented in (FHWA 2022) is shown in Table 3.

**Table 3. Range of Pavement Marking Service Life Estimates (FHWA 2022)..**

| Pavement Marking 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 |

## 2.11 Pavement Marking Management System (PMMS)

The Pavement Marking Management System (PMMS) is a comprehensive solution that effectively handles all aspects of pavement markings, including data collection, documentation, quality assurance procedures, and database management. Various state DOTs have successfully implemented PMMS to enhance roadway safety and visibility. For instance, the Florida Department of Transportation (FDOT) implemented a PMMS with documentation, quality assurance procedures, and a database (Choubane et al. 2018). The Minnesota DOT developed its PMMS in 1999 and has continuously updated it by creating different Pavement Marking Management Tools (PMMTs) (Smadi and Hawkins 2012; Zhang 1999). Similarly, the Iowa DOT implemented the Iowa Pavement Marking Management System (IPMMS), which encompasses guidelines for data collection, marking application, performance evaluation, data visualization, operational planning, and local-agency management (Hawkins et al. 2006; Hawkins and Smadi 2010). While there is extensive literature on pavement markings, there is limited research specifically focused on assisting transportation agencies in developing PMMS. Based on the existing literature, there is only one survey-based study, to the best of the authors' knowledge, that involved the participation of 32 state and local highway agencies. These studies involved field measurements of pavement marking retroreflectivity, which were initially conducted in the fall of 1994 (Migletz et al. 1999). The literature review revealed a lack of studies comprehensively reviewing pavement marking management practices across multiple state DOTs. Therefore, this study intends to provide valuable insights by disseminating a survey and offering recommendations for best practices and considerations in developing and implementing PMMS.

### 2.11.1 Pavement Marking Management Plan (PMMP)

The PMMP outlines the strategy for maintaining and updating pavement markings on roads and highways and covers the assessment of existing conditions, selection of appropriate materials and methods, development and implementation of budget, schedule, and inspection and maintenance procedures, and helps to optimize the use of limited funding (Sassani et al. 2021). Transportation agencies allocate significant budgets to maintain markings and ensure their effectiveness. However, pavement marking management poses substantial challenges due to incomplete understanding and lack of standardization across transportation agencies. To address these difficulties, there is a growing emphasis on developing pavement marking management plans, which offer an organized approach to pavement marking management.

Historically, infrastructure asset management systems have given more attention to large-scale assets such as roads and bridges, neglecting the management of lower-cost assets such as pavement markings. The emphasis on infrastructure asset management has shifted towards a more comprehensive approach, which includes the management of lower-cost assets like pavement markings, and the goal of NCHRP Synthesis Topic 37-03 was to explore asset management practices for various non-pavement, non-bridge infrastructure assets, including traffic signals, signing, lighting, pavement markings, culverts, and sidewalks. A nationwide survey showed that most agencies chose the previous budget plus adjustments option as the best way to describe their processes. Minimum initial retroreflectivity ($R_L$) values used by DOTs are 175 to 700 mcd/$m^2$/lux for white markings and 100 to 350 mcd/$m^2$/lux for yellow markings. (Markow 2007). To effectively manage pavement markings or ideally establish a PMMP, transportation agencies can benefit from existing guidelines such as those outlined in NCHRP Synthesis 37-01 and PMMP developed by other agencies. Existing research and PMMPs provide insights, but no suitable solution exists for every organization and region. Moreover, state transportation agencies in the United States of America have numerous documents on pavement marking, but the information is scattered and lacks comprehensive PMMP guidance.

The PMMP and PMMS of other agencies were found to be limited to only a few DOTs, and relevant studies are briefly summarized in Table 4.

**Table 4. Summary of Literature Review for PMMP.**

| DOT | Findings used in this research | References |
|---|---|---|
| Iowa DOT | Provided a PMMS model framework for the effective selection and design of future projects, assessment of funding scenarios, and displaying analysis results based on asset management (AM) practices. The cost-effectiveness of marking material is checked by evaluating performance targets and policy goals. | (Hawkins et al. 2005; Hawkins and Smadi 2010; Sassani et al. 2021; Smadi et al. 2010) |
| Pennsylvania DOT | Service-life estimation of different marking materials by life cycle cost analysis is used to make a data-driven PMMS. | (Sasidharan et al. 2009) |
| Florida DOT | Developed a PMMS utilizing sensor-based, non-contact, and mobile technology to collect retroreflectivity data by Mobile Retroreflectivity Unit (MRU), which is stored in a comprehensive database. This system enables data-driven decision-making by evaluating and managing statewide pavement marking retroreflectivity efficiently and cost-effectively. | (Choubane et al. 2018) |
| Minnesota DOT | To enhance the longevity of pavement markings, MnDOT employs various recessing techniques such as grooving, inlaying, installing sinusoidal rumble strips, or slightly raising the traveled lanes. Wet reflective and wet recoverable products were utilized to improve visibility in adverse weather conditions. MnDOT recommends using materials based on the remaining service life. | (Hallmark et al. 2019; Mark A. Gieseke 2022) |
| California DOT | Caltrans has issued a comprehensive policy focusing on warranty-based markings and setting a minimum retroreflectivity standard of 150 mcd/m$^2$/lux. The policy emphasizes durable materials (permanent tape, methyl methacrylate, and enhanced wet-night visibility thermoplastic traffic striping) and factors like pavement type, climate conditions, and cost. | (Falsetti 2017; Saetern and Associates 2016) |
| Oregon DOT | Manages pavement markings in a proactive manner by using a thorough database, a cooperative workgroup, and a rigorous pavement marking plan. Regular data reviews and stakeholder participation help to ensure roadway safety and effectiveness across Oregon's transportation network. These activities include maintenance tasks, purchase choices, and enhanced processes and practices. | (Van Schalkwyk 2010) |
| Texas DOT | TxDOT follows a performance-based approach for pavement marking maintenance. A life cycle cost analysis tool has been developed by Pike et al. to consider various costs associated with pavement markings material and construction costs, grooving costs, special requirements, marking removal costs, administrative costs, agency costs, and societal costs (delay costs and crash costs). | (Lopez 2004; Pike and Bommanayakanahalli 2018; Zhang 1999) |

### 2.11.2 Pavement Marking to accommodate Autonomous Vehicles using Machine Vision Technology

Autonomous vehicles (AV) and machine vision (MV) capabilities represent a significant advancement in transportation technology, capable of operating and navigating without human intervention by utilizing sensors, cameras, and advanced technologies to gather data and make informed decisions. Lane markings are essential in advanced driver-assistance systems (ADAS) like lane departure warning (LDW) and lane-keeping assistance (LKA) systems, which rely on recognizing and interpreting these markings to ensure vehicle safety and prevent unintentional lane departures. Efforts are underway by organizations such as Society of Automative Engineers (SAE), American Association of State Highway and Transportation Officials (AASHTO), and The National Committee on Uniform Traffic Control Devices NCUTCD) to develop standards and specifications for pavement markings that accommodate both conventional vehicles and those equipped with ADAS technologies (Hallmark et al. 2019).

The NCHRP project “NCHRP 20-102(06): Road Markings for Machine Vision” aims to evaluate how pavement marking features influence the effectiveness of machine learning image recognition technologies in identifying various types of road markings (Pike 2018). The project considers multiple variables and examines the use of embedded antennas in pavement markings to enhance detection by measurement equipment. Recommendations for pavement marking specifications that facilitate MV technologies are being developed to ensure efficient recognition of markings. Previous research on pavement marking related to MV vehicles has been summarized in Table 5.

**Table 5. Selected Literature Review on the Relationship between Machine Vision and Road Marking Quality.**

| Author | Significant findings |
|---|---|
| Hadi et al. (2007) | Lane departure warning systems demonstrated improved performance as pavement marking retroreflectivity increased. |
| Hadi and Sinha (2011) | Proper nighttime guidance requires sufficient retroreflectivity levels of road markings for all MV systems. |
| Matowicki et al. (2016) | The malfunction occurred with an MV vehicle on a road where the pavement markings had a retroreflectivity level of only 50 mcd/m²/lux or less. |
| Davies (2017) | Broader line widths were observed to yield better detection results, even at lower retroreflectivity levels. Higher retroreflectivity levels were generally easier to detect. During laboratory-created rain conditions, the detection results were relatively poor. |
| Carlson and Poorsartep (2017) | Contrast ratio (luminance difference between the road surface and marking) is also needed for the reliability of MV technology for drivers' assistance. It was also found that recognition of the markings was adversely affected by glare. |
| Carlson (2017) | Road marking identification can be seriously hampered in circumstances with low contrast ratios. Incorrect line assignment has also been noted on poorly maintained roadways and when crack seals are present, giving the appearance of "phantom markings." Strong sunlight that causes glare has also been recognized as a factor that makes it challenging to identify road markings. |
| Pike et al. (2018) | The contrast ratio provided by contrasting colors during the daytime and $R_L$ during the nighttime was essential for successful MV operation. |
| Narote et al. (2018) | A review of advances in pattern recognition highlighted the significant role of contrast ratio in the accurate recognition of road markings. |
| Burghardt et al. (2020) | High-end premium solutions with premium glass beads (having retroreflectivity of about 1,000 mcd/m²/lux) offer excellent results in terms of retroreflectivity, durability, overall price, and environmental friendliness for horizontal road markings. |
| Cafiso and Pappalardo (2020) | $R_L$ played a limited role in the daylight and dry pavement test conditions. An inadequate luminance coefficient of road markings correlated with failures of lane support systems. |
| Storsæter et al. (2021) | Contrast ratio emerged as the best predictor of lane departure warning performance. |
| Burghardt et al. (2023) | The use of 'premium' structured road markings with high retroreflectivity was prioritized over standard flat markings. These premium markings offer enhanced visibility and water drainage capabilities. Additionally, a combination of LiDAR and camera systems is necessary to enable dependable steering by MV equipment in challenging conditions. |

### 2.12 Chapter Summary

This chapter comprehensively explored pavement markings, covering seven key parts. The first two parts dived into the details of pavement markings, including their types, colors, components, and classification. Moving forward, the third part focused on evaluating the performance of pavement markings, discussing evaluation criteria and techniques. Part 4 addressed the pavement markings in Wyoming, describing their implementation in a specific context and the snowplow operation in Wyoming. The subsequent two parts explored factors that affect pavement marking performance and degradation, including different models used for analysis. The final two parts provided a literature review and a template for a PMMS), and PMMP, emphasizing the integration of machine vision technology to accommodate autonomous vehicles.

# CHAPTER 3: METHODOLOGY

This chapter briefly outlines the methodology for developing a pavement marking management plan to enhance Wyoming's PMMP. The focus is on determining factors affecting pavement marking retroreflectivity, developing a pavement marking retroreflectivity degradation model, pavement marking management system of different transportation agencies, and finally, proposing a template for a pavement marking management plan based on the asset management plan. The research provides guidelines, information, and resources in key areas to enhance pavement marking practices and identify cost-effective pavement management solutions in Wyoming.

The procedure of creating a comprehensive pavement marking management plan involves four distinct steps. These steps are as follows:

1. Pavement marking retroreflectivity data collection.
2. Analysis of factors affecting pavement marking retroreflectivity using a statistical model.
3. Developing Pavement marking retroreflectivity performance degradation models over ages and determination of pavement marking service lives.
4. PMMS based on the experiences of the State Department of Transportation.
5. Establishment of a template for a comprehensive PMMP for Wyoming aligning with the TAMP- 2018.

The overall methodology is summarized in Figure 7. The detailed methodology of various analyses will be described in their respective chapters.

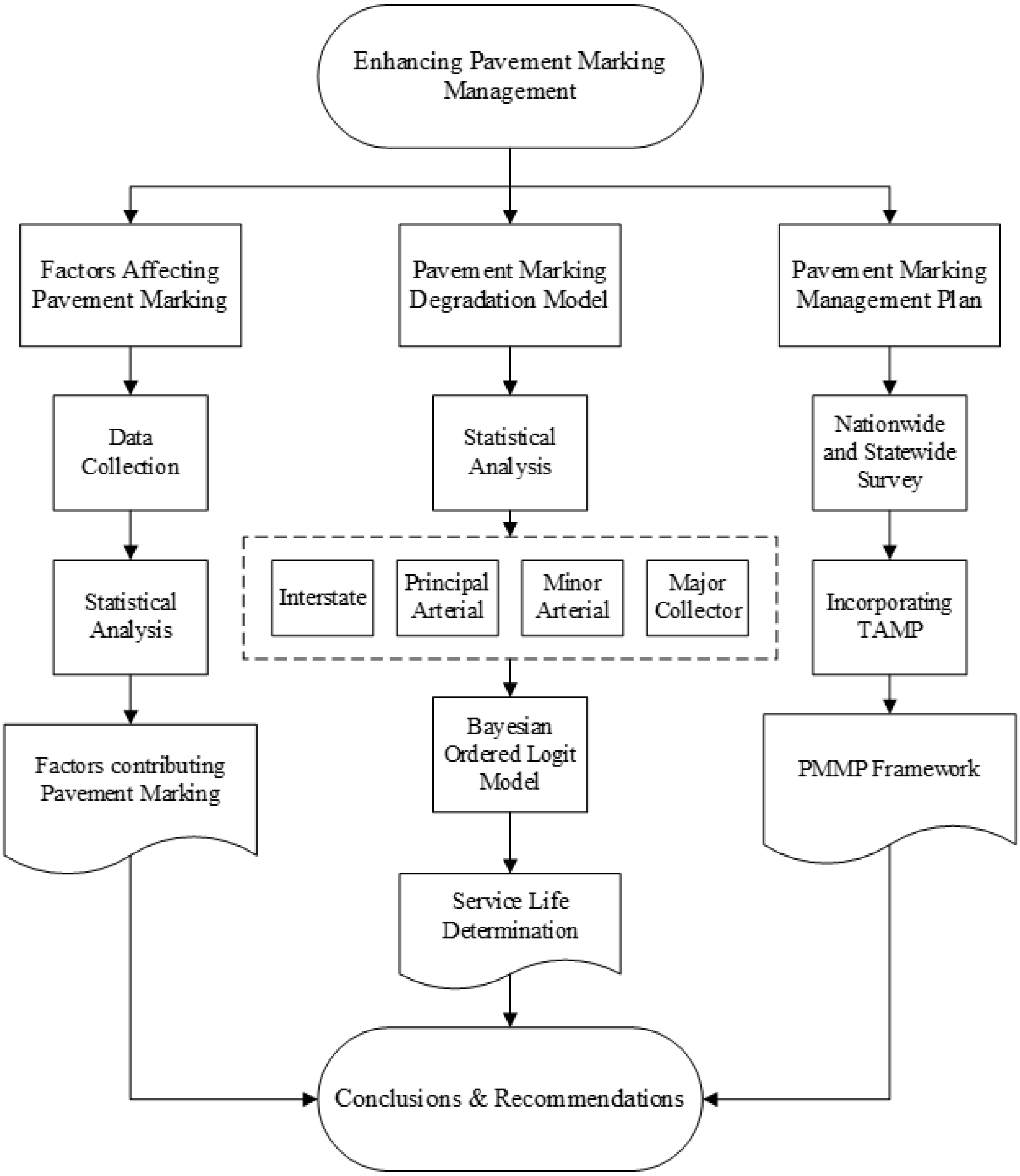



**Figure 7. Flowchart. Flowchart of research methodology.**

## 3.1 Pavement Marking Retroreflectivity Data Collection

### 3.1.1 Site Selection Criteria

In the process of site selection for retroreflectivity testing, several criteria were established to ensure the representative nature and feasibility of the chosen test sites. The following facts were considered during the test site selection process:

- The length of a test section must be long enough to provide a one-mile-long test section.
- The number of test sites must be sufficient for statistically valid results.
- The sites must be selected from different regions to represent Wyoming's geographic, traffic, and winter maintenance variations.
- Minimizing travel distance and travel time between sites was a key consideration.
- The data collection process had to be performed within the allocated budget.

### 3.1.2 Data Collection Site Selection for Wyoming

To understand how the different factors affect pavement marking in the different highways, retroreflectivity data were collected from four types of roads: interstate, principal arterial, minor arterial, and major collector in Wyoming. The minimum sample size was determined first to make a cost-effective and statistically representable dataset of pavement marking retroreflectivity following Equation 2 (Israel 1992).

$$\text{Sample Size for infinite population, } n_0 = \frac{Z^2 * p * (1-p)}{e^2}$$

$$\text{Adjusted Sample Size for required population, } n = \frac{n_0}{1+\frac{(n_0-1)}{N}} \tag{2}$$

Where, Z = The area under the normal curve (1.96 for 95 percent Confidence Level)

p = Population Proportion (assumed to be 50 percent)

e = Margin of error (generally 5 percent)

N= Total Population

As WYDOT manages 6,744 miles (10,855 km) of roads, 364 miles (586 km) of roadway is the minimum sample size determined by considering a 95 percent confidence level and a 5 percent margin of error. Therefore, a total of 528.5 miles (850.1 km) of roadway were selected to represent a good statistical model. The location of the test sections is roughly shown in Table 6. Longitudinal pavement marking retroreflectivity data were collected from four functional classifications of roads, including urban and rural areas, with Annual Average Daily Traffic (AADT) ranging from 81 to 23,966. These test sections were chosen based on the: material and type of pavement markings, location (urban or rural), pavement surface type (asphalt or concrete pavement), snowplow priority level, and traffic volume.

## Table 6. Selected Roadways for Pavement Marking Retroreflectivity Data Collection.

| Highway | Route | Functional Classification | Begin MP | End MP | Length of segments (mile) | Direction | Measured line position | County | Service Level for Snowplow | AADT Range | AADTT Range | Location |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I80 | ML80I | Interstate | 280 | 310 | 30 | EB | WEL<br>LL<br>YEL | Albany | IA | 5524-6423 | 2988-3201 | Rural |
| I80 | ML80D | Interstate | 310 | 280 | 30 | WB | | Albany | IA | 6035-8821 | 3000-3201 | Rural |
| I80 | ML80I | Interstate | 310 | 322 | 12 | EB | | Albany | IA | 5844-7334 | 2977-3000 | Urban |
| I80 | ML80D | Interstate | 322 | 310 | 12 | WB | | Albany | IA | 6317-9166 | 2950-2998 | Urban |
| I80 | ML80I | Interstate | 322 | 340 | 18 | EB | | Albany | IA | 6234-7334 | 2761-3200 | Rural |
| I80 | ML80D | Interstate | 340 | 322 | 18 | WB | | Albany | IA | 5420-6318 | 2761-3200 | Rural |
| I80 | ML80I | Interstate | 340 | 360 | 20 | EB | | Laramie | IA | 7198-8200 | 2705-3580 | Rural |
| I80 | ML80D | Interstate | 360 | 340 | 20 | WB | | Laramie | IA | 5921-10227 | 2705-3577 | Rural |
| I80 | ML80I | Interstate | 360 | 371 | 11 | EB | | Laramie | IA | 5248-9070 | 2400-3577 | Urban |
| I80 | ML80D | Interstate | 371 | 360 | 11 | WB | | Laramie | IA | 4904-10227 | 2400-3577 | Urban |
| I25 | ML25I | Interstate | 0 | 15 | 15 | NB | WEL<br>LL<br>YEL | Laramie | IA | 4469-13500 | 840-1213 | Urban |
| I25 | ML25D | Interstate | 15 | 0 | 15 | SB | | Laramie | IA | 4448-10373 | 840-1906 | Urban |
| I25 | ML25I | Interstate | 15 | 25 | 10 | NB | | Laramie | IA | 3408-4469 | 647-982 | Rural |
| I25 | ML25D | Interstate | 25 | 15 | 10 | SB | | Laramie | IA | 3292-4448 | 647-982 | Rural |
| I25 | ML25I | Interstate | 25 | 65 | 40 | NB | | Laramie | IB | 3070-3453 | 574-916 | Rural |
| I25 | ML25D | Interstate | 65 | 25 | 40 | SB | | Laramie | IB | 3070-3464 | 574-982 | Rural |
| I25 | ML25I | Interstate | 65 | 86 | 21 | NB | | Platte | IB | 3179-3692 | 484-574 | Rural |
| I25 | ML25D | Interstate | 86 | 65 | 21 | SB | | Platte | IB | 3179-3420 | 484-574 | Rural |
| US 85 | ML180 | Principal Arterial | 4 | 12.5 | 8.5 | NB | WEL<br>LL<br>YCL | Laramie | II | 2950-22587 | 235-950 | Urban |
| US 85 | ML180 | Principal Arterial | 12.5 | 4 | 8.5 | SB | | Laramie | II | 2950-22587 | 285-950 | Urban |
| US 85 | ML85 | Principal Arterial | 18 | 26 | 8 | NB | | Laramie | II | 3469 | 367 | Rural |
| US 85 | ML85 | Principal Arterial | 43 | 53 | 10 | NB | | Laramie | II | 1946-2412 | 326-392 | Rural |
| US 85 | ML85 | Principal Arterial | 72 | 82 | 10 | NB | | Goshen | II | 1889-2507 | 281-340 | Rural |
| US 287 | ML23 | Principal Arterial | 380 | 390 | 10 | NB | | Albany | IA | 15992 | 1094 | Urban |
| US 287 | ML23 | Principal Arterial | 394 | 404 | 10 | NB | WEL<br>LL<br>YCL | Albany | IA | 4237-15992 | 826-1127 | Urban |
| US 287 | ML23 | Principal Arterial | 420 | 425 | 5 | NB | | Albany | IA | 4886 | 884 | Urban |
| US 30 | ML56 | Principal Arterial | 359 | 370 | 11 | EB | WEL<br>LL | Laramie | IA | 1006-23966 | 175-377 | Urban |

| Highway | Route | Functional Classification | Begin MP | End MP | Length of segments (mile) | Direction | Measured line position | County | Service Level for Snowplow | AADT Range | AADTT Range | Location |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | YCL | | | | | |
| WY 212 | ML212 | Principal Arterial | 2 | 12 | 10 | EB | WEL YCL | Laramie | II | 3096-19730 | 81-1105 | Urban |
| WY 219 | ML1108 | Principal Arterial | 1.9 | 5.4 | 3.5 | EB | | Laramie | II | 2069-5449 | 99-100 | Urban |
| WY 34 | ML109 | Minor Arterial | 10 | 20 | 10 | EB | WEL YCL | Albany | IIA | 602-1161 | 39-71 | Rural |
| WY 34 | ML109 | Minor Arterial | 35 | 45 | 10 | EB | | Platte | II | 633-1161 | 39-97 | Rural |
| WY210 | ML107 | Minor Arterial | 0 | 10 | 10 | NB | | Laramie | II | 2353-6497 | 82-99 | Urban |
| WY 789 | ML18 | Minor Arterial | 0 | 10 | 10 | NB | | Sweetwater | II | 892 | 230 | Rural |
| WY 789 | ML18 | Minor Arterial | 20 | 30 | 10 | NB | | Carbon | II | 892-1618 | 230-331 | Rural |
| WY 213 | ML6792 | Major Collector | 7 | 17 | 10 | NB | | Laramie | II | 644 | 237 | Rural |
| WY 211 | ML211 | Major Collector | 0.5 | 3.5 | 3 | EB | | Laramie | IIIA | 1735-2659 | 73 | Urban |
| WY 211 | ML211 | Major Collector | 20 | 30 | 10 | EB | | Laramie | IIIB | 81 | 28 | Rural |
| WY 316 | ML1604 | Major Collector | 0 | 7 | 7 | EB | | Platte | IIIB | 275-1651 | 27-56 | Rural |
| | | Total | | | **528.5** | | | | | | | |

*MP= Milepost, EB= East bound, WB=West bound, NB= North bound, SB= South bound, WEL= White edge line, LL= Lane line, YEL= Yellow edge line, YCL= Yellow Center line

## 3.2 Data Collection Process

Pavement marking visibility is assessed by pavement marking retroreflectivity. Agencies use retroreflectivity to measure serviceability, setting minimum thresholds for reapplication. Monitoring pavement marking performance can be done subjectively through visual inspections or objectively using retroreflectometers (Sitzabee et al. 2009b). Two types of retroreflectometers – Handheld and vehicle-mounted retroreflectometers are being used to evaluate retroreflectivity. Past studies (Carlson et al. 2010; Malyuta 2015; Masliah et al. 2007; Pike 2009) used handheld retroreflectometer and Laserlux mobile retroreflectometers for the retroreflectivity data collection. WYDOT has particularly focused on inventorying and objectively marking retroreflectivity using vehicle-mounted technology. So, WYDOT has adopted mobile retroreflectivity units (MRUs)- Laserlux Mobile Retroreflectometer (LLG7), which employ non-contact sensor-based technology to continuously assess pavement markings at highway speeds. MRU offers versatility, ease of use, and improved efficiency compared to traditional handheld measurements (Choubane et al., 2018). In addition, utilizing MRUs eliminates the need for traffic maintenance, enhances safety, and ensures accurate and reliable data collection for informed decision-making.

### 3.2.1 Laserlux Mobile Retroreflectometer

Laserlux Mobile Retroreflectometer (LLG7) is the newest and most versatile vehicle-mounted retroreflectometers for pavement markings. The LLG7 is installed in a testing vehicle, traveling at the speed of the traffic stream. It has proven laser-based optics that scans pavement markings more than 400 times per second and an auto-positioning system for continuous measurement and geometry management. The LLG7 also has a high-definition video recording feature. One of the important components of the Laserlux retroreflectometers includes an externally mounted laser scanner that measures marking retroreflectivity and an in-vehicle computer system that controls data collection and stores measured readings.

LLG7 has been designed according to the European Committee for Standardization specification EN 1436. This test follows 30m geometry, which simulates the pavement marking's retroreflective performance at 100 ft (30m) in front of the vehicle. This is required per (ASTM E 1710) (ASTM 2018). The measurement geometry of the instrument is based on a viewing distance of 100 ft (30m), a headlight mounting height of 2.13ft (0.65m) directly over the stripe, and an eye height of 3.94ft (1.2m) directly over the stripe as shown in Figure 8. The entrance angle (the angle between the illumination axis and the retroreflector axis) is fixed at 88.76 Degrees (co-entrance angle 1.24 Degrees). The observation angle (the angle between the illumination axis and the observation axis) is fixed at 1.05 Degree, and the presentation angle (the angle between the observation half-plane and the half-plane that originates on the illumination axis and that contains the retroreflector axis) shall be 0 Degree. The instrument was calibrated at each test section before starting data collection.

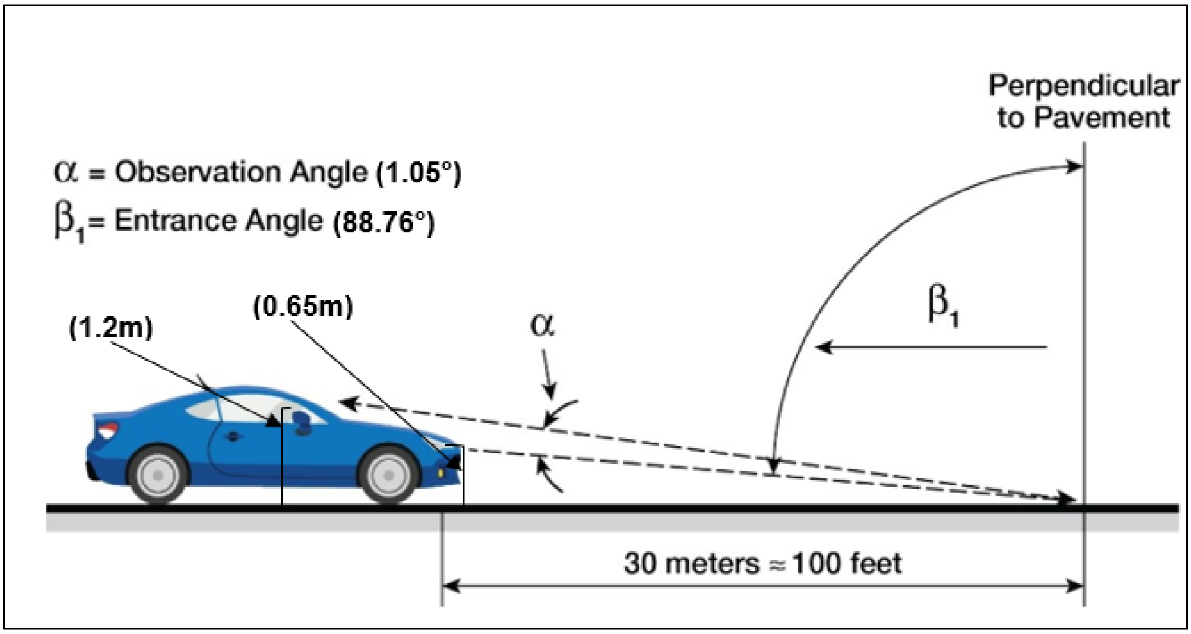
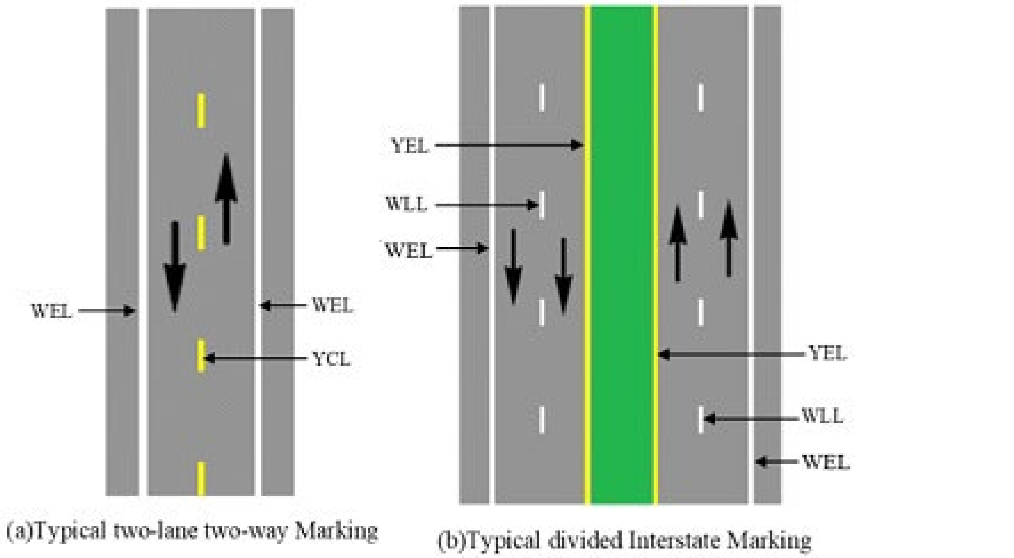



**Figure 8. Illustration. Standard 30-meter Geometry Diagram for MRU (FHWA 2022).**

All test sites were recorded with a begin milepost and an end milepost. Laserlux measured the pavement marking continuously, and the onboard computer stored average retroreflectivity for every 0.1 miles (0.16 km) test section measured from the beginning milepost. As a result, the average retroreflectivity of each 0.1-mile site was determined by averaging all readings in this length and measured in the unit mcd/m$^2$/lux. The instrument manual's standard operating procedure was followed strictly during field data collection. Sometimes the markings were missing from short segments of the test section due to wearing or due to the presence of access roads. Such situations were handled by a facility available in the Laserlux system, which allowed adjusting a minimum threshold retroreflectivity value to accept a scanned reading. Such a reading was discarded if a scan resulted in a value less than the specified minimum threshold. In this case, the minimum threshold values were set as 50 mcd/m2/lux. A global positioning system (GPS) device was used to record the coordinates of each data point of the test location. The pavement stripe nomenclature included the color (White and Yellow) followed by the line type (edge line, center line, and lane line), as shown in Figure 9.




*WEL= White Edge line, YEL= Yellow Edge line, YCL= Yellow Centerline, WLL= White Lane line

**Figure 9. Illustration. Pavement Marking Nomenclature for Various Highways.**

### 3.3 Analysis of Factors Affecting Pavement Marking Retroreflectivity

Binary logistic regression models were developed to examine the relationship between pavement marking retroreflectivity and potential contributing factors. A model with the whole dataset and four individual models were developed for all four types of roads based on functional classification. In this study, the response variable was assumed to follow a logistic distribution, as pavement marking retroreflectivity is binary. In this discrete probability distribution, a value of 1 represents a “success” with probability π, while 0 signifies a “failure” with probability 1-π. For this model, pavement marking retroreflectivity was categorized as either above the marginal level or below the marginal level. This categorization was chosen to determine the extent of effects below the marginal level. To analyze the data, odds ratios were estimated to interpret the effect of significant factors on the likelihood of maintaining retroreflectivity above the marginal level. The model’s performance, including the predictive ability and accuracy of the model, was then evaluated using Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) curve.

### 3.4 Pavement Marking Retroreflectivity Degradation Model

The first step of developing the pavement marking degradation model involved $R_L$ data collection from four different highways in Wyoming using mobile retroreflectometers at three different time periods (December 2021, May 2022, and December 2022). Then all required data were compiled in a comprehensive dataset. The $R_L$ data were analyzed to compare the deterioration over time based on factors such as marking configuration and winter effects. Scatter plots of retroreflectivity with respect to different parameters were created to understand the trend of $R_L$

deterioration as part of preliminary data analysis. The percentage degradation over time was used to estimate compliance with FHWA standards and approximate service lives of individual markings. Additionally, this study included the Bayesian Ordered Logit Model to test the effects of independent variables on retroreflectivity degradation. The independent variables incorporated into the model were road geometry, pavement surface and locations, marking age, color, line position, material, traffic condition, and winter effects, selected based on the literature review and preliminary data analysis. An initial model was developed using randomly selected 80 percentof the data points and validated the variables in the model using the remaining 20 percentof the data. The final prediction model was developed using the best-fit model's parameter estimates of independent variables established by the initial model and applied to the full data set. Finally, service life was calculated from the prediction model.

### 3.5 Pavement Marking Management System (PMMS)

Transportation agencies are facing challenges in effectively managing pavement markings, primarily due to advancements in-vehicle technologies. Recognizing this issue, the National Committee on Uniform Traffic Control Devices has proposed revisions to the existing pavement marking standards. Consequently, it has become crucial to examine the practices employed by different states regarding pavement markings. To address this need, the Wyoming Technology Transfer Center undertook a comprehensive research project aimed at developing a pavement marking management system for the Wyoming Department of Transportation. As part of this project, an online survey was conducted to gather information on the pavement marking management systems implemented by various state DOTs. The survey focused on aspects such as development processes, data collection strategies, and considerations for pavement marking retroreflectivity. With responses received from 29 DOTs, this chapter presents a summary of their feedback, providing valuable insights into evaluating pavement marking management systems on a national scale.

### 3.6 Pavement Marking Management Plan (PMMP)

This effort aims to establish a template for the comprehensive PMMP for Wyoming and a fully-fledged management system that includes budgeting, labor resources, and updated specifications to meet annual marking needs and ensure long-lasting applications statewide by analyzing existing practices, developing guidelines, and incorporating strategies from other agencies. Additionally, the study addresses the demand for advanced automobile technologies utilizing machine vision (MV) systems by incorporating updated standards. The template of PMMP in this study is developed by integrating the core concepts of the TAMP, current standards, practices, and recommendations of district engineers of WYDOT through a nationwide and statewide survey, and insights from previous literature and practices of other DOT. Furthermore, the study evaluated state-of-the-art recommendations and updated standards to effectively manage pavement markings to accommodate autonomous vehicles.

### 3.7 Chapter Summary

This chapter presented the methodology intended to Enhancing Pavement Marking Management Practices in Wyoming and developing a Pavement Marking Management Plan. The methodology includes three main parts. The first part is the determination of the factors affecting pavement marking retroreflectivity by the Binary Logistic Regression Model. The second part provides a pavement marking retroreflectivity degradation model. Four Bayesian Ordered Logit Models were developed for four functional classification highways- Interstate, Principal Arterial, Minor Arterial, and Major Collector roads. And in the development of a template of a Pavement Marking Management Plan (PMMP) through a combination of a Nationwide Survey, Statewide Survey, and incorporating Transportation Asset Management Plan (TAMP-2018) was described in the Third part.

# CHAPTER 4: FACTORS AFFECTING PAVEMENT MARKING RETROREFLECTIVITY

## 4.1 Introduction

This chapter describes the factors affecting the retroreflectivity ($R_L$) of longitudinal pavement marking using only the first dataset collected in December 2021 on four functional classes of roads in Wyoming. All the selected roads used in this analysis were stripped between April to October of 2021, and the age of all tested markings ranged from 0.83 to 7.5 months at the time of testing and did not experience any snowplow operation. Two different approaches were considered for this study. WYDOT set a marginal level of retroreflectivity of 125 mcd/m$^2$/lux for white lines and 100 mcd/m$^2$/lux for yellow lines for all types of highways in the jurisdiction of WYDOT. So, the WYDOT's prescribed marginal level has been used in this analysis to predict the probability of retroreflectivity above the threshold. The whole dataset was used in one approach, while in another, the dataset was classified into four groups based on functional classification. In both approaches, a binary logistic regression model was developed to investigate the factors affecting the probability of $R_L$ above the prescribed threshold value. A total of six categorical variables and eight continuous variables were incorporated into the logistic regression models.

## 4.2 Data Compilation

The initial step in pavement marking retroreflectivity evaluation is to compile and analyze the retroreflectivity data to determine factors affecting pavement marking retroreflectivity. This section assists in complete data analysis and guides the data accumulation process. Different data types and their sources need to be known beforehand to acquire a precise and comprehensive database. To create a comprehensive database, multiple data sources were utilized in this study. Marking characteristics (Color, Stripe, Line type) and climate conditions (Temperature and humidity) were recorded in the retroreflectivity dataset at the time of retroreflectivity measurement. Traffic conditions (AADT, AADTT, and Speed limit) and geometric data (Horizontal curve and vertical grade) were collected from the WYDOT Traffic and Roadway Geometry database. Marking material information was also provided by WYDOT. Each dataset contained information in data points at every 0.1 mileposts. To ensure consistency and synchronization of the data, all datasets used in this study were aligned and synchronized based on the milepost.

## 4.3 Data's Descriptive Statistics

A total of 16,310 $R_L$ data measurements were taken, among which 64.3 percent were taken on the Interstate, 20.6 percent on the principal arterial, 7.6 percent on the minor arterial, and 7.5 percent on the major collector. Priority was given to Interstate during data collection, resulting in the most collected data. Figure 10 shows the box plot of $R_L$ data showing the mean, standard deviation (SD), and range for four highway types. Note that the $R_L$ values greater than mean+2SD were considered outliers and removed from the analysis. The mean, range, and SD of data on the Interstate were higher than other functional classifications of roads. The mean $R_L$ shows a decreasing trend from Interstate to minor arterial. The higher $R_L$ value in Interstate is attributed to the high priority of the pavement marking management for the Interstate by WYDOT.

Considering the position of the pavement marking line, 62 percent were for the edge line, 12 percent for the center line, and 26 percent for the lane line among total observations. The collected data included three types of marking materials: polyurea, epoxy, and waterborne. In the whole dataset, 24 percentwas epoxy, 17 percentpolyurea, and 59 percentwas waterborne material.

The marking age for each test section was determined by the time elapsed from the marking installation date to the data collection date. The marking ages ranged from 0.83 to 7.5 months. On average, the markings had an age of 4.12 months.

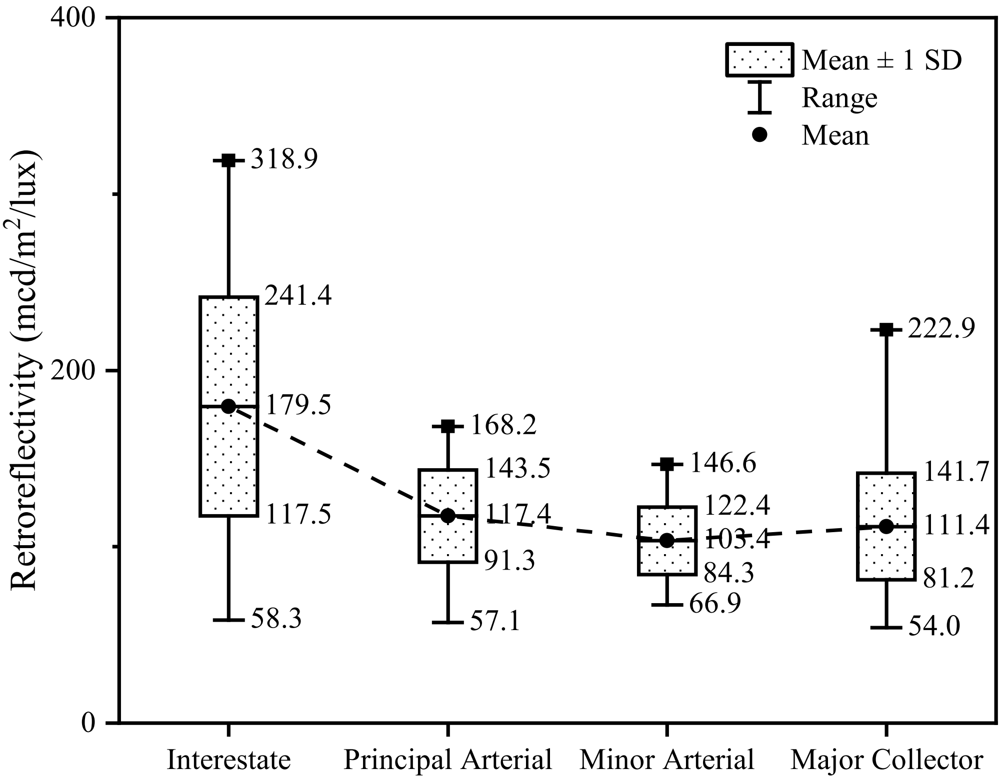



**Figure 10. Chart. Box plot of Retroreflectivity Data showing Mean, Standard Deviation, and Range.**

All the collected categorical variables are defined as 0 or 1 or from 1 to 3. Moreover, eight continuous variables were used in this analysis, and the mean, SD, and range of all parameters are shown in Table 7.

**Table 7. Descriptive Statistics of the Variables.**

| Summary of categorical variables | | | | |
|---|---|---|---|---|
| Variable type | Variable name | Description | **Frequency** | **Percentage** |
| **Response variable** | | | | |
| **Retroreflectivity** | | 1= Retroreflectivity above marginal value | 12,991 | 79.65 |
| | | 0= Retroreflectivity below marginal value | 3,319 | 20.35 |
| **Categorical Explanatory Variables** | | | | |
| **Pavement marking characteristics** | Color | 1= White | 10,772 | 66.05 |
| | | 0= Yellow | 5,538 | 33.95 |
| | Material | 1= Epoxy | 3,886 | 23.82 |
| | | 2= polyurea | 2,774 | 17.00 |
| | | 3= Waterborne | 9,650 | 59.16 |
| | Stripe | 0= Solid line | 10,794 | 66.18 |
| | | 1= Skip line | 5,516 | 33.82 |
| | Line type | 1= EL (Edge Line) | 10,093 | 61.88 |
| | | 2= CL (Centerline) | 1,995 | 12.23 |
| | | 3= LL (Lane Line) | 4,222 | 25.89 |
| **Road Geometry and Location** | Location | 1= Urban | 4,475 | 27.44 |
| | | 0= Rural | 11,835 | 72.56 |
| | Pavement type | 1= Concrete | 1,635 | 10.02 |
| | | 0= Asphalt | 14,675 | 89.98 |

| Continuous Explanatory Variables | | **Mean** | **Std Dev** | **Range** |
|---|---|---|---|---|
| **Marking Age** | Marking Age (Months) | 4.12 | 1.67 | 0.83-7.5 |
| **Road Geometry and Location** | Degree of Curvature of Horizontal Curve (degree) | 0.51° | 1.17° | 0-13.2° |
| | Vertical Grade | -0.2 | 1.6 | (-11.81)-(+7.1) |
| **Traffic condition** | Speed limit (mph) | 70 | 13 | 20-80 |
| | Average Annual Daily Traffic (AADT) (Vehicles/day) | 5,190 | 3,543 | 81-23,966 |
| | Average Annual Daily Truck Traffic (AADTT) (Vehicles/day) | 1,364 | 1,226 | 28-3,580 |
| **Climate condition** | Temperature (F) | 55 | 7 | 40-72 |
| | Humidity (percentage) | 19 | 9 | 2.1-42 |

### 4.4 Model Development

In the preliminary study, the dataset was analyzed and categorized to determine the variation of the pavement marking retroreflectivity with the change of different parameters. The second stage of this study was to select an appropriate analyzing method to determine potential significant parameters affecting pavement marking retroreflectivity. Statistical analysis gained popularity among researchers in modeling pavement marking retroreflectivity performance. Depending on the influencing factors, the trend of data, and abnormalities, several authors used (i) linear regression models (Kopf 2004; Lee and Hwang 2000), (ii) exponential models (Andrady 1997; Bektas et al. 2016), and nonlinear models (Thamizharasan et al. 2003). Due to the high variability of $R_L$, machine learning approaches were also used. Using $R_L$ data of 126 miles (203 km) at 11 sections in North Carolina, (Karwa and Donnell (2011) reported a nonlinear degradation rate of pavement marking retroreflectivity using artificial neural networks. The statistical model named ordinary or binary logistic regression is widely popular due to its ability to predict binomial responses using categorical and numeric data (Alrejjal et al. 2022; Smadi et al. 2008). Since this study focuses on the factors influencing the probability of $R_L$ above or below a prescribed threshold value, the binary regression model was deemed suitable. The $R_L$ of 100 mcd/m$^2$/lux for the yellow line and 125 mcd/m$^2$/lux for the white line were considered marginal levels to predict the probability of retroreflectivity above the threshold. The response variable $R_L$ was used as "0" for "below marginal" and "1" for "above marginal".

In the binary logistic regression framework, the probability, $P_i$ of retroreflectivity above marginal level $i$ is defined as follows:

$$\boldsymbol{log\left[\frac{P_i}{1-P_i}\right] = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_m x_{im}} \tag{3}$$

The equation includes m explanatory variables, denoted by $x_i$ in the vector of explanatory variables, with their respective coefficients represented by the $\beta$'s. The intercept parameter is represented by $\beta_0$. The logit equation can be modified as following equation:

$$\boldsymbol{P_i = \frac{\exp(\beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} \ldots + \beta_m x_{im})}{1 + \exp(\beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} \ldots + \beta_m x_{im})}} \tag{4}$$

Odds ratios are estimated to interpret the effect of the significant factors on the likelihood of staying retroreflectivity above the marginal level. The odds of a variable ($X_1$) can be calculated as follows:

$$\boldsymbol{OR = \frac{\left[\frac{P(Y=1|X_1=1)}{P(Y=0|X_1=1)}\right]}{\left[\frac{P(Y=1|X_1=0)}{P(Y=0|X_1=0)}\right]}} \tag{5}$$

Logistic regression analysis was conducted on the pavement marking retroreflectivity using the commercially available program SAS. In particular, the relationship of the marking retroreflectivity condition was modeled as a function of six categorical and eight numeric variables, as shown in Table 7. A 95 percent significance level was used to determine whether any independent variables were significant or not. The baseline categorical variables in the models were defined by "0" for binary variables, as shown in Table 7. For example, the yellow line was used as a baseline for color. Conversely, "1" was used as a baseline categorical variable for other categorical variables. For the evaluation of the adequacy of the original model and the best-fit model, several criteria were checked for all the attempted models, including forward selection and backward elimination, such as multicollinearity, standardized residuals, AIC (Akaike information criterion) value, ROC Curve (Receiver Operating Characteristic curve), concordance index, influence diagnostics, and goodness of fit test. Models satisfied with the above criteria and the lowest AIC value and the highest AUC value (i.e., the area under the curve) of the ROC Curve were chosen as the best-fit model. The association between the predicted and the observed responses can evaluate the model's goodness of fit.

### 4.5 Data Analysis and Results

WYDOT uses a marginal threshold of 100 mcd/m$^2$/lux for the yellow marking and 125 mcd/m$^2$/lux for the white marking to predict the serviceable condition of the pavement marking retroreflectivity. Statistical analysis was conducted on 16,310 observations of the retroreflectivity dataset using the marginal $R_L$ value as a threshold value currently used by WYDOT. It was assumed that the $R_L$ above this prescribed threshold is serviceable and does not need restriping. On the other hand, the $R_L$ below the threshold is supposed not to provide enough retroreflectance to the drivers and other road users, and the marking need to be restriped soon before reaching the MUTCD minimum value. Figure 11 shows the percent frequency of collected data for various highways. It was found that 10.1 percentof Interstate, 39 percentof principal arterial, 31 percentof minor arterial, and 46 percentof major collector highways are below the marginal $R_L$. Additionally, retroreflectivity levels for the white edge line, yellow edge line, and white lane line for I-80 are shown in Figure 12. Figure 12 shows a similarity in location for the below marginal retroreflectivity levels among three lines, which strengthens the logic for choosing horizontal curve, vertical grade, and traffic volume as the potential parameter for the probability of retroreflectivity level below marginal level.

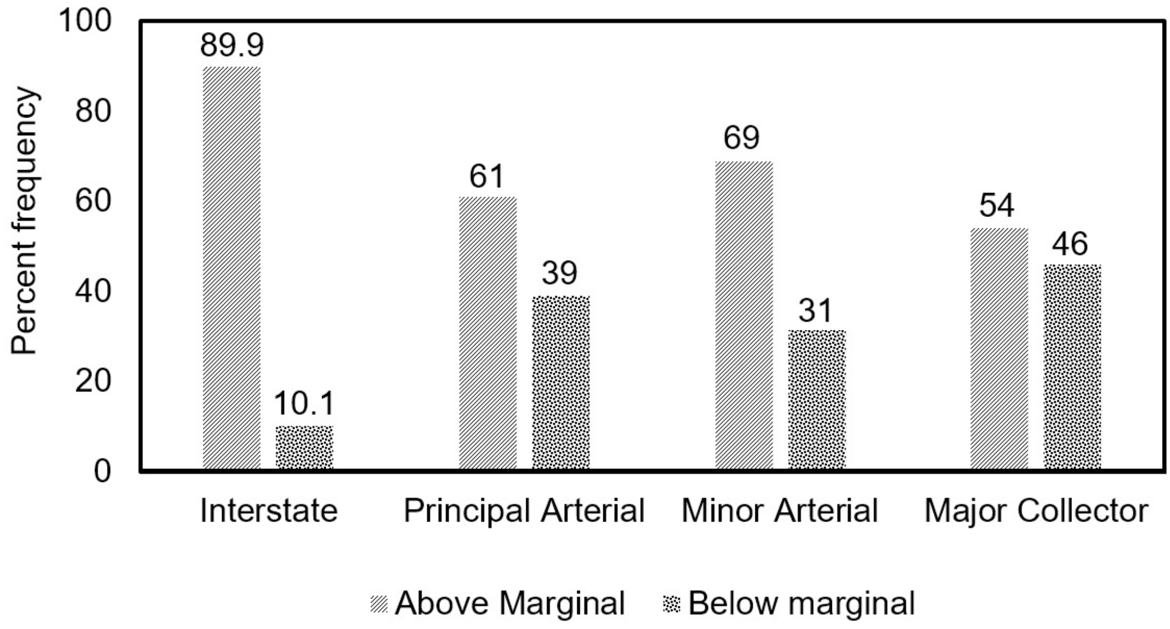



**Figure 11. Chart. Percent Frequency of Different Pavement Marking Retroreflectivity Ranges in the Different Highways of Wyoming.**

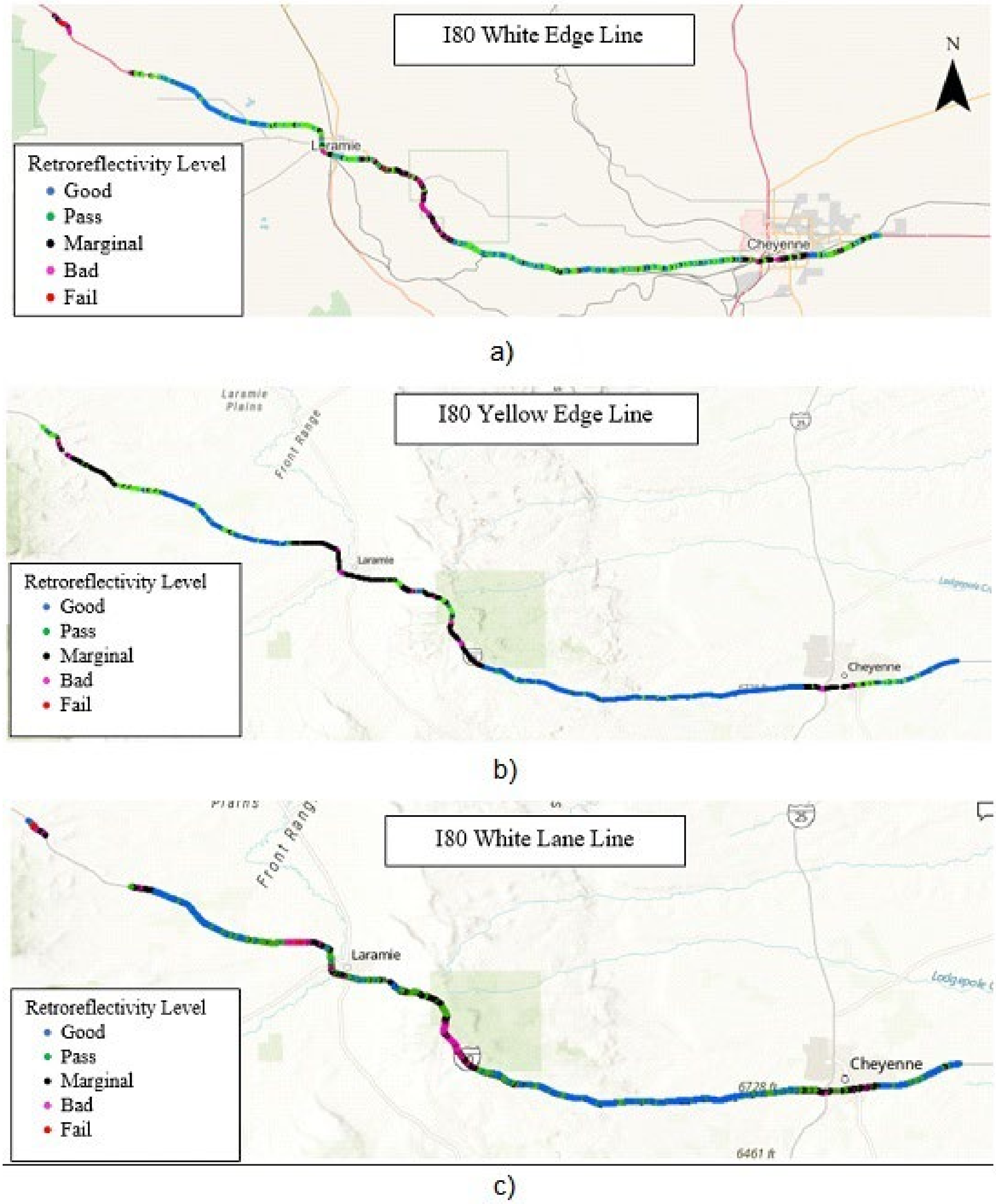



**Figure 12. Map. Pavement Marking Retroreflectivity Level in Different Line Positions of I-80.**

A total of six categorical variables and eight continuous variables were used in the analysis. Two different analyses were adopted to investigate the potential influence of several factors on road marking retroreflectivity. In the first analysis, the whole dataset of measured retroreflectivity and other parameters were used to understand the factors affecting the probability of $R_L$ above the marginal value. Table 8 provides the parameter estimates of the best-fit model, where all the estimates showed were significant at the 95th percentile confidence level.

**Table 8. Parameter Estimates and the Odds Ratio Estimates of The Best-Fit Model for Analysis 1.**

| Analysis of Maximum Likelihood Estimates and Odds Ratio Estimates | | | | | | | |
|---|---|---|---|---|---|---|---|
| Parameter | | DF | Estimate | Standard Error | Wald Chi-Square | Pr > ChiSq | Odds Ratio Estimates |
| Intercept | | 1 | 2.8718 | 0.1205 | 567.6684 | <.0001 | |
| **Marking Age** | | 1 | -0.1982 | 0.00746 | 705.3107 | <.0001 | 0.820 |
| **Pavement Marking Characteristics Attributes** | | | | | | | |
| Color | White vs Yellow | 1 | -0.3301 | 0.0528 | 39.0660 | <.0001 | 0.719 |
| Material | Polyurea vs Epoxy | 1 | 1.6716 | 0.1112 | 213.8966 | <.0001 | 5.321 |
| Material | Waterborne vs Epoxy | 1 | -1.1531 | 0.1246 | 595.6890 | <.0001 | 0.316 |
| Line type | Center Line vs Edge Line | 1 | -0.2195 | 0.0564 | 13.7766 | 0.0002 | 0.802 |
| Line type | Lane Line vs Edge Line | 1 | -0.2100 | 0.0661 | 10.8071 | 0.0389 | 0.811 |
| **Road Geometry and Location Attributes** | | | | | | | |
| Location | Urban vs Rural | 1 | 0.2207 | 0.0644 | 8.6418 | 0.0033 | 1.247 |
| Degree of curvature of Horizontal Curve | | 1 | -0.3109 | 0.0480 | 59.7643 | <.0001 | 0.733 |
| **Traffic Condition Attributes** | | | | | | | |
| AADT | | 1 | 0.002 | 0.0107 | 4.8968 | 0.0269 | 1.002 |
| AADTT | | 1 | -0.008 | 0.0249 | 11.3106 | 0.0008 | 0.992 |
| **Association of Predicted Probabilities and Observed Responses** | | | | | | | |
| Percent Concordant | | | | | | 78.8 | |
| AUC | | | | | | 0.789 | |

The direct interpretation of the coefficients of the parameter estimates is complicated and unwarranted for the logistic model (Alrejjal et al. 2022). Therefore, to facilitate the interpretation of the model, odds ratios are used to interpret the effect of the significant parameters. Odds ratios of all significant parameters are shown in Table 8. variables on the probability of the pavement marking $R_L$ above the marginal value, assuming statistically controlled for all other factors. In the study, the Odds ratio estimates demonstrate the average change in probability of having $R_L$ above marginal value due to the impact of an explanatory variable, assuming that all other variables are controlled. The odds ratios of the significant variables indicate the effects of one unit of change of each variable on the probability of retroreflectivity. An odds ratio greater than 1 demonstrates that increasing one unit on the variable would increase the probability of retroreflectivity staying above the marginal level. On the other hand, An odds ratio less than 1 demonstrates that an increase of one unit on the variable would decrease the probability of retroreflectivity staying above the marginal level. Road and traffic condition changes with the change in functional classification. Pavement marking material, maintenance, and traffic condition also change depending on the functional classification of the highway (Lindly and Wijesundera 2003; Parker and Meja 2003; Smadi et al. 2010; Thamizharasan et al. 2003). Consequently, the dataset was further categorized into four different groups and analyzed by logistic regression, which is defined as analysis 2. A total of four models were developed based on the Interstate, principal arterial, minor arterial, and major collector datasets to identify the significant factors affecting the probability of the $R_L$ above marginal value in the different highways in Wyoming. The results of these analyses are shown in Table 9 and Table 10.

**Table 9. Parameter Estimates of the Best-fit Model for Analysis 2.**

| Analysis of Maximum Likelihood Estimates | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Interstate | | Principal Arterial | | Minor Arterial | | Major Collector | |
| Parameter | Estimate | Pr > ChiSq | Estimate | Pr > ChiSq | Estimate | Pr > ChiSq | Estimate | Pr > ChiSq |
| Intercept | 3.9639 | <.0001 | 3.0467 | <.0001 | 2.4786 | <.0001 | 1.3141 | 0.0406 |
| **Marking Age** | -0.2740 | 0.0034 | -0.2552 | <.0001 | -0.2617 | <.0001 | -0.1772 | <.0001 |
| **Pavement Marking Characteristics Attributes** | | | | | | | | |
| Color- White | -0.5701 | <.0001 | -0.5793 | <.0001 | NS | | NS | |
| Material-Polyurea | 2.1256 | <.0001 | NA | | NA | | NA | |
| Material-Waterborne | NS | | -1.0496 | <.0001 | NA | | NA | |
| Line- Center Line | NA | | NS | | -0.2372 | 0.0117 | -0.1165 | 0.014 |
| Line- Lane Line | -0.2332 | 0.0039 | -0.3685 | <.0001 | NA | | NA | |
| **Road Geometry and Location Attributes** | | | | | | | | |
| Location-Urban | 0.5602 | <.0001 | 1.1921 | <.0001 | 1.1005 | <.0001 | 0.1401 | 0.0426 |
| Degree of Curvature | -0.4162 | <.0001 | -0.3237 | <.0001 | -0.5136 | <.0001 | -0.1101 | 0.0278 |
| **Traffic Condition Attributes** | | | | | | | | |
| AADT | -0.1713 | <.0001 | 0.0075 | <.0001 | -0.0182 | <.0001 | NS | |
| AADTT | -0.1331 | <.0001 | NS | | 0.0099 | 0.0445 | NS | |
| **Association of Predicted Probabilities and Observed Responses** | | | | | | | | |
| Percent Concordant | 75.1 | | 76.2 | | 89.5 | | 79.2 | |
| AUC | 0.77 | | 0.781 | | 0.908 | | 0.816 | |

*NA= Not available, NS= Not significant in the best-fit model

**Table 10. Odds Ratio Estimates of the Best-fit Model for Analysis 2.**

| Odds Ratio Estimates | | | | |
|---|---|---|---|---|
| Effect | Interstate | Principal arterial | Minor arterial | Major Collector |
| **Marking Age** | 0.760 | 0.775 | 0.770 | 0.838 |
| **Pavement Marking Characteristics Attributes** | | | | |
| Color White vs Yellow | 0.565 | 0.560 | NS | NS |
| Material: Polyurea vs Epoxy | 8.378 | NA | NA | NA |
| Material: Waterborne vs Epoxy | NA | 0.350 | NA | NA |
| Line: Centerline vs Edge Line | NA | NS | 0.789 | 0.89 |
| Line: Lane line vs Edge Line | 0.792 | 0.691 | NA | NA |
| **Geometric and Road location Attributes** | | | | |
| Location- Urban vs Rural | 1.751 | 3.294 | 3.006 | 1.150 |
| Degree of curvature | 0.659 | 0.723 | 0.598 | 0.895 |
| **Traffic Condition Attributes** | | | | |
| AADT | 0.842 | 1.008 | 0.982 | NS |
| AADTT | 0.875 | NS | 1.009 | NS |

*NA= Not available, and NS= Not significant in the best-fit model

The following subsections discuss the effects of different variables on the probability of the pavement marking $R_L$ above the marginal value.

### 4.5.1 Pavement Marking Age

The impact of pavement marking age on $R_L$ was evaluated in this analysis. The findings of this study revealed a significant correlation between marking age and pavement marking retroreflectivity level. In both Analysis 1 and Analysis 2, a similar effect was observed. In Analysis 1, a one-month increase in pavement marking age resulted in an 18 percent decrease in the likelihood of achieving retroreflectivity levels above the marginal threshold while keeping all other factors constant (as shown in Table 8). This relationship held the same for the Interstate, principal arterial, minor arterial, and major collector roads, where the probability of achieving retroreflectivity levels above the marginal threshold decreased by 16 to 24 percent with increasing each month of marking age (Table 10).

### 4.5.2 Pavement Marking Characteristics Attributes

Pavement marking characteristics, such as color, material, line types, and marking age, can affect the $R_L$ level. Regarding marking color, Table 8 shows that if all other factors remain the same, the probability of having $R_L$ above the marginal level in white color will decrease by 28.1 percentthan that of yellow color. In other words, the white marking substantially reduced the odds of having $R_L$ exceeding the marginal value compared to the yellow marking. Similar results were found in Analysis 2, where the probability of having $R_L$ above the marginal level in white color decreases by around 44 percentin the Interstate and principal arterial highway if all other factors are controlled.

The analysis shows a significant difference in the probability of achieving retroreflectivity above the marginal level among different pavement marking materials. It is noticed from Table 8 that the probability of having $R_L$ above marginal was significantly lower for the epoxy and the waterborne material compared to the polyuria marking material. Table 8 shows that marking material polyurea has a 5.321 times higher probability of having $R_L$ above marginal value than epoxy when all other variables are held constant. The likelihood of waterborne marking material having $R_L$ above the marginal value is 68.4 percentlower than that of epoxy material after statistically controlling for the other factors. Similarly, Table 10 illustrates that polyurea has an 8.378 times higher probability of achieving $R_L$ above the marginal level than the epoxy material on the Interstate. At the same time, the waterborne material will decrease the likelihood of achieving $R_L$ above the marginal level by 65 percentcompared to epoxy in the principal arterial road. In the minor arterial and major collector, only waterborne paint material was used. Therefore, no effect could show in these two types of roads.

The center and lane lines have a comparatively lower probability of having $R_L$ above the marginal value than the edge line, as shown in Table 8. The center line has a 19.8 percentlower, and the lane line has an 18.9 percentlower likelihood of having $R_L$ above the marginal value. A possible reason for having a lower probability of $R_L$ in the center line and lane line is the more contact of pavement marking with vehicle wheels due to overtaking and lane changing. A similar result was found in Analysis 2. Table 10 shows that the probability of having RL above marginal in the Interstate is 20.8 percentlower for the lane line compared to the edge line. Additionally, the trend in Analysis 2 for the principal arterial, minor arterial, and major collector was similar to Analysis 1. In the minor arterial and major collectors, the center line has a lower probability of having $R_L$ above the marginal level compared to the edge line (Table 10).

For stripe type (solid line or skip line), it was found that the stripe type is insignificant in all analyses due to having a p-value >0.05. Consequently, stripe type was removed from the models for Analyses 1 and 2.
For stripe type (solid line or skip line), it was found that the stripe type is insignificant in all analyses due to having a p-value >0.05. Consequently, stripe type was removed from Analyses 1 and 2 models.

### 4.5.3 Road Geometry and Location Attributes

The effects of geometric properties and the location of the road on the pavement marking retroreflectivity were investigated in both analyses. The degree of curvature of a horizontal curve is defined as the amount of curvature or sharpness of the curve, and a larger degree of curvature indicates a sharper curve, while a smaller degree of curvature represents a more gradual curve. The odds ratio for the degree of curvature of the horizontal curve in Table 8 shows that the increase of the degree of curvature by 1 Degree decreases the probability of having $R_L$ exceeding the marginal value by 26.7 percent, statistically controlling for the other factors, representing that a sharp curve affects $R_L$ more compared to the gradual curve or straight road section. A possible explanation for this finding is the general tendency of the vehicle to go around a curve and, consequently, more wear and tear in the pavement marking in the horizontal curve. So, the probability of having $R_L$ above the marginal value decreases with the sharpness of the curve. The impact of the degree of curvature was almost similar in Analysis 2 also (Table 10).

The location based on facility types, such as urban and rural, also affects the pavement marking retroreflectivity. Since the location is a categorical variable, "rural" was used as a baseline. The odd ratio >1 indicates the urban area has higher odds of having $R_L$ above the marginal level than the rural area. This observation is consistent in both analyses (Table 8 and

Table 10). As a result, the probability of having $R_L$ above marginal in urban locations is higher than in rural locations.

Pavement type (asphalt or concrete) and the vertical grade were found insignificant in all analyses due to a p-value >0.05. Consequently, those parameters were removed from the Analysis 1 and 2 models.

### 4.5.3 Traffic Condition Attributes

The posted speed limit was chosen as an independent variable along with Average Annual Daily Traffic (AADT) and Average Annual Daily Truck Traffic (AADTT), assuming all vehicles run at the posted speed limit. The speed limit was found insignificant in both analyses, so it was removed from the models.

The analysis considered AADT and AADTT as potential variables included in the model with a scale factor of 1000. In Analysis 1, both AADT and AADTT were found to be statistically significant parameters, with odds ratios of 1.002 and 0.992, respectively (Table 8). However, the odds ratio is close to 1, suggesting no substantial impact on the probability of achieving $R_L$ levels above the marginal value. This finding aligns with previous studies that have shown no association between $R_L$ level and factors such as speed limit, AADT, and truck percentage (Sarasua et al. 2003; Thamizharasan et al. 2003). However, Analysis 2 yielded a different result specifically for the Interstate. In the Interstate, an increase of 1000 nos AADT and AADTT resulted in a respective decrease of 15.8 percent to 12.5 percent in the probability of having $R_L$ above the marginal level (according to

Table 10). No substantial effect of AADT and AADTT was found for other models, as the odds ratio is either close to 1 or not significant. These findings also align with a study by Abboud and Bowman (2002), conducted in Alabama, which indicated that ADT (Average Daily Traffic) had a significant influence on pavement marking degradation, along with time. The different results observed specifically for the Interstate could be attributed because the Interstate typically experiences higher traffic volumes and truck percentages than other functional classifications of roads, resulting in more wear and tear on pavement markings. The increased traffic flow may lead to more frequent contact with vehicles, causing faster deterioration of the markings and reduced retroreflectivity.

### 4.5.4 Climate Attributes

The temperature and humidity were not associated with the probability of having $R_L$ above the marginal level. Both analyses found similar results, so those parameters were removed from the models. The result of this study is consistent with some previous studies. Temperature and humidity were not significant factors in the study performed in South Carolina for waterborne white edge marking (Robertson et al. 2013).

## 4.6 Conformance and verification of the model

The association between the predicted probabilities and the observed responses was evaluated to check the fitness of the model. The goodness-of-fit test for a binary logistic regression model is conducted to assess the overall performance and adequacy of the model in explaining the relationship between the predictors and the binary outcome variable. Several statistical measures are commonly used to evaluate the goodness of fit in binary logistic regression. The percent concordant measures the percentage of cases where the predicted probabilities correctly rank the observed outcomes. A higher percent concordant indicates a higher level of agreement between the predicted probabilities and the observed outcomes. It ranges from 0 to 100, with 100 indicating perfect agreement. The association of all attempted models for both analyses is presented in Table 8 and Table 9. Overall, the percent concordant was in a range of 75.1 to 89.5, which means 75.1 percent to 89.5 percent of observations are in agreement with predictors when predicting the probability of retroreflectivity. Similarly, the area under the curve (AUC) of the receiver operating characteristics (ROC) curves is shown in Figure 13 as a goodness-of-fit parameter. The AUC value demonstrates the model's prediction accuracy. An AUC value close to one indicates a good fit for the model. Figure 13 shows a good model fit, with 77 percent to 91 percent of the observations agreeing with predictors. Based on the reported associations, the models are believed to be reasonably accurate.

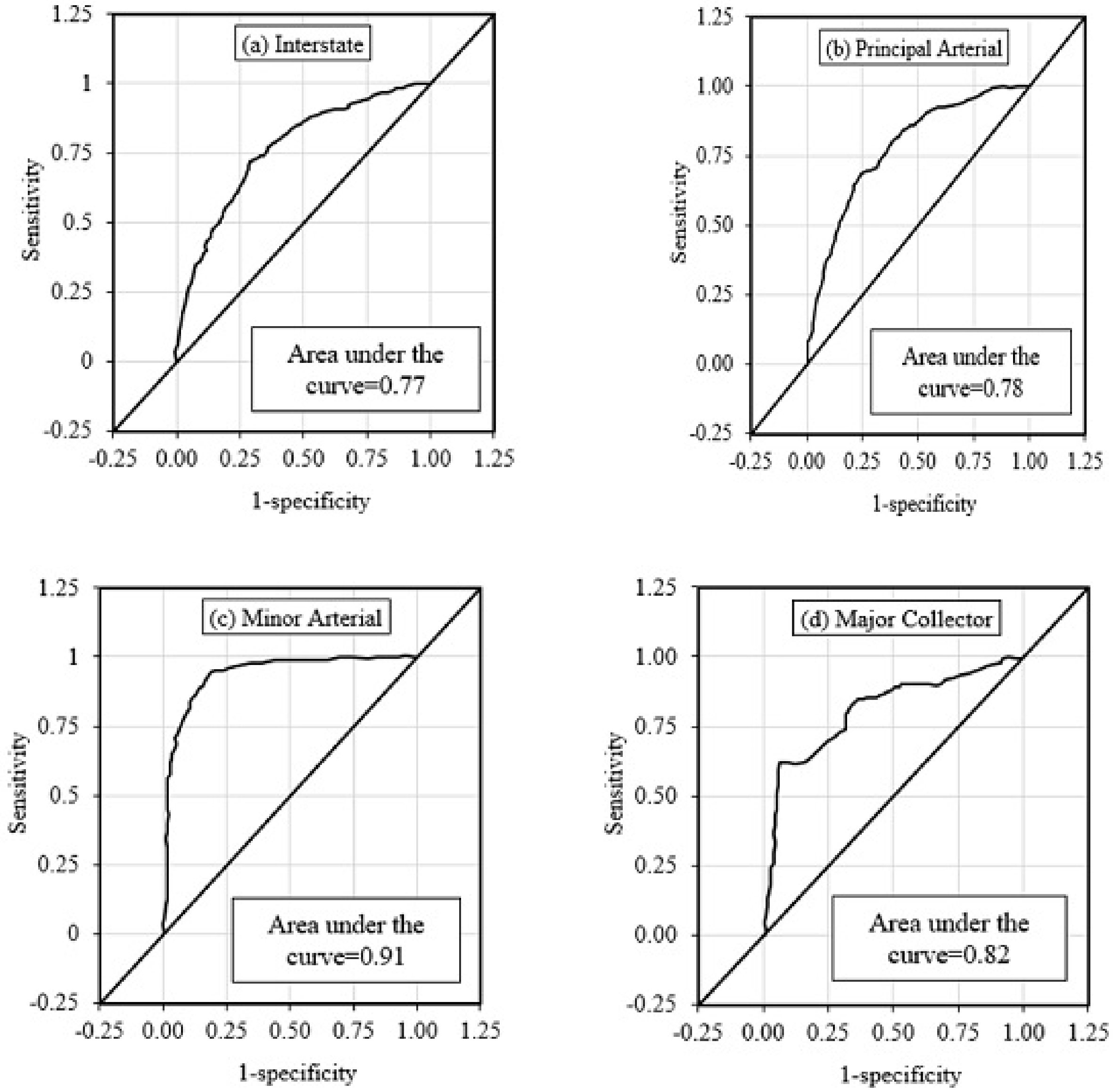



**Figure 13. Graph. Receiver Operating Characteristics (ROC) Curve with the Corresponding Area Under Curve (AUC): (A) Interstate, (B) Principal Arterial, (C) Minor Arterial, (D) Major Collector.**

### 4.7 Chapter Summary

This study focuses on the factors affecting pavement marking retroreflectivity and developing an extensive retroreflectivity data collection protocol by using a mobile retroreflectometer. WYDOT collected 16,310 retroreflectivity measurements from the Interstate, principal arterial, minor arterial, and major collector highways in Wyoming. Furthermore, road geometry, pavement characteristics, traffic, and material data were collected and incorporated into the analysis. Binary logistic models were developed using those data concerning the parameters affecting the probability of the pavement marking retroreflectivity above the marginal level. The $R_L$ of 100 mcd/m$^2$/lux for the yellow line and 125 mcd/m$^2$/lux for the white line were used as a marginal level. Additionally, the developed models were verified by conformance statistics, indicating reasonable prediction accuracy.

The analyses were conducted in two analyses considering a total of fourteen variables. In the first analysis, the whole dataset of measured retroreflectivity and selected parameters were used, and in the second analysis, the entire dataset was categorized based on four functional classifications. Interestingly, both analyses yielded similar trends for almost all variables, indicating the consistency and reliability of the prediction models employed. A more accurate and comprehensive understanding of the factors influencing retroreflectivity can be achieved by utilizing separate models for different different functional classification of roads because of having diverse characteristics, including variations in traffic patterns, pavement conditions, etc. Therefore, an individual model is important.

The impact of marking age on retroreflectivity was determined, highlighting that as the age of the pavement markings increases, their retroreflective properties deteriorate. The probability of having retroreflectivity above the marginal level decreased with the increase of the degree of curvature of the horizontal curve. At the horizontal curve, the decreasing trend of pavement marking retroreflectivity is possibly attributed to additional wear and tear in the curve due to the wandering of the vehicles. Additionally, the probability of having $R_L$ above marginal was lower in rural locations than urban roads. The analysis indicates that the marking material polyurea performed better than the material Epoxy and Waterborne. Waterborne material had the lowest probability of having retroreflectivity above marginal value. Marking color is also a significant factor for pavement marking retroreflactance. White color marking was found to have a lower probability of serviceable $R_L$ than the yellow marking. The analysis also reveals that the pavement markings located in the travel path (either center or lane lines) had a lower probability of retroreflectivity above marginal than those located at the edge of the pavement. A lower probability of retroreflectivity in the centerline and lane line is possibly due to more contact between pavement marking and vehicle wheels during overtaking and lane changing.

# CHAPTER 5: PREDICTING RETROREFLECTIVITY DEGRADATION OF PAVEMENT MARKING

## 5.1 Introduction

This chapter presents a Bayesian ordered logit model that incorporates Markov Chain Monte Carlo simulation to predict the degradation trend of $R_L$ using data collected from four functional classifications of highways in Wyoming over a 1-year period, encompassing intervals of approximately six months (December 2021, May 2022, and December 2022). The model identifies several factors significantly affecting $R_L$ deterioration, including marking characteristics, line position, geometric attributes, traffic, and snowplow operation. The probability of monitored pavement markings transitioning from one service life level to another is estimated by considering five levels of $R_L$, and the service life of different materials was determined. Finally, this chapter highlights the significance of analyzing different functional classifications of roads and identifying unobserved heterogeneity to obtain accurate and unbiased results regarding $R_L$ degradation.

## 5.2 Data Preparation

In this study, a comprehensive database was created to develop a degradation model by utilizing multiple data sources. The retroreflectivity dataset included marking characteristics at the time of measurement, while additional data on traffic conditions, geometric attributes, and snowplow activities were collected from various sources. All datasets were synchronized and aligned based on milepost information to ensure consistency and accuracy.

### 5.2.1 Pavement Marking Characteristics Data

The retroreflectivity data were collected from a total of 528.5 miles (850.1 km) of the roadway. The marking material data and installation date were collected from WYDOT and incorporated into the dataset. Retroreflectivity data were measured three times in the 12 months from December 2021 to December 2022, as WYDOT employs an annual restriping cycle for pavement markings. Only those observations were considered for the degradation model that was not restriped during the analysis period. During the retroreflectivity data collection process, the retroreflectivity database recorded essential information regarding marking color, line position, and stripe type. Additionally, the marking material and installation date were provided by WYDOT, enabling the calculation of the marking age at the time of each data collection.

### 5.2.2 Roadway Characteristics Geometric Data

Data on roadway classification, geometric, and location characteristics (location, pavement type, and horizontal curve) of selected roadways were extracted from different databases of WYDOT and incorporated into the retroreflectivity databases precisely aligned with specific milepost changes occurring at every 0.1 miles.

### 5.2.3 Traffic Characteristics Data

Average Annual Daily Traffic (AADT) is the average daily traffic along a roadway segment, and Average Annual Daily Truck Traffic (AADTT) is the average daily truck traffic along a roadway segment. WYDOT records and maintains all the traffic data, including AADT, AADTT, etc., every year. So, traffic volume data were extracted from WYDOT 2021 Vehicle Miles Book database and incorporated for each 0.1-mile section.

### 5.2.4 Snowfall Data

To identify the effect of snow-related activities on pavement marking retroreflectivity, snowfall data (number of days having snowfall) were collected from the National Oceanic and Atmospheric Administration (NOAA) website for the entire period from installation to the last data collection date. At first, the nearest weather stations were identified for each test section by matching the latitude and longitude coordinates of the test sections with those of the weather stations. Figure 14 visually presents the distribution of NOAA weather stations throughout Wyoming. Usually, Roads are plowed if the snow accumulation exceeds a predetermined threshold. However, the minimum snow depth required for snow removal or other winter weather operations by WYDOT is not fixed. So, the number of days with snowfall was calculated for the analysis period with snow depth greater than or equal to 1 inch. The WYDOT Snowplow Priority map was used to direct WYDOT's snow removal operations, and the total number of days with snow activities was determined for each road segment.

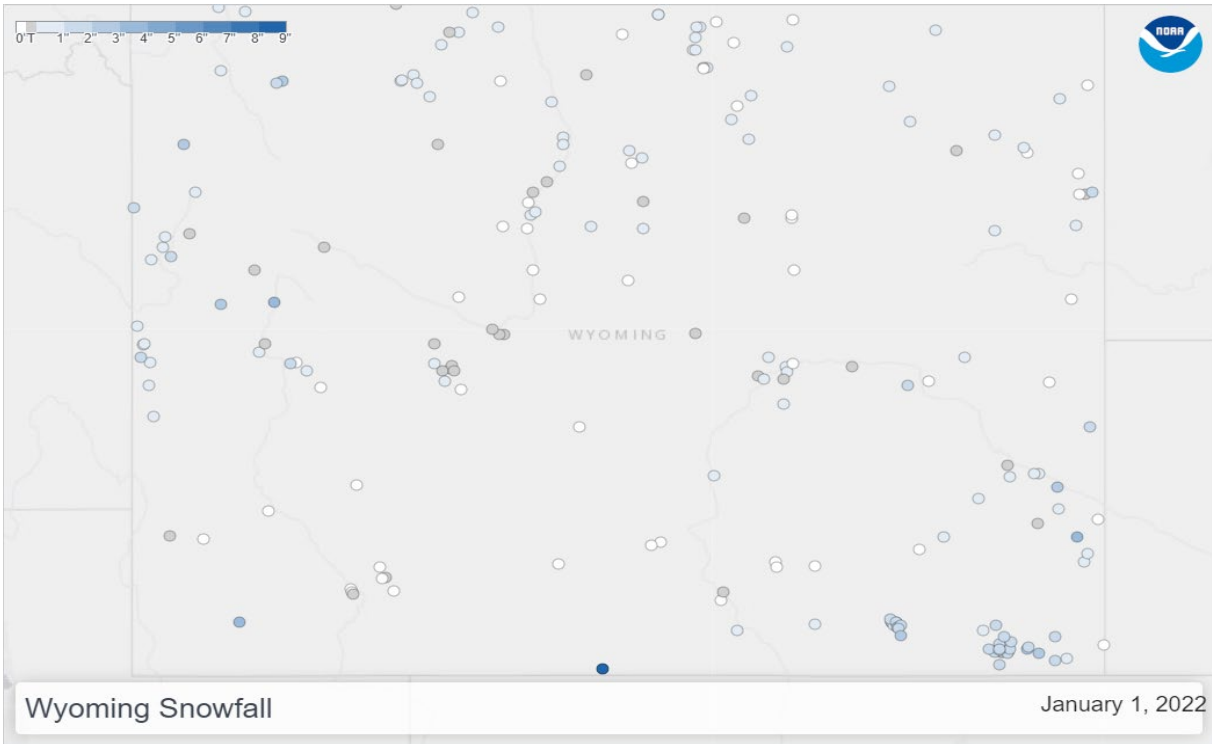



**Figure 14. Map. NOAA Website Interface showing the Weather Stations in Wyoming for Snowfall Data (NOAA 2023).**

WYDOT implements a snowplow priority map and service level classification to direct and schedule snow removal operations. The snowplow priority map divides the road network based on its importance and usage. High-priority routes, such as major highways and roads with heavy traffic volumes, are prioritized for snow removal, as shown in Figure 15.

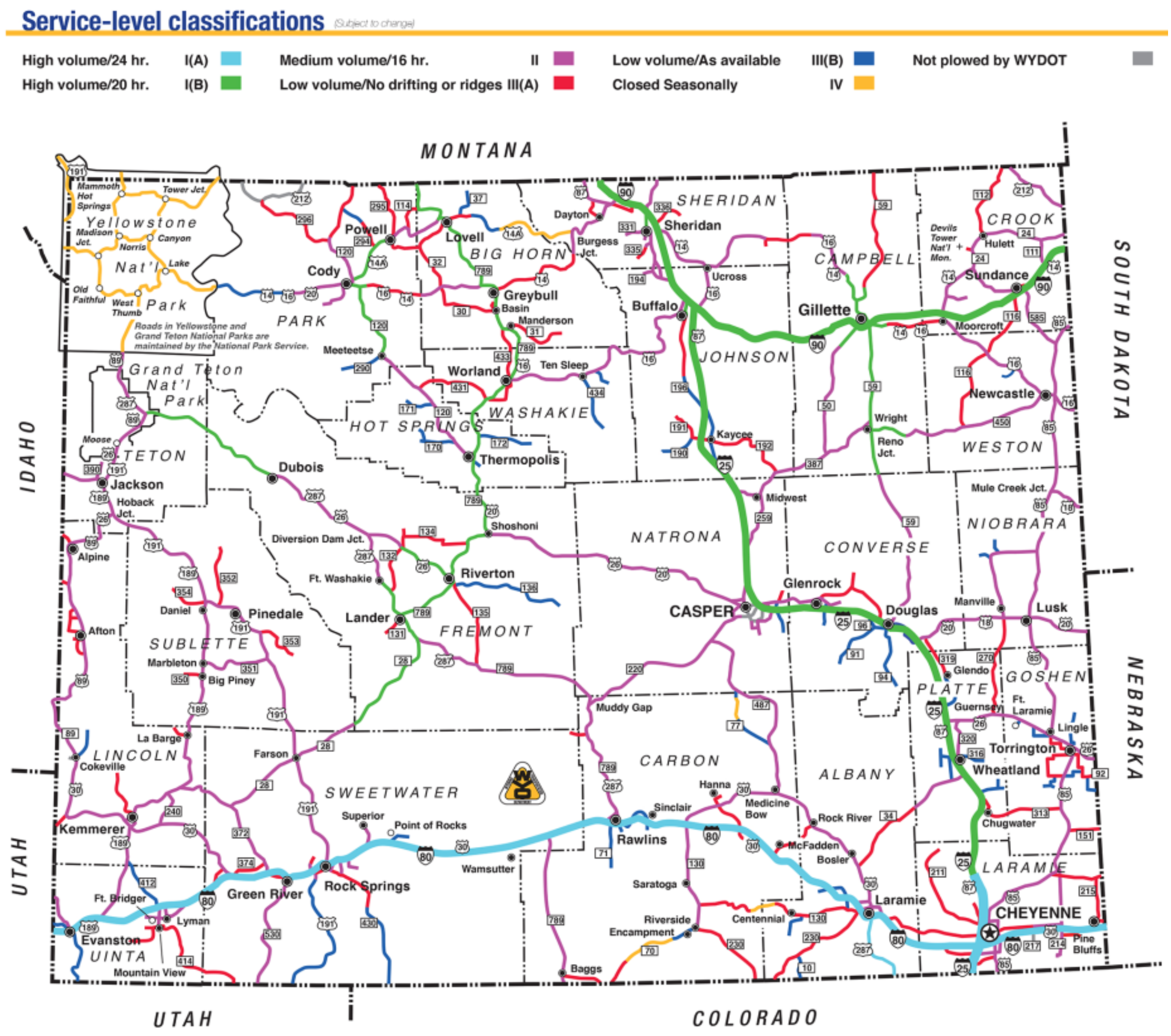



Figure 15. Map. Snowplow Priority Map of WYDOT (WYDOT, 2023).

Snowplowing services are classified into different road volumes. High volume (IA, IB) roads, including interstates and principal arterial routes, receive priority service with crews working up to 24 hours a day on IA highways and up to 20 hours a day on IB highways to maintain a clear and safe roadway. Medium volume (II) roads, which generally encompass lesser-used minor arterial and collector routes, receive service with crews working up to 16 hours a day. Low volume (IIIA, IIIB) roads, consisting of less busy minor arterial and collector routes, are cleared after high and medium volume routes, with minimal service provided for Level based on resource availability. The number of snowplowing days was calculated by comparing the priority levels to IA roads. For instance, if roads experienced 50 days of snowfall exceeding 1 inch, then there would be 50 snowplowing days for IA roads. For IB roads, the snowplowing days were adjusted proportionally, resulting in 42 days (calculated as 50 * 20 / 24), while for IB roads, it was determined to be 33 days (calculated as 50 * 16 / 24). As IIIA and IIIB roads generally receive minimum service levels, the snowplowing days were considered 0 for these road categories.

## 5.3 Model Development

This analysis included the Bayesian Ordered Logit Model to test the effects of independent variables on retroreflectivity degradation. The independent variables incorporated into the model were road geometry, pavement surface and locations, marking age, color, line position, material, traffic condition, and winter effects, selected based on the literature review and preliminary data analysis. An initial model was developed using randomly selected 80 percent of the data points and validated the variables in the model using the remaining 20 percent of the data. Then, the final prediction model was developed using the best-fit model's parameter estimates of independent variables established by the initial model and applied to the full data set.

### 5.3.1 Development of the Bayesian Ordered Logit Model

Pavement marking retroreflectivity data was collected over time, known as longitudinal data (Fitzmaurice et al. 2008). Moreover, the dataset used in this analysis exhibited variability and inconsistency in the recorded $R_L$ data, which has also been a concern in previous studies (Kopf 2004; Migletz et al. 2001; Sarasua et al. 2003), so the response variable was categorized into five levels to improve model stability and precision. So, the Bayesian ordered logit model has been selected for this analysis of longitudinal and categorical data because this model is commonly utilized in predicting infrastructure performance in transportation engineering fields such as pavement conditions degradation and safety analysis (Ahmed 2022; Compare et al. 2017; Lu et al. 2019; Xu et al. 2022). Therefore, a five-level Bayesian Ordered Logit Model with fixed and random effects was utilized to investigate the impact of various predictor variables on pavement marking retroreflectivity degradation.

One advantage of Bayesian analysis is the incorporation of prior knowledge and uncertainty about model parameters through prior probability distributions, which can be informative, weakly informative, or noninformative. Informative priors are based on previous studies, while weakly informative priors allow for unbiased estimates within a sensible range, and noninformative priors draw information from the likelihood. In this study, weakly informative prior was used, which was recommended by (Lemoine 2019), as the prior distribution was drawn from the preliminary data analysis of the collected data and assumed to be normally distributed.

Markov Chain Monte Carlo (MCMC) sampling techniques have proven beneficial for analyzing degradation data related to pavement markings due to their simplicity and minimal computational effort (Chimba et al. 2018; Mazzoni et al. 2022). There are several Markov Chain Monte Carlo (MCMC) sampling techniques, such as the Gibbs sampler, Metropolis-Hastings algorithm, or a combination of both using freeware, WinBugs, have been widely used to obtain samples from the posterior distribution (Brooks et al. 2011). However, the no U-turns Hamiltonian MCMC method has been gaining momentum due to its effectiveness and robustness over other sampling techniques (Hoffman and Gelman 2014). To evaluate longitudinal pavement marking retroreflectivity, we developed Bayesian ordered logit models using the NUT HMC sampling technique and Stan programming language in R®. The variation in pavement marking location plays a crucial role in explaining unobserved heterogeneity caused by varying maintenance, weather conditions, and snow operations across different counties. To address this unobserved heterogeneity, a random-effects ordered logit model with a fixed-effects model was proposed to examine the unobserved variance.

Let $Y_{ik}$ represent the ordered response variable of the pavement marking retroreflectivity levels with k categories, ranging from Good to Fail. Equation 6 describes the fixed effect Bayesian Ordered Logit Model, which included the intercept $\alpha_k$, coefficients $\beta_k$ for each independent variable, and explanatory variables $X_{ik}$.

$$logit\big(P(Y_i \le k)\big) = log \frac{P(Y_i \le k)}{1 - P(Y_i \le k)} = \alpha_k - \big(\beta_1 X_{i_1} + \beta_2 X_{i_2} + \cdots\big) \tag{6}$$

In Equation 7, a random effect Bayesian Ordered Logit Model is presented where the intercept term incorporates a random parameter, $u_k$, that represents the random effects of the variable. It is assumed that $u_k$ follows a normal distribution with a mean of 0 and a standard deviation of σ2, denoted as N(0, σ2).

$$logit\big(P(Y_i \le k)\big) = log \frac{P(Y_i \le k)}{1 - P(Y_i \le k)} = (\alpha_k + u_k) - \big(\beta_1 X_{i_1} + \beta_2 X_{i_2} + \cdots\big) \tag{7}$$

The cumulative probability, denoted as $P(Y_i \le k)$, represents the probability that the outcome variable is at or below level k. The cumulative probability $P(Y_i \le k)$ for the $k^{th}$ level can be calculated using the following general form of cumulative probability Equation 8:

$$P(Y_i \le k) = \frac{e^{((\alpha_k + u_k) - (\beta_1 X_1 + \beta_2 X_2 \ldots\ldots\ldots + \beta_K X_K))}}{1 + e^{((\alpha_k + u_k) - (\beta_1 X_1 + \beta_2 X_2 \ldots\ldots\ldots + \beta_K X_K))}} \tag{8}$$

The individual probabilities $P_k$ can then be calculated using the following Equation 9 :

$$P(Y_i = k) = P(Y_i \le k) - P(Y_i \le k - 1) \tag{9}$$

Where $P(Y_i \le k - 1)$ is the cumulative probability for level k-1 and $P(Y_i \le k)$ is the cumulative probability for level k. The predicted probabilities of the outcome variable falling into each level are constrained between 0 and 1.

The ratio between the probability of an event occurring and the probability of it not occurring is known as the odds, which can be obtained using Equation 10.

$$\left(\frac{P(Y_i \leq k)}{1-P(Y_i \leq k)}\right) = e^{(\alpha_k + u_k) - (\beta_1 X_{i_1} + \beta_2 X_{i_2} + \cdots)} \tag{10}$$

Bayesian statistics focus on the posterior distribution, p(θ|Y), where θ represents the model parameters, which are unknown quantities, and y represents the data, which are known quantities. The posterior distribution is generally computed using the following equation.

$$Posterior = \frac{LikelihoodxPrior}{AverageLikelihood} \tag{11}$$

$$p(\theta|y) = \frac{p(y|\theta)xp(\theta)}{p(y)} \tag{12}$$

The likelihood, p(Y|θ), is the data distribution given the parameters, while the prior distribution, p(θ), represents the uncertainty in the parameters before seeing the data. The marginal likelihood, p(Y), is a normalizing constant to ensure that the posterior is an actual probability distribution. The product of the likelihood and prior is proportional to the posterior, and the marginal likelihood is rarely of direct interest, which is clarified in Equation 13:

$$p(\theta|y) \propto p(y|\theta)xp(\theta) \tag{13}$$

An intra-class correlation (ICC) coefficient is applied to assess the data's random effects, quantifying the proportion of variations that would not have been accounted for in the model that ignores data clustering (Szmaragd et al. 2013). The ICC ranges from 0 to 1, with a value close to 0 suggesting limited variability that can be attributed to group-level differences and a value close to 1 indicating significant variations among groups, and a hierarchical model is warranted to appropriately model the data (McElreath 2020). The ICC is determined by examining the between-county variance. For this study, the ICC was determined, which is formulated as follows (Kidando et al. 2019):

$$ICC = \frac{\sigma_c^2}{\sigma_c^2 + \sigma_v^2} \tag{14}$$

where, $\sigma_c{}^2$ is the between-group variance, and $\sigma_v{}^2$ is residual variance. $\sigma_v{}^2$is equal to $\frac{\pi^2}{3}$ =3.29 for the standard hierarchical logistic distribution (Ahmed et al. 2020).

In this study, a 95 percent Bayesian credible interval (95 percent BCI) was utilized to identify significant predictors, which is the central portion (2.5 percent- 97.5 percent) of the posterior distribution that excludes zero (Gelman et al. 2014). Odds ratios were used to interpret the effect of significant variables on the response in pavement marking retroreflectivity degradation.

### 5.3.2 Model Estimation and Comparison Method

Multicollinearity among explanatory variables was assessed using correlation tests, variance inflation factor (VIF), and tolerance tests to evaluate a Bayesian ordered logit model's performance. In this study, the results of all the above three measures were used to confirm the absence of multicollinearity among the explanatory variables.

There are several measures to assess model goodness of fit, and the Watanabe-Akaike Information Criterion (WAIC) is becoming more popular as a performance metric for Bayesian models (Watanabe 2013). WAIC can average likelihoods over the posterior distribution, and the WAIC measure is computed by the following formula (Gelman et al. 2014):

$$WAIC = -2LPPD + 2P_{WAIC} \tag{15}$$

Log-pointwise predictive density (LPPD) is calculated using the number of MCMC samples calculated from the posterior distribution, and $P_{WAIC}$ is the effective number of parameters. In a word, WAIC is a measure of out-of-sample predictive accuracy, LPPD is a measure of goodness of fit, and $P_{WAIC}$ is a measure of model complexity in Bayesian statistics. Lower WAIC values are better for out-of-sample predictive accuracy; Higher LPPD values indicate a better fit to the data, and higher $P_{WAIC}$ values indicate greater model complexity, so lower $P_{WAIC}$ is preferred. However, all those parameters were determined using the statistical software R®.

## 5.4 Data's Descriptive Statistics

Retroreflectivity data were categorized into five groups per WYDOT's designation, as detailed in Table 11.

**Table 11. Pavement Marking Retroreflectivity Levels used by WYDOT.**

| Pavement Marking Retroreflectivity Qualitative level | Retroreflectivity of Yellow marking (mcd/m²/lux) | Retroreflectivity of White Marking (mcd/m²/lux) |
|---|---|---|
| Good =1 | 200+ | 250+ |
| Pass =2 | 150-200 | 175-250 |
| Marginal =3 | 100-150 | 125-175 |
| Bad =4 | 60-100 | 80-125 |
| Fail =5 | 50-60 | 50-80 |

A total of 14,877 retroreflectivity measurements were collected, with 59 percent from the interstate and 41 percent from the other three functional classes of highways. The descriptive statistics of both the response and explanatory variables are presented in Table 12 and Table 13, respectively. Table 12 shows the mean value of the pavement marking retroreflectivity ($R_L$) category across all four functional classes of highways over the three seasons analyzed. For the interstate, the age of pavement markings ranged from 0.8 months to 17.9 months, AADT ranged from 3,070 to 13,500 vehicles per day, and AADTT ranged from 484 to 3,577 trucks per day. The cumulative snowplowing days ranged from 1 to 53 in the analysis period. AADT, AADTT, and the number of snowplowing days were lower for the principal arterial, minor arterial, and major collector compared to the interstate. The Cumulative number of Traffic Passages (CTP) and the Cumulative number of Truck Traffic Passages (CTTP) are considered as model variables used to represent the cumulative exposure of vehicles and heavy vehicles since marking installation as the product of AADT/AADTT and time, measured in 10,000 of vehicles passages shown in Equation 16, and 17, where 30.4 is the month to days conversion factor.

$$\text{CTP} = \text{AADT/Lane} * \text{Marking Age (Months)} * 30.4 * 10^{-4} \tag{16}$$

$$\text{CTTP} = \text{AADTT/Lane} * \text{Marking Age (Months)} * 30.4 * 10^{-4} \tag{17}$$

Some binary variables were incorporated into the model such as location, pavement type, horizontal curve, color, stripe type, and line type, with “rural location,” “asphalt pavement,” “straight section,” “solid line,” and “edge line” as the baseline. Marking material was a categorical variable with three categories (polyurea, epoxy, and waterborne), with epoxy being the baseline. Table 13 reveals that the yellow color, urban section, concrete pavement, and curve section had significantly fewer observations than their counterparts in all four functional classifications of highways. In the interstate data sections, the percentage of Epoxy, Polyurea, and Waterborne marking was 4.54 percent, 71.51 percent, and 23.95 percent, respectively. In the principal arterial, Epoxy and Waterborne materials were 29.46 percent and 70.54 percent, respectively. In the minor arterial and major collector, marking material was waterborne, and pavement was limited to asphalt only. The lateral line locations were categorized as white edge line, white lane line, yellow edge line/ yellow center line. On the interstate, white edge-line data was 34.63 percent, yellow edge line 37.05 percent and white lane line data was 28.31 percentage. However, in the principal arterial, minor arterial, and major collector, the white edge line data was 51 percentage, 83.94 percentage, and 60.09 percentage, respectively.

## Table 12. Summary Statistics of the Quantitative Variables.

| Quantitative variables | | Interstate | | | Principal Arterial | | | Minor Arterial | | | Major Collector | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Dec. 2021 | May 2022 | Dec. 2022 | Dec. 2021 | May 2022 | Dec. 2022 | Dec. 2021 | May 2022 | Dec. 2022 | Dec. 2021 | May 2022 | Dec. 2022 |
| **Response Variable** | | | | | | | | | | | | | |
| Retroreflectivity | Mean | 1.9 | 3.8 | 4.5 | 2.4 | 3.6 | 4.5 | 2.6 | 3.8 | 4.5 | 2.3 | 3.5 | 4.11 |
| | SD | 0.7 | 0.9 | 0.7 | 0.7 | 0.8 | 0.9 | 0.8 | 0.7 | 0.5 | 0.7 | 0.6 | 0.4 |
| | Min | 1 | 1 | 2 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| | Max | 3 | 5 | 5 | 4 | 5 | 5 | 4 | 5 | 5 | 3 | 5 | 5 |
| **Explanatory Variables** | | | | | | | | | | | | | |
| Marking Age | Mean | 5.3 | 10.5 | 16.6 | 6.6 | 10.9 | 17.7 | 3.1 | 8.4 | 13.59 | 5.5 | 10.6 | 17.39 |
| | SD | 1.5 | 1.5 | 1.5 | 4.5 | 4.5 | 4.5 | 0.1 | 0.5 | 1.1 | 0.1 | 0.1 | 0.2 |
| | Min | 0.8 | 5.7 | 12 | 2.1 | 6.1 | 13.5 | 2.9 | 7.6 | 12.1 | 5.4 | 10.6 | 17.2 |
| | Max | 6.5 | 11.7 | 17.9 | 14.6 | 19.8 | 20.1 | 3.2 | 9.3 | 15.3 | 5.6 | 10.8 | 17.7 |
| Snowplow (Number of snowplowing days) | Mean | 2 | 30 | 31 | 4.7 | 26 | 28 | 0 | 17.3 | 20.1 | 0 | 6.1 | 9.3 |
| | SD | 0.8 | 9.1 | 9 | 2.9 | 8.9 | 9.1 | 0 | 4.9 | 6 | 0 | 5.9 | 5.8 |
| | Min | 1 | 17 | 18 | 1 | 13 | 14 | 0 | 10 | 11 | 0 | 0 | 0 |
| | Max | 4 | 52 | 53 | 9 | 40 | 42 | 0 | 24 | 28 | 0 | 12 | 13 |
| AADT | Mean | | 7,404 | | | 6,507 | | | 1,513 | | | 625 | |
| | SD | | 1,698 | | | 6,250 | | | 1,037 | | | 547 | |
| | Min | | 3,070 | | | 1,006 | | | 602 | | | 81 | |
| | Max | | 13,500 | | | 23,966 | | | 6,497 | | | 2,659 | |
| AADTT | Mean | | 3,244 | | | 397 | | | 158 | | | 148 | |
| | SD | | 695 | | | 244 | | | 81 | | | 102 | |
| | Min | | 484 | | | 81 | | | 39 | | | 27 | |
| | Max | | 3,577 | | | 1,127 | | | 331 | | | 237 | |

Note: SD = standard deviation; Min = minimum; Max = maximum; Dec.= December

**Table 13. Summary Statistics of the Categorical Explanatory Variables.**

| Categorical Explanatory Variables | Description | Interstate | | Principal Arterial | | Minor Arterial | | Major Collector | |
|---|---|---|---|---|---|---|---|---|---|
| | | Freq. | percentage | Freq. | percentage | Freq. | percentage | Freq. | percentage |
| Location | Rural | 6,331 | 72.07 | 1,194 | 50.61 | 2,130 | 90.03 | 1,300 | 95.03 |
| | Urban | 2,453 | 27.93 | 1,165 | 49.39 | 236 | 9.97 | 68 | 4.97 |
| Pavement type | Asphalt | 7,440 | 84.7 | 1,785 | 75.67 | 2,366 | 100 | 1,368 | 100 |
| | Concrete | 1,344 | 15.3 | 574 | 24.33 | NA | NA | NA | NA |
| Horizontal Curve | Straight | 5,199 | 59.19 | 1,725 | 73.12 | 1,699 | 71.81 | 1,117 | 81.65 |
| | Curve | 3,585 | 40.81 | 634 | 26.88 | 667 | 28.19 | 251 | 18.35 |
| Color | Yellow | 3,255 | 37.06 | 742 | 31.5 | 380 | 16.06 | 546 | 39.91 |
| | White | 5,529 | 62.94 | 1,617 | 68.5 | 1,986 | 83.94 | 822 | 60.09 |
| Material | Epoxy | 399 | 4.54 | 695 | 29.46 | NA | NA | NA | NA |
| | Polyurea | 6,281 | 71.51 | NA | NA | NA | NA | NA | NA |
| | Waterborne | 2,104 | 23.95 | 1,664 | 70.54 | 2,366 | 100 | 1,368 | 100 |
| Stripe | Solid line | 6,297 | 71.7 | 1,579 | 66.94 | 2,054 | 86.81 | 856 | 62.57 |
| | Skip line | 2,487 | 28.3 | 780 | 33.06 | 312 | 13.19 | 512 | 37.43 |
| Line type | WEL | 3,042 | 34.63 | 1,203 | 51.0 | 1,986 | 83.94 | 822 | 60.09 |
| | YEL | 3,255 | 37.05 | NA | NA | NA | NA | NA | NA |
| | YCL | NA | NA | 742 | 31.5 | 380 | 16.06 | 546 | 39.01 |
| | WLL | 2,487 | 28.31 | 414 | 17.5 | NA | NA | NA | NA |

Note: NA = Not Available; Freq= Frequency

### 5.5 Effect of Marking Age on Retroreflectivity Degradation

The degradation of pavement markings can be influenced by various variables such as pavement type, marking color, material, line type, time, and snowplow. To investigate the effect of each parameter, data were classified into four categories based on functional classification. Additionally, data were further classified based on line type, color, and material for each functional classification. Figure 16 shows a decreasing relationship of retroreflectivity with time, where higher degradation occurred in the time period between the first and second measurements (December 2021 to May 2022) compared to the second data and third measurements (May 2022 to December 2022). The average monthly degradation rate for the analysis period is mentioned for each of the four functional classifications of the highway, and a significantly higher degradation is found on the interstate.

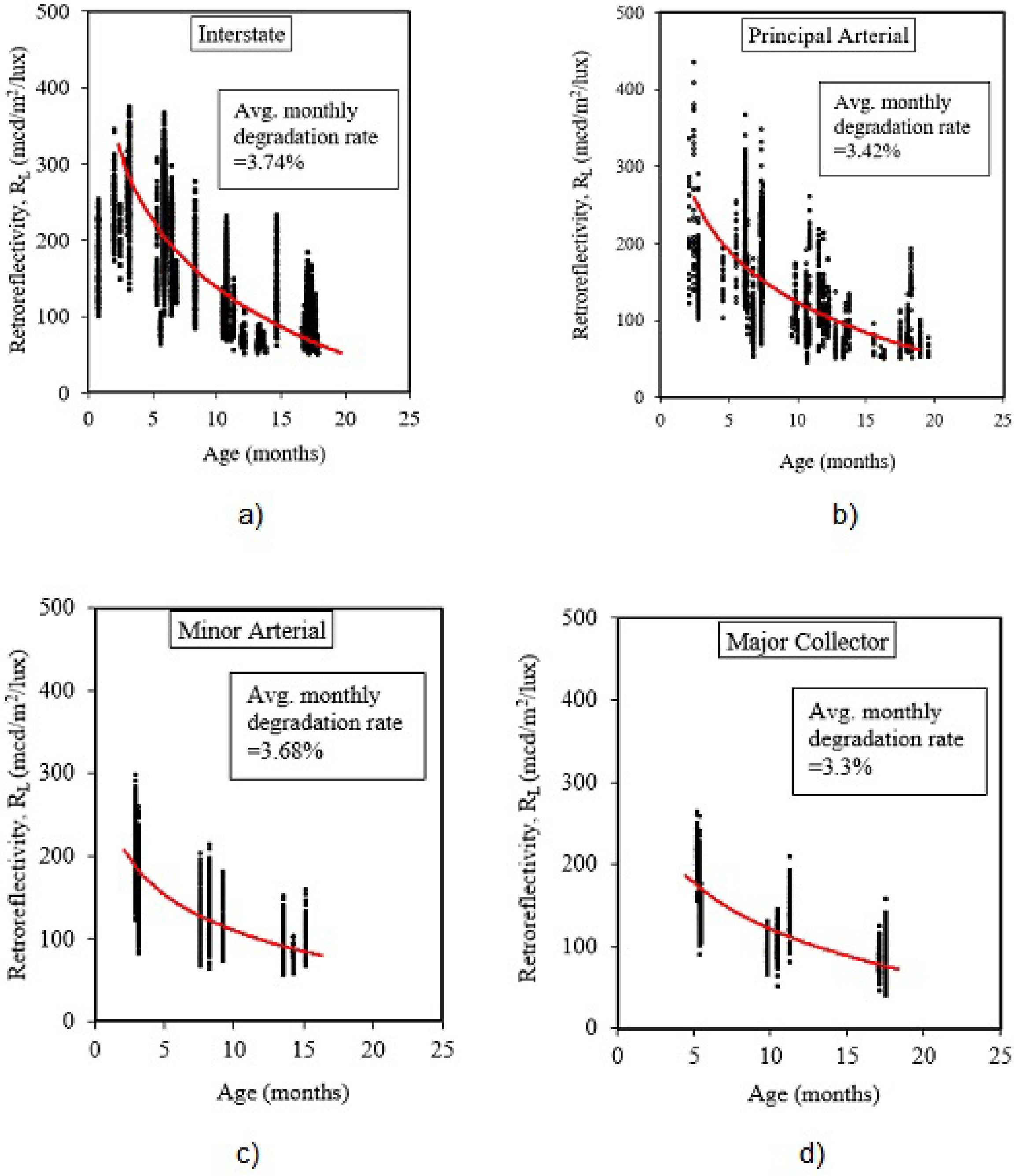



**Figure 16. Graph. Effects of Marking Age on Pavement Marking Retroreflectivity for Interstate, Principal Arterial, Minor Arterial, and Major Collector.**

Figure 17 demonstrates that the yellow edge line on the interstate has a lower retroreflectivity degradation rate compared to the white edge line and lane line. The average monthly degradation rate for the yellow edge line, white edge line, and white lane line are 3.39 percentage, 3.6 percentage, and 4.34 percentage, respectively.

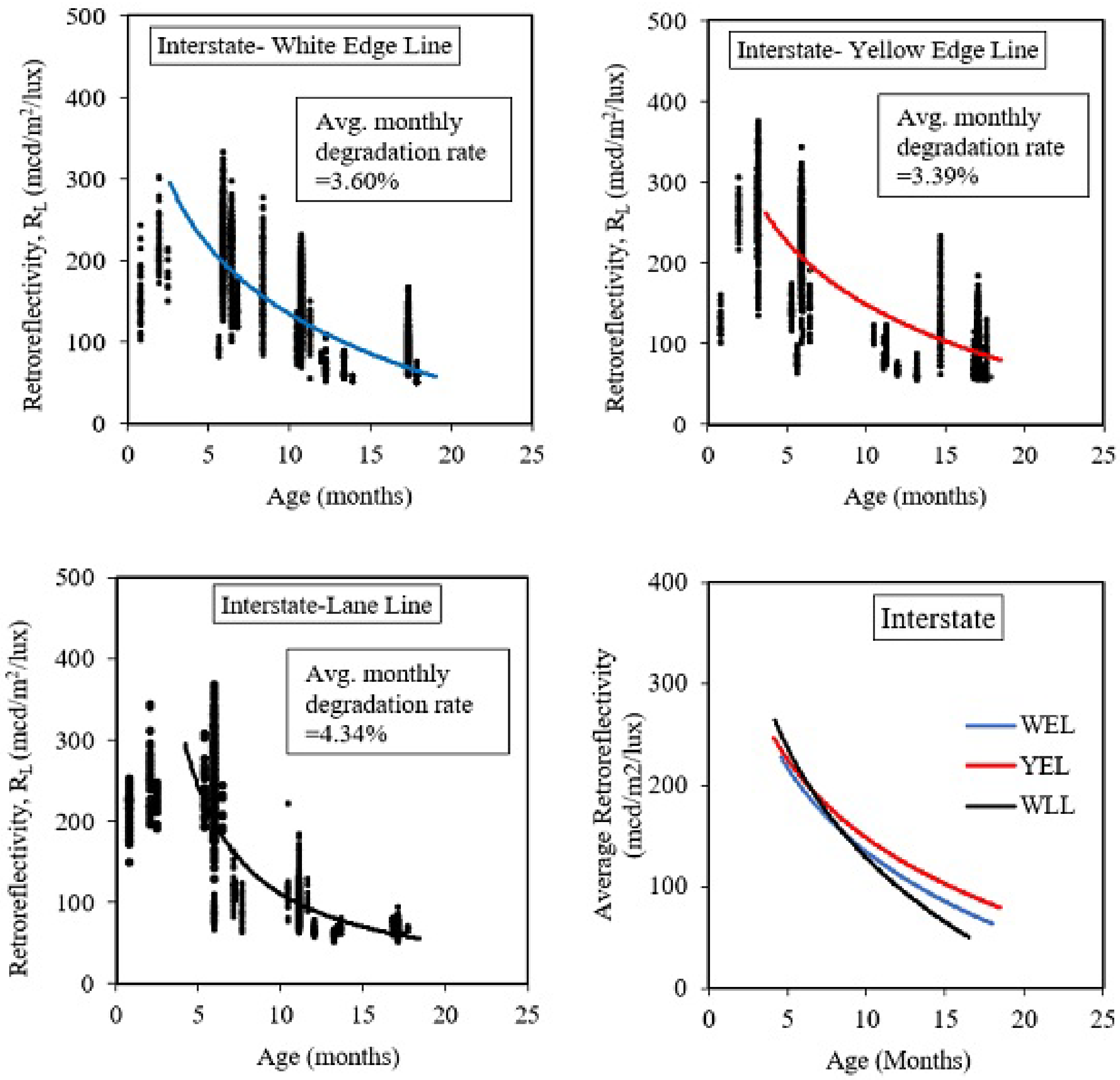



**Figure 17. Graph. Effects of Marking Line Position on Pavement Marking Retroreflectivity for Interstate.**

Figure 18 shows that the degradation rate of principal arterial white lane lines and yellow center lines are significantly higher than the white edge lines. So, it is observed that the middle line of the principal arterial degrades faster than the edge line.

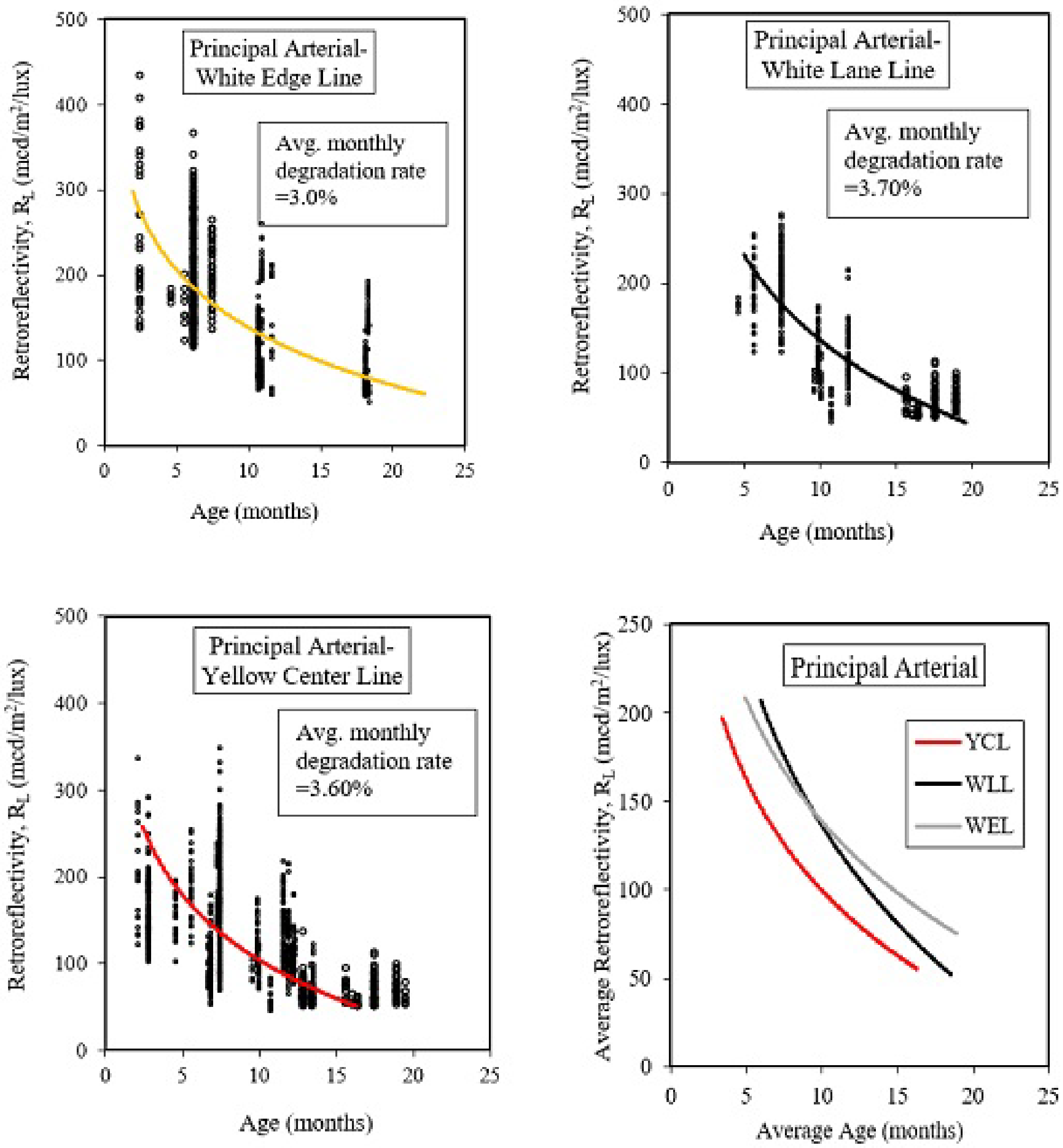



**Figure 18. Graph. Effects of Line Position on Pavement Marking Retroreflectivity for Principal Arterial.**

Figure 19 indicates that the yellow centerlines on minor arterial and major collector roads show a higher degradation than white edge lines. The pavement marking degradation pattern is similar for the minor arterial and major collector roads.

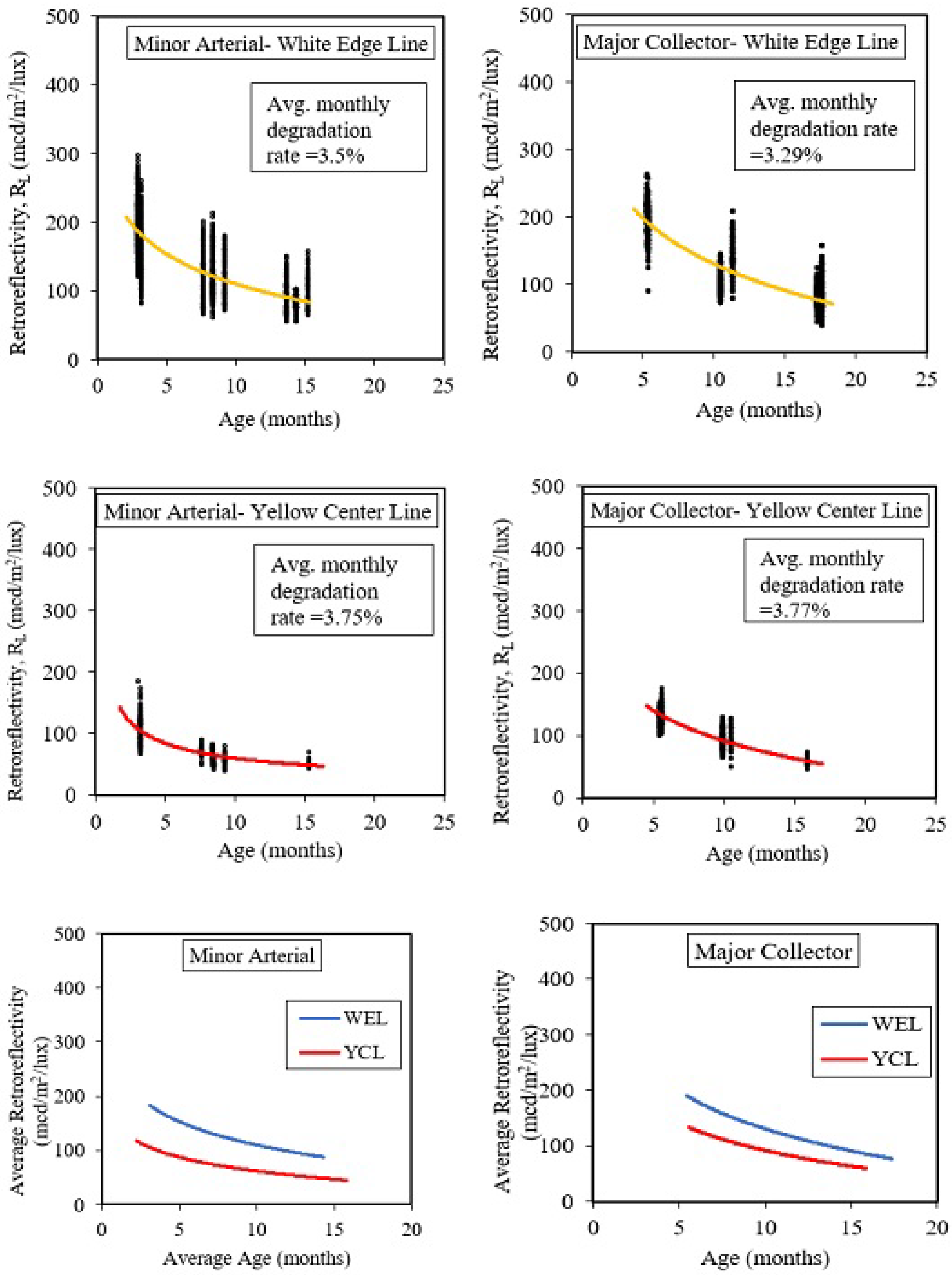



**Figure 19. Graph. Effects of Line Position on Pavement Marking Retroreflectivity for Minor Arterial and Major Collector.**

Figure 20 illustrates the correlation between the degradation of retroreflectivity in pavement markings and the choice of marking material. The analysis shows a significant decline in retroreflectivity as marking age increases, irrespective of the materials used. In this analysis test section, durable materials were applied in road sections experiencing heavy traffic volume and frequent snowplowing. In contrast, waterborne markings were utilized in areas with relatively lower traffic and reduced snowplow activity. Remarkably, the average AADT and AADTT were 7,560 and 3,261 for polyurea, 9,151 and 2,265 for epoxy, and 4,935 and 1,749 for waterborne material. Furthermore, when examining the average monthly degradation rates, it was found that polyurea exhibited a monthly rate of 3.54 percentage, epoxy experienced 3.80 percentage, and waterborne material had a slightly higher degradation rate of 4.02 percentage.

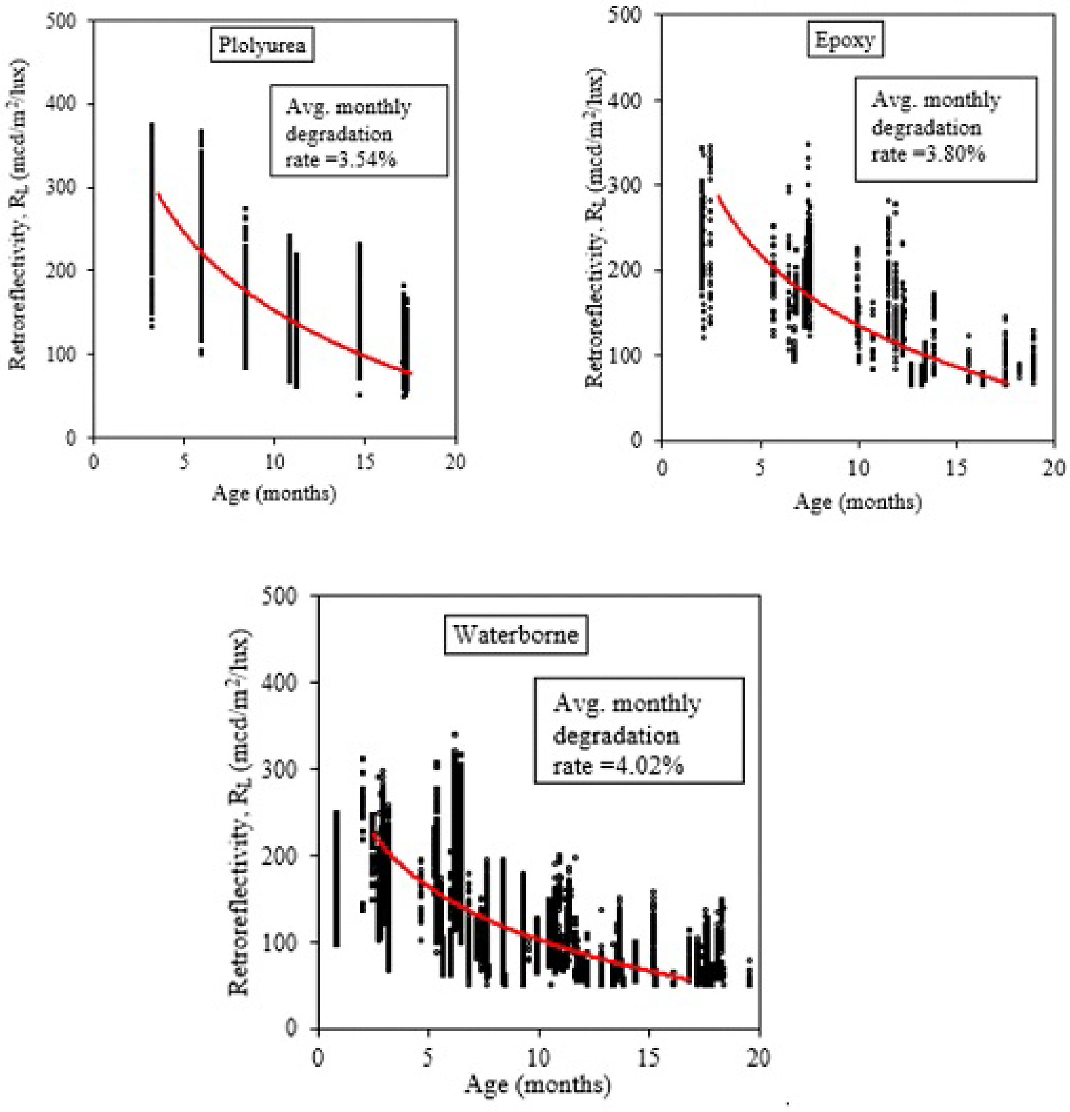



**Figure 20. Graph. Effects of Pavement Marking Material on Pavement Marking Retroreflectivity.**

## 5.6 Pavement Marking Retroreflectivity Prediction Modeling

### 5.6.1 Model Estimation and Diagnostics

The statistical models in this study were estimated using Bayesian inference with the 'brms' package in R®. To obtain the posterior distribution of samples, three MCMC chains applying the NUT HMC sampling procedure were run for each model. The simulation encompassed 3,000 iterations, where 1,000 of them were designated as burn-ins. This resulted in 6,000 posterior samples acquired from running 2,000 sets through 3 chains. The number of iterations and warm-up samples was decided based on model specification, achieving the maximum number of independent samples and satisfactory convergence of all chains (Brooks et al. 2011).

Trace plots and the Gelman-Rubin convergence diagnostic were obtained to ensure model convergence, with a potential scale reduction factor, Rhat=1 (Gelman and Rubin 1992), indicating convergence was ensured. The trace plots showed that the chains reached a stable state, characterized by a constant mean and variance. An ICC was calculated to investigate the validity of using a hierarchical model and to quantify the unobserved variability of $R_L$ within the same county. The calculated value indicated that 18 percent, 40 percent, 28 percent, and 13 percent of unexplained variation resulted from the county-specific unobserved factors for the four different models. Although no specific threshold for ICC would necessitate hierarchical Bayesian modeling, McElreath contends that hierarchical models should be the default approach when unobserved heterogeneity is associated with the model (McElreath 2020). Bayesian-ordered logit models with both fixed- and random effects were considered in this study. The random-effects model was preferred over fixed effects due to lower WAIC values and unobserved heterogeneity. The estimates for parameters, odds ratios (OR), and 95 percentBCI, as well as the area under the curve (AUC) for receiver operating characteristics (ROC) curves, are presented in Table 14 and Table 15 as indicators of goodness of fit for separate models. The association between predicted probabilities and observed responses was evaluated to assess the model's fitness, and the AUC value reflects the model's predictive accuracy. The results suggest strong agreement between predictors and $R_L$ degradation, with values ranging from 79.5 percentto 89.3 percentage, indicating a very good model fit overall.

**Table 14. Parameter Estimates for the Factors Affecting Pavement Marking Retroreflectivity in Interstate and Principal Arterial.**

| Variables | Interstate | | | | Principal Arterial | | | |
|---|---|---|---|---|---|---|---|---|
| | Estimates | 2.5% | 97.5% | ICC | Estimates | 2.5% | 97.5% | ICC |
| Random effects<br>Between-County variance | 0.74 | 0.66 | 0.81 | 0.18 | 2.18 | 1.98 | 2.39 | 0.40 |
| | Estimates | 2.5% | 97.5% | OR | Estimates | 2.5% | 97.5% | OR |
| Intercept[1] | 1.91 | 1.59 | 2.22 | | 12.57 | 8.53 | 16.74 | |
| Intercept[2] | 3.71 | 3.38 | 4.04 | | 16.02 | 11.94 | 20.24 | |
| Intercept[3] | 6.19 | 5.83 | 6.55 | | 19.2 | 15.08 | 23.49 | |
| Intercept[4] | 9.05 | 8.66 | 9.45 | | 22.05 | 17.9 | 26.36 | |
| **Marking age** | | | | | | | | |
| Marking age (months) | 0.39 | 0.37 | 0.4 | 1.48 | 0.41 | 0.37 | 0.45 | 1.51 |
| **Pavement marking characteristics** | | | | | | | | |
| Material (Polyurea vs. Epoxy) | -1.15 | -1.48 | -0.82 | 0.32 | NA | | | |
| Material (Waterborne vs. Epoxy) | 0.62 | 0.28 | 0.94 | 1.86 | 2.42 | 1.04 | 3.79 | 11.2 |
| Line (YEL vs. WEL) | -2.24 | -2.37 | -2.12 | 0.11 | NA | | | |
| Line (WLL vs. WEL) | 0.5 | 0.39 | 0.62 | 1.65 | 1.24 | 1.86 | 2.63 | 3.45 |
| Line (YCL vs. WEL) | NA | | | | 0.28 | 0.13 | 0.43 | 1.32 |
| **Road Location and geometric attributes** | | | | | | | | |
| Location (Urban vs. Rural) | 0.7 | 0.54 | 0.86 | 2.01 | 0.95 | 0.27 | 1.63 | 2.59 |
| Pavement Type (Concrete vs. Asphalt) | 0.73 | 0.57 | 0.89 | 2.07 | 0.41 | 0.76 | 0.05 | 1.51 |
| Horizontal Curve (Curve vs Straight) | 0.17 | 0.05 | 0.29 | 1.19 | 0.42 | 0.15 | 0.7 | 1.52 |
| **Traffic Characteristics** | | | | | | | | |
| CTP | NS | | | | 0.62 | 0.32 | 0.93 | 1.86 |
| **Winter Attributes** | | | | | | | | |
| Snowplow (Number of snowplowing days) | 0.11 | 0.11 | 0.12 | 1.12 | 0.05 | 0.03 | 0.06 | 1.05 |
| **Model Statistics** | | | | | | | | |
| Number of observations | 8,784 | | | | 2,359 | | | |
| Effective number of variables, $P_{waic}$ | 17.0 | | | | 18.6 | | | |
| AUC | 86.7 | | | | 79.5 | | | |

**Table 15. Parameter Estimates for the Factors Affecting Pavement Marking Retroreflectivity in Minor Arterial and Major Collector.**

| Variables | Minor Arterial | | | | Major Collector | | | |
|---|---|---|---|---|---|---|---|---|
| | Estimates | 2.5% | 97.5% | ICC | Estimates | 2.5% | 97.5% | ICC |
| Random effects | | | | | | | | |
| Between-County variance | 1.11 | 0.96 | 1.28 | 0.28 | 0.7 | 0.48 | 0.91 | 0.13 |
| | Estimates | 2.5% | 97.5% | OR | Estimates | 2.5% | 97.5% | OR |
| Intercept[1] | 5.85 | 3.05 | 8.73 | | 2.75 | 2.25 | 3.27 | |
| Intercept[2] | 9.39 | 6.55 | 12.34 | | 6.13 | 5.55 | 6.75 | |
| Intercept[3] | 12.01 | 9.13 | 14.99 | | 10.55 | 9.7 | 11.46 | |
| Intercept[4] | 15.83 | 12.9 | 18.84 | | 16.9 | 15.62 | 18.30 | |
| **Marking age** | | | | | | | | |
| Marking age (months) | 0.16 | 0.08 | 0.25 | 1.17 | 0.78 | 0.71 | 0.86 | 2.18 |
| **Pavement marking characteristics** | | | | | | | | |
| Material (Polyurea vs. Epoxy) | NA | | | | NA | | | |
| Material (Waterborne vs. Epoxy) | NA | | | | NA | | | |
| Line (YEL vs. WEL) | NA | | | | NA | | | |
| Line (WLL vs. WEL) | NA | | | | NA | | | |
| Line (YCL vs. WEL) | 1.49 | 1.22 | 1.77 | 4.44 | 2.68 | 2.36 | 3.01 | 14.6 |
| **Road Geometry and Location and attributes** | | | | | | | | |
| Location (Urban vs. Rural) | 1.57 | 1.2 | 1.93 | 4.81 | 0.74 | 0.14 | 1.35 | 2.10 |
| Pavement Type (Concrete vs. Asphalt) | NA | | | | NA | | | |
| Horizontal Curve (Curve vs. Straight) | 0.47 | 0.21 | 0.72 | 1.60 | 0.37 | 0.01 | 0.73 | 1.45 |
| **Traffic Characteristics** | | | | | | | | |
| CTP | 0.72 | 0.45 | 0.99 | 2.05 | NS | | | |
| **winter Attributes** | | | | | | | | |
| Snowplow (Number of snowplowing days) | 0.14 | 0.12 | 0.16 | 1.15 | 0.13 | 0.1 | 0.17 | 1.14 |
| **Model Statistics** | | | | | | | | |
| Number of observations | 2,366 | | | | 1,368 | | | |
| Effective number of variables, $P_{waic}$ | 10.1 | | | | 10.0 | | | |
| AUC | 81.3 | | | | 89.3 | | | |

The following prediction models in Equation 18-21 were proposed based on the significant parameters in Interstate, Principal Arterial, Minor Arterial, and Major Collector based on $R_L$ degradation model results in Table 14 and Table 15.

$$logit\left(\frac{P(Y_i \leq k)}{1 - P(Y_i \leq k)}\right) = (\alpha_k + u_k)\,((0.7 \times Location + 0.73 \times Pavement + 0.17 \times Curve + 036 \times Age - 1.15 \times Mat.poly + 0.6 \times Mat.Wb + 0.5 \times WLL - 2.24 \times YEL + 0.11 \times Snowplow)) \tag{18}$$

**Principal Arterial:**

$$logit\left(\frac{P(Y_i \leq k)}{1 - P(Y_i \leq k)}\right) = (\alpha_k + u_k) - ((0.95 \times Location + 0.41 \times Pavement + 0.42 \times Curve + 041 \times Age + 2.42 \times Mat.Wb + 1.24 \times WLL + 0.28 \times YCL + 0.62 \times CTP + 0.05 \times Snowplow)) \quad (19)$$

**Minor Arterial:**

$$logit\left(\frac{P(Y_i \leq k)}{1 - P(Y_i \leq k)}\right) = = (\alpha_k + u_k) - ((1.57 \times Location + 0.47 \times Curve + 0.16 \times Age + 1.49 \times Line + 0.72 \times CTP + 0.14 \times Snowplow)) \quad (20)$$

Where, $\alpha_1$= 5.85, $\alpha_2$= 9.39, $\alpha_3$= 12.01 and $\alpha_4$= 15.83, $u_k$ = 1.11

**Major Collector:**

$$logit\left(\frac{P(Y_i \leq k)}{1 - P(Y_i \leq k)}\right) = = (\alpha_k + u_k) - ((0.74 \times Location + 0.37 \times Curve + 0.78 \times Age + 2.68 \times Line + 0.13 \times Snowplow)) \quad (21)$$

Where, $\alpha_1$= 2.75, $\alpha_2$= 6.13, $\alpha_3$= 10.55 and $\alpha_4$= 16.9, $u_k$ = 0.7

### 5.6.2 Significant Factor Analysis

The results in Table 14 and Table 15 show that various factors significantly impact $R_L$ degradation, including road location, pavement marking characteristics, traffic characteristics, geometrical characteristics, and winter effects. Odds ratios shown in the tables explain how much a variable affects $R_L$ degradation, with >1 indicating an increase and <1 indicating a decrease, while a ratio of 1 means no impact, assuming other variables remain constant. However, the significance of these factors varied by functional class model, with some factors being significant in one model but not in others. Additionally, some factors were found to be positively correlated in one model but negatively correlated in another. These discrepancies highlight the importance of examining $R_L$ degradation across various functional classifications of highways. Table 16 summarizes the effects of statistically significant factors on $R_L$ degradation, allowing for a comparison of the effects in different models.

**Table 16. Model Comparisons for the Interstate, Principal Arterial, Minor Arterial, and Major Collector.**

| Odds Ratio Estimates | | | | | |
|---|---|---|---|---|---|
| Attributes | Variables | Interstate | Principal Arterial | Minor Arterial | Major Collector |
| Marking Age | Pavement Marking age (months) | ↑1.48 | ↑1.51 | ↑1.17 | ↑2.18 |
| Pavement marking characteristics | Material (Polyurea vs. Epoxy) | ↓0.32 | NA | NA | NA |
| | Material (Waterborne vs. Epoxy) | ↑1.86 | ↑11.2 | NA | NA |
| | Line (YEL vs. WEL) | ↓0.11 | NA | NA | NA |
| | Line (WLL vs. WEL) | ↑1.65 | ↑3.45 | NA | NA |
| | Line (YCL vs. WEL) | NA | ↑1.32 | ↑4.44 | ↑14.6 |
| Road geometry Location attributes | Location (Urban vs. Rural) | ↑2.01 | ↑2.59 | ↑4.81 | ↑2.10 |
| | Pavement Type (Concrete vs. Asphalt) | ↑2.07 | ↑1.51 | NA | NA |
| | Horizontal Curve (Curve vs. Straight) | ↑1.19 | ↑1.52 | ↑1.6 | ↑1.45 |
| Traffic Characteristics | CTP | NS | ↑1.86 | ↑2.05 | NS |
| Winter Attributes | Number of snowplowing days | ↑1.12 | ↑1.05 | ↑1.15 | ↑1.14 |

#### a) Pavement Marking Age

The retroreflectivity degradation of pavement marking is influenced by various characteristics, such as marking age, color, material, and line types. However, pavement marking age is significant in all four models, and the results showed that $R_L$ degrades over time by 1.48, 1.51, 1.17, and 2.18 times for every 1-month increase in marking age for the Interstate, Principal Arterial, Minor arterial, and Major collector, respectively (Table 16). However, variations in the results of the four models may be attributed to changes in pavement type, material, maintenance, and other factors.

### b) Pavement Marking Characteristics and Attributes

The marking materials (polyurea, epoxy, and waterborne) showed a significant difference in degradation trends at the 95 percent confidence level in Table 14 and Table 15. Material (polyurea vs. epoxy) and (waterborne vs. epoxy) are significant factors for the interstate and principal arterial. Table 16 shows that polyurea material has 0.32 times lower retroreflectivity degradation in interstate. Waterborne material has a higher degradation rate than epoxy in interstate and principal arterial.

For stripe type (solid line or skip line), it was found that the stripe type is not a significant factor in all models. Consequently, stripe type was removed from the models.

Table 14 and Table 15 present that marking line position with color is a significant variable in all models. The white edge line (WEL) was considered a reference line for all models. Table 16 indicates that the yellow edge line has a 0.11 times lower likelihood of degradation than the white edge line, and the white lane line has 1.65 times higher degradation than the edge line. In the principal arterial model, the white lane line and yellow center line have 3.45 and 1.32 times higher degradation than the white edge line.

However, for minor arterial and major collector roads, all edge lines are white, and the center lines are yellow. The yellow center line has 4.44, and 14.59 times higher degradation than white edge lines on minor arterial and major collector roads, respectively, as shown in Table 16. From all models, it was found that Middle lines (White lane line, yellow center line) have higher degradation of pavement marking retroreflectivity compared to edge lines. Middle lines typically experience greater contact with vehicle wheels due to overtaking, lane changing, and potentially more exposure to snowplow operations, which can lead to abrasion or erasure of the markings over time, ultimately reducing their retroreflectivity. This study confirms the findings about the impact of lateral line location on pavement marking degradation from earlier research (Craig III et al. 2007; Sitzabee et al. 2009a).

To observe the effect of the color of the marking, the white edge line should be compared with the yellow edge line, and the yellow center line should be compared with the white lane line. This approach is necessary because the edge line and middle line of pavement markings serve distinct functions and exhibit varying rates of retroreflectivity degradation. Upon conducting observations on the Interstate, it was found that the yellow edge line has a lower degradation rate than the white edge line, and the Principal arterial white lane line also has a higher degradation rate than the yellow center line. Those results confirmed that yellow marking has lower degradation compared to white marking. From previous research, the degradation rate of white markings was found to be significantly faster than yellow markings (Hummer et al. 2011; Sathyanarayanan et al. 2008; Sitzabee et al. 2009a).

### c) Road Geometry and Location Attributes

Location significantly affects $R_L$ degradation in all models (Table 14 and Table 15). Table 16 shows that urban areas have higher retroreflectivity degradation than rural areas, with odds ratios of 2.01, 2.59, 4.81, and 2.10 for the interstate, principal arterial, minor arterial, and major collector, respectively. The reason for higher degradation is likely due to higher traffic volume and different traffic patterns in urban areas, leading to more wear and tear on pavement markings. Although no previous research has investigated the effect of location on $R_L$ degradation, several studies recommended that future research consider both urban and rural locations (Hussein et al. 2020).

The pavement type (concrete or asphalt) is an important factor affecting $R_L$ degradation on Interstate and Principal arterial roads. However, no concrete pavement was tested on minor arterial and major collector roads. Table 16 indicates that concrete pavement is 2.07 and 1.51 times more prone to degradation than asphalt pavement on Interstate and Principal arterial roads, respectively. The reason for this higher degradation in concrete pavement is possibly due to its harder and more rough surface, which is more susceptible to wear and tear from weather and traffic. This finding is consistent with Thamizharasan et al. (2003), where authors reported that the epoxy-concrete linear model demonstrated a more significant decline compared to the thermoplastic-asphalt models.

The presence of horizontal curves (as opposed to straight sections) is a significant factor in all pavement marking retroreflectivity models (Table 14 and Table 15). Table 16 indicates that horizontal curve sections increase retroreflectivity degradation by 1.19, 1.52, 1.6, and 1.45 times for Interstate, Principal Arterial, Minor Arterial, and Major Collector roads, respectively, compared to straight sections. The degradation of pavement markings on curved sections is accelerated due to increased wear and tear caused by greater centrifugal forces on vehicles negotiating the curve, and it is also more likely to experience abrasion from drivers cutting corners. Notably, no prior studies have been conducted to investigate the $R_L$ degradation of various road configurations, including horizontal curves. Bahar et al. (2006) hypothesized that the primary factor for $R_L$ degradation is horizontal curve exposure.

### d) Traffic Condition Attributes

The Cumulative Traffic Passages (CTP) significantly impact the retroreflectivity degradation of pavement markings in principal arterial and minor arterial roads, with a 1.86 and 2.05 times higher reduction in retroreflectivity after every 10,000 vehicles pass, while the Cumulative Truck Traffic Passages (CTTP) do not affect retroreflectivity degradation and are excluded from the models (Table 14 and Table 15). Higher traffic volumes in principal and minor arterial roads accelerate the faster deterioration of pavement markings retroreflectivity. In contrast, traffic volume does not impact $R_L$ degradation in interstate and major collector roads, likely due to differences in pavement marking material, traffic volumes, navigations, and road conditions. Truck percent were found not to be associated with retroreflectivity degradation in prior studies (Sarasua et al. 2003; Thamizharasan et al. 2003). However, other studies reported that CTP significantly impacts pavement marking degradation over time (Abboud and Bowman 2002; Lindly and Wijesundera 2003).

**e) Winter Attributes**

The number of snow plowing days has been found to be a significant factor affecting pavement marking retroreflectivity in all models. The number of snowplowing days degraded $R_L$ by 12 percent, 5 percent, 15 percent, and 14 percent for the interstate, principal arterial, minor arterial, and major collector, respectively. The degradation rate in minor arterial and major collectors is very close, showing the impact of a snowplow on waterborne material and asphalt surface. These findings suggest that the variation in the results by functional classifications of roads may be due to differences in pavement marking material, pavement type, maintenance practices, etc.

### 5.6.3 Illustration of the Use of the Prediction Model through an Example

One potential application of the developed pavement marking prediction model is to predict pavement marking service life under various conditions. Additionally, the model provides users with the probability and odds ratio, which gives a level of confidence in determining the predicted service life.

The following assumptions were made to demonstrate an example application of the model: The location is rural, with asphalt pavement, straight section, white marking color, the line type is edge line, an epoxy material, and an average of four snowplowing days per month. Based on the model equation, Table 17 displays the predicted probability ($P_1$, $P_2$, $P_3$, $P_4$, and $P_5$) and odds ratio for pavement marking retroreflectivity staying at five different levels (Good, Pass, Marginal, Bad, Fail).

If the odds ratio is >1, the probability of staying at a higher $R_L$ level is greater than moving to a lower $R_L$ level. From Table 17, it can be seen that the assumed $R_L$ will likely stay at Level 1 (Good) for six months, at Level 2 or above (Good or Pass) for 11 months, and at Level 3 or above (above marginal level) for 17 months. After 25 months, it is predicted to be in the lowest category (fail). Figure 21 and Figure 22 also display the changes in the probability and odds ratio with time. It is important to note that if any of the assumptions change, the probability and odds ratio will change accordingly.

**Table 17. Predicted Probability and Odds - An Illustrative Example.**

| Marking age (months) | P1 | P2 | P3 | P4 | P5 | Odds of staying at Level 1 | Odds of staying at Level 2 or above | Odds of staying at Level 3 or above | Odds of staying at Level 4 or above |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.86 | 0.11 | 0.02 | 0.00 | 0.00 | 6.4 | 38.5 | 459.4 | 8,022.5 |
| 2 | 0.82 | 0.15 | 0.03 | 0.00 | 0.00 | 4.4 | 26.8 | 320.5 | 5,597.1 |
| 3 | 0.76 | 0.19 | 0.05 | 0.00 | 0.00 | 3.1 | 18.7 | 223.6 | 3,904.9 |
| 4 | 0.68 | 0.25 | 0.06 | 0.01 | 0.00 | 2.2 | 13.1 | 156.0 | 2,724.4 |
| 5 | 0.60 | 0.30 | 0.09 | 0.01 | 0.00 | 1.5 | 9.1 | 108.9 | 1,900.7 |
| 6 | 0.51 | 0.35 | 0.12 | 0.01 | 0.00 | 1.1 | 6.4 | 75.9 | 1,326.1 |
| 7 | 0.42 | 0.39 | 0.17 | 0.02 | 0.00 | 0.7 | 4.4 | 53.0 | 925.2 |
| 8 | 0.34 | 0.42 | 0.22 | 0.02 | 0.00 | 0.5 | 3.1 | 37.0 | 645.5 |
| 9 | 0.26 | 0.42 | 0.28 | 0.04 | 0.00 | 0.4 | 2.2 | 25.8 | 450.3 |
| 10 | 0.20 | 0.40 | 0.35 | 0.05 | 0.00 | 0.2 | 1.5 | 18.0 | 314.2 |
| 11 | 0.15 | 0.36 | 0.41 | 0.07 | 0.00 | 0.2 | 1.1 | 12.6 | 219.2 |
| 12 | 0.11 | 0.31 | 0.47 | 0.10 | 0.01 | 0.1 | 0.7 | 8.8 | 152.9 |
| 13 | 0.08 | 0.26 | 0.52 | 0.13 | 0.01 | 0.1 | 0.5 | 6.1 | 106.7 |
| 14 | 0.06 | 0.21 | 0.55 | 0.18 | 0.01 | 0.1 | 0.4 | 4.3 | 74.4 |
| 15 | 0.04 | 0.16 | 0.55 | 0.23 | 0.02 | 0.0 | 0.2 | 3.0 | 51.9 |
| 16 | 0.03 | 0.12 | 0.53 | 0.30 | 0.03 | 0.0 | 0.2 | 2.1 | 36.2 |
| 17 | 0.02 | 0.09 | 0.48 | 0.37 | 0.04 | 0.0 | 0.1 | 1.4 | 25.3 |
| 18 | 0.01 | 0.06 | 0.42 | 0.44 | 0.05 | 0.0 | 0.1 | 1.0 | 17.6 |
| 19 | 0.01 | 0.05 | 0.36 | 0.51 | 0.08 | 0.0 | 0.1 | 0.7 | 12.3 |
| 20 | 0.01 | 0.03 | 0.29 | 0.57 | 0.10 | 0.0 | 0.0 | 0.5 | 8.6 |
| 21 | 0.00 | 0.02 | 0.23 | 0.60 | 0.14 | 0.0 | 0.0 | 0.3 | 6.0 |
| 22 | 0.00 | 0.02 | 0.17 | 0.61 | 0.19 | 0.0 | 0.0 | 0.2 | 4.2 |
| 23 | 0.00 | 0.01 | 0.13 | 0.60 | 0.26 | 0.0 | 0.0 | 0.2 | 2.9 |
| 24 | 0.00 | 0.01 | 0.09 | 0.57 | 0.33 | 0.0 | 0.0 | 0.1 | 2.0 |
| 25 | 0.00 | 0.01 | 0.07 | 0.51 | 0.41 | 0.0 | 0.0 | 0.1 | 1.4 |
| 26 | 0.00 | 0.00 | 0.05 | 0.44 | 0.50 | 0.0 | 0.0 | 0.1 | 1.0 |
| 27 | 0.00 | 0.00 | 0.03 | 0.37 | 0.59 | 0.0 | 0.0 | 0.0 | 0.7 |
| 28 | 0.00 | 0.00 | 0.02 | 0.30 | 0.67 | 0.0 | 0.0 | 0.0 | 0.5 |
| 29 | 0.00 | 0.00 | 0.02 | 0.23 | 0.75 | 0.0 | 0.0 | 0.0 | 0.3 |
| 30 | 0.00 | 0.00 | 0.01 | 0.18 | 0.81 | 0.0 | 0.0 | 0.0 | 0.2 |

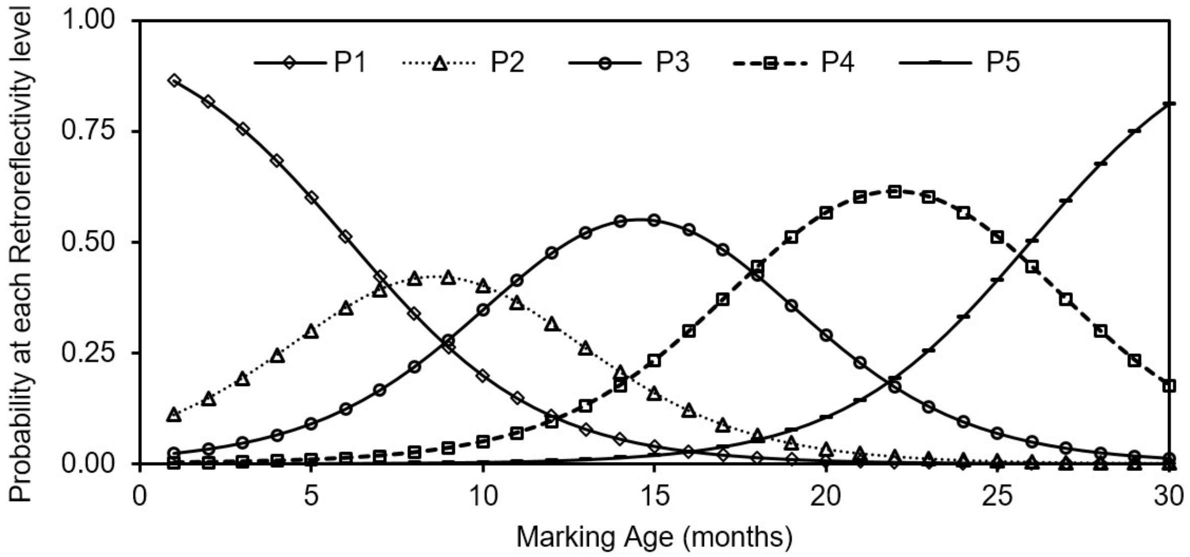



**Figure 21. Graph. Predicted Probability with Marking Age for The Five Levels of Pavement Marking Retroreflectivity.**

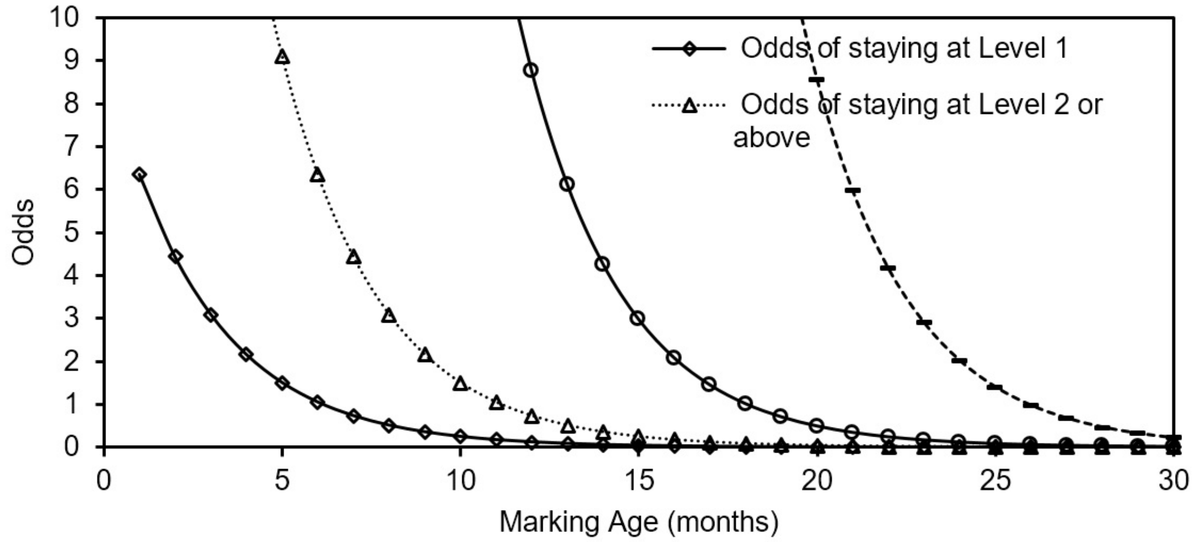



**Figure 22. Graph. Change of Predicted Odds with Marking Age.**

### 5.6.4 Service Life Estimation

The range of predicted service life of $R_L$ on various highways was calculated, considering different marking materials and line types, using Equations 18-21. The results are summarized in

Table 18. It is important to note that the model and service life estimated in this study are specific to the marking characteristics, materials, and road conditions.

**Table 18. Summary of Pavement Marking Retroreflectivity Service Life by Different Category.**

| Functional Classification | Marking Material | Line Type | Range of estimated service life (Months) |
|---|---|---|---|
| Interstate | Polyurea | White edge line | 17-22 |
| | | White lane line | 17-21 |
| | | Yellow edge line | 23-27 |
| | Epoxy | White edge line | 13-19 |
| | | White lane line | 13-16 |
| | | Yellow edge line | 20-26 |
| | Waterborne | White edge line | 11-18 |
| | | White lane line | 10-16 |
| | | Yellow edge line | 18-24 |
| Principal Arterial | Epoxy | White edge line | 24-29 |
| | | White lane line | 21-26 |
| | | Yellow center line | 23-27 |
| | Waterborne | White edge line | 17-21 |
| | | White lane line | 14-18 |
| | | Yellow center line | 17-20 |
| Minor Arterial | Waterborne | White edge line | 13-26 |
| | | Yellow center line | 9-16 |
| Major Collector | Waterborne | White edge line | 12-14 |
| | | Yellow center line | 9-12 |

The service life of Epoxy and Waterborne markings differs across highway functional classification, with Epoxy markings having longer lifespans on principal arterials than on interstate highways. In contrast, Waterborne markings show significant differences in service life among principal arterials, minor arterials and major collectors, which may be affected by pavement condition, distress, and maintenance factors. Although minor arterials and major collectors were expected to have longer-lasting markings due to lower traffic volume and snowplow operations, further research is needed to identify the reasons for these variations to optimize maintenance strategies and ensure road safety.

### 5.7 Chapter Summary

Ensuring road safety is of utmost importance, and maintaining pavement markings with sufficient retroreflectivity is a key factor in achieving this goal. Accurate prediction of retroreflectivity and service life determination is essential for optimizing maintenance efforts. This study provides valuable insights into the degradation process of pavement markings and their retroreflectivity levels over time. The use of Bayesian-ordered logit models and the No-U-Turn Hamiltonian Monte Carlo technique allowed for accurate prediction of retroreflectivity levels and service life determination, while the inclusion of random intercepts in the modeling procedure revealed unobserved heterogeneity due to the variation of $R_L$ levels within-county. These findings have significant implications for highway agencies, as they can use this information to prioritize their maintenance efforts and optimize retroreflectivity operations, ultimately contributing to enhanced road safety for all users.

Furthermore, this study highlights the significance of considering various factors that impact pavement marking retroreflectivity degradation rates, such as marking characteristics, geometric locations, pavement surface, traffic flow, and snowplow operations. The results indicate that urban roads and travel path markings (middle line) are more prone to degradation and that the degradation rate is higher for white markings in interstate and principal arterial highways but the opposite for minor arterial and major collector highways. Additionally, the higher pavement marking retroreflectivity decreasing trend observed at horizontal curves is possibly due to the additional wear and tear caused by the wandering of vehicles. These insights can inform the selection of pavement marking materials and application methods to ensure longer-lasting retroreflectivity and more efficient maintenance.

In addition to the degradation model, the probability of monitored pavement markings transitioning from one service life level to another was estimated by considering five levels of $R_L$. The $R_L$ degradation followed a nonlinear trend, with degradation rates decreasing as time increased. Furthermore, by setting the minimum marginal retroreflectivity levels at 125 and 100 mcd/m$^2$/lux for white and yellow markings, respectively, it was found that the service life of white and yellow markings differs based on road classification, marking material, and line position.

# CHAPTER 6: PAVEMENT MARKING MANAGEMENT SYSTEM (PMMS) BASED ON THE EXPERIENCES OF THE STATE DEPARTMENT OF TRANSPORTATION

## 6.1 Introduction

Pavement Marking Management System (PMMS) is a key component of Pavement Marking Management Plan (PMMP). PMMS consolidates data and processes, providing a comprehensive framework for efficiently managing pavement markings across diverse agency practices. To successfully develop and implement a Pavement Marking Management System (PMMS), several factors, such as data collection guidelines, marking application strategy, performance curves, data mapping and visualization tools, and operations planning, need careful consideration. However, establishing a consistent PMMS is challenging due to the existence of diverse management practices, site characteristics, and materials used among different agencies. In addition to these challenges, new machine vision vehicle technologies have introduced further complexities in managing pavement markings. Existing standards primarily serve human road users and may not effectively address the needs of machine vision systems. Therefore, exploring and documenting pavement marking practices across different states is important for developing a comprehensive pavement management system. So, the Wyoming Technology Transfer Center (WYT2C) performed a nationwide survey. The survey was designed to gather valuable insights and information from various sources, aiding in the formulation of effective strategies for managing pavement markings. The survey collected information on the pavement marking strategy, including marking material selection, data collection, restriping, and retroreflectivity standards from various state Departments of Transportation (DOTs). The survey included the option for adding comments and provided some open-ended questions so respondents could provide recommendations to improve the quality of pavement marking. The results of this survey offer insights into the evaluation of pavement marking management practices at a national level.

## 6.2 Methodology

The survey on pavement marking management was conducted by sending it to representatives from all state DOTs, who then forwarded it to the appropriate individuals. Feedback was received from twenty-nine state DOTs, and these states are highlighted on the map displayed in Figure 23. According to the 2019 Highway Statistics, the participating state DOTs collectively own approximately 2.7 million miles (4.4 million kilometers) of roads, which accounts for almost 65 percent of the entire U.S. Road network (Highway Statistics 2019). Additionally, the participating states represent a diverse range of agencies with distinct goals and resources, and these states are situated in different climate zones. Consequently, the survey results are expected to provide valuable insights into pavement marking practices and related programs, leading to multiple recommendations.

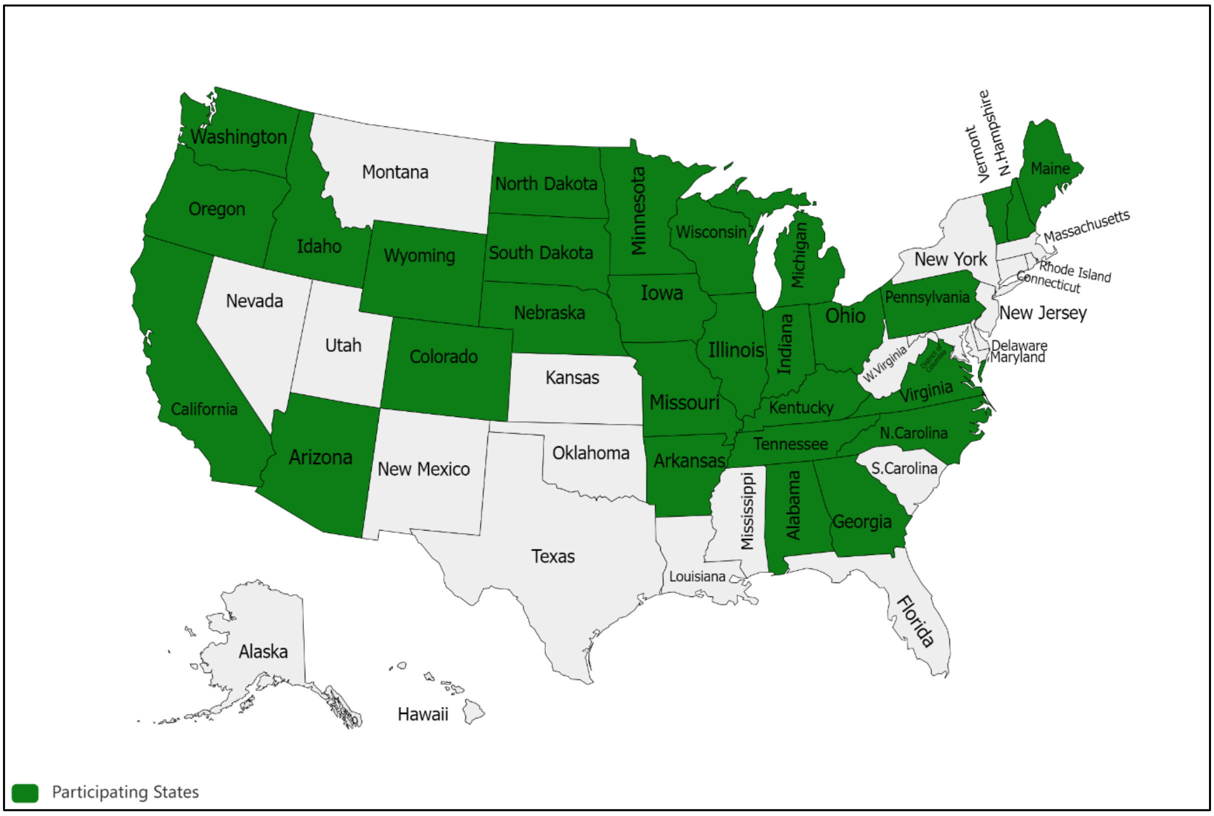



**Figure 23. Map. Participating States in the Pavement Marking Management System (PMMS) Survey (source of base map: https://freevectormaps.com/united-states/US-PPT-02-0002?ref=atr and then altered to fit to the context)**

The responses gathered from the survey questionnaire will be discussed in the following subsections.

## 6.3 Survey Results

### 6.3.1 Criteria for Selecting Pavement Marking Material

When selecting pavement marking material, several criteria come into play to ensure the best choice for meeting public needs. Each state DOT responded to several criteria related to pavement marking material selection criteria for the survey question. As shown in Figure 24, the five primary criteria most considered by DOTs are durability, maintenance cost, price, ease of striping, and traffic volume. However, different DOTs prioritized other criteria, such as road classification, snowplowing, location, line type, history of nighttime crashes, and regional plan.

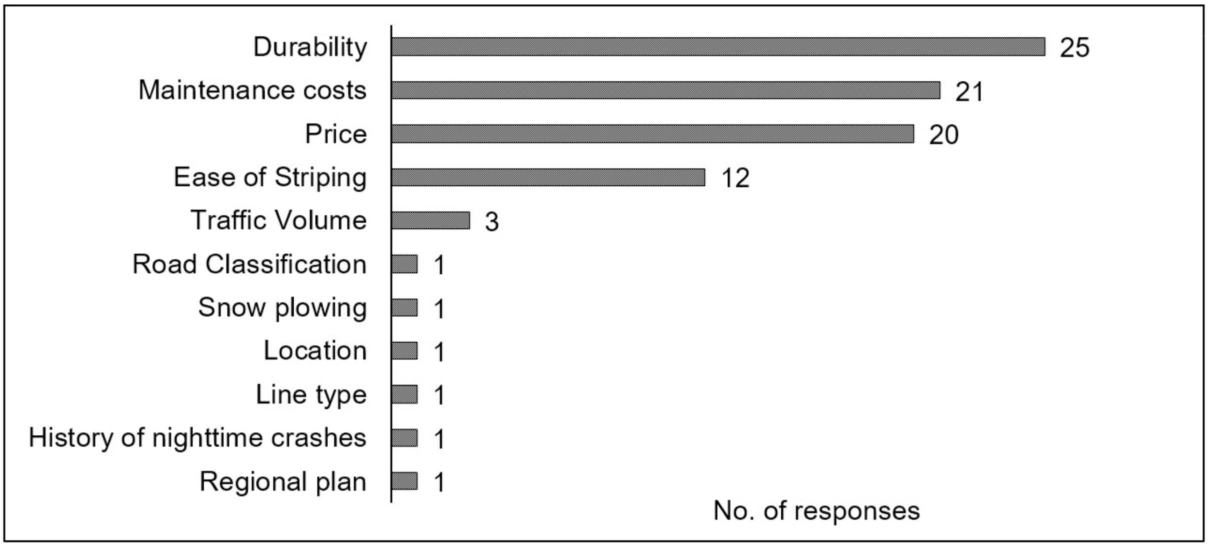



**Figure 24. Chart. Pavement Marking Material Selection Criteria.**

### 6.3.2 Pavement Marking Materials used by different DOTs

A wide range of pavement marking materials are available in the market. So, choosing a cost-effective material for a specific road classification is sometime challenging. Based on the survey responses, it was found that most of the state DOTs use various materials to strip different roads. Figure 25 shows that among all those materials, tape emerged as the most used material on the interstates compared to other materials. On the other hand, water-based paint was found to be the most used material for rural principal arterials, rural minor arterials, rural major collectors, and rural minor collectors. Notably, thermoplastic was the second most used material for all functional classifications of roads. Epoxy-based paint, polyurea, and Methyl Methacrylate (MMA) are also used in all functional classifications of roads. In each functional classification, some responses fell under the "other" category. These responses highlighted special conditions and unique applications of pavement markings. Some of these special conditions included the use of sprayable thermoplastic, tape for intersection turn lane markings, crosshatch markings, turn arrows, and the application of polyurea on new and concrete pavements.

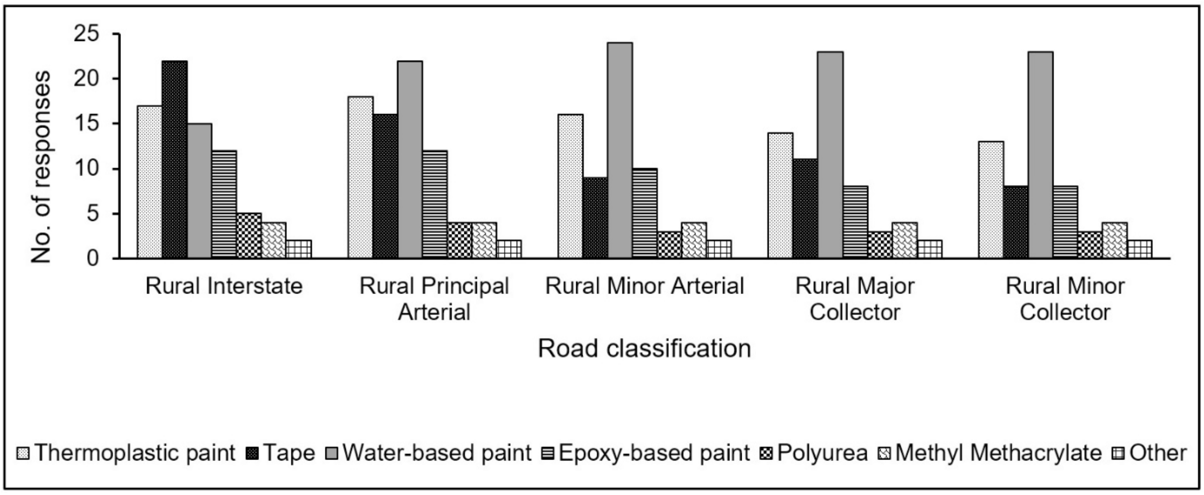



**Figure 25. Chart. Pavement Marking Material used in Different Road Systems by different DOTs.**

High traffic volume, truck traffic, and snowplow operation degrade pavement marking faster. So, using more durable materials in those locations is a common strategy. It was a survey question to DOTs about their strategy for material selection in those more degradation-prone locations. Figure 26 shows the survey responses, and it is found that most DOTs have a strategy for using more durable marking material in locations of high traffic and high truck traffic. In addition, among the total twenty-nine responses, fourteen responded positively about using more durable marking material on roads with frequent snowplows.

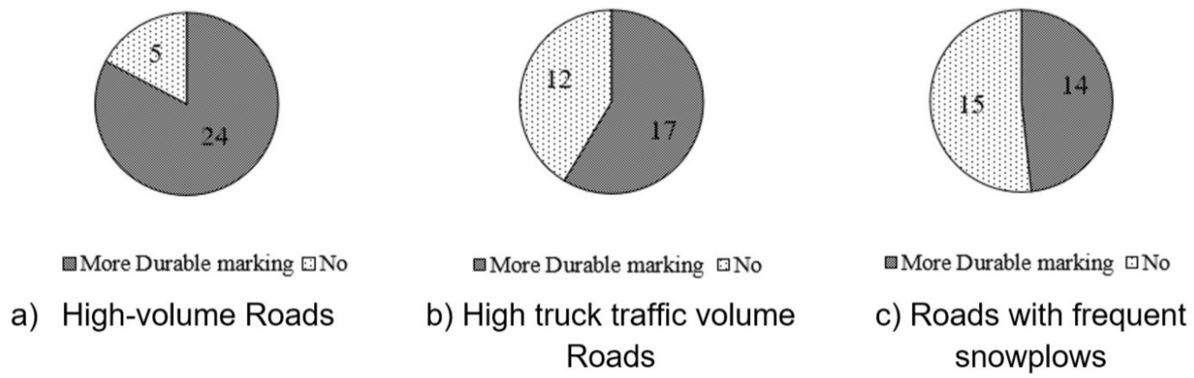



**Figure 26. Chart. Use of More Durable Marking Material in more Degradation-Prone Locations.**

### 6.3.3 Pavement Marking Retroreflectivity Data Collection

Past studies (Carlson et al. 2010; Malyuta 2015; Masliah et al. 2007; Pike 2009) used handheld retroreflectometer and Laserlux mobile retroreflectometer for the retroreflectivity data collection. Based on the survey response of twenty-nine DOT, twenty-eight DOT responded regarding this question, and it was found that fourteen DOT reported using both Handheld and Vehicle mounted retroreflectometers, and eleven DOTs indicated solely relying on handheld retroreflectometers. Among these eleven responses, one DOT added a comment that they have handheld retroreflectometers for occasional data collection. Two DOTs mentioned others and revealed that they have handheld retroreflectometer, but retroreflectivity data collection and evaluation of longitudinal pavement marking is done by a contract company equipped with a Mobile Retroreflectivity Unit (MRU).

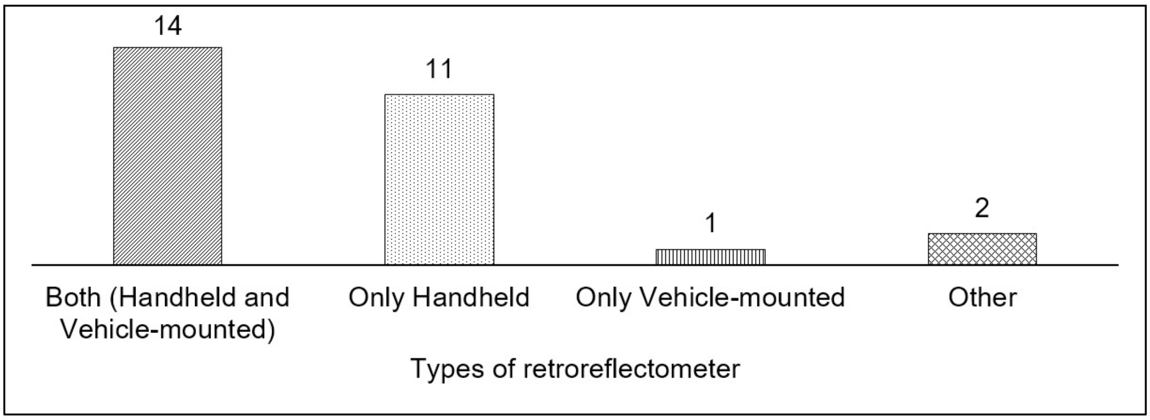



**Figure 27. Chart. Types of Retroreflectometer Used by Different DOTs.**

In the survey, DOTs were questioned regarding their pavement marking retroreflectivity data collection frequency. The responses showed that the majority of DOTs collect retroreflectivity data on an annual basis. However, eight DOTs stated that they did not collect pavement marking retroreflectivity quality data. These DOTs provided comments indicating that they evaluate the retroreflectivity manually or follow different restriping frequencies for various types of marking. Six DOTs collected retroreflectivity data for interstate roads as needed, and seven DOTs did the same for other functional classifications of roads. Additionally, two DOTs specified that they gather retroreflectivity data after the installation of markings to ensure their quality and justify the payment.

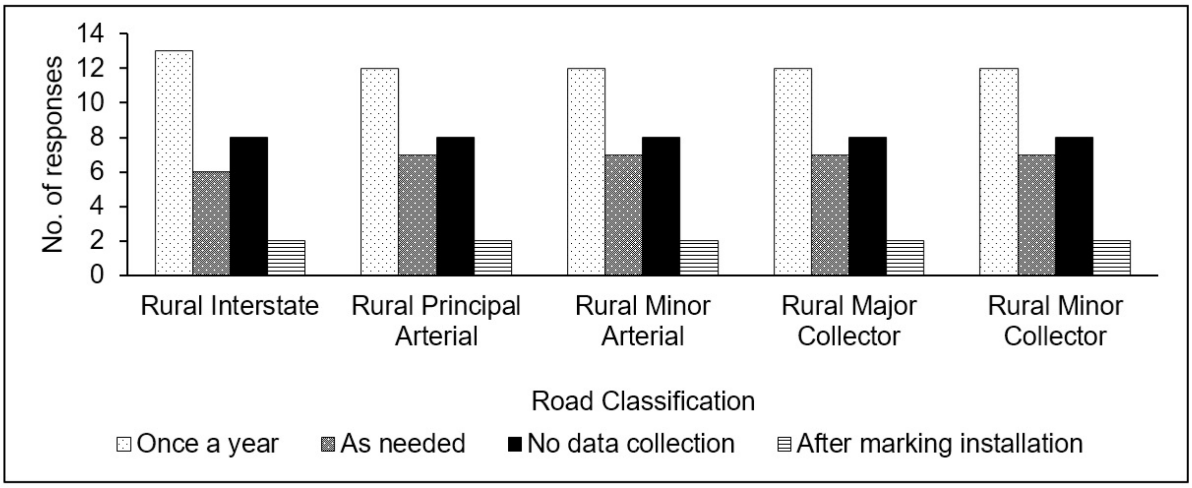



**Figure 28. Chart. Pavement Marking Retroreflectivity Data Collection Frequency.**

There were several other questions regarding Pavement marking retroreflectivity (PMR) data collection, Skid resistance data collection, performance curve based on PMR data, and pavement marking management database. The responses are presented in Figure 29. It was found that only four state DOTs (Georgia, Kentucky, Missouri, and North Carolina) developed performance curves based on the collected retroreflectivity data. Additionally, eight DOTs possessed a fully-fledged pavement marking management database that was updated on a regular basis and accessible by its personnel. Only one DOT (Indiana DOT) collected the skid resistance of pavement marking. Ten DOTs mentioned that they collect data immediately after applying pavement marking, and most DOTs collected retroreflectivity data in both travel directions of the roads. Only one DOT mentioned that they collect night-time retroreflectivity data during the wet condition, and One DOT prioritized more frequent retroreflectivity data collection on roads with higher traffic volumes. Surprisingly, no DOT responded affirmatively regarding more frequent data collection for roads with higher truck traffic volumes or more frequent snowplow locations.

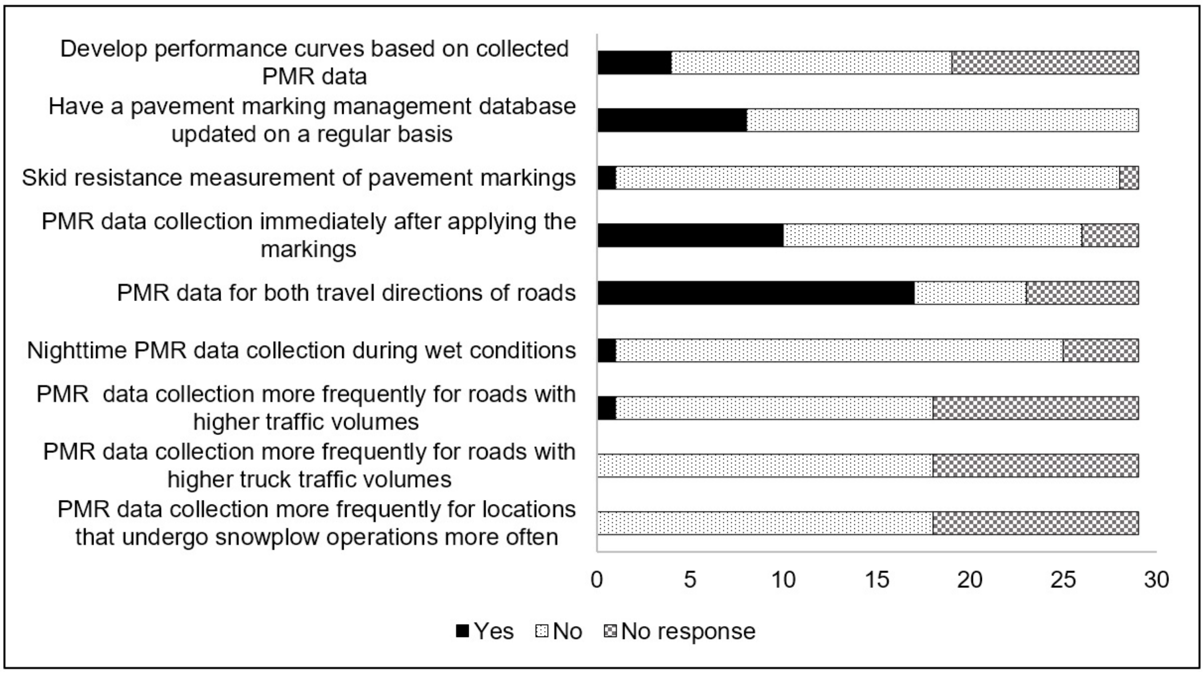



**Figure 29. Chart. Miscellaneous Questions regarding Data Collection and Database Management.**

### 6.3.4 Pavement Marking Restriping Strategy and Minimum Retroreflectivity Level for Restriping

A well-planned pavement marking restriping strategy is essential for the cost-effective pavement marking management system. From the survey responses shown in Figure 30, it was found that for each road facility, most DOTs responded that their restriping strategy is "as needed," which depends on material type and traffic volume. The second most reported restriping strategy was the annual restriping approach. Few DOTs also responded for Semi-annual, once every year and a half, and Bi-annual restriping.

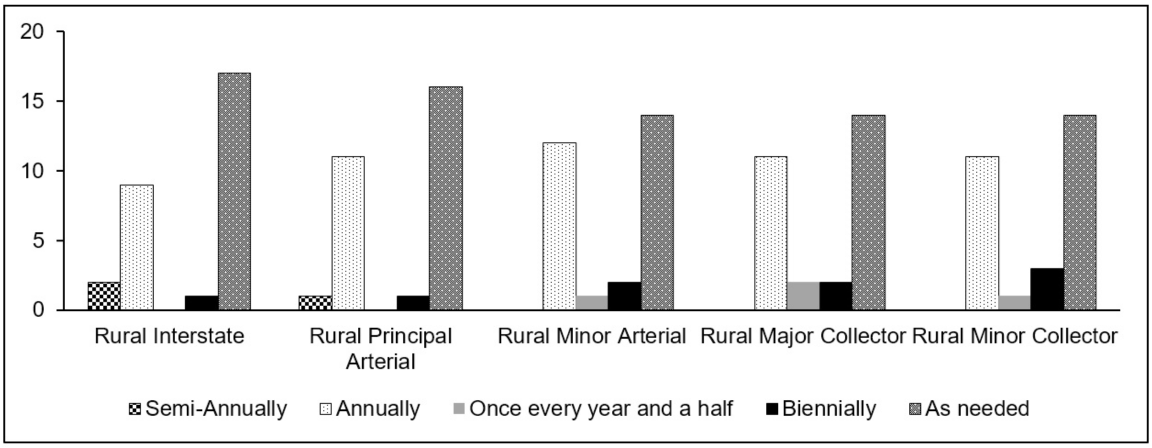



**Figure 30. Chart. Pavement Marking Restriping Strategy For different Road Systems by DOTs.**

The findings emphasize the need for a more thorough investigation into the specific pavement marking materials used and the corresponding restriping strategies. For each functional classification, DOTs mentioned various materials for different restriping strategies. However, in the case of a restriping strategy of once every year and a half, waterborne paint was exclusively used in the rural minor arterial, rural major collector, and rural minor collectors. Figure 31 presents the approximate minimum restriping intervals adopted by DOTs for various material types on the interstate. Two DOTs mentioned a restriping interval of 0.5 years, with one exclusively using water-based paint and the other using both epoxy-based and water-based paint. Most DOTs specified a restriping interval of one year for water-based paint, surpassing other materials. Only tape and thermoplastic were used for a restriping interval of four years.

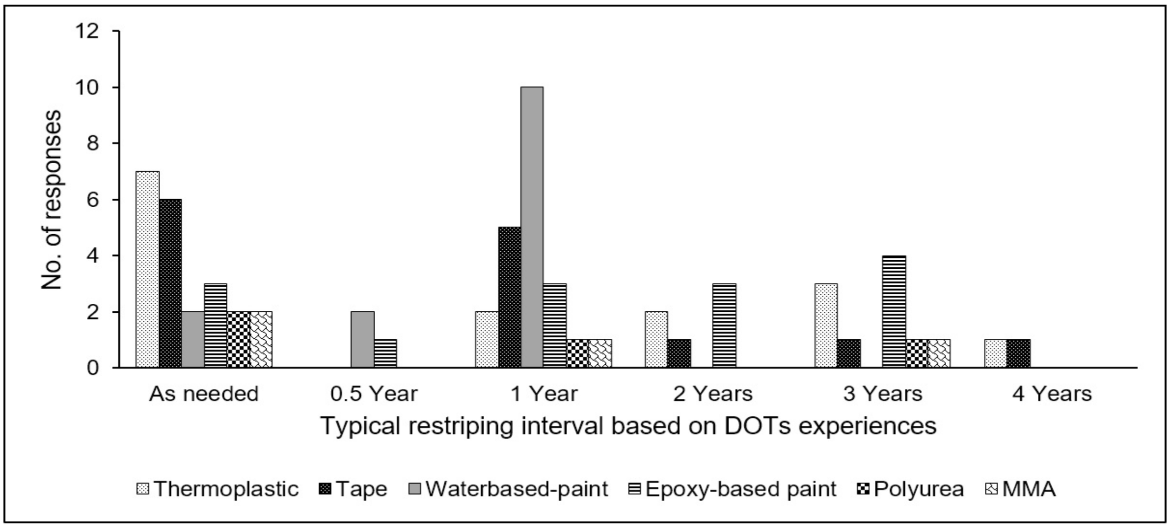



**Figure 31. Chart. Typical Restriping Interval in Rural Interstate Based on DOTs Experiences.**

In addition to restriping intervals, several DOTs commented on the typical service life of different materials based on their experiences. These comments have been summarized in Table 19, presenting a range of approximate service life values.

**Table 19. Range of Service Lives of Different Materials Based on the Experiences of DOTs.**

| Marking Material | Range of Service life (Years) based on the experiences of DOTs |
|---|---|
| Thermoplastic | 1-5 |
| Tape | 1-10 |
| Water-based paint | 0.5-2 |
| Epoxy-based paint | 1-3 |
| Polyurea | 1-3 |
| MMA | 1-3 |
| Raised pavement marking | 1.5-2 |
| Grooved durable marking | 7-10 |
| High build paint | 5-6 |

Among the responses from the twenty-nine DOTs, nineteen DOTs responded to the question regarding the minimum retroreflectivity levels required for pavement marking maintenance. Figure 32 illustrates the responses obtained, revealing that a majority of DOTs indicated that they do not currently conduct maintenance based on retroreflectivity values and responded as not applicable. Interestingly, variations in the minimum retroreflectivity levels were reported for white and yellow line markings. For white lines, the reported levels ranged from 100 to 375 mcd/m$^2$/lux, with the highest response being for a level of 150 mcd/m$^2$/lux (three DOTs). In the case of yellow markings, the reported levels ranged from 100 to 250, with the highest response recorded for a level of 100 mcd/m$^2$/lux (four DOTs).

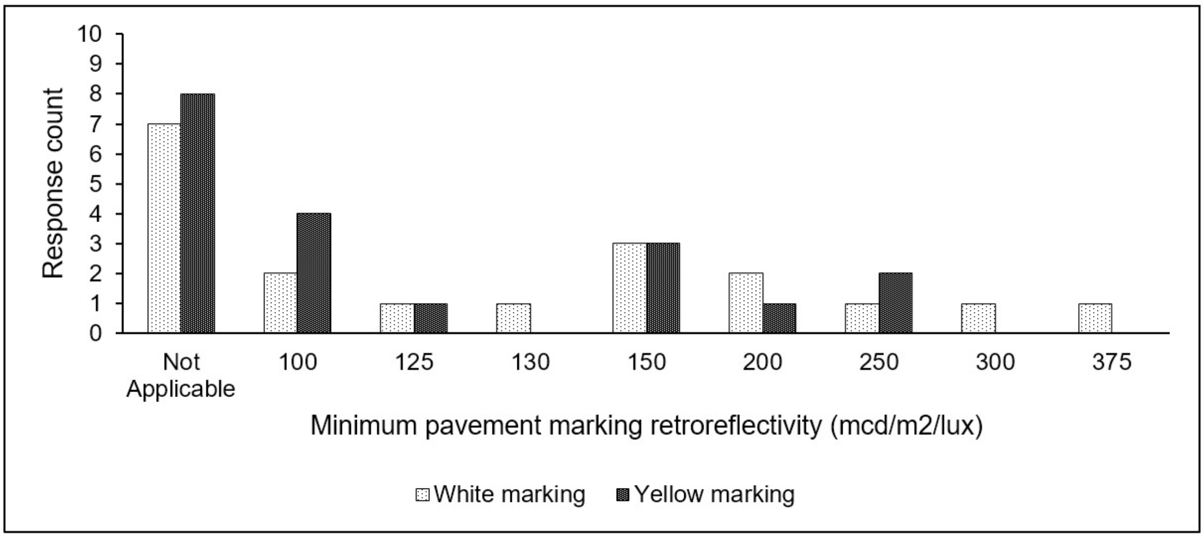



**Figure 32. Chart. Minimum Pavement Marking Retroreflectivity Level used by different DOTs for Restriping.**

Most DOT's responses were different for the white and yellow markings. For example, Arizona state DOT mentioned a minimum pavement marking retroreflectivity level of 200 mcd/m$^2$/lux for white lines of two-lane highways with posted speed limits that are 55 mph or greater and 250 mcd/m$^2$/lux for yellow lines of all roads with posted speed limits that are 55 mph or greater. To gain a comprehensive understanding, it would be reasonable to present the individual responses from each DOT for white and yellow pavement markings, summarized in Table 20.

**Table 20. Minimum Pavement Marking Retroreflectivity Level Used by Different DOTs for Restriping.**

| Agency | Minimum Retroreflectivity (mcd/m$^2$/lux) | |
|---|---|---|
| | White | Yellow |
| Arizona | 200* | 250* |
| California | 150 | 150 |
| Colorado | 125 | 100 |
| Georgia | 150 | 150 |
| Indiana | 130 | NA |
| Maine | 250 | 100 |
| Minnesota | 100 | 100 |
| Missouri | 150 | 125 |
| New Hampshire | 200 | 150 |
| North Carolina | 375 | 250 |
| Tennessee | 300 | 200 |
| Washington | 100 | 100 |

*Conditional with posted speed limits 55 mph or greater

### 6.3.5 Pavement Marking Management Practices based on the Pavement Surface Type

In the survey question asking DOTs about the differences in pavement marking management practices based on the roadway surface type, Eighteen DOT indicated that there are indeed differences, while seven responded that there are no differences. Valuable comments regarding pavement marking applications on various pavement types accompanied these positive responses. The DOTs practices and recommendations are summarized in the following section.

#### a) Practices and Recommendations for Pavement Surface Type

1. Delay the application of pavement markings on newly placed Hot Mix Asphalt (HMA).

2. Prioritize higher-quality markings on concrete pavement. Tape and epoxy can be considered for marking concrete surfaces, while it is recommended to avoid thermoplastic on concrete.
3. Contrast markings are recommended on high-traffic concrete pavements.
4. Robust, grooved markings can be installed on their higher ADT routes (typically concrete interstates, truck bypasses, and local routes) for longer service life without maintenance operations. On new or higher volume asphalt roadways, they still try to groove and install durables whenever higher performance is warranted.

**b) Practices and Recommendations for Surface Treatments**

1. For open-graded asphalts and chip seals, using a thick layer of durable materials like polyurea or paint coatings is recommended while avoiding using tape.
2. Increase application rates for certain open surface textures and decrease rates for re-application over existing markings.
3. Grooving should be avoided on the micro surface.
4. Roadway surface with rough texture might require additional applications of waterborne paint. Waterborne paint can be considered for deteriorated edge conditions.
5. Match pavement markings with seal coat maintenance schedules for asphalt roadways. For example, asphalt roadways typically receive seal coats every 7-10 years, and the corresponding pavement markings should fit well with that schedule.
6. When working on seal coats, cape seals, and micro seals, it is recommended to use alternative marking materials specifically designed for these surfaces due to the challenges they pose for normal marking materials. Applying two coats of paint with separated by a month is effective for low-volume roads, while for higher-volume roads, two coats of higher-type liquid markings should work better.

### 6.3.6 Practices for Pavement Markings covered by Crack Seals

Crack sealing can result in uneven surfaces or overspill onto the pavement markings, leading to reduced visibility, as seen in Figure 33.

**Figure 33. Photo. Crack Sealing on Pavement Marking.**

According to the survey responses, most DOTs adopted different practices when it came to marking crack sealing, while a few DOTs did not have specific practices for it. Common practices and recommendations were derived from their feedback, and they are summarized as follows:

1. Restriping is typically carried out after crack sealing, considering the marking loss and retroreflectivity values of the markings.
2. Unless crack sealing has severely compromised the markings, restriping is usually scheduled for the following year as part of regular maintenance operations. Immediate restriping is attempted in cases of significant deterioration.
3. Crack seal details are designed to minimize excess sealer material on the road surface, thereby reducing the impact on marking visibility.
4. It is advisable to coordinate restriping efforts with maintenance forces or integrate striping into crack seal projects.
5. Restriping tasks are often handled by district field teams on an ad-hoc basis.

#### 6.3.7 Pavement Marking Practices that accommodate Vehicles with Machine Vision Technologies

The National Committee on Uniform Traffic Control Devices (NCUTCD) provides suggestions to the FHWA for amendments to the MUTCD. Recommendations include wider longitudinal pavement markings of 6” for expressways, freeways, and their connecting ramps. For non-freeways with speed limits of 55 mph or higher and average daily traffic volumes of 6,000 vehicles or more, edge lines should also be 6 inches wide to facilitate machine vision systems in recognizing pavement markings (NCUTCD, 2020). So, the most critical recommendation for MV vehicles is that longitudinal markings, including edge lines, centerlines, and lane lines, be 6 in, which is 2 in wider than that used by the Wyoming Department of Transportation (WYDOT Traffic Program, 2012).

The survey collected feedback regarding implementing wider (6") pavement markings to accommodate vehicles with machine vision technologies. The results in Figure 34 indicate that twelve DOTs (Arizona, Arkansas, California, Colorado, Georgia, Iowa, Maine, Michigan, Nebraska, New Hampshire, Ohio, and Tennessee) out of the twenty-nine DOTs are currently implementing wider pavement markings.

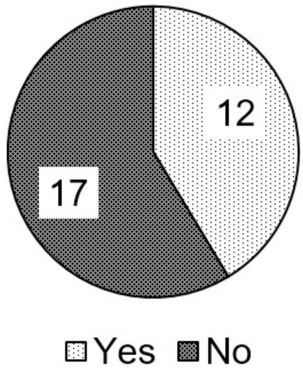



**Figure 34. Chart. Implementation of the suggestion of NCUTCD regarding Wider (6”) Pavement Marking that accommodate vehicles with machine vision technologies.**

### 6.3.8 Use of Contrast Marking

When black edge lines are provided alongside other markings, it is considered a form of contrast marking. Seven types of contrast marking are available in the United States of America, as shown in Figure 35.

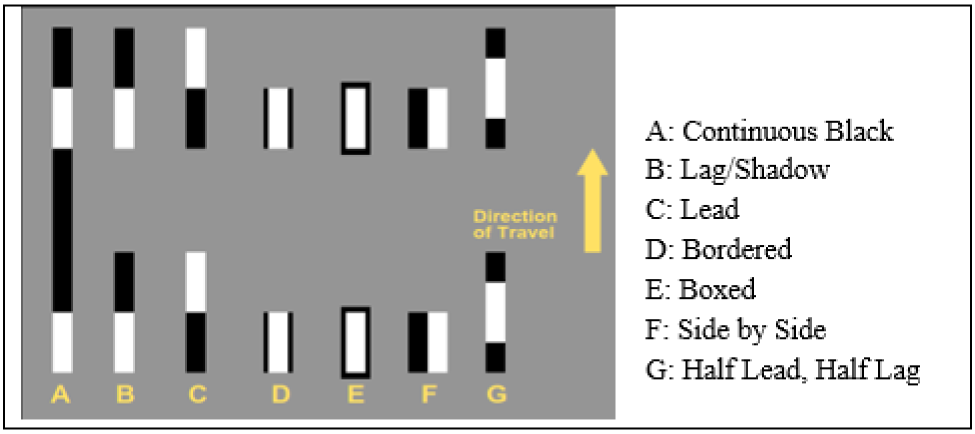



**Figure 35. Illustration. Contrast Marking Pattern in the United States of America (Carlson et al. 2007).**

The survey included a question regarding contrast pavement marking with black edges. As shown in Figure 36, the results revealed that five DOTs indicated that they implemented non-contrast pavement marking. On the other hand, twenty-four DOTs confirmed that they considered contrast marking. This result suggests a prevalent trend among DOTs to implement contrast marking to improve the visibility and contrast ratio of the pavement marking.

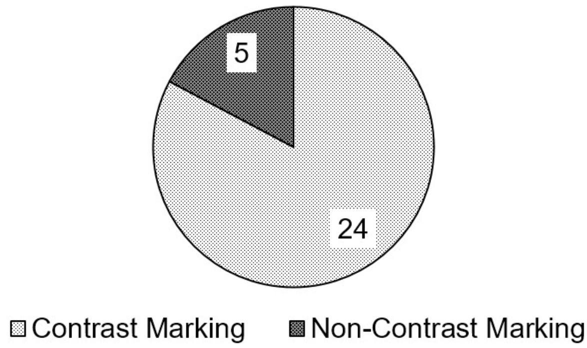



**Figure 36. Chart. Contrast Marking Usage in Different Departments of Transportation.**

The Alliance of Automobile Manufacturers recommended using white and black markings on concrete pavements to enhance contrast (National Committee on Uniform Traffic Control Devices Task Force 2019). Therefore, another survey involving twenty-eight DOTs regarding contrast marking on Portland Cement Concrete Pavement (PCCP) was conducted. As shown in

Figure 37, the results revealed that two DOTs exclusively indicated that they implemented non-contrast marking on PCCP. On the other hand, eight DOTs confirmed that they solely employed contrast marking for this purpose. Interestingly, most respondents, sixteen DOTs in total, reported utilizing a combination of both contrast and non-contrast marking on PCCP. This result suggests a prevalent trend among DOTs to implement a contrast marking on PCCP. In addition to these responses, two DOTs specified that they did not utilize any form of contrast or non-contrast marking, and this was due to the absence of PCCP surfaces.

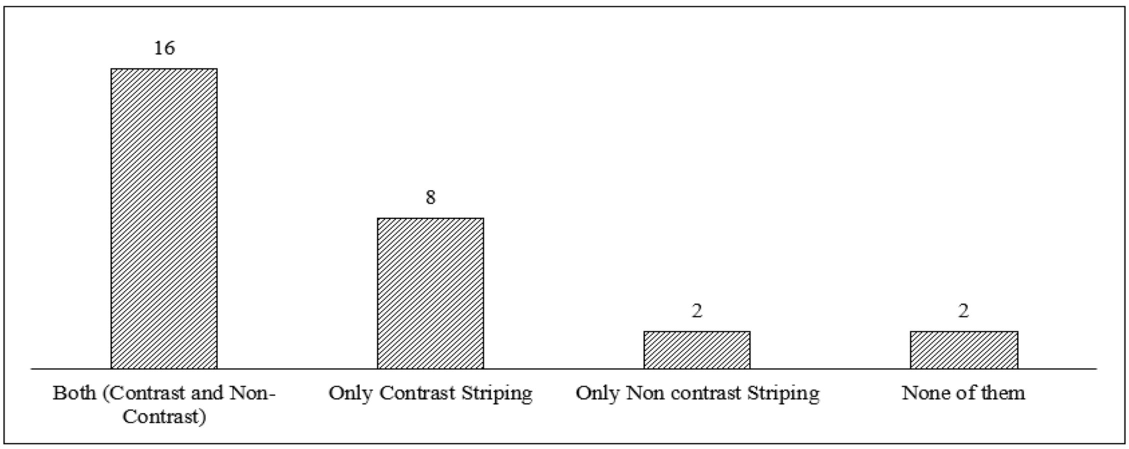



**Figure 37. Chart. Contrast Marking on PCCP in Different Departments of Transportation.**

There are many different designs of contrast pavement markings. The survey included seven different designs that are known to have been used in the past (Figure 35). Table 21 indicates the designs that are in use by different states. Type: D- Bordered marking is most used as the easiest of the contrast marking designs to implement and maintain. Type B is the second most used contrast marking.

**Table 21. Design Used for the Contrast Marking on PCCP.**

| Marking Design | Number of States | Percentage |
|---|---|---|
| A | 1 | 3 |
| B | 12 | 30 |
| C | 4 | 10 |
| D | 19 | 48 |
| E | 3 | 8 |
| F | 1 | 3 |
| G | 0 | 0 |

Survey results indicated that, by far, tape is the most commonly used contrast marking material. Survey responses regarding the usage of different materials for contrast marking on PCCP is summarized in Table 22.

**Table 22. Material Used for the Contrast Marking on PCCP.**

| Material used for Contrast Marking | Number of States | Percentage |
|---|---|---|
| Tape | 10 | 25 |
| Epoxy | 6 | 15 |
| Paint | 4 | 10 |
| Polyurea | 4 | 10 |
| Preformed plastic | 3 | 8 |
| MMA | 1 | 3 |
| Waterborne | 1 | 3 |
| Modified urethane | 1 | 3 |
| Grooved contrast wet reflective epoxy | 1 | 3 |
| Grooved contrast permanent epoxy | 1 | 3 |

### 6.4 Chapter Summary

These findings provide insights for transportation agencies across the nation, offering information on pavement marking management practices, pavement marking retroreflectivity data collection, implementation of updated standards for pavement marking, etc. The survey results have been summarized below based on responses from twenty-nine states of the Department of Transportation (DOTs).

1. Durability was the primary criterion for selecting pavement marking materials, with the other four most important factors such as maintenance cost, price, ease of striping, and traffic volume.
2. Tape was commonly used for rural interstates, while water-based paints were preferred for other facilities. High-volume roads and roads with heavy truck traffic were prioritized for the use of more durable pavement marking materials. Several DOTs also considered using durable markings in areas with frequent snowplow operations.
3. Hand-held and vehicle-mounted retroreflectometers were the primary tools for collecting retroreflectivity data. Some DOTs used only hand-held or vehicle-mounted devices, while others outsourced data collection to companies equipped with hand-held devices.
4. Most DOTs collected pavement marking quality data once a year, while some collected data as needed or after marking installation. Some DOTs did not collect retroreflectivity data but determined restriping frequency based on expected service life.
5. Annual restriping of roadway facilities was common, with the choice of restriping based on marking material type and service life. Water-based paint was the most used material for annual restriping. Grooved, durable marking and high-build paint were also mentioned for longer service life.
6. Recommendations were made for specific pavement types, such as using more durable materials for concrete and high-volume asphalt pavements. Delaying pavement marking application on newly placed Hot Mix Asphalt (HMA) was also suggested.
7. For locations with open-graded asphalt, chip seals, and crack seals, recommendations included using thick layers of durable materials like polyurea or paint coatings. The use of tape was discouraged for open-graded asphalt and chip seals.
8. Twelve DOTs among twenty-nine DOTs are following NCUTCD s recommendation regarding wide (6”) pavement marking to accommodate vehicles with machine vision technologies.
9. Most DOTs use contrast markings (markings with black edges) following the recommendations for accommodating machine vision technologies. Among the survey respondents, it was found that tape is the most commonly used material for contrast marking on PCCP (Portland Cement Concrete Pavement). Additionally, Design B (Boardered contrast marking) was the preferred design choice.

# CHAPTER 7: DEVELOPING A TEMPLATE FOR PAVEMENT MARKING MANAGEMENT PLAN FOR WYOMING

## 7.1 Introduction

This chapter focuses on developing a template for Wyoming's comprehensive pavement marking management plan (PMMP), optimizing resource utilization, and incorporating the latest standards and machine vision systems. Following the principles from the Transportation Asset Management Plan (TAMP-2018), the aim is to establish a template encompassing inventory assessment, objectives, performance analysis, cost analysis, financial planning, and an investment strategy. While WYDOT created a TAMP for pavement and bridges in 2018 as mandated by the Moving Ahead for Progress in the 21st Century (MAP-21) Act, there is currently no dedicated pavement marking management plan. By integrating core concepts from TAMP and input from WYDOT district engineers through a statewide survey, this PMMP aims to ensure long-lasting, up-to-date pavement markings.

## 7.2 Study Methodology

As part of the Moving Ahead for Progress in the 21st Century (MAP-21) Act, the national highway performance program requires that states develop a risk-based asset management plan for the roads on the national highway system (NHS). In response to this, the Wyoming Department of Transportation (WYDOT) developed a Transportation Asset Management Plan (TAMP) in 2018. The template for Wyoming PMMP developed in this study was based on this asset management plan. A copy of this template is shown in Appendix 1. That template was developed based on the responses from a survey which was conducted statewide by the Wyoming Technology Transfer Center (WYT2C). Engineers from Wyoming’s five districts responded to the survey. The objective of the survey was to gather information on the current pavement marking striping and management practices employed across the districts. This study then synthesized the survey findings to develop a template for PMMP specifically tailored for WYDOT. Additionally, a thorough analysis of four years of traffic striping data (FY 2018 to FY 2021) provided by WYDOT was conducted. This study explored various updated pavement marking standards supporting machine vision technology integration from different guidelines and literature as part of the long-term planning process. These efforts aimed to ensure that the PMMP aligns with the latest advancements and best practices in the field.

## 7.3 Fundamentals and Core Concepts of PMMP

A pavement marking management plan (PMMP) is a comprehensive and systematic approach that involves the operation, maintenance, and enhancement of pavement markings. It integrates engineering and economic analysis, utilizing reliable information to determine a well-structured sequence of actions such as maintenance, preservation, repair, rehabilitation, and replacement. The purpose of the PMMP is to maximize the value of pavement marking in terms of serviceability while minimizing its life-cycle cost with limited financial resources.

PMMP outlines strategies for maintaining and updating markings, ensuring safety, and optimizing limited funding. It covers assessment, material selection, budgeting, scheduling, inspection, and maintenance procedures. Additionally, The PMMP emphasizes using systematic approaches in the planning, operations, and maintenance of pavement markings.

In line with the requirements of The Moving Ahead for Progress in the 21st Century MAP-21, specifically the National Highway Performance Program (NHPP), states are mandated to develop a risk-based asset management plan for roads within the National Highway System (NHS). Adhering to this risk-based approach, the PMMP incorporates six essential elements. These elements include:

1) Inventory and condition of pavement marking,
2) Pavement marking management objectives and measures,
3) Performance-gap analysis between goals and conditions,
4) Life-cycle cost and risk-based management analyses,
5) The financial plan outlines the future pavement marking management and
6) Investment strategy

The following subsections thoroughly discuss the above components, ensuring a comprehensive and effective PMMP framework.

### 7.3.1 Inventory and Condition of Pavement Marking

The Wyoming Department of Transportation (WYDOT) manages and maintains around 6,744 miles of roadway in the state of Wyoming, distributed amongst five engineering districts, as shown in Figure 38.

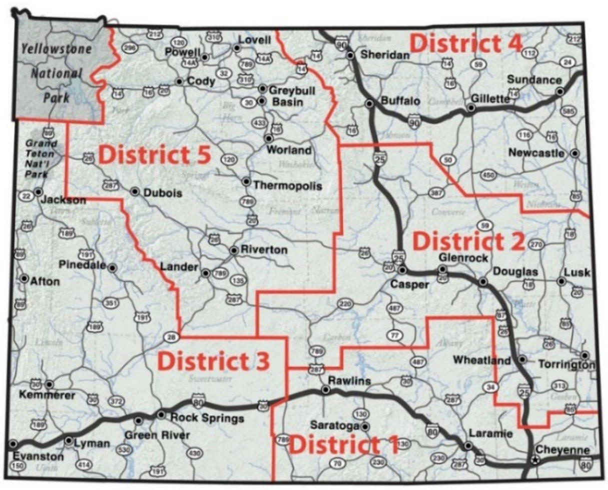



**Figure 38. Map. Wyoming Department of Transportation Engineering Districts (WYDOT, 2023).**

WYDOT categorizes its road network into three groups as described below:

- **Interstates** are high-speed roadways with four lanes, divided design, and controlled access that serve as major routes for high traffic volumes and freight transportation.
- **Non-Interstate NHS** are federally designated principal arterials and expressways that are not classified as interstates.
- **Non-NHS** comprise the remaining roadways managed by the state.

As part of PMMP, inventory and condition assessments of pavement markings were created for Wyoming. This information assists in prioritizing maintenance efforts, allocating resources, and ensuring effective guidance for road users. Table 23 summarizes pavement inventory mileage by ownership (Hafez et al. 2021).

**Table 23. 2018 Pavement Inventory.**

| WYDOT Pavement Inventory (Centerline Miles) | | | | | | |
|---|---|---|---|---|---|---|
| | **District 1** | **District 2** | **District 3** | **District 4** | **District 5** | **Total** |
| **NHS** | | | | | | |
| Interstate | 247 | 241 | 187 | 238 | 0 | 913 |
| Non-Interstate NHS | 111 | 515 | 392 | 315 | 758 | 2091 |
| Total NHS | **358** | **756** | **579** | **553** | **758** | **3,004** |
| **Non-NHS** | | | | | | |
| State | 773 | 795 | 815 | 745 | 612 | 3740 |
| **TOTALS** | **1,131** | **1,551** | **1,394** | **1,298** | **1,370** | **6,744** |

For pavement marking, desired conditions for each road category are specified in terms of the percentage of lane miles with each qualitative category of pavement marking retroreflectivity (Olsen et al. 2018). The lane mile is used as a unit of measurement to establish the length and number of lanes on a specific highway or road. It is determined by multiplying the road's centerline mileage by its number of lanes. The Pass mile is also sometimes used to calculate the length of pavement marking. The pass mile represents the total distance traveled by vehicles on the road section.

The amount of pavement marking lane miles in Wyoming's five districts varies, and WYDOT manages about 25,000 lane miles in five districts. 4,000 to 5,000 lane miles are managed by District 1, and 6,000-7,000 lane miles are managed by District 2, 6,200 to 7,300 lane miles are managed by District 3. The pavement markings in Districts 4 and 5 typically cover 5,000 to 6,000 lane miles. The approximate inventory of five different districts of WYDOT is shown in

**Table 24. Approximate inventory of five districts of WYDOT.**

| District | Annual Striping (Lane miles) | Annual Restriping time (months) | White Paint (gallons) | Yellow Paint (gallons) | Beads (Pounds) |
|---|---|---|---|---|---|
| District 1 | 4,000-5,000 | 6 | 58,500 | No Response | 468,000 |
| District 2 | 5,000-6,000 | 7-8 | No response | No response | No response |
| District 3 | 6,200-7,300 | 8 | 45,000 | 28,500 | No Response |
| District 4 | 5,000-6,000 | 8 | No response | No response | No response |
| District 5 | 5,000-6,000 | 7 | 31,500 | 28,500 | 396,000 |

Pavement striping activities are typically scheduled to commence in April, extending through October and occasionally into November each year. So, Districts need 6 to 8 months to complete all restriping. Additionally, districts were inquired about their utilization of paints and beads for this purpose. Based on the responses of three districts, it was found that the quantities of paint and beads required vary based on the unique specifications of roads within each district. On average, it was determined that every district necessitates approximately 45,000 gallons of white paint, 28,500 gallons of yellow paint, and 432,000 pounds of beads to fulfill its needs.

### 7.3.2 Sections of PMMP Analysis

Any PMMP analysis report normally contains three sections addressing-

- **Network-level analysis** determines current and projected segment information, considering the State Transportation Improvement Program (STIP), budget projections, road marking conditions, and performance modeling.
- **Inventory** provides an overview of management sections, including pavement marking conditions, traffic levels, history, and STIP status.
- **Project-level analysis** recommends pavement marking funding strategies for each district based on WYDOT's asset management philosophy, aiding in project selection for the STIP by considering projected conditions and optimizing fund allocation through a simulation of an unlimited budget, incorporating mileage counts, functional classifications, and traffic percentages across districts to optimize the six-year STIP.

### 7.3.2 Pavement Marking Management Objectives and Measures

The mission of WYDOT is to “Provide a safe, high quality, and efficient transportation system” in Wyoming. The following six goals have been established to define and achieve the mission:

1) Improve safety on the state transportation system,
2) Serve the customers,
3) Take care of all pavement markings on state-maintained roads,
4) Improve agency efficiency and effectiveness,
5) Develop and care for our people, and
6) Exercise good stewardship of our resources.

PMMP involves determining the optimal timing for restriping, evaluating multiple scenarios with different funding and strategies to prioritize preservation projects, and aiming for the highest overall pavement marking condition given limited resources and budgetary requirements. Considering those factors, the following pavement marking management goals were identified:

a) Enabling informed selection and design of future installation projects.
b) Evaluating pavement marking funding strategies accurately.

### 7.3.3 Pavement Marking Management Measures

#### a) Pavement Marking Retroreflectivity

Agencies use retroreflectivity as a measure of serviceability, setting minimum thresholds for reapplication. Monitoring of pavement marking retroreflectivity performance can be done based on:

- Subjectively through visual inspections or
- Objectively using retroreflectometers (Sitzabee et al. 2009b).

Innovative methods like laser scanning and image analysis have emerged as promising tools in data collection, and it is important to evaluate their suitability for Wyoming before implementation.

#### b) Skid Resistance of Pavement Marking

Low skid resistance in pavement markings poses a significant threat to the safety of vulnerable road users, such as motorcyclists, bicyclists, and pedestrians, especially at intersections on state roadways. Skid resistance is considered a key indicator for pavement marking along with retroreflectivity as outlined in the European Technical Standard EN 1436 (EN 1998). Glass beads in pavement markings improve skid resistance and retro-reflectivity (Xu et al. 2021). The importance of skid resistance in pavement marking is also emphasized in several studies (Burghardt et al. 2022; Coves-Campos et al. 2018; Markow 2008). Enhancing skid resistance using aggregates like corundum or bauxite can reduce the risk of slips and improve safety in situations involving deceleration, turning movements, and pedestrian and bicyclist traffic (Mark A. Gieseke 2022). Durable marking material Thermoplastic and cold plastic also contain anti-skid additives (Burghardt et al. 2022; Xu et al. 2021). Enhanced skid resistance should be incorporated in crosswalk blocks, bike lanes, roundabouts, railroad crossing pavement messages, stop lines, and stop ahead pavement messages (Mark A. Gieseke 2022).

#### c) Pavement Marking Performance Monitoring System

To monitor the performance of pavement marking retroreflectivity, a data-driven system is recommended. Currently, WYDOT utilizes the Mobile Retroreflectivity Unit - Laserlux Mobile Retroreflectometer (LLG7) for data collection. The LLG7 offers advantages such as improved efficiency, cost-effectiveness, accuracy, wider coverage, real-time analysis, and enhanced safety compared to handheld retroreflectometers. To effectively accommodate both human-driven and autonomous vehicles, monitoring factors such as retroreflectivity level, lane width, skid resistance of pavement markings, and contrast ratio is recommended.

## 7.4 Performance-Gap Analysis between Goals and Conditions

Available measures should be categorized by context and evaluated based on pre-defined criteria such as mobility, safety, and environmental impact. Evaluation criteria can include some characteristics such as- connecting policies to objectives, being sensitive to changes, and having wide acceptance among professionals (Sassani et al. 2021; Systematics 2009; Systematics et al. 2006). Pavement markings should be in a state that enables drivers to see them easily at any time of the day (Carlson et al. 2013). Cost and environmental effects are two other measures suggested for PMMP consideration. Therefore, the performance measures are divided into two categories:

(a) primary measures: durability, visibility, retroreflectivity, and skid resistance.
(b) secondary measures: cost and environmental impact.

Pavement marking performance-gap analysis evaluates the gap between the expected performance of pavement markings and the actual performance in terms of visibility, durability, and longevity. The objective of the analysis is to identify areas for improvement and implement measures to enhance the performance of pavement markings and ensure safe and efficient roadways.

## 7.5 Life-Cycle Cost and Risk-Based Management Analyses

### 7.5.1 Pavement Marking Life-Cycle Cost Analysis

Life-cycle cost analysis (LCCA) is a vital component of the pavement marking management plan (PMMP). It encompasses a comprehensive evaluation of costs associated with various options throughout the entire lifespan of the markings, from initial installation to eventual removal. By utilizing historical condition data and deterioration models, LCCA in pavement marking calculates future conditions, determining the most cost-effective solution. This analysis plays a crucial role in optimizing the use of limited resources, prioritizing maintenance and preservation efforts, and making informed decisions regarding the future of the pavement marking program. By incorporating annual budgets and pursuing the lowest life-cycle cost while maximizing pavement marking lifespan, the framework for LCCA addresses three essential areas, as illustrated in Figure 39.

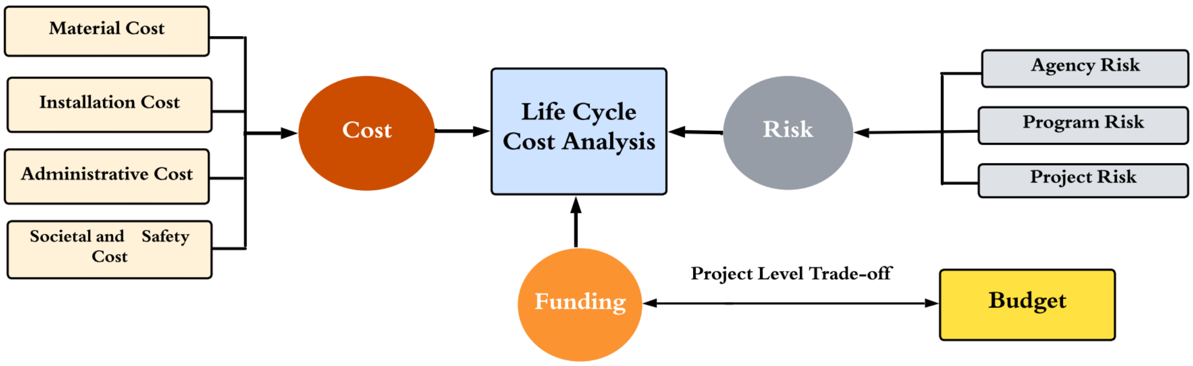



**Figure 39. Flowchart. Required Areas for Establishing Wyoming's LCCA.**

### a) Costs

The PMMP recommends budget amounts based on performance targets. Trade-offs occur at the project level, considering functional classifications and factors like installation costs, service life, and additional costs associated with restriping and maintenance. The factors considered in an LCCA for pavement markings are classified as follows:

- Primary Costs
    - Material Costs
    - Cost of pre-striping preparations
    - Direct installation costs
    - Grooving Costs (when grooving is performed)
    - Costs imposed by special requirements or conditions (when there is a need for wet retro requirements, warranty, etc.)
    - Marking Removal Costs (when removal is done before applying the new markings)
- Secondary Costs
    - Administrative Costs
    - Organizational Costs
    - Costs related to societal effects of pavement markings operations

-Delay Costs
-Crash Costs caused by marking operations
- Costs related to decreased road safety because of poor or ineffective marking performance.

Durable pavement marking materials, although more expensive initially, have the potential to provide long-term benefits through extended restriping intervals and reduced maintenance costs.

### b) Risks

Risk can be defined as a probability or threat of damage, injury, liability, loss, or any other negative occurrence caused by external or internal vulnerabilities, which may be avoided through preemptive action. The “Risk-Based Transportation Asset Management: Evaluating Threats, Capitalizing on Opportunities” suggests that risk exists at three levels: (1) agency risk, (2) program risk, and (3) project risk, which are described in the following paragraphs.

- Agency Risk

The Agency Risk, the highest risk level, is the lack of adequate funding to preserve and maintain the existing pavement marking. The funding shortfall is the primary long-term risk to WYDOT’s maintained assets. Inflation also contributes to the agency’s risk of inadequate funding.

- Program Risk

WYDOT considers program risk as an event that hinders traffic movement, commerce, or both across Wyoming’s transportation systems. These risks are usually addressed or mitigated during the project design and development process and fall into one or more of three broad categories: (1) natural, (2) environmental, and (3) man-made.

- Project Risk

Project risk encompasses the challenges and issues that can affect the successful completion of individual pavement marking projects. For example, weather conditions, pavement conditions, environmental clearances, road closures, funding constraints, and cost increases are project risks that may hinder project execution.

### c) Funding

Funding for pavement marking management is distributed among five districts, and approximately \$1.1 to \$1.5 million was spent annually by each district of WYDOT, as shown in Table 25 by analyzing 4-year traffic striping data.

**Table 25. The Total Cost Associated with Pavement Marking in Different Districts.**

| District | Annual pavement marking cost by different Districts of WYDOT (million dollars) | | | |
|---|---|---|---|---|
| | FY18 | FY19 | FY20 | FY21 |
| **District 1** | 1.38 | 1.36 | 1.47 | 1.50 |
| **District 2** | 1.28 | 1.37 | 1.35 | 1.38 |
| **District 3** | 1.15 | 1.23 | 1.23 | 1.29 |
| **District 4** | 1.45 | 1.47 | 1.32 | 1.29 |
| **District 5** | 1.12 | 1.34 | 1.50 | 1.50 |

The current pavement marking inventory, the impact of increased pricing, and the recommendations provided by five districts in Wyoming were summarized based on survey responses and shown in Table 26. District engineers recommend an increase in the annual budget, and the recommendation is in the range of 30 to 90 percentbased on the opinion of 5 districts.

**Table 26. Effects of Increased Pricing and Related Recommendations and Strategies of Different Districts in WYDOT.**

| District | Effects of increased pricing | Recommendation for Future Budget | Recommendation for budget increase (%) | Current strategies used for planning future restriping |
|---|---|---|---|---|
| District 1 | Fewer lane miles striped and depreciated markings | Increase | 30-40% minimum | Odd/even years |
| District 2 | longer before the road is rehabilitated, and the decrease in surface quality reflects in the paint quality and durability | Increase | NA | For the rural striping, all rural centerlines once per year. Non-interstate roads that receive edge-line get stripped every other year. All lines on the interstate are painted once with the skip line being painted twice. |
| District 3 | Potential shortage of pavement marking availability and not able to meet minimum reflectivity standards and fewer roads with paint | Increase | $1 million (90%) | Predetermined priority schedule, Rural: all centerline annually, edge-line every two years (half one year, the other half second year). |
| District 4 | Hasn't directly impacted D4 yet, but it being an issue in the future. D4 will most likely need to cut work in certain areas to come in under budget. | Increase | NA | In addition to regular schedules, upcoming construction projects and maintenance work are identified.<br>For thermoplastic markings, a list of needs is determined from visual inspection and considering traffic volumes. |
| District 5 | No effect yet, may see a reduction in the quantity of materials | Increase | 50% | Rural: stripe all centerline and lane-line annually/stripe 1/2 edge-line even years; other 1/2 on odd years.<br>Urban: all striping two times/year |

*NA=Not Applicable

An analysis was conducted on the inventory of waterborne pavement markings, revealing a decrease in the number of pass miles stripped over the period from 2019 to 2022. This decline was attributed to the increased total costs per mile (including material, equipment, labor, and other costs) associated with waterborne markings during that time. The findings and trends are presented in Figure 40.

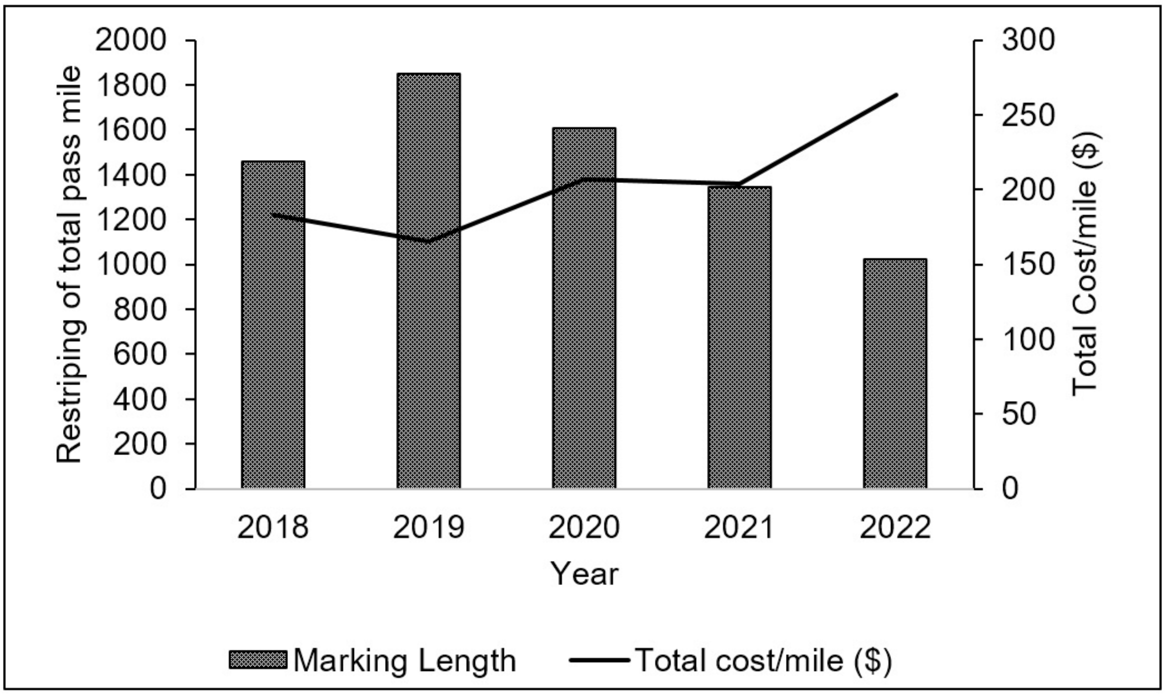



**Figure 40. Chart. 5-Years Pavement Marking Inventory for Waterborne Marking.**

### 7.5.2 Pavement Marking Degradation Model

WYDOT uses various pavement marking materials, including epoxy, polyurea, preformed tapes, and waterborne material, depending on the specific needs of each roadway. Marking conditions vary with marking age. The retroreflectivity of newly applied pavement markings is influenced by various factors, such as

- Glass beads (the type and amount of glass beads used, the embedment depth, the size, and clarity)
- Binder material (the type of binder material, the thickness of the material, the pavement surface roughness, etc.)
- Other factors (pavement friction, dirt, or other blinding materials)

Various external factors, such as the geometric location of roads, horizontal curves, traffic volume, snowplow operations, and marking age, can influence the deterioration rate and future condition of pavement markings. These factors should be considered when determining the funding level needed to maintain the pavement marking system and selecting future installation strategies. Major factors affecting pavement marking durability are shown in Figure 41.

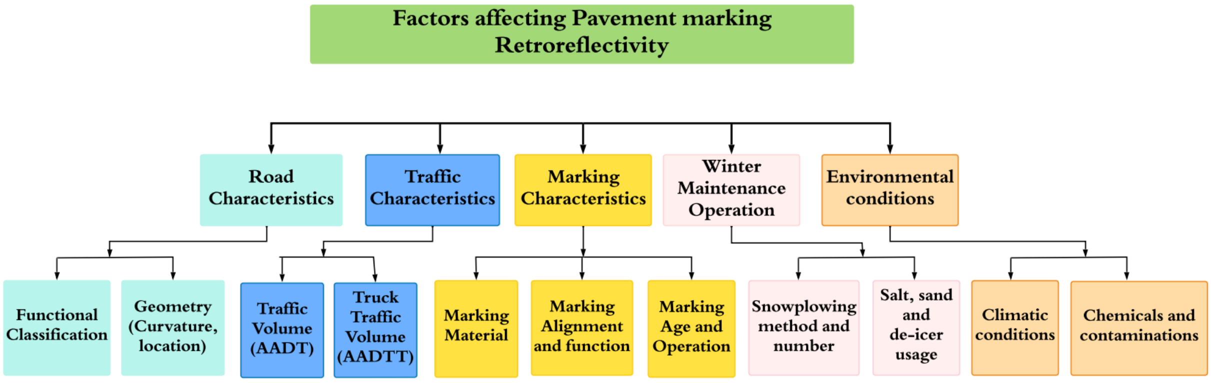



**Figure 41. Flowchart. Significant Factors Affecting Pavement Marking Durability and Retroreflectivity.**

### 7.5.3 Service Life of Pavement Marking

The primary goal of PMMP is to optimize the utilization of available resources to maintain all pavement markings within its jurisdiction in a state of serviceable condition. District Engineers follow different strategies for determining the service life of pavement marking material, and each district mentioned several strategies regarding this topic. In WYDOT districts, service life is determined by the expertise of district engineers, established literature, district engineers' professional judgment, manufacturers' information, and pre-determined schedules. Additionally, three districts mentioned not using service life in every case, as shown in Figure 42.

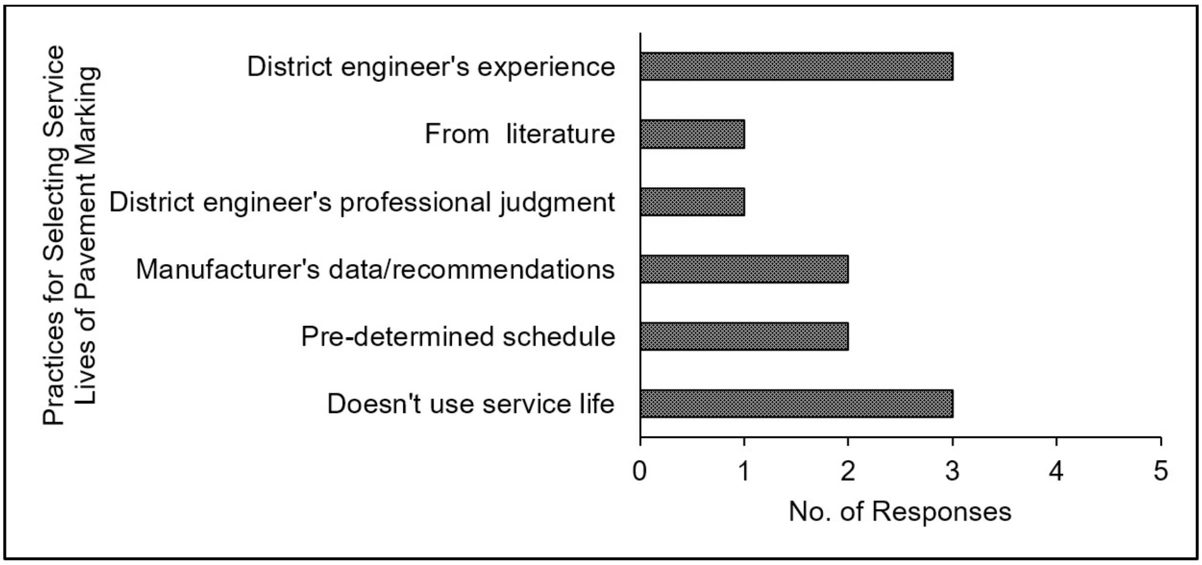



**Figure 42. Practices for Selecting Service Lives of Pavement Marking by Districts of WYDOT.**

The district engineers believe service life varies based on road volume. The range of service lives of pavement marking based on the district's experience is summarized in Table 27. Notably, in snowplow areas, all materials are considered to have a service life of one year. WYDOT incorporates small percentages of Methyl methacrylate (MMA) and Hot liquid thermoplastic to ensure durability.

**Table 27. Range of Service Lives of Marking Material based on the experience of different districts in Wyoming.**

| Range of Service Lives of Marking Material | | |
|---|---|---|
| Material Name | Low volume Roads | High Volume Roads |
| Paint (non-epoxy) | 1-5 | <1-3 |
| Epoxy-based paint | 2 | 2 |
| Paint/epoxy with glass beads | 1-5 | 1-3 |
| Thermoplastic | 3-7 | 1-7 |
| MMA | 3-5 | 2-3 |
| Hot liquid thermoplastic | 15-20 | 15-20 |
| Materials in the snowplow area | 1 | 1 |

### 7.5.4 Risk-Based Pavement Marking Management

WYDOT incorporates a risk-based approach in managing pavement marking and classifying routes based on economic generators, traffic counts, or proximity to population centers. This classification helps WYDOT make trade-offs in maintaining pavement marking conditions, with lower trafficked non-NHS roads accepting a higher level of risk and lower overall condition compared to others. In addition, WYDOT considers optimizing funding scenarios that incorporate a mix of strategies to maximize cost-benefit outcomes for pavement marking.

#### a) WYDOT Risk Management Plan

In compliance with The Moving Ahead for Progress in the 21st Century (MAP-21) Act (passed in July 2012, and The Fixing America's Surface Transportation (FAST) Act (passed in December 2015), WYDOT has developed and implemented a risk-based asset management plan for the NHS to enhance its condition and performance. The PMMP final rule defines risk management as a comprehensive process that involves identifying, analyzing, evaluating, and addressing potential risks to assets and the performance of the NHS. WYDOT has chosen to approach this process at the programmatic level. During the development of the risk management plan, WYDOT executives, program managers, and planning and administration staff utilized the framework depicted in Figure 43 to identify, assess, evaluate, and prioritize program-level risks.

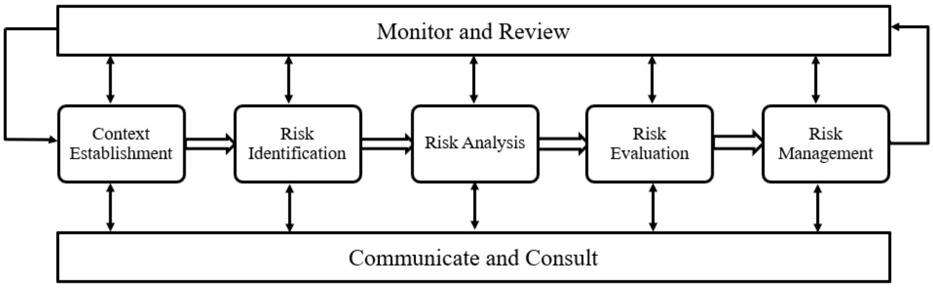



**Figure 43. Flowchart. WYDOT Risk Management Plan Development Framework (Hafez et al. 2021).**

The financial plan outlines the future pavement marking management:

### I. Financial Plan: STIP

State Transportation Improvement Program (STIP) serves as a multi-year financial plan for transportation projects by addressing network deficiencies and needs within each segment. PMMP optimizes restriping strategies based on deficiencies, needs, and trade-offs between transportation needs while meeting funding constraints and safety goals.

### II. Expected Future Funding Levels

STIP funding levels are subject to change based on Congressional and state appropriations. WYDOT anticipates relatively steady funding levels in the next 10-year period, but STIP remains flexible to accommodate changes. WYDOT faces challenges such as funding changes, construction cost fluctuations, environmental considerations, and volatility in construction material costs. Annual inflation rates are considered for cost volatility in future-level project cost estimation.

### III. Maintaining and Preserving Pavement Marking

Maintaining and preserving pavement marking above the threshold level is a critical priority for WYDOT. They have established a policy that includes regular inspections, proactive measures to prevent deterioration, and the use of high-quality materials and skilled professionals. Adequate funding should be allocated to ensure the implementation of these measures. The following strategies are considered by districts of WYDOT for the maintenance and preservation of pavement marking.

a) Set a schedule for regular preservative maintenance.
b) Immediate repairs for damaged markings.
c) Focus on worst-condition markings.
d) Corrective approach to meet performance targets within constraints.
e) Regular monitoring for effective resource allocation.

## IV. Pavement Marking Management Process Enhancement

Enhancing the Pavement Marking Management Process in Wyoming has been a priority for WYDOT, with efforts focused on optimizing project selection and allocating a significant portion of the budget to pavement and safety assets. The emphasis on enhanced pavement marking is also aligned with the Wyoming Strategic Highway Safety Plan, aiming to improve safety, particularly in dark conditions, and reduce fatalities and injuries on the roads. The recently published Wyoming Strategic Highway Safety Plan (SHSP) serves as a guiding document for achieving the national goal of "Towards Zero Deaths," with enhanced pavement marking being an essential treatment recommended in the plan. More visible pavement markings can greatly improve roadway safety and reduce accidents.

To establish an efficient PMMP, WYDOT District Engineers recommend adequate allocation of resources like manpower, materials, equipment, and safety devices. Understanding pavement markings performance curves helps determine appropriate strategies for future restriping. The following recommendations are made:

- Districts should establish predetermined restriping schedules, considering factors such as traffic volume, construction projects, and maintenance work in addition to regular restriping activities.
- Center lines and lane lines typically experience more wear than edge lines; they should be restriped earlier if possible.
- In rural areas, pavement marking can be done annually, while urban areas may require restriping twice per year.
- Roads with more horizontal curves and higher snowplow operation should be restriped earlier.

To identify districts' strategies for 5-year and 10-year plans for pavement marking, District Engineers have recommended the following strategies:

- Incorporate the latest pavement marking standards that accommodate machine vision (MV) systems.
- Establish a centralized database to store all pavement marking management data.
- Seek additional funding specifically allocated for the pavement marking maintenance program.

In the 5-year and 10-year plans for pavement marking, the focus has been on prioritizing incorporating the latest pavement marking standards compatible with MV systems. Considering this priority, the next section will explore the Pavement Marking Standards to Support Machine Vision Technologies, addressing the importance of these advancements in enhancing road safety and efficiency.

## V. Pavement Marking Standards to Support Machine Vision Technologies

Amending pavement marking standards benefits Connected and Autonomous Vehicles (CAVs) and vehicles with Advanced Driver Assistance Systems (ADAS) and human-driven cars, leading to improved road safety for all vehicles and economic benefits through road restriping investments. The most frequently mentioned suggestions in the existing literature have been summarized in Table 28.

## Table 28. Pavement Markings to Accommodate Machine Vision Issues.

| Issue | Key findings and recommendations | References |
|---|---|---|
| Marking Width | Wider marking of 6 in (15cm) compared to a narrow marking of 4 in (10cm) can potentially reduce accidents by up to 38%. | (Park et al. 2012) |
| | A minimum pavement marking width of 6 in (150mm) is suggested to facilitate detectability by MV systems. | European Union Road Federation (2013) |
| | The 6-in markings performed better than the 4-in markings, which had higher $R_L$. Hence, the 50% increase in width compensated for the reduced retroreflectivity and might have extended the markings' service lives. | (ATSSA 2019; Carlson 2017; Davies 2017; Pike 2018). |
| | Mobileye, a major manufacturer of camera sensors, suggested pavement marking widths between 4.7 and 6 in (12 and 15 cm). | ATSSA (2019) |
| | The current MUTCD specifies widths between 4 to 6 in. The NCUTCD suggested amending the MUTCD such that pavement marking widths be 6 in as well. | (National Committee on Uniform Traffic Control Devices 2020). |
| Broken Line | Broken longitudinal markings having 15 ft in length with 25 ft spacings are suggested. | ATSSA (2019) |
| | The Alliance of Automobile Manufacturers suggested that modifying the broken line marking standards would assist in their detectability by MV systems. However, they did not specify the configuration. | (National Committee on Uniform Traffic Control Devices Task Force 2019). |
| Retroreflectivity ($R_L$) | Higher $R_L$ resulted in increased driver comfort, with a particular advantage for elderly drivers. | (Burns et al. 2006; Diamandouros and Gatscha 2016; Horberry et al. 2006). |
| | For older drivers, the minimum $R_L$ should be greater than 150 mcd/m$^2$/lux. | (Parker and Meja 2003). |
| | To accommodate MV requirement $R_L$ should be over 50 mcd/m²/lux. | (Carlson 2017). |
| | For comfortable driving, $R_L$>150 mcd/m$^2$/lux is advised for all colors. | (European Union Road Federation 2013; Gibbons et al. 2012) |
| Contrast Ratio | The contrast ratio between the marking and the pavement should be more than 2:1, and MV produces superior results with a contrast ratio of 3:1. | (Carlson 2017). |
| | Glare usually reduces contrast ratio and clarity and increase crashes. | (Sun et al. 2018) |
| | Sun glare, fog, rain, snow, and pavement marking seals can also impact detectability | (Road Readiness Criteria for Automated Vehicle Technologies (Society of Automotive Engineers Levels 1 through 3), 2020). |
| Clarity | Sharp edges in road markings offer advantages for detection by eliminating ambiguities caused by seal marks and enhancing visibility for drivers and MV systems. Black lines along the edges of the longitudinal markings may be used since they enhance the contrast of the markings. Yet, they were not strongly suggested. | (Carlson 2017) |
| | Detection of longitudinal pavement markers with black edges having various thicknesses was tested, and the 2-in and 1-in edges performed well. | (Whitney et al. 2018) |

| Issue | Key findings and recommendations | References |
|---|---|---|
| | The Alliance of Automobile Manufacturers recommended the use of white and black markings on concrete pavements to enhance contrast. | (National Committee on Uniform Traffic Control Devices Task Force 2019). |
| Uniformity | Uniform and standardized pavement markings minimize confusion, uncertainty, and reduce crashes. | (Carlson 2017; Xu et al. 2021). |
| | The use of raised pavement markings, such as ceramic buttons or Botts' dots, is discouraged due to potential displacement and loss of adhesion, which can confuse ADAS and CAV cameras. | (Road Readiness Criteria for Automated Vehicle Technologies (Society of Automotive Engineers Levels 1 through 3), 2020). (National Committee on Uniform Traffic Control Devices Task Force 2019). |
| | Caltrans is substituting Bott's dots with thermoplastic material. | (Richards 2017) |
| | ATSSA (2019) also recommended against the use of Bott's dots. | ATSSA (2019) |
| Dashed lines on entrances and exits | Alliance of Automobile Manufacturers recommended dashed lines on highway entrances and exits. The dashed line was recommended to be greater than 10 in. The dashed markings were suggested to be greater than 3 ft in length and spaced greater than 5 ft apart. | (National Committee on Uniform Traffic Control Devices Task Force 2019). |
| Solid edge lines | Automobile Manufacturers also suggested solid edge lines that are otherwise unused in some instances. | (National Committee on Uniform Traffic Control Devices Task Force 2019). |
| Gore area marking | The NCUTCD recommended that the use chevron or hatch markings in the gore area, even though they are not required in the current MUTCD. The Alliance of Automobile Manufacturers expressed concern at the use of chevron markings since they might confuse the vehicles' machine vision systems. Hence, they recommended standardizing the hatch patterns before use. | (National Committee on Uniform Traffic Control Devices 2020), (National Committee on Uniform Traffic Control Devices Task Force 2019). |
| HOV lane marking | Clearly marked high-occupancy vehicle (HOV) lanes with double or triple solid lines, yellow on the left edge, and dashed lines for access and exit points are suggested. | (National Committee on Uniform Traffic Control Devices Task Force 2019). |
| Wok Zone detection | Work zone detectability is another area of concern for MV vehicles. | (Automotive Safety Council and ATSSA) (Road Readiness Criteria for Automated Vehicle Technologies (Society of Automotive Engineers Levels 1 through 3), 2020) |

The highest priority recommendation in the pursuit of incorporating advanced pavement marking standards, compatible with modern vehicle (MV) systems, was to adopt wide (6") markings and implement broken lines spaced at 15 ft markings spaced 25 ft apart instead of the previous 10 ft markings spaced 30 ft apart. The required additional material quantities for striping longitudinal markings considering updated lane width and broken line specifications were calculated (shown in Table 29). To improve the longitudinal markings from 4” to 6” width, an additional 8.8 gallons of marking material per mile is required. Similarly, to enhance the broken lines from 10 ft markings spaced 30 ft apart to 15 ft markings spaced 25 ft apart, an additional 5.5 gallons of marking material per mile is needed. WYDOT specifies a marking thickness of 16 mils (Wyoming Department of Transportation Traffic Program 2012).

**Table 29. Pavement Marking Material Quantities Calculations.**

| Line Type | Marking Width (in) | Marking thickness (mils) | Markings (mi/1mi) | Required Quantity (gal/mi) |
|---|---|---|---|---|
| Solid | 4 | 16 | 1 | 17.6 |
| | 6 | | (Continuous Markings) | 26.3 |
| | | | Difference | 8.8 |
| Broken | 4 | 16 | 0.25 (10 ft Markings Spaced 30 ft Apart) | 4.4 |
| | 6 | | 0.375 (15 ft Markings Spaced 25 ft Apart) | 9.9 |
| | | | Difference | 5.5 |

Material cost, bead cost, and applied cost of paint material in WYDOT are shown in Table 30.

**Table 30. Paint Cost, Beads Cost, Total Material Cost and Applied Cost.**

| Year | Paint Cost $/ Gal | | Beads Cost | Total Material cost $/Gal | | Applied Cost/Gal ($) |
|---|---|---|---|---|---|---|
| | Yellow | White | $/lb | Yellow | White | |
| 2017 | 6.9 | 7.3 | 0.28 | 9.2 | 9.6 | 26.0 |
| 2018 | 7.1 | 7.6 | 0.27 | 9.3 | 9.7 | 26.0 |
| 2019 | 8.0 | 8.3 | 0.29 | 10.3 | 10.6 | 29.0 |
| 2020 | 8.3 | 8.4 | 0.3 | 10.8 | 10.8 | 30.0 |
| 2021 | 7.9 | 8.1 | 0.3 | 10.3 | 10.5 | 30.0 |

### 7.6 Investment Strategy

The investment strategy in pavement marking management involves considering available resources and determining the analytical capabilities required for effective decision-making. Depending on the agency's needs, PMMP can be equipped with additional features such as risk assessment, life-cycle cost analysis, and environmental life cycle assessment (LCA). A flow chart representing WYDOT's investment strategy process following TAMP-2018 is presented below in Figure 44.

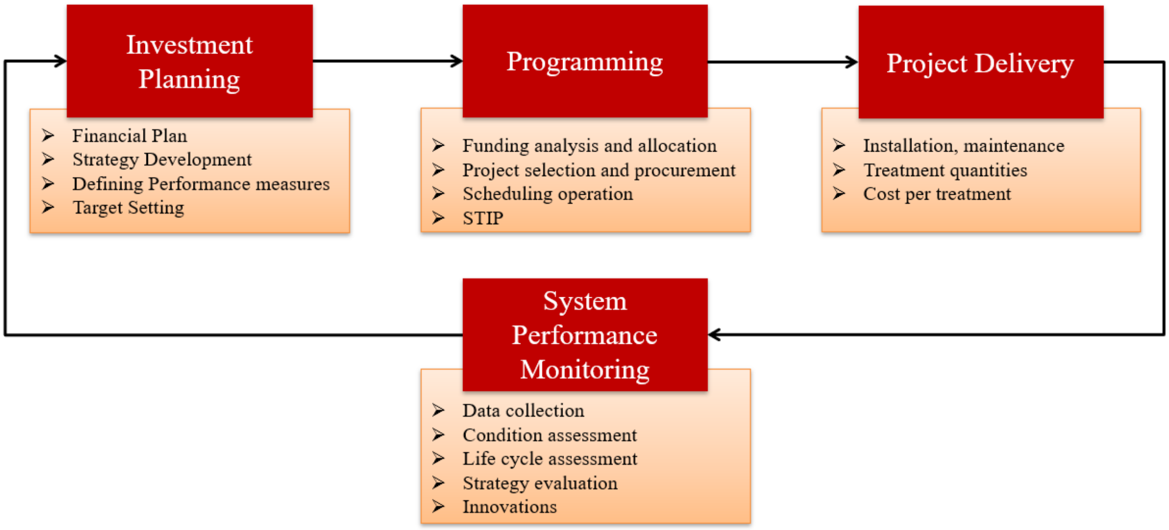



**Figure 44. Flowchart. WYDOT's Investment Strategy Process.**

### a) Investment Planning

Investment planning is a prerequisite for allocating funds and establishing priorities in a state's transportation programs while considering budget limitations. This comprehensive process includes financial planning and life cycle planning. The target setting for these systems involves analyzing historical data, financial plans, and input from district engineers to determine funding distribution.

### b) Programming

The programming function is vital as it converts recommended management system treatments into tangible short-term projects documented in the Statewide STIP. The Programming Section provides the Engineer with a report comparing required treatment quantities to the actual work programmed in the STIP. District engineers often cluster treatment types within certain years of the six-year STIP to optimize resource utilization. The Programming Section collaborates with the management systems to track estimated costs and budget allocations for pavement marking work.

### c) Project Delivery

District engineers are responsible for implementing the necessary treatments, with the Programming Section tracking the treatment types and quantities in the STIP. A report comparing required and programmed treatments helps optimize resource utilization. Cost estimates per pavement marking work are tracked, ensuring adequate budget allocation.

#### d) System Monitoring

System monitoring ensures the effectiveness of pavement marking treatments. It tracks performance, identifies areas for improvement, and allows for adjustments as needed.

### 7.7 Chapter Summary

This chapter described each component of the pavement marking management plan along with the challenges of pavement marking management. Besides the pavement marking practices, this chapter highlights the significance of asset management practices in pavement marking management and presents a template for the pavement marking management plan (PMMP). The developed PMMP for Wyoming provides a comprehensive approach, considering budget constraints and newly recommended marking specifications for advanced driver assistance systems (ADAS). The implementation of the PMMP has led to several significant conclusions, which are summarized below:

1) A general PMMP framework consists of six core elements: 1) Inventory and condition, 2) objectives and measures, 3) Performance-gap analysis, 4) Life-cycle cost analysis, 5) Financial plan, and 6) Investment strategy, which incorporates all the relevant standard, practice, and strategy.
2) PMMP framework includes data-driven strategies for various aspects such as project selection, budgeting, procurement of goods and services, and contracting. Therefore, the data management component of PMMP should ensure positional and attribute accuracy, completeness, and consistency.
3) This report acknowledges that establishing performance targets for pavement markings can be done by defining retroreflectivity thresholds with the current specifications of MUTCD 2022. Predicting retroreflectivity over time utilizes retroreflectivity degradation curves. Winter maintenance operations, lane position, and horizontal curve are recommended to be given higher weight in performance prediction models.
4) The recommended approach for material selection in PMMP is the life cycle cost analysis (LCCA), which incorporates many possible factors to determine the total cost of installing and maintaining a pavement marking asset. Other factors, such as traffic delays and administrative costs, safety costs, and, most importantly, environmental effects, can play a significant role in the overall cost of an individual type of marking. Risk and funding should also be considered along with cost.
5) Inspection activities in PMMP are done from pre-installation to throughout the service life of pavement markings, enabling to make data-driven management decisions.
6) Unification of markings is necessary for reliable MV and universality of AV. Efforts existed to standardize pavement markings for the uniformity of the

marking system. It was recommended that specifications and standards of different modifications be accumulated to move forward.

# CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

Pavement markings are vital elements that guide and safeguard road users. Ensuring road safety is of utmost importance, and maintaining pavement markings with sufficient retroreflectivity is a key factor in achieving this goal. Accurate predicting retroreflectivity and service life determination are essential for optimizing maintenance efforts. While the Wyoming Department of Transportation (WYDOT) performs regular resurfacing of pavement markings, there is a pressing need for a comprehensive and rigorous management program to ensure their cost-effective management. To establish such a pavement marking management plan, it is essential to identify the factors that impact pavement markings and develop degradation models that can predict their performance over time. These models will enable the determination of the service life of pavement markings, aiding in proactive maintenance and ensuring their continued effectiveness. Additionally, as advanced vehicle technologies like advanced driver assistance systems (ADAS) and connected/autonomous vehicles (CAVs) become more prevalent, updating pavement marking standards becomes imperative to enhance their compatibility with these systems.

This research investigated the factors influencing pavement marking retroreflectivity in Wyoming, developed pavement marking degradation models, and established a pavement marking management plan framework. The ultimate objective of this report is to provide decision-makers with valuable insights to implement effective strategies that ensure the presence of adequately visible pavement markings and enhance operational efficiency in Wyoming. To accomplish the objective, the following tasks were carried out:

d) Data collection protocols were developed by selecting pavement marking test sections across the interstate, principal arterial, minor arterial, and major collector roads in Wyoming.

e) A comprehensive database was developed for pavement marking in Wyoming, incorporating measured pavement marking retroreflectivity data from 528.5 miles of roads for three types of marking material-polyurea, epoxy, and waterborne paint, traffic volumes. Retroreflectivity measurements were conducted using mobile retroreflectometers for the white edge line, lane line, yellow edge line, and yellow centerline on the interstate and principal arterial roads. White edge lines and yellow centerlines were also tested on minor arterial and major collector roads. Additionally, marking age, climate characteristics, snowplow information, and roadway geometry information was included in the database.

f) Factors affecting pavement marking retroreflectivity were analyzed, and the impact of road geometry, marking characteristics, traffic attributes, and climate conditions on retroreflectivity was determined by the binary logistic regression model.

g) Pavement marking retroreflectivity performance degradation models over ages were developed for four classification highways in Wyoming by statistical analysis using a Bayesian Ordered Logit Model, and pavement marking service life was determined for different types of materials and different line positions.

h) A Pavement Marking Management System (PMMS) for Wyoming was developed by analyzing existing practices through a nationwide survey.

i) A comprehensive Pavement Marking Management Plan (PMMP) for Wyoming was established by following Transportation Asset Management Plan and pavement marking performance model. This task was done by analyzing existing practices through a statewide survey and addressing the requirements of advanced automobile technologies, such as machine vision systems and autonomous vehicles.

### 8.1 Factors Affecting Pavement Marking

Binary logistic models were developed to identify the factors affecting the likelihood of the pavement marking retroreflectivity above the marginal level. The models were developed using pavement marking retroreflectivity data collected in December 2021 with a range of 0.83 to 7.5 months of age, specifically did not experience any snowfall. The $R_L$ of 100 mcd/m$^2$/lux for the yellow line and 125 mcd/m$^2$/lux for the white line were used as a marginal level. Additionally, the developed models were verified by conformance statistics, indicating reasonable prediction accuracy. The evaluation was conducted in two analyses considering a total of thirteen variables. In the first analysis, the whole dataset of measured retroreflectivity and selected parameters were used, and in the second analysis, the whole dataset was categorized based on four functional classifications. Both analyses yielded similar results suggesting the accuracy of prediction models. From this analysis, the following conclusions were drawn:

- The probability of having retroreflectivity above the marginal level decreased with the increase of the degree of curvature of the horizontal curve. At the horizontal curve, the decreasing trend of pavement marking retroreflectivity is possibly attributed to additional wear and tear in the curve due to the wandering of the vehicles.

- The probability of having $R_L$ above marginal was lower in the rural location compared to the urban roads.

- The analysis indicates that the marking material polyurea showed better performance compared to the material Epoxy and Waterborne. Waterborne material had the lowest probability of having retroreflectivity above marginal value.
- Marking color is also a significant factor for pavement marking retroreflactance. White color marking was found to have a lower probability of serviceable $R_L$ than the yellow marking.
- The analysis also reveals that the pavement markings located in the travel path (either center or lane line) lines had a lower probability of retroreflectivity above marginal than those located at the edge of the pavement. A lower probability of retroreflectivity in the centerline and lane line is possibly due to having more contact between pavement marking with vehicle wheels during overtaking and lane changing.

### 8.2 Pavement Marking Retroreflectivity Degradation Model

This analysis provides valuable insights into the degradation process of pavement markings and their retroreflectivity levels over time. Using Bayesian-ordered logit models and the No-U-Turn Hamiltonian Monte Carlo technique allowed for accurate prediction of retroreflectivity levels and service life determination. At the same time, the inclusion of random intercepts in the modeling procedure revealed unobserved heterogeneity due to the variation of $R_L$ levels within-county. These findings have significant implications for highway agencies, as they can use this information to prioritize their maintenance efforts and optimize retroreflectivity operations, ultimately contributing to enhanced road safety for all users.

- The $R_L$ degradation followed a nonlinear trend, with degradation rates decreasing as time increased.
- Urban roads and travel path markings (middle line) are more prone to degradation, and the degradation rate of white markings is higher than that of yellow markings.
- The higher pavement marking retroreflectivity decreasing trend observed at horizontal curves is possibly due to the additional wear and tear caused by the wandering of vehicles. These insights can inform the selection of pavement marking materials and application methods to ensure longer-lasting retroreflectivity and more efficient maintenance.
- The probability of monitored pavement markings transitioning from one service life level to another was estimated by considering five levels of $R_L$.
- Furthermore, by setting the minimum marginal retroreflectivity levels at 125 and 100 mcd/m$^2$/lux for white and yellow markings, respectively, it

was found that the service life of white and yellow markings differs based on road classification, marking material, and line position.

### 8.3 Pavement Marking Management System

The critical aspect and steps involved in developing and implementing PMMP is a proper pavement marking management system to meet agency needs. To gather nationwide practices and strategies, a survey was conducted, providing valuable input for the development of the PMMP framework. The development of the PMMS has led to several significant conclusions, which are summarized below:

- Durability was the primary criterion for selecting pavement marking materials, with the other four most important factors as maintenance cost, price, ease of striping, and traffic volume.
- Tape was commonly used for rural interstates, while water-based paints were preferred for other facilities. High-volume roads and roads with heavy truck traffic were prioritized for using more durable pavement marking materials. Several DOTs also considered using durable markings in areas with frequent snowplow operations.
- Most DOTs collected pavement marking quality data once a year, while some collected data as needed or after marking installation. Some DOTs did not collect retroreflectivity data but determined restriping frequency based on expected service life.
- Annual restriping of roadway facilities was common, with the choice of restriping based on marking material type and service life. Water-based paint was the most used material for annual restriping. Grooved, durable marking and high-build paint were also mentioned for longer service life.
- Recommendations were made for specific pavement types, such as using more durable materials for concrete and high-volume asphalt pavements. Delaying pavement marking application on newly placed Hot Mix Asphalt (HMA) was also suggested.
- For locations with open-graded asphalts, chip seals, and crack seals, recommendations included using thick layers of durable materials like polyurea or paint coatings. The use of tape was discouraged for open-graded asphalts and chip seals.
- To accommodate vehicles with machine vision technologies, a significant number of DOTs follow NCUTCDs recommendation regarding wide (6”) pavement marking. So, the most critical recommendation is that width of longitudinal markings should be 6 inches, which is 2 inches wider than the WYDOT used.
- Recommendations for concrete pavements included using contrast markings (markings with black edges). Only a few DOTs mentioned non-contrast markings exclusively, while others followed recommendations for contrast markings.

## 8.4 Pavement Marking Management Plan

Transportation asset management practices play a crucial role in the management of pavement markings. They provide a structured approach to ensure these assets' effective maintenance and preservation. As part of this, a model framework is presented for the pavement marking management plan (PMMP). This framework, shown in Appendix 1, serves as a strategic guide for implementing comprehensive and efficient pavement marking management practices. Following the principles of the transportation asset management plan, the PMMP framework was proposed, serving as a guide for managing pavement markings in a cost-effective manner. The implementation of the PMMP has led to several significant conclusions, which are summarized below:

- A general PMMP framework consists of six core elements 1) Inventory and condition, 2) objectives and measures, 3) Performance-gap analysis, 4) Life-cycle cost analysis, 5) Financial plan, and 6) Investment strategy, which incorporates all the relevant standard, practice, and strategy.
- PMMP framework includes data-driven strategies for various aspects such as project selection, budgeting, procurement of goods and services, and contracting. Therefore, the data management component of PMMP should ensure positional and attribute accuracy, completeness, and consistency.
- Predicting retroreflectivity over time utilizes retroreflectivity degradation curves. Winter maintenance operations, lane position, and horizontal curve are recommended to be given higher weight in performance prediction models.
- The recommended approach for material selection in PMMP is the life cycle cost analysis (LCCA), which incorporates many possible factors to determine the total cost of installing and maintaining a pavement marking asset. Other factors, such as traffic delays and administrative costs, safety costs, and, most importantly, environmental effects, can play a significant role in the overall cost of an individual type of marking. Risk and funding should also be considered with the cost.
- Inspection activities in PMMP should be done from pre-installation to throughout the service life of pavement markings, enabling data-driven management decisions to be made.

## 8.5 Recommendations

Findings from this study are anticipated to assist highway agencies in prioritizing the roadway segments and thus can optimize pavement marking management. The following recommendations are proposed based on the findings of this study:

- The proposed template for the PMMP shown in Appendix 1 should be fully populated and implemented by WYDOT.

- To optimize pavement marking maintenance efforts, using higher-quality marking materials on road sections with higher RL degradation rates, especially those with many horizontal curves, in urban areas, and in travel paths (lane and center lines) is recommended. Additionally, road sections with a higher service level of snowplow priority should be prioritized for restriping.

- Durability, maintenance cost, price, ease of striping, and traffic volume should be considered for the material selection.
- Proposed expected service life of pavement marking should be used for restriping schedule. Most durable paint can be considered for more degradation-prone locations, but before using new pavement marking material, an in-depth study and benefit-cost analysis are performed to determine whether other materials would be beneficial.
- Using more durable materials for concrete and high-volume asphalt pavements is recommended from this analysis and the recommendation of other DOTs. Delaying pavement marking application on newly placed Hot Mix Asphalt (HMA) is also suggested.
- For locations with open-graded asphalts, chip seals, and crack seals, recommendations included using thick layers of durable materials. The use of tape should be avoided for open-graded asphalts and chip seals.
- To accommodate vehicles with machine vision technologies, the most critical recommendation is that the width of longitudinal markings should be 6 inches, which is 2 inches wider than the WYDOT used.
- Recommendations for concrete pavements included using contrast markings (markings with black edges).
- Life cycle cost analysis (LCCA) is a recommended approach for material selection in PMMP.
- Unification of markings is necessary for reliable MV and universality of AV. Efforts existed to standardize pavement markings for the uniformity of the marking system. It was recommended that specifications and standards of different modifications be accumulated to move forward.

This research paves the way for future research opportunities by suggesting areas of improvement. To enhance service life predictability, it is recommended that future studies develop a robust model encompassing factors such as initial retroreflectivity, material compositions, application methods, application temperature, installation quality, and detailed information on snowplow recording, blade types, and chemicals used. While the findings are promising, more frequent data collection for a longer duration beyond the expected service life is advisable to ensure durable markings meet the required threshold for both colors. This study used a standard bead size and a consistent application process throughout Wyoming. Hence, bead-related factors were not considered. However, future studies should investigate the impact of glass bead application in pavement marking, considering factors such as bead size, distribution, embedding techniques, orientation, surface treatments, composition, and long-term performance. Additionally, conducting a cost-effectiveness analysis to evaluate alternative higher-quality bead options for maintaining superior retroreflectivity levels over an extended period would be valuable.

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# Appendix 1: Template of WYDOT Pavement Marking Management Plan


Wyoming Department of
Transportation (WYDOT)
WYOMING
TRANSPORTATION
DEPARTMENT
Pavement Marking
Management Plan
Template
2023

# TABLE OF CONTENTS

PMMP: July 2023

## I. Enabling Legislation

Historically, infrastructure asset management systems have given more attention to large-scale assets such as roads and bridges, neglecting the management of lower-cost assets such as pavement markings. However, the emphasis on infrastructure asset management has shifted towards a more comprehensive approach, which includes the management of all assets, including lower-cost ones like pavement markings. For example, the Moving Ahead for Progress in the 21st Century (MAP-21) Act has mandated the development of a risk-based asset management plan for roads on the national highway system. In response, the Wyoming Department of Transportation (WYDOT) developed the Transportation Asset Management Plan (TAMP) in 2018, which was used as the basis for the development of the Wyoming Pavement Marking Management Plan (PMMP) template. The implementation of PMMP is a step towards a comprehensive, integrated asset management approach.

The Pavement Marking Management Plan (PMMP) template outlines the strategy for maintaining and updating pavement markings on roads and highways with the goal of ensuring safe and effective markings. The PMMP covers the assessment of existing conditions, selection of appropriate materials and methods, development of a budget and implementation schedule, and development of inspection and maintenance procedures. By maintaining effective and visible pavement markings, the PMMP helps to ensure the safety of motorists, and by prioritizing maintenance activities based on need, it helps to optimize the use of limited funding.

The use of systematic approaches for pavement marking planning, operations, and maintenance are the core concept of the PMMP. PMMP should include the following six elements:

1) Inventory and condition of pavement marking along with data collection guidelines,
2) Pavement marking management objectives and measures,
3) Performance-gap analysis between goals and conditions,
4) Life-cycle cost and risk-based management analyses,
5) Financial plan for the future, and
6) Investment strategy

On August 5, 2022, the Federal Highway Administration (FHWA) published a final rule that added a standard for maintaining minimum retroreflectivity levels for pavement markings to Section 3A.03 of the Manual on Uniform Traffic Control Devices (MUTCD). This standard provides flexible methods for maintaining the retroreflectivity of pavement markings, specifically longitudinal markings such as center lines, lane lines, and edge lines. The MUTCD includes a variety of potential methods to accommodate the differing needs of agencies in terms of staffing, equipment, budget, road systems, and expertise. The information in Section 3A.03 also helps agencies ensure that pavement markings are replaced before they become too worn to meet the needs of nighttime driving.

## II. WYDOT'S Mission, Vision, and Goals for Pavement Marking Management

The WYDOT's mission is to "Provide a safe, high quality, and efficient transportation system" in Wyoming. To help define and achieve its mission, WYDOT established the following six goals:

1) Improve safety on the state transportation system,
2) Serve our customers,
3) Take care of all Pavement marking on state-maintained roads in Wyoming,
4) Improve agency efficiency and effectiveness,
5) Develop and care for our people, and
6) Exercise good stewardship of our resources.

WYDOT's mission statement and goals support the WYDOT asset management approach for transportation improvements and funding distribution. WYDOT's PMMP especially focuses on the goal of Taking care of all physical aspects of the state transportation system by emphasizing the maintenance of existing pavement marking.

WYDOT uses a standard to gauge its effectiveness and document targets and measures for the pavement marking conditions on the interstates, NHS, and non-NHS. For one of the WYDOT's goals, Take care of all physical aspects of the transportation system, WYDOT addresses the MAP-21 elements of (1) listing pavement marking inventory and conditions, (2) stating pavement marking management objectives and measures, and (3) providing a performance- gap analysis. Through this PMMP, WYDOT will provide inventory and measurement of the pavement marking system, list pavement marking conditions, generate goals, and offer a performance-gap analysis between goals and conditions.

Further, WYDOT demonstrates the MAP-21 element of life-cycle cost analysis through its goal to "Improve agency efficiency and effectiveness" using life-cycle cost analysis and recognizing annual maintenance costs to infrastructure. Finally, WYDOT meets Congress' requirements to have processes for financial plans, investment strategies, risk, and resilience through WYDOT's goal to exercise good stewardship of our resources. WYDOT strives to ensure that the financial future is accurately predicted with a funding split to maintain our Pavement marking in proper condition. WYDOT recognizes the risks that are inherent in future predictions and analyzes reasonable alternatives.

### Definition of Pavement Marking Management

"The term "pavement marking management" means a strategic and systematic process of operating, maintaining, and improving pavement marking, with a focus on both engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that would achieve and sustain the desired state of good repair over the life cycle of the pavement marking at minimum practicable cost." The objective of the pavement marking management system is to minimize the life-cycle Cost of Pavement marking while maximizing its value with constrained fiscal funding (Roy et al. 2023).

### WYDOT and Pavement Marking Management

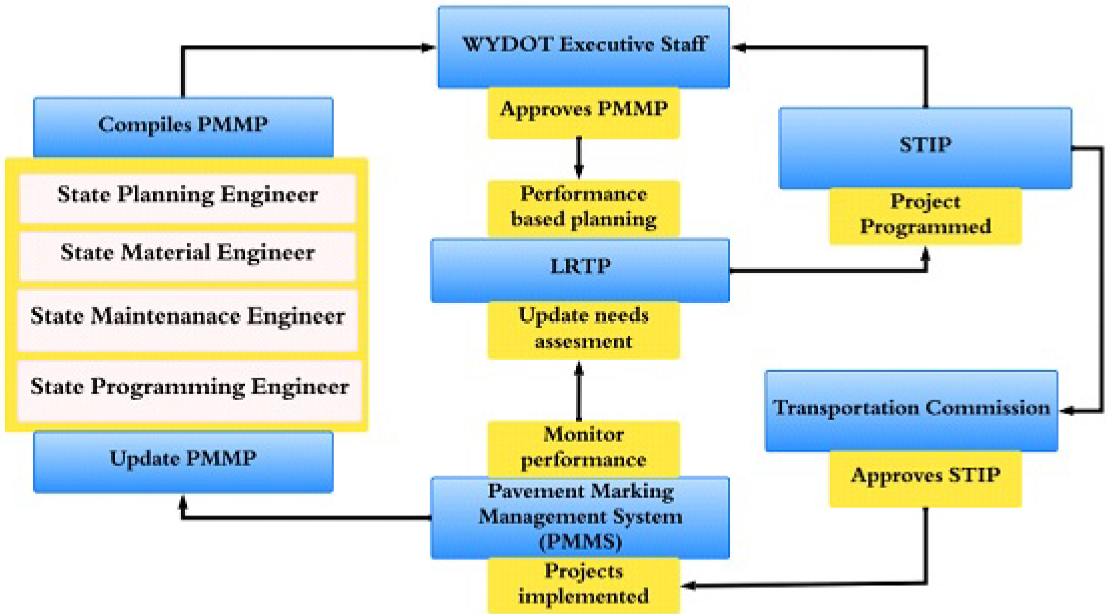
The objective of WYDOT's pavement marking management system is to minimize the life-cycle cost of the pavement marking while maximizing its value with constrained fiscal funding.

WYDOT's pavement marking management program aims to maintain the overall Pavement marking condition at the highest possible level, given finite funding. WYDOT's pavement marking management strategy consists of determining the best point to apply a restriping in its life cycle, then running multiple scenarios, using various funding and strategy, to determine the best mix of preservation projects for Wyoming's pavement marking. The investment strategies outlined in this plan establish a methodology for resource allocation that generates the greatest return on investment, promotes system-wide asset sustainability, and facilitates progress toward the achievement of national performance goals. The seven MAP-21 national performance goals relate to infrastructure management, safety enhancements, congestion mitigation, system reliability, freight movement, economic vitality, environmental sustainability, and reduced project delivery delays.

WYDOT's program managers coordinate and compile the PMMP. The structure for constructing the plan is shown in Table 31, and the flow chart of the WYDOT PMMP process is shown in Figure 45.

**Table 30. WYDOT PMMP Working Group.**

| PMMP Working Group | Role in Compiling the PMMP |
|---|---|
| **State Traffic Engineer** | Serves as an executive of the PMMP working group |
| **District Traffic Engineers, Traffic Design Engineers, Traffic Operations( data collection)** | Statewide Pavement Marking Conditions and Programs |
| **Traffic Design Engineers, Contracts and Estimates, State Maintenance Engineer** | Documents the life-cycle Cost of the pavement marking |
| **Traffic Design Engineers, State Highway Safety Engineer** | Compiles Statewide Pavement Marking Conditions and Programs, Financial Plan, and Investment Plan and generates the draft document. |
| **WYDOT executive staff provides guidance and approves the PMMP** | |




*LRTP= Long Range Transportation Plan; STIP= State Transportation Improvement Program

**Figure 45. Flowchart. WYDOT PMMP Process.**

## III. Statewide Pavement Marking Inventory, Conditions, and Programs

The Wyoming Department of Transportation (WYDOT) manages and maintains 6,806 miles of roadway in the state of Wyoming, which are distributed amongst five engineering districts, as shown in Figure 46.

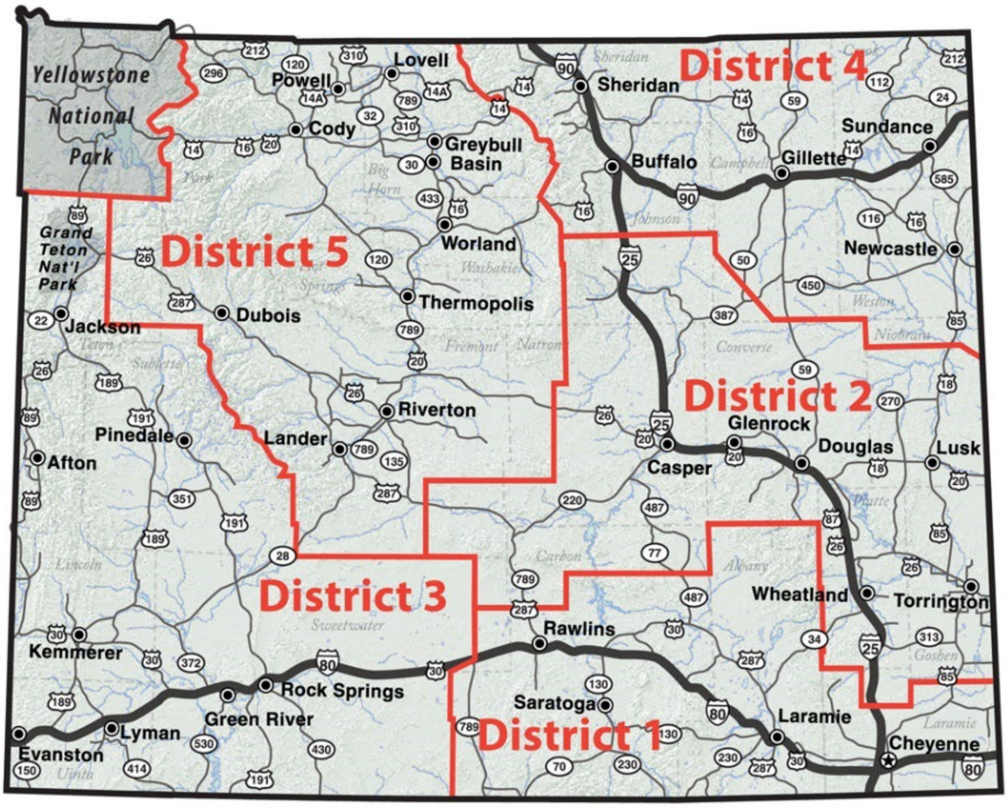



**Figure 46. Map. Wyoming Department of Transportation engineering districts (WYDOT, 2023).**

The Pavement Marking Management System manages the inventory and condition of WYDOT-maintained roads. These roadways include the interstate National Highway System (NHS), the non-interstate NHS, and non-NHS systems. As seen in Figure 47, WYDOT divides its road network into three categories:

**Interstates:** High-speed, typically four-lane, divided, and controlled access roadways that carry the highest traffic volumes and the most freight load.

**Non-Interstate NHS:** Federally designated roadways that are functionally classified as principal arterials and expressways but not as interstates.

**Non-NHS:** The remaining roadways that th state manages.

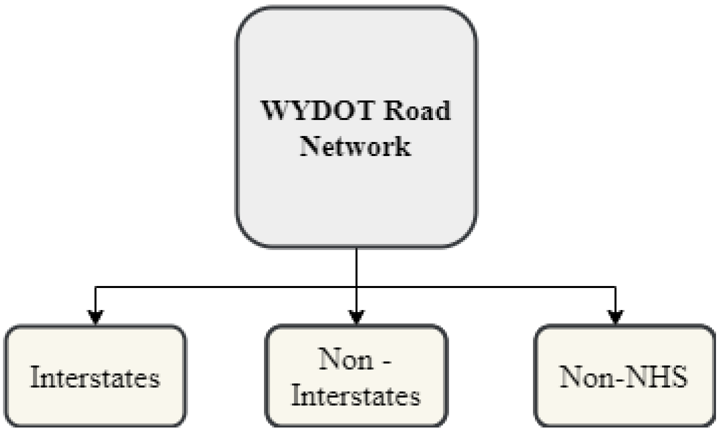



**Figure 47. Flowchart. WYDOT Road Network Classifications.**

## Pavement Marking Inventory and Condition Assessment

WYDOT manages 6,806 centerline miles of the state-owned highway network.

The Wyoming state-owned highway network consists of 6,806 centerline miles, including NHS mileage owned or controlled by either the federal or local governments, of which WYDOT manages only 6,806 centerline miles. WYDOT owns roads such as interstate ramps, service roads, frontage roads, and turnouts that are not measured as part of the state-owned highway system or actively managed.

To assess pavement marking conditions using the PMMP, WYDOT uses marking application history and highway classification to group pavement marking into pavement marking management sections. WYDOT identifies each section by location, direction (if interstate), and functional classification and analyzes each section based on current and projected conditions. Both contracted, and in-house data collection feed the PMMS and allow the determination of each pavement section's marking brightness and visibility.

WYDOT conducts pavement marking inventory and condition assessment as part of its pavement marking management program. The purpose of this assessment is to gather information on the location, type, and condition of pavement markings, such as lane lines, crosswalks, and symbols, on state highways and roads. This information is used to prioritize maintenance and preservation activities, allocate resources, and ensure that pavement markings are effective in guiding and directing road users. The assessment is typically done using visual inspection and measurement techniques, and the results are recorded and analyzed to determine the overall condition of the pavement markings.

**Pavement Marking Management Objectives**

The following pavement marking management objectives are fully functional in the PMMP:

a) Providing information to allow effective selection and design of future installation projects,
b) Estimating future conditions versus funding scenarios accurately to evaluate current pavement marking funding strategies, and
c) Displaying analysis results in understandable formats to allow WYDOT executive staff to easily interpret the information.

Data on pavement marking should be stored and available for decision-makers and planners to access when necessary. Project selections are based on WYDOT's PMMP as part of its asset management program, which recommends projects for each district. This preservation strategy maximizes future network conditions based on anticipated funding levels. The pavement marking management plan template aims to maintain existing pavement markings through timely installation and limit the pavement markings from reaching "poor/unacceptable" conditions. In Wyoming, pavement marking materials are budgeted annually by the state engineers and delivered to the district by the vendors via a statewide contract produced by the main office.

WYDOT developed its Transportation Asset Management Plan (TAMP) in response to the national highway performance program required under the MAP-21 Act. To further develop a pavement marking management plan (PMMP) template for the state, a survey was conducted by the Wyoming Technology Transfer (WYT2) Center to gather information about the current pavement marking striping and management practices of the five districts in Wyoming. The survey results were used to summarize the findings and develop the PMMP for the WYDOT.

**Risks to WYDOT Pavement Marking**

WYDOT manages pavement marking based on a risk-based approach, classifying routes based on importance and traffic volume. Due to funding constraints, WYDOT's approach to pavement marking is reactive and focuses on minimizing inconvenience caused by failures rather than preventing them from happening. Although some areas with higher than usual natural and environmental risks receive additional monitoring, WYDOT is unable to address a significant percentage of existing risks with preventative measures and still maintain a functioning transportation system.
The state's transportation system is dispersed over a large area, and WYDOT has shifted from a highway improvement program to an asset management program to slow down the decline of the system.

All the current funding scenarios use an optimized system that will incorporate a mixture of treatments to maximize the benefit to cost for the Pavement marking in interstate, non-interstate NHS, and non-NHS systems.

**Pavement Marking Management Measures**

In terms of pavement marking visibility, there are two aspects to consider: daytime and nighttime visibility. Daytime visibility is determined by a marking's color, intactness, and wear and can be evaluated subjectively through methods such as visual inspection. On the other hand, nighttime visibility relies on a marking's ability to reflect light and is measured by retroreflectivity. Overall, the performance and serviceability of pavement marking materials are evaluated by their retroreflectivity, which is described as a ratio of the intensity of light returned in the driver's direction to the intensity of their vehicle's headlights. In simple words, retroreflectivity measures how well the pavement marking is visible to road users. Retroreflectivity is expressed in units of millicandelas per meter square per lux (mcd/$m^2$/lux). Retroreflectivity is often used as a surrogate measure of durability, and agencies set minimum retroreflectivity thresholds to determine when reapplication is needed.

The Manual on Uniform Traffic Control Devices (MUTCD) requires the pavement markings to be visible at night and retroreflective unless ambient illumination provides suitable visibility (MUTCD 2022). On August 5, 2022, the Federal Highway Administration (FHWA) published a final rule about pavement marking retroreflectivity. This rule incorporated a standard for maintaining minimum pavement marking retroreflectivity levels. According to this new standard, the $R_L$ of longitudinal pavement marking must be at or above 50 mcd/$m^2$/lux for a speed limit of ≥ 35 mph and 100 mcd/$m^2$/lux or above for a posted speed limit ≥70 mph (FHWA 2022). Although FHWA recommended the new standard for minimum retroreflectivity value for restriping, various DOTs (i.e., Department of Transportation) use their own policies for restriping. Since pavement marking retroreflectivity differs significantly by location, pavement marking type, pavement surface, climate, and traffic (FHWA 2022). An effective pavement marking management plan template could save resources and improve driver safety. Therefore, a comprehensive idea of factors affecting of retroreflectivity is essential to propose an effective management plan.

Retroreflectivity has been used as a key indicator in investigating pavement marking performance (FHWA 2022). Small glass beads are applied to binder materials to make the pavement marking retroreflective. Glass beads are applied in such a way that they are partially embedded and partially exposed. If the beads are affected or worn out of the binder material, the retroreflectivity will deteriorate even though the marking may still be present (FHWA 2022).

Pavement marking Retroreflectivity is WYDOT's pavement marking health measure, and it is currently the main driverfor project selection.

WYDOT evaluates Pavement marking conditions using retroreflectivity values from 5 different categories that provide a relative comparison of different markings. Pavement marking retroreflectivity is classified as Good, Pass, Marginal, Bad, and Fail. White and Yellow Pavement marking retroreflectivity levels varied differently because these two colors significantly differed in data trending characteristics. Qualitative and quantitative descriptions of the five levels of retroreflectivity are:

- Good: Meets or exceeds the minimum retroreflectivity levels.
- Pass: Meets the minimum retroreflectivity levels.
- Marginal: Approaching the minimum retroreflectivity levels.
- Bad: Below the minimum retroreflectivity levels but still visible.
- Fail: Below the minimum retroreflectivity levels and not visible.

**Table 31. Retroreflectivity Classifications and Values used by WYDOT.**

| Pavement Marking Retroreflectivity Qualitative level | Retroreflectivity of Yellow marking (mcd/m$^2$/lux) | Retroreflectivity of White Marking (mcd/m$^2$/lux) |
|---|---|---|
| Good | 200+ | 250+ |
| Pass | 150-200 | 175-250 |
| Marginal | 100-150 | 125-175 |
| Bad | 60-100 | 80-125 |
| Fail | 50-60 | 50-80 |

These models predict the change in pavement marking retroreflectivity (PMR) as existing conditions are projected into the future. When restriping is applied to a given section, the PMR is reset to a pre-determined level until the collection of new data. The various future restriping affects the models in a wide range of ways, such as creating a steeper deterioration rate for short-term restriping strategies and lengthening the curve for more robust strategies. WYDOT's PMMP includes a feature to compare actual data condition points to the performance models. In most cases, the model is conservative compared to the actual data points (i.e., the data points lie underneath the curve). These models are set up this way to account for annual maintenance that is not directly shown in the pavement marking module. All curves use the general form of steepening rates of deterioration with age.

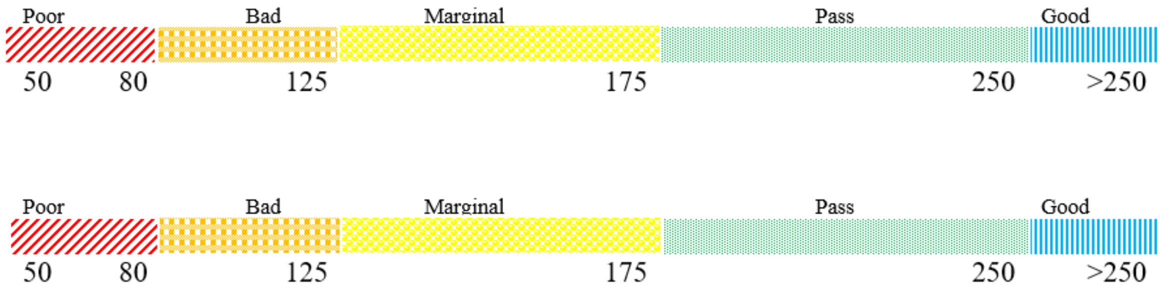



**Figure 48. Illustration. Retroreflectivity Index based on retroreflectivity values in millicandelas per meter square per lux (mcd/m²/lux).**

Table 33 summarizes Pavement Inventory Mileage by ownership of five different districts, and Figure 49 shows the total pavement inventory of Wyoming.

**Table 32. 2018 Pavement Inventory**

| Wyoming Pavement Inventory (Ownership based on Centerline Miles) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | District 1 | District 2 | District 3 | District 4 | District 5 | Yellowstone | Total |
| **NHS** | | | | | | | |
| Interstate | 247 | 241 | 187 | 238 | - | - | 913 |
| Non-Interstate NHS | 111 | 515 | 392 | 315 | 758 | - | 2,091 |
| Non-WYDOT NHS | - | - | 55 | - | 1 | 6 | 62 |
| Total NHS | **358** | **757** | **634** | **553** | **759** | **6** | **3,066** |
| **Non-NHS** | | | | | | | |
| State | 773 | 795 | 815 | 745 | 612 | - | 3,740 |
| Total Non-NHS | **773** | **795** | **815** | **745** | **612** | - | **3,740** |
| | | | | | | | |
| TOTALS | **1,131** | **1,552** | **1,449** | **1,297** | **1,371** | **6** | **6,806** |

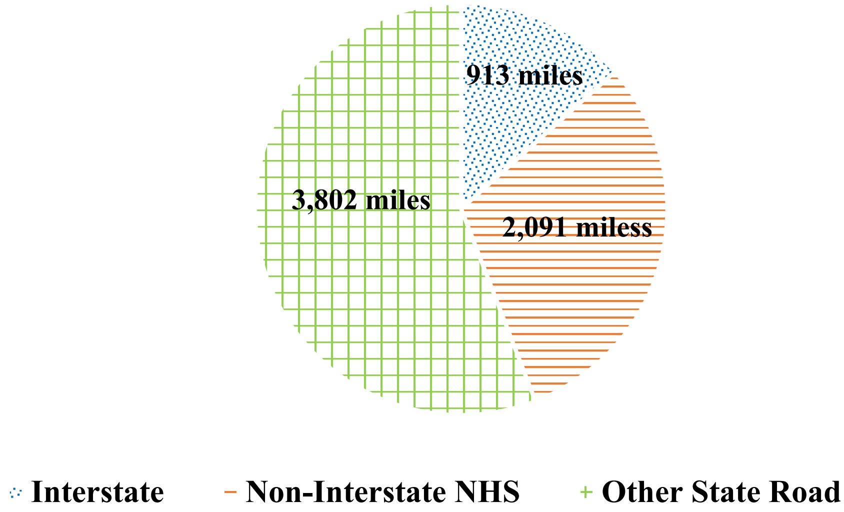



**Figure 49. Chart. Wyoming Pavement Inventory.**

The five districts in Wyoming have different inventories of pavement marking materials, as shown in Table 34. District 1 had the highest consumption of 58,500 gallons of white paint and 468,000 pounds of beads. District 3 consumed 45,000 gallons of white paint and 28,500 gallons of yellow paint. Districts 2 and 4 did not respond when asked about their inventory. District 5 reported having 31,500 gallons of white paint, 28,500 gallons of yellow paint, and 396,000 pounds of beads.

**Table 33. Approximate quantity and units of different district's inventory.**

| District | White Paint | Yellow Paint | Beads |
|---|---|---|---|
| 1 | 58,500 gallons | No Response | 468,000 pounds |
| 2 | No response | No response | No response |
| 3 | 45,000 gallons | 28,500 gallons | No Response |
| 4 | No response | No response | No response |
| 5 | 31,500 gallons | 28,500 gallons | 396,000 pounds |

For pavement marking, desired conditions for each road category are specified in terms of the percentage of lane miles with each qualitative category of pavement marking retroreflectivity (Olsen et al. 2018). The lane mile is used as a unit of measurement to establish the length and number of lanes on a specific highway or road. It is determined by multiplying the road's centerline mileage by its number of lanes. The pass mile is also sometimes used to calculate the length of pavement marking. The pass mile represents the total distance traveled by vehicles on the road section.

Table 35 shows the annual miles of pavement marking done by each district and the time it took to complete those miles. Districts 1 and 4 did approximately 4,000 pass miles annually and took six to eight months to complete those miles. District 2 did the annual miles of 1,537 miles in seven to eight months, and District 4 completed approximately 4000 miles in seven months. 6,200 to 7,300 lane miles were done by District 3, and it took eight months to complete those miles.

**Table 34. Annual miles of pavement marking and time taken to do those miles by different districts.**

| District | Miles | Time |
|---|---|---|
| 1 | 4,000 Pass miles | 6 months |
| 2 | 1,537 miles | 7-8 months |
| 3 | 6,200 to 7,300 lane miles | 8 months |
| 4 | 4,000+ Pass miles | 8 months |
| 5 | 4,100 to 4,200 miles | 7 months |

The Pavement Marking Management System Analysis Report contains three sections addressing (1) network-level analysis, (2) inventory, and (3) project-level analysis. A further discussion of these sections is found below.

Network level analysis determines current and projected segment information. This analysis accounts for the current State Transportation Improvement Program (STIP) and budget projections—including inflation, treatment type, current road marking conditions, and performance modeling—to create projections for proposed work for a 5-year projection.

Inventory provides a general overview of each management section detailing pavement marking conditions, traffic level, construction and marking history, and STIP status. Pavement marking management sections are also identified for degradation of marking concerns.

Project level analysis sets funding recommendations for each WYDOT district according to WYDOT's asset management philosophy. This analysis lists the recommended pavement marking funding strategy for optimizing funds for restriping in each district to aid district managers in selecting projects for the STIP. These candidates are a projected condition for the last year of the STIP and are determined by creating an unlimited budget to bring forward all recommended treatments. The recommended pavement funding strategy suggests mileage counts for each district and functional classifications that should be met on a rolling average for the six-year STIP. These values are determined based on percentages of traffic and each district's total miles and total miles of suggested treatment candidates.

**Pavement Marking Performance Monitoring System**

Agencies should base requirements for pavement marking visibility not on roadway characteristics or geometry but on drivers' need for visual information to maneuver safely and effectively. Therefore, methodologies to determine drivers' retroreflectivity needs should be incorporated into Pavement Marking Management Systems (PMMS). Methods to investigate human factors in drivers' retroreflectivity needs include

Pavement marking performance can be monitored in two ways:

- Subjective evaluation
- Objective evaluation

Retroreflectivity can be measured subjectively through visual inspections or driver feedback or objectively through vehicle-mounted or handheld retro reflectometers. Subjective evaluation of pavement marking presence is common, in which image processing methods are emerging as alternatives. Novel methods such as laser scanning and image analysis have the potential to increase data collection speed and efficiency. However, it is advisable to explore new methods after proper vetting. All three primary performance measures (presence, retroreflectivity, and durability) have subjective, objective, and time-dependent aspects. Retroreflectivity is mostly objective, while presence is mostly subjective but can be quantified through innovative methods. Durability is the pavement marking's ability to maintain presence and retroreflectivity over time.

WYDOT follows the final rule of FHWA for maintaining minimum retroreflectivity levels for pavement markings. WYDOT uses Laserlux Mobile Retroreflectometer (LLG7), the newest and most versatile vehicle-mounted retroreflectometer for pavement markings. The LLG7 is installed in a testing vehicle, traveling at the speed of the traffic stream. This test follows 30m (98ft) geometry, which is required per (ASTM E 1710) (ASTM 2018). The measurement geometry of the instrument is based on a viewing distance of 30m (98ft), a headlight mounting height of 0.65m (2.13ft) directly over the stripe, and an eye height of 1.2m (3.94ft) directly over the stripe. The instrument is calibrated at each test section before starting data collection. A global positioning system (GPS) device was used to record the coordinates of each data point of the test location. The pavement stripe nomenclature included the color (White and Yellow) followed by the line type (edge line, center line, and lane line). For pavement marking, WYDOT is developing new analytics that will represent the exact conditions that FHWA requires for pavement marking retroreflectivity. This new analytics system will also develop a new way of managing the existing pavement sections. WYDOT will be able to manage the existing sections and suggest restriping based on optimizing the overall conditions from the target ranges set in the PMMS. To meet the federal requirements, WYDOT began collecting seasonal data on the different highways in 2021.

As WYDOT continues to develop the new analytics, the target values for pavement marking conditions will be determined and be an exact representation of projections for pavement marking retroreflectivity reporting. Highways will be classified as “Good,” “Pass,” “Marginal,” “Bad,” or “Fail” and will have a broader range of “Above Marginal” and “Below Marginal” categories than WYDOT’s current analytics. WYDOT remains optimistic about the upcoming changes and believes this system will prove beneficial and effective for future analyses and management purposes.

**Pavement Marking Performance Gap Analysis**

1. **State Pavement Marking Performance Measures**

Performance measures and targets are crucial in achieving policy goals and objectives related to an asset. NCHRP Synthesis 551 offers guidance on identifying them (Systematics et al. 2006). Available measures should be categorized by context and evaluated based on pre-defined criteria such as mobility, safety, and environmental impact. Evaluation criteria can include connecting policies to objectives, being sensitive to changes, and having wide acceptance among professionals (Sassani et al. 2021; Systematics 2009; Systematics et al. 2006).

- Linking policies to objectives by emphasizing results rather than outputs.
- Reflecting the long-term features of assets, making them suitable for life-cycle analysis and performance models.
- Sensitivity to changes so that variations can be traced back to their source.
- Obtaining measures with reasonable effort.
- Objectivity, simplicity, and quantifiability in measurement.
- Applicability to performance prediction models, especially for asset conditions.
- Professional acceptance and predictability.
- Compatibility with existing resources, including standards and specifications.
- Measurability with reasonable precision and accuracy.
- User experience reflection.
- Interpretation consistency.
- A benefit-to-cost ratio greater than 1.
- Reliability of data collection practices.
- Representation of controllable asset characteristics.

- Versatility in the application.

It is desirable to have a performance metric that applies to several assets or serves a variety of objectives as opposed to one that is just applicable to one asset or offers a single sort of information. Organizations should establish their priorities and choose performance metrics in accordance with those priorities, keeping in mind that various assets could call for various requirements. The two main performance parameters for pavement marking are durability and visibility, such that pavement markings should be in a state that enables drivers to easily see them at any time of the day (Carlson et al. 2013). Durability is determined by elements relating to the qualities of the pavement marking or the conditions under which it is used, while visibility is measured by presence and retroreflectivity. Durability and visibility are performance indicators. Cost and environmental effects are two other measures that are suggested for PMMS. Therefore, the performance measures are divided into two categories: (a) primary measures, which include durability, visibility, and retroreflectivity; and (b) secondary measures, which include cost and environmental impact.

2. State Pavement Marking Targets

WYDOT establishes its state pavement marking targets based on the MUTCD and the guidance provided by the FHWA. The MUTCD is the national standard for all traffic control devices, including pavement markings, and provides detailed specifications for materials, application, and maintenance of pavement markings. The FHWA provides additional guidance on best practices for pavement marking programs and helps states establish targets that meet or exceed the minimum standards set by the MUTCD.

WYDOT considers the MUTCD recommendations when setting its own state pavement marking targets. This includes minimum retroreflectivity levels, maximum allowable fade or wear, and minimum time between reapplication of markings, as well as guidelines for inspection and maintenance. The department also considers local conditions, such as weather and road characteristics, when determining its targets to ensure that pavement markings are effective and visible to all road users in Wyoming. WYDOT regularly assesses its Pavement marking program to ensure that it is meeting these targets and taking appropriate action to address any deficiencies.

## 3. Pavement Marking Condition Goals

The goal of the pavement marking management plan template in Wyoming is to maintain the existing pavement markings by timely installation and prevent them from reaching “Bad/Fail” conditions.
The pavement marking condition goals for the WYDOT centered around ensuring the safety and efficiency of the roadways in the state. Some common goals for Pavement marking conditions for WYDOT include:

- Visibility: WYDOT would aim to ensure that the pavement markings are always visible and easily recognizable to drivers, regardless of weather or lighting conditions.
- Durability: WYDOT would aim to ensure that the pavement markings are durable and can withstand the wear and tear of normal driving conditions.
- Longevity: WYDOT would aim to ensure that the pavement markings are long-lasting and can retain their visibility and durability for an extended period.
- Consistency: WYDOT would aim to ensure that the pavement markings are consistent throughout the state, with similar materials, colors, and sizes being used on all roads.
- Compliance with Regulations: WYDOT would aim to ensure that the pavement markings meet all relevant federal, state, and local regulations and guidelines.

These goals guide the pavement marking performance-gap analysis process for WYDOT and inform the recommendations for improvements to the pavement marking conditions in the state.

## 4. Current Pavement Marking Conditions

The Pavement marking conditions vary depending on various factors, such as the age of the markings, the type of materials used, and the weather conditions in the area. However, pavement markings maintained by WYDOT are designed to be visible and durable under normal driving conditions. WYDOT uses a variety of materials for pavement markings, including paint, thermoplastic, and preformed tapes, depending on the specific needs of each roadway. It is worth noting that conditions can change over time, so marking conditions vary from month to month.

## Pavement Marking Life-Cycle Cost

Life-cycle cost (LCC) should be incorporated in WYDOT's Pavement marking management performance modeling software by calculating future worth conditions of pavement (for more information on the components of life-cycle cost, see Section V). Historic condition versus age data forms the backbone of WYDOT's Pavement marking performance models. WYDOT measures the condition of each management segment biennially and continuously maintains a detailed construction treatment history. Grouping similar pavement types and traffic levels provides a detailed set of data points used to create deterioration curve models. A pavement marking module in Agile Assets should be added to calculate annual changes in condition for future years based on a system-wide, incremental cost methodology. The system allows the entry of annual budget amounts for various future treatment types. Further, the system uses average costs per square yard for the different treatment types; the costs are continually reviewed for accuracy. Regarding the lowest LCC, WYDOT has determined Pavement marking types provide the lowest cost per added life. Pavement marking materials are selected to optimize the total life of Wyoming's road sections while considering minimizing construction activity and the corresponding inconvenience to the driving public.

The total cost of waterborne pavement marking is shown in Table 36, and the total cost was

**Table 35. The Cost associated with Traffic Striping by Waterborne Material.**

| Year | Material cost ($) | Equipment cost ($) | Labor cost ($) | Other costs ($) | Total cost ($) | Total pass mile | Total cost/mile ($) |
|---|---|---|---|---|---|---|---|
| 2018 | 193943 | 33030 | 37209 | 2425 | 266606 | 1457 | 183 |
| 2019 | 221635 | 42283 | 40768 | 335 | 305020 | 1848 | 165 |
| 2020 | 237203 | 41332 | 52368 | 1009 | 331912 | 1606 | 207 |
| 2021 | 171931 | 50796 | 44980 | 7521 | 275229 | 1346 | 204 |
| 2022 | 174558 | 53972 | 38852 | 862 | 268243 | 1021 | 263 |

WYDOT's basic optimization approach allows for more durable material on higher-traffic roadways. In each district, a minimum number of miles per year must be restriped using durable material set up in the recommended asset management funding strategy. The management system selects project candidates using benefit-cost analysis (BCA).

## Maintenance

WYDOT's pavement marking maintenance work provides the just- in-time repairs required to ensure a serviceable system exists and is critical in providing the lowest life-cycle costs.

As part of WYDOT's Pavement marking management approach, maintenance crews actively perform routine repairs on all WYDOT-maintained roadways. The pavement marking deterioration models include the effects of the surface maintenance that WYDOT performs; therefore, maintenance is considered a critical component of pavement marking's life-cycle costs. Maintenance work is performed by contract and in-house.

### Deterioriation Rate

The retroreflectivity of newly applied pavement markings is influenced by various factors as follows:

- Glass beads: the type and amount of glass beads used, the embedment depth, the retroreflectivity index, the size and clarity of the beads, etc.
- Binder material: the type of binder material, the thickness of the material, the pavement surface roughness, etc.
- Other factors: Pavement friction, dirt or other blinding materials, and the marking level can also affect retroreflectivity.

The size and type of the beads play an important role. The color of the binder material can also have an impact, with yellow markings having lower retroreflectivity than white markings in newly applied pavement markings.

Various factors, such as the geometric location of roads (urban or rural), horizontal curves, traffic demand, snowplow operations, and age of the marking, can influence the deterioration rate and future condition of pavement markings. Higher traffic volumes, truck traffic, and snowplow operations can increase pavement marking deterioration rates, and insufficient funding can cause further deterioration and worsen pavement marking conditions, leading to long-term effects. These factors should be considered when determining the funding level needed to maintain the pavement marking system and selecting future installation strategies.

A lack of sufficient funding can cause increased deterioration rates and worsening Pavement marking conditions. To understand current and future demands on Wyoming's systems, accurately estimated current and projected traffic levels and vehicle types are important. WYDOT's Planning Program has approximately 125 permanent automated traffic counter installations throughout the state that continuously gathers about 170 daily traffic counts. Traffic surveys collect and analyze this data and continue to monitor and predict future traffic growth. Same trend—a sharp increase in traffic as the field is developed, followed by a moderate to slight decline once development is completed. Major factors affecting Pavement marking durability are shown in Figure 6.

Interstate 80 passes through Wyoming, carrying traffic from California to New York while serving as a major truck route for the United States. The percentage of truck traffic on Wyoming's portion of I-80 is among the highest in thenation—with truck traffic at 47 percent of all traffic. Traffic volumes on Wyoming's portion of I-80 average 7,500 to 26,000 vehicles per day. Traffic on I-80 has increased by 1.6 percent annually for the past 20 years, while truck traffic has increased by 1.8 percent annually. The increase in truck traffic has significantly impacted I-80 Pavement marking deterioration rates and has created a substantial drain on funding, as noted in the previous section.

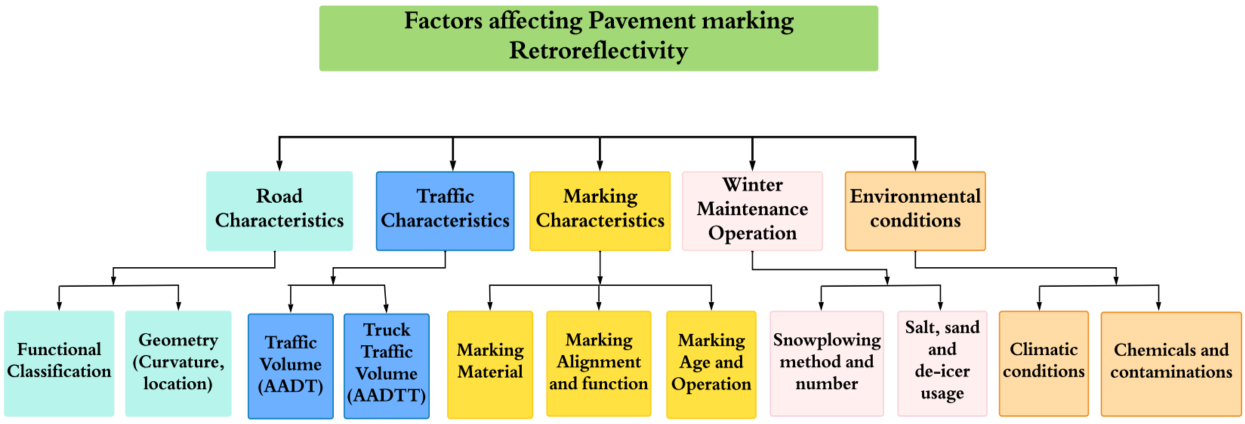



**Figure 50. Flowchart. Significant factors affecting pavement marking durability and retroreflectivity.**

**Financial Assessment**

The PMMS analytics projected that continued use of past spending strategies would cause all road systems to deteriorate rapidly.

Pavement Marking Management's goal is to maintain pavement marking conditions above the marginal level within all functional classifications, but current funding levels are insufficient to accomplish this goal for pavements. The PMMS projected that all road systems would deteriorate at past spending levels, so WYDOT increased pavement marking management funding.

WYDOT continues to seek additional funding to maintain pavements marking condition above marginal level

WYDOT's PMMP estimates pavement marking deteriorating conditions on interstate highways, non-interstate NHS, and non-NHS routes. The Interstate System is not being ignored; rather, the substantially higher number of trucks, especially on I-80, causes a deterioration rate that is much steeper than the other systems. There are insufficient funds to keep 913 centerline miles of interstate in the same condition without completely sacrificing the other WYDOT-maintained system's 5,893 centerline miles of pavement. Additionally, there is a significantly high deterioration rate on the non-NHS routes due to insufficient funds related to ownership.

**Pavement Marking Work Types**

Pavement marking maintenance work involves restoring or preserving the visibility and reflectivity of pavement markings on roads and highways. This work is important for ensuring the safety of drivers and improving the overall efficiency of the transportation network. Some common pavement marking maintenance activities include:

- Cleaning: This involves removing dirt, debris, or other contaminants from the surface of the pavement markings. This can be done using high-pressure water, abrasive blasting, or other methods.

- Touch-up: This involves applying small amounts of paint or other material to areas where the markings have worn away or faded.

- Restriping: This involves applying new markings over the existing markings to restore visibility and reflectivity. This is typically done when the markings have become severely worn or faded.

- Repair: This involves fixing damaged or missing pavement markings, such as by filling cracks or replacing missing sections.

- Replacing: This involves removing the existing markings and applying new markings to the pavement. This may be necessary if the existing markings have become too damaged or faded to be repaired.

-Pavement marking maintenance activities are typically performed on a routine basis, such as on an annual or bi-annual schedule, to ensure that the markings remain visible and effective in guiding drivers. The frequency and extent of pavement marking maintenance work will depend on a variety of factors, including traffic volume, climate conditions, and the age and condition of the markings.

**Risks to WYDOT Pavement Markings**

Risk-Based Pavement Marking Management: Managing Risks to pavement marking suggests that the act of classifying routes by importance based on economic generators, traffic counts, or near population centers is a form of risk management. WYDOT makes trade-offs in its management of pavement marking conditions based on the interstate, non-interstate NHS, and non-NHS, recognizing that more risk is being taken on the lower trafficked non-NHS roads and, therefore, allows their overall condition to be lower than the others.

Due to existing funding constraints, WYDOT's approach to monitoring risk is reactive. Although some areas with higher than usual natural and environmental risks receive additional monitoring, WYDOT is unable to address a significant percentage of existing risks with preventative measures and still maintain a functioning transportation system. Generally, WYDOT finds that reacting quickly and effectively to failures after they happen is a more effective use of funding than attempting to prevent failures from happening., WYDOT responds effectively and efficiently to minimize the inconvenience due to bad Pavement marking conditions.

The transportation system in Wyoming is dispersed over a large geographical area with little redundancy in routing or capacity. Due to funding limitations, WYDOT is presently unable to maintain the existing transportation system in its existing condition; consequently, WYDOT has moved from a highway improvement program to an asset management program in an effort to slow the decline of the state's transportation system.

## IV. Pavement Marking Life-Cycle Cost Analysis

Pavement marking life-cycle cost analysis is a comprehensive evaluation of the costs associated with different Pavement marking options over the entire life of the marking, from initial installation to eventual removal. This analysis considers not only the initial cost of the marking, but also ongoing maintenance costs, replacement costs, and costs associated with any potential safety or operational issues that may arise.

WYDOT uses pavement marking life-cycle cost analysis to determine the most cost-effective solution for its pavement marking program. This includes considering the different types of pavement marking materials and systems, such as waterborne paint, thermoplastic, and preformed tape, and evaluating their respective life-cycle costs.

The analysis helps the department determine the best use of its limited resources, prioritize maintenance and preservation activities, and make informed decisions about the future of its pavement marking program.

The results of the pavement marking life-cycle cost analysis are used to guide the department's decision-making process and help ensure that its pavement marking program is sustainable, efficient, and effective in improving road safety for all users.

To establish a framework for LCCA within WYDOT, identifying the three areas of LCCA (as shown in Figure 51) and how WYDOT is addressing these areas is important. The three areas are described below.

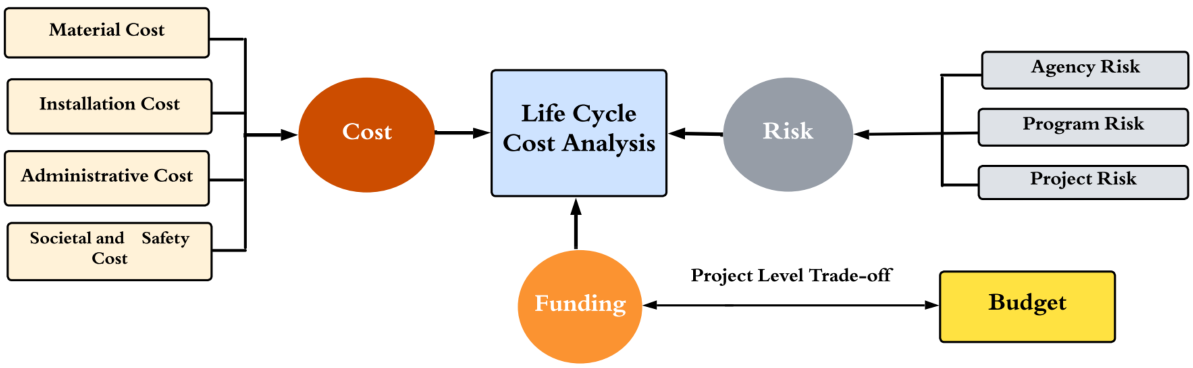



**Figure 51. Flowchart. Required Areas for Establishing Wyoming's LCCA.**

### Costs

The PMMP produces recommended budget amounts based on performance targets mentioned before. Trade-offs are conducted at the project level between functional classifications.

The evaluation of pavement markings in terms of their life-cycle cost is an essential aspect of contemporary asset management. This involves analyzing the installation costs and estimated service life of the markings, considering factors such as the use of durable marking materials and additional costs associated with restriping and maintenance. Although the benefits of performing a life-cycle cost analysis (LCCA) for pavement markings are numerous, such analysis is not widely used by transportation agencies, with only a small percentage of agencies conducting benefit-cost LCCA in pavement marking management.

The PMMP recommends budget amounts based on performance targets. Trade-offs occur at the project level, considering functional classifications and factors like installation costs, service life, and additional costs associated with restriping and maintenance. The factors considered in an LCCA for pavement markings are classified as follows.

- Primary Costs
    - Material Costs
    - Cost of pre-striping preparations
    - Direct installation costs
    - Grooving Costs (when grooving is performed)
    - Costs imposed by special requirements or conditions (when there is a need for wet retro requirements, warranty, etc.)
    - Marking Removal Costs (when removal is done before applying the new markings)

- Secondary Costs
    - Administrative Costs
    - Organizational Costs
    - Costs related to societal effects of pavement markings operations

        -Delay Costs
        -Crash Costs caused by marking operations
        - Costs related to decreased road safety because of poor or ineffective marking performance.

Durable Pavement marking materials, although more expensive initially, have the potential to provide long-term benefits through extended restriping intervals and reduced maintenance costs.

**Risks**

FHWA's report and the "Risk-Based Transportation Asset Management: Evaluating Threats, Capitalizing on Opportunities" suggests that risk exists at three levels: (1) agency, (2) program, and (3) project, as seen in Figure 51. In this Figure, the Agency Risk, the highest risk level, is the lack of adequate funding to preserve and maintain the existing pavement marking. Where the Program Risk, the next risk level, is common to clusters of projects, programs, or entire business units. These risks are usually addressed by or mitigated during the project design and development process and fall into one or more of three broad categories: (1) natural, (2) environmental, and (3) man-made. Finally, Project Risk, the third and lowest risk level, is involved in bringing individual projects to contract.

### Funding for Pavement Marking

Table 37 shows the dollar amount spent annually on striping and marking by different districts. It can be seen from Table 36 that approximately \$1.1 to \$1.4 million was spent annually by different districts. However, district 4 did not respond. As shown in Table 38, all the districts responded that the future budget for pavement marking should be increased. District 1 recommended an increase of 30 to 40 percent minimum, while District 3 recommended an increase of \$1 million. District 5, on the other hand, recommended an increase of 50 percentage.

**Table 36. The approximate dollar amount spent annually on striping and marking by different districts.**

| District | Answer |
|---|---|
| 1 | \$1.2 million |
| 2 | \$1.2 million |
| 3 | \$1.1 million |
| 4 | No response |
| 5 | \$1.4 million |

**Table 37. Future budget for Pavement marking by different districts.**

| District | Answer | How much |
|---|---|---|
| 1 | Increase | 30-40 minimum |
| 2 | Increase | NA |
| 3 | Increase | \$1 million |
| 4 | Increase | NA |
| 5 | Increase | 50 percent |

Table 39 shows the effects of increased pricing of pavement marking materials. It can be seen in Table 9 that increased pricing did not impact Districts 4 and 5 yet, but the other three districts were impacted by increased pricing. For example, District 1 specified that the increased pricing would result in fewer lane miles being stripped. District 2 noted that the quality and durability of pavement marking would be compromised because of increased pricing. Also, District 3 mentioned the shortage of Pavement marking materials as well as not being able to meet minimum retroreflectivity standards.

**Table 38. Effects of increased pricing of Pavement marking materials in different districts.**

| District | Answer |
|---|---|
| 1 | Fewer lane miles striped and depreciated markings |
| 2 | longer before the road is rehabilitated, and the decrease in surface quality reflects in the paint quality and durability |
| 3 | Potential shortage of pavement marking availability and not being able to meet minimum reflectivity standards and fewer roads with paint. |
| 4 | It hasn't directly impacted D4 yet, but I foresee it being an issue in the future. D4 will most likely need to cut work in certain areas to come in under budget. |
| 5 | No effect yet may see a reduction in the quantity of materials. |

### Service Life of Pavement Marking

The objective of PMMP is to make efficient use of available resources to keep all the pavement markings under its jurisdiction in good condition of service. Different districts were asked how they determine the service lives of pavement marking. Table 40 summarizes the results. It can be seen from Table 39 that Districts 1, 2, and 5 did not use service life. However, Districts 1, 3, and 4 mentioned that they determined the service life of Pavement marking from the district engineer's experience. Districts 2 and 3 used a pre-determined schedule to determine the service life of pavement marking. District 3, on the other hand, used all the categories mentioned in the table to determine the service life of pavement marking.

**Table 40. Determination of service life of pavement marking by different districts.**

| District | From the District engineer's experience | Obtained from literature | District engineer's professional judgment | Manufacturer's data/recommendations | Pre-determined schedule | Doesn't use service life |
|---|---|---|---|---|---|---|
| 1 | ✓ | | | | | ✓ |
| 2 | | | | | ✓ | ✓ |
| 3 | ✓ | ✓ | ✓ | ✓ | ✓ | |
| 4 | ✓ | | | ✓ | | |
| 5 | | | | | | ✓ |

Table 41 and Table 42 show the estimation of the service life of pavement striping and markings in years for low and high-volume roads, respectively. It can be seen from Table 41 that non-epoxy-based paint had a service life of 1-2 years in low-volume roads, except for District 3. District 3 mentioned that the service life of both non-epoxy-based paint and epoxy with glass beads was 2-5 years on low-volume roads. It appears that thermoplastic had longer service life. Service life was 3-5 years for District 1, 4-7 years for District 3, and 5 years for District 5 when thermoplastic was considered. District 4 mentioned that the service life for epoxy-based paint was two years for low-volume roads. District 1 also used Methyl methacrylate (MMA), the service life of which was 3-5 years. Also, district 4 used hot liquid thermoplastic, which had a service life of 15-20 years.

**Table 39. District's estimate of the service life of pavement striping and markings in low-volume roads.**

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| Service life for low-volume roads in Years | | | | | |
|---|---|---|---|---|---|
| District | Paint (non-epoxy) | Epoxy-based paint | Paint/epoxy with glass beads | Thermoplastic | Other |
| 1 | 1-2 | N/A | N/A | 3-5 | Methyl methacrylate-MMA (3-5) |
| 2 | N/A | N/A | N/A | N/A | N/A |
| 3 | 2-5 | N/A | 2-5 | 4-7 | All materials in snowplow areas (1) |
| 4 | 1 | 2 | N/A | 5 | Hot liquid thermoplastic (15-20) |
| 5 | 1-2 | N/A | 1-2 | N/A | N/A |

Table 42 shows the service life of different Pavement marking striping for high-volume roads. The service life of epoxy-based paint with glass beads for District 1 was 2-3 years, whereas for District 3, it was 1-3 years, and for District 5, it was 1-2 years. Also, district 1 mentioned that the service life for thermoplastic was 2-3 years. The service life of thermoplastic was 5-8 years for District 2, 1-3 years for District 3, and 3 years for District 4. Again, the service life of paint (non-epoxy based) was 1-3 years for District 3, less than one year for District 4, and 1-2 years for District 5. The service life of MMA was 2-3 years for District 1, and the service life of hot liquid thermoplastic was 15-20 years for District 4. District 4 also mentioned that the service life of Epoxy-based paint was two years.

**Table 40. District's estimate of the service life of pavement striping and markings in high volume roads.**

| Service life for high volume roads in Years | | | | | |
|---|---|---|---|---|---|
| District | Paint (non-epoxy) | Epoxy-based paint | Paint/epoxy with glass beads | Thermoplastic | Other |
| 1 | N/A | N/A | 2-3 | 2-3 | MMA (2-3) |
| 2 | N/A | N/A | | 5-8 | |
| 3 | 1-3 | | 1-3 | 1-3 | All materials in snowplow areas (1) |
| 4 | <1 | 2 | N/A | 3 | Hot liquid thermoplastic (15-20) |
| 5 | 1-2 | | 1-2 | N/A | N/A |

### Valuation

WYDOT uses the modified Governmental Accounting Standards Board 34 (GASB 34) standard method for calculating the valuation of Wyoming's infrastructure assets; however, GASB 34 values are based on historical acquisition and construction costs and do not reflect current market valuation or replacement costs. While WYDOT reports GASB 34 information to FHWA, as required by law, WYDOT's management systems use actual or expected costs for calculating LCCAs.

## V. Performance-Gap Analysis

Pavement marking performance-gap analysis is the process of evaluating the gap between the expected performance of pavement markings and the actual performance in terms of visibility, durability, and longevity. The objective of the analysis is to identify areas for improvement and implement measures to enhance the performance of pavement markings and ensure safe and efficient roadways. The pavement marking performance-gap analysis process for PMMP involves the following steps:

- Data Collection: WYDOT collects data on the current pavement marking conditions on the roads in the state. This inventory includes information on the type of marking materials used, the age of the markings, and any reported issues with visibility or durability.
- Field Inspections: WYDOT conducts field inspections to assess the performance of the pavement markings. This involves observing the markings for issues such as fading, wear and tear, and any other signs of degradation.
- Analysis and Evaluation: WYDOT analyzes the data collected and evaluate the performance of the pavement markings. The department would compare the actual performance of the markings to the expected standards and identify areas for improvement.
- Consultation with Stakeholders: WYDOT consults with relevant stakeholders, such as road maintenance personnel, transportation departments, and local communities, to gather their input on the performance of the pavement markings.
- Recommendations for Improvement: Based on the analysis and evaluation, WYDOT makes recommendations for improvements to the Pavement marking performance in the state. This could include changes to the type of materials used, improved maintenance practices, or the implementation of new technologies.
- Implementation of Measures: WYDOT implements the measures recommended in the analysis to enhance the performance of the pavement

markings in the state. This could include repainting or replacing markings, updating maintenance practices, or implementing new technologies.

**Performance Targets**

For the purpose of Pavement marking management, WYDOT considers a State of Good Repair (SOGR) to be a condition in which its physical infrastructure assets (both individually and system-wide) are functioning according to design standards and expected service life and sustained through a systematic program of maintenance, preservation, and replacement, in order to provide a safe, high quality and efficient transportation system. WYDOT's targets for pavement marking are found in Sections III, Statewide Pavement Condition and Programs; these targets are fiscally constrained based on a trade-off analysis of what the management systems could maximize while still balancing other needs in the other goal areas. The method of measurement is also covered in these sections.

The targets are not to maintain the system in its existing condition forever. As the investment plan was developed, WYDOT made difficult decisions about the minimum levels of service the transportation system users need for a safe, high-quality, and efficient transportation system. WYDOT has a relatively fixed funding stream that is not indexed to inflation. In the short term of less than five years, the system should be able to maintain the existing condition, but the impact of inflation begins to compound in the mid-to-long-term projections. Pavement marking measures are covered in detail in Section III of this document.

Most projects that maintain or improve systems take many years from inception, through design, and being let to contract; therefore, evaluating the measures and setting targets annually is not effective or practical. Currently, WYDOT evaluates and sets targets every four years, but they may be evaluated more often depending on changes to funding levels.

The current investment plan allots adequate funds to maintain the pavement marking targets for the next ten years; consequently, no gaps exist between the desired targets and projected conditions.

**Effectiveness**

In Wyoming's case, effectiveness goals can be described as what is needed to "Provide a safe, high-quality, and efficient transportation system." WYDOT performs a biennial public survey to gather information about the public's perception of our operations and the transportation infrastructure's condition. From this survey and other inputs, WYDOT determines acceptable target levels.

WYDOT's effectiveness goal is to maintain the condition of Wyoming's transportation infrastructure at its current level. WYDOT continues to seek additional funds to maintain pavement marking conditions above the marginal level.

## VI. Financial Plan: Stip

State Transportation Improvement Plan (STIP) is usually a multi-year financial plan that outlines transportation projects and funding sources, and it may vary from year to year. WYDOT uses a corridor-based system for high-level analysis of Wyoming's transportation network. The major connecting routes are analyzed as contiguous routes to determine the deficiencies and needs of each individual sub-segment that makes up the corridor. This analysis is used to determine the items in a given segment that may be causing an impediment to the safe, efficient flow of traffic in the state. A corridor-based system revolves around the idea of creating a uniform and consistent experience when traveling from one location to another. Pavement marking management is used to optimize individual restriping strategies (contracted improvement projects) to the corridor analysis based on the physical needs of the corridor. Through an extensive public involvement process—with input from engineering studies, pavement marking management, long-range corridor plans, and the approval of the Transportation Commission—contract improvement projects are combined to create the STIP. This document forms the framework to track whether future investments meet the previously established goals.

Good management practices recognize that decision-makers must be given the information, resources, and authority to perform to the standards that the organization sets while also being held accountable for meeting those standards with limited resources and multiple worthy transportation needs vying for the same limited funding. These transportation needs can be defined as the difference (gap) between the infrastructure's desired condition state and its actual condition state. At some level, trade-offs must be made between multiple needs. For example, somehow, the cost and benefit of restriping an interstate approach marking must be weighed against the cost and benefit of restriping close to a rest area.

The district engineers perform the trade-off analysis between individual projects. Using their public information program, annual meetings with local governments, and input from program managers, the district engineers choose the projects that move into the fiscally constrained STIP. The district engineers are held accountable for ensuring the projected condition of pavement marking and safety within their districts are met while working within pre-determined funding constraints.

### Anticipated Funding Expenditures for 2023

In 2023, WYDOT expects to expend $417 million (almost 50 percent of available funding) on highway improvements and contract maintenance. For the year 2023, WYDOT anticipates annual highway improvement contract maintenance funding to average $150 million. The following chart (Figure 52) graphically illustrates how WYDOT expects to use the 2023 Transportation Commission allocation of revenue.

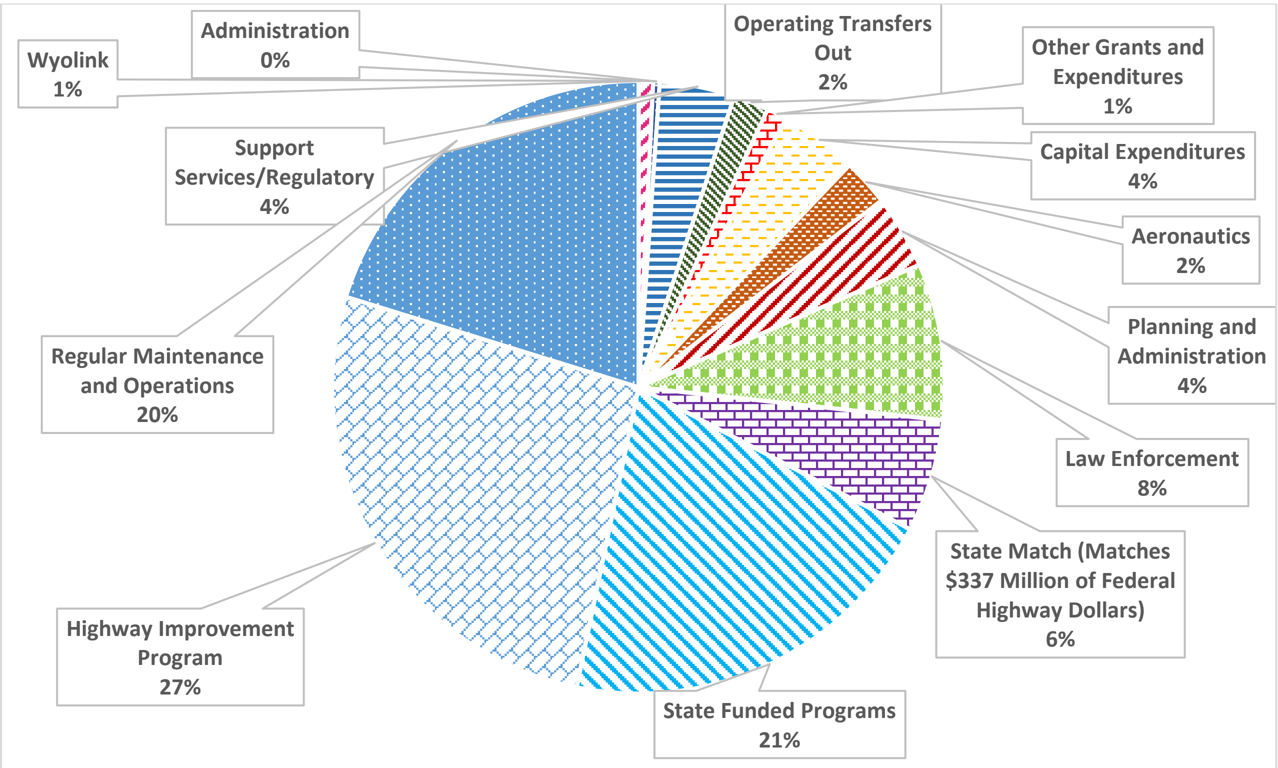


**Figure 52. Chart. 2023 Transportation Commission Funding Allocation.**

## Expected Future Funding Levels

The STIP is a six-year, fiscally constrained program that documents WYDOT's investment plan used for managing Wyoming's transportation assets. Actual funding levels may vary due to changes in Congressional and state appropriations. While WYDOT anticipates relatively steady funding levels over the next 10-year period, all assumptions, calculations, and projections in the STIP and PMMP are based on the continuation of current funding levels from the state and federal government.

WYDOT expects funding levels to increase one percent per year; however, with inflation estimates at 4 percent, real spending ability will decrease.

Because both the nature of projects and funding is dynamic and subject to many sources of change, the STIP is inherently fluid. WYDOT uses recommendations from the PMMP and Safety Management System to assist in programming projects to meet performance measures. Challenges WYDOT faces include funding changes, increased construction costs, right-of-way acquisition, environmental issues, and cost volatility for construction materials.

WYDOT attempts to account for cost volatility by calculating an annual inflation rate when generating project costs.

## VII. Investment Plan

A graphical representation of WYDOT's investment planning process is presented below in Figure 53.

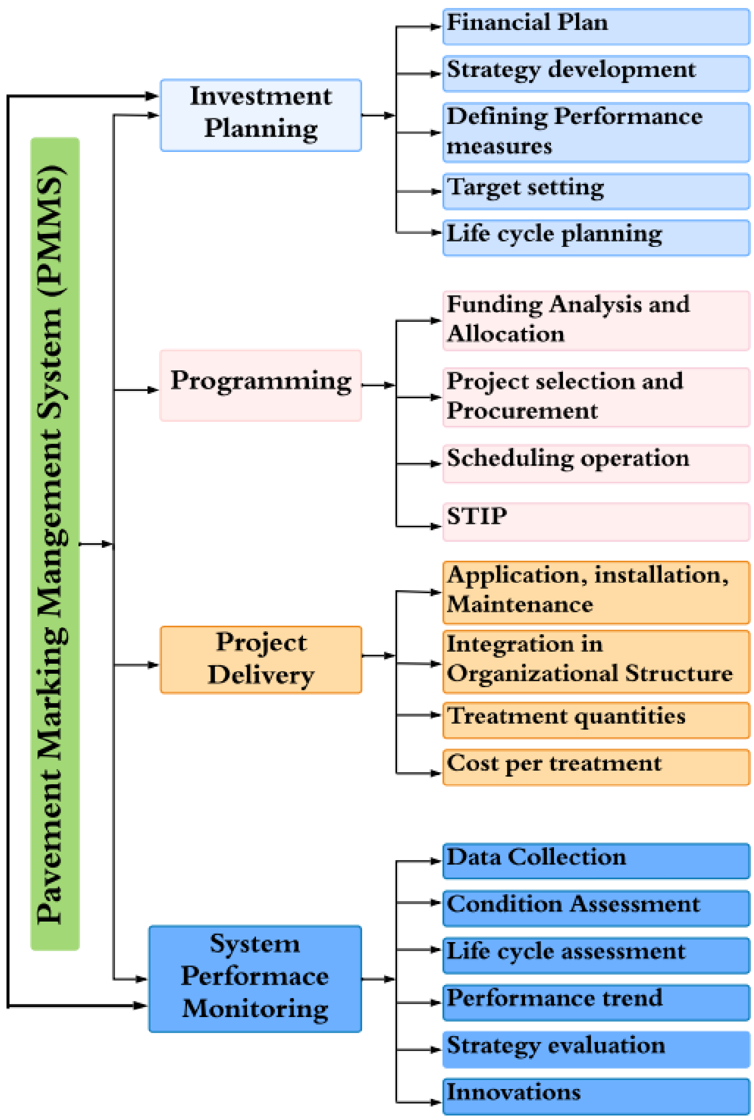


**Figure 53. Flowchart. WYDOT's Investment Planning Process.**

The investment planning process identifies the funding allocation and likely overall.

## Investment Planning

The investment plan describes the necessary trade-offs across system program areas and provides a system-level understanding of the size and mix of investments in a given area.

WYDOT concentrates infrastructure spending on pavement, bridge, and safety, and these areas each have measures assigned both internally and at the federal level. A measure can be defined as the yardstick used to compare against other similar assets. These measures give an indication of the public's ability to achieve a proposed level of mobility and safety while traveling the state. Most projects that maintain or improve these systems take many years from inception, through design, to construction; therefore, evaluating the measures and setting targets annually is not useful or practical.

The target setting for these systems is centralized in Cheyenne and directed by the Assistant Chief Engineer for Engineering and Planning. The process begins with the Programming section providing historical data and a future financial plan for funding splits between the districts encompassing district-specific, statewide, and earmarked projects. The district engineers use this data to provide input for the funding splits. The management systems calculate the predicted versus actual conditions as part of the historical review.

The Assistant Chief Engineer provides the management systems with guidance on current spending trends and scenarios to evaluate before setting targets.

WYDOT recognizes that the investment strategy to maintain Wyoming's transportation system at an optimal level utilizes most of its resources. Other risks can influence the way the resources are managed. These risks have been identified in the Risk Management Plan Process section of this document as well as proposed mitigation strategies should these risks impact the performance of Wyoming's transportation system.

**Programming**

The programming function involves gathering the recommended management system treatments into short-term projects listed in the STIP. Programming also serves as a means to document the specific commitments WYDOT has made. These projects are explicitly linked to the system-level investment plan.

The management systems use the funding guidance and targets to create a mix of treatment types broken down by system and district. Treatment types and quantities are calculated to provide the optimal life cycle for the asset, or the highest critical crash reduction based on the available (allocated) funding.

To meet future performance targets, assets must be moved from one projected (condition state) performance level to a higher level. Strictly tracking projects based on miles of pavement marking is important. Targets are set based on the current condition, which is quantified by the visibility and retroreflectivity of roads.

The management systems produce a list of candidate projects to assist the district engineers in project selection, along with guidance on mileage and treatment types needed to achieve the targets that the Assistant Chief Engineer previously set. Scenarios have shown that as long as the district engineers select projects from the candidate list for the mileage indicated, they will achieve the projected targets.

The district engineers use the treatment type requirements, budget, and candidate lists to construct their fiscally constrained STIP. They take the difference between their district's treatment requirements and budget and apply trade-off analysis to determine the best areas to spend any remaining funds. These funds are extremely limited, estimated to vary between $1 and $1.5 million annually for each district. The district engineer, for example, must decide which road should receive part of the remaining limited funding.

Funding is distributed to the various asset categories based on the asset management system recommendations. As projects progress through the design process and then construction, the asset categories are tracked and updated as changes occur. This tracking is done to monitor and update the asset management recommendations. If funding is increased for a given asset category, a like amount of funding must be removed from the other asset categories.

**Project Delivery**

The district engineers are held accountable for applying the needed treatment. The Programming Section tracks the treatment types and quantities that each district programs into the STIP. The Programming Section provides the Engineer with a report that compares the previously determined required treatment quantities to the actual work programmed in the STIP. Often a district engineer will cluster treatment types in one or two years of the six-year STIP to more effectively use the limited resources to meet their targets, so the report is by cumulative treatment amounts. The trade-off that the district engineers perform may also cause them to apply additional funds to an asset.

The Programming Section works with the management systems to track the estimated cost per pavement marking work. Multiplying this cost by the marking works quantity needed to reach the desired condition results in an estimated required budget allocation. If the cost estimate for a work is too low compared to the actual cost, the district engineer may not have adequate resources to meet the targets; while if the estimate is too high, it may tie up funds that could be better spent on other assets.

System disruptions such as mobility needs, disasters, modal shifts, or other risks can sometimes throw off the project delivery schedule. A deliberate process is used when a district is forced into underperforming in the treatments. The preferred option is to over-perform in the years leading up to or immediately after the disruption. The management systems show that delays of a few years, while not optimal, still result in positive, low life-cycle costs. However, there can be cases where the disruptions are long-term enough that the lowest life-cycle cost options are not achievable. In this case, new targets would have to be set.

## System Monitoring

Management systems track treatments over time to ensure they are providing the benefits projected and adjust treatments if necessary. This may show construction techniques or project selections need to be modified to achieve the projected benefits. Management systems also track performance trends to assist in the maintenance of the management systems.

Innovation should be leveraged in the systems monitoring step, which would directly impact WYDOT's project delivery cycle. If less costly treatments can be found that achieve the life-cycle benefits, this would impact target setting, effectively lowering the cost per treatment. This innovation would free up funds to begin addressing other currently underfunded transportation needs the district engineers face.

WYDOT tracks the planned and actual expenditure of marking funds by calculating the percentage of each project falling into each of the nine asset categories consisting of the following:

**Table 41. Asset Categories.**

| Sl. | Asset Category | Description |
|---|---|---|
| 1 | Pavement | All roadway surfacing that is not the result of a mobility improvement. |
| 2 | Bridge | All bridges that are on or off of the state-owned highway system. |
| 3 | Mobility | Items include additional lanes, intersection improvements for traffic flow, turning lanes, etc. |
| 4 | Safety | These are items that affect the safety of the transportation system (such as guardrail, side slopes, signs, etc.) |
| 5 | Environmental Sustainability | Air quality improvements, wetland banking, animal-vehicle crash mitigation, archeological and historical preservation, etc. |
| 6 | Maintenance | Items for the general maintenance of the roadways (such as fencing, sign, or guardrail replacement; crack sealing; pothole patching; snow removal, etc.) |
| 7 | Urban | Transportation-related items within an urban boundary |
| 8 | Community Development | Items that enhance community livability (such as sidewalks, ADA upgrades, pathways, etc.) |
| 9 | Other | Other non-defined items |

The calculated STIP expenditures for each of the nine asset categories for STIP years 2023 through 2028 are presented in Figure 54.

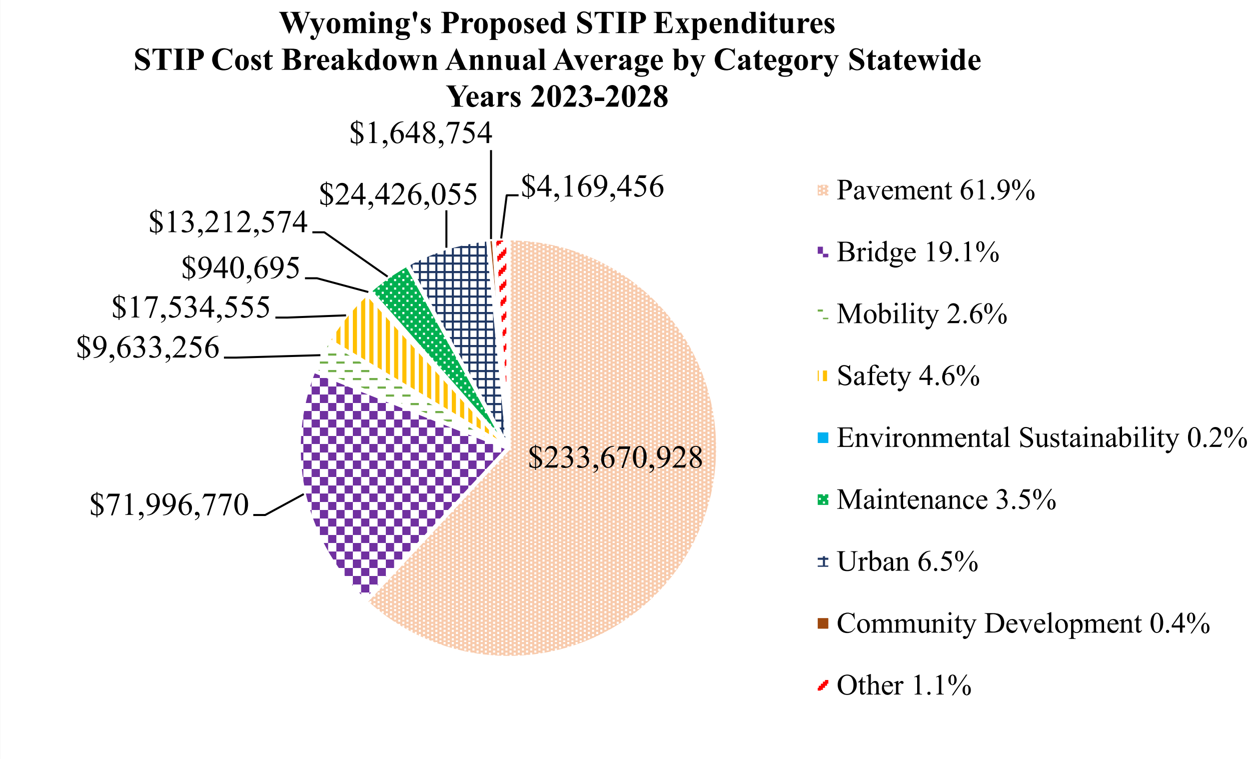


**Figure 54. Chart. Wyoming's Proposed STIP Expenditures (2023-2028).**

## VIII. Planning for Pavement Marking

To develop PMMP, planning for pavement marking is important. At this stage, all the districts were asked about their strategies for planning future restriping. Also, districts' vision for 5-year and 10-year plans for pavement marking was investigated. Table 44 shows the current strategies used by different districts for planning future restriping. Districts 1 and 5 followed the strategy of restriping on odd/even years. District 5 striped half of the edge line on even years and the other half on odd years. Also, district 5 striped all center lines and lane lines annually in rural areas but striped urban areas twice per year. District 2 restriped interstate once a year and non-interstate, which had an edge line every other year. District 3, on the other hand, had a pre-determined priority schedule. All rural centerlines were stripped annually, while edge-line were stripped every two years. District 4 considered traffic volume, construction projects, and maintenance work in addition to their regular restriping.

**Table 42. Current strategies that are used for planning future restriping.**

| District | Current strategies |
|---|---|
| 1 | Odd/even years |
| 2 | For the rural striping, we stripe all rural centerlines once per year. Non-interstate roads that receive edge-line get stripped every other year. All lines on the interstate are painted once, with the skip line being painted twice. |
| 3 | Pre-determined priority schedule, Rural: all centerline annually, edge-line every two years (half one year, the other half second year). |
| 4 | In addition to our regular schedule, we also identify upcoming construction projects and maintenance work. For thermoplastic markings, we utilize our list of needs determined from visual inspection and take into account traffic volumes. |
| 5 | Rural: stripe all centerline and lane-line annually/stripe 1/2 edge-line even years; other 1/2 on odd years.<br>Urban: all striping two times/year |

Next, it was the intention of the study to identify districts' strategies for 5-year and 10-year plans for pavement marking. As shown in Table 45, Districts 1, 3, and 5 mentioned that they wanted to have pavement marking standards that would accommodate machine vision systems. Districts 1 and 3 also mentioned that they would like to have a database containing all the pavement marking management data as well as additional funding for the pavement marking maintenance program. Districts 2 and 4 did not respond to this question. Also, districts were asked whether they would like to have a policy for applying pavement markings for different functional classifications of roads or a policy for pavement markings on various funding levels. None of the five districts would like to have a policy like that. None of the districts also wanted to have performance curves by different marking material types, road functional classifications, traffic volume, etc.

**Table 43. Districts' vision for 5-year and 10-year plans for pavement marking.**

| | District 1 | District 2 | District 3 | District 4 | District 5 |
|---|---|---|---|---|---|
| A policy for applying pavement markings for different functional classifications of roads | | | | | |
| A policy for pavement marking based on various funding levels | ✓ | | ✓ | | ✓ |
| Latest pavement marking standards intended to accommodate machine vision systems | ✓ | | ✓ | | |
| A database containing all the pavement marking management data | | | | | |
| Accurate performance curves by marking material type, road functional classification, traffic load, and district at which the material is applied | ✓ | | ✓ | | |
| Additional funding will be provided for the pavement marking maintenance program. | | | | | |

Next, districts were asked whether they needed more resources for manpower, material, equipment, or safety/warning devices. Table 46 summarizes the results. All districts mentioned that they needed more resources for manpower. Except for District 2, all the districts mentioned that they needed more resources for material as well. District 3 only mentioned that they need more resources for safety/warning devices. And lastly, Districts 1 and 4 needed more resources for equipment.

**Table 44. District's need for more resources.**

| | District 1 | District 2 | District 3 | District 4 | District 5 |
|---|---|---|---|---|---|
| Manpower | ✓ | ✓ | ✓ | ✓ | ✓ |
| Material | ✓ | | ✓ | ✓ | ✓ |
| Equipment | ✓ | | | ✓ | |
| Safety/warning devices | | | ✓ | | |

## IX. Risks to the Wyoming Transportation System

Risk can be defined as a probability or threat of damage, injury, liability, loss, or any other negative occurrence that is caused by external or internal vulnerabilities and that may be avoided through preemptive action.

Risk-based asset management considers the prospect of hazards and uncertainty while taking pre-emptive action to mitigate potential failures. FHWA's series of reports on risk, produced in 2012 and 2013, guide risk evaluation in asset management. Report 1, Risk-Based Transportation Asset Management: Evaluating Threats, Capitalizing on Opportunities, suggests three levels of risk exist: (1) agency risk, (2) program risk, and (3) project risk.

**Agency Risk**

The greatest known risk to Wyoming's transportation network is agency risk: the lack of adequate funding to preserve and maintain the existing infrastructure and an inability to expand the system to meet future needs. WYDOT continues to seek additional funding to maintain pavement markings above the marginal level based on service life. The additional funding does not include any fundingneeded to meet safety needs.

Currently, the biggest risk to Wyoming's highways is a possible future reduction in federal funding due to trust fund shortfalls.

Pavement marking needs a constant funding stream every year to maintain a safe and efficient transportation system. With the impending shortfall in the Highway Trust Fund (HTF)in 2021, a 30 percent funding shortfall remains the highest long-term risk to the assets WYDOT maintains.

Another consideration affecting the agency's risk of inadequate funding is inflation. Long-range projections predict future funding levels will be flat, with any funding increases projected to be well below the rate of inflation. WYDOT has compared the region's Construction Price Index with other factors and is currently using a 4 percent annual inflation rate for future cost projections. While in the short-term, this has little impact, long-term projections (10 years or more into the future) show a growing funding shortfall compared to the expected pavement maintenance and bridge preservation, repair, and rehabilitation needs.

**Program Risk**

WYDOT considers program risk to be an event that prevents the traveling public, commerce, or both from successfully moving from one location to another across Wyoming's transportation systems. Using this definition, WYDOT considers three broad categories of risk: (1) natural, (2) environmental, and (3) man-made. These programmatic risk categories are described below:

**Natural Risks** consist of earthquakes, avalanches, landslides, and rock falls. These risks tend to disrupt the traveling public for longer periods and are very random and unpredictable. Natural risks are considered and mitigated during each project's design phase using industry and national design standards. Historical data is also considered and is used to determine the frequency or likelihood of re-occurrence.

**Environmental Risks** in Wyoming consist of wind, blizzards, and flooding or stormwater runoff. These risks can disrupt the traveling public for long periods of time, but they are usually shorter-lived events that disrupt traffic for a short time. Environmental risks tend to occur more often (cyclically) than natural risks. These risks are predictable in that their occurrence is considered in the cost-benefit analysis of each project's design; for example, pavement marking materials are selected to pass the snowplow process of a given design frequency (20, 30, or 40), and the possibility of a larger number occurring during the structure's life is considered an acceptable risk.

**Man-Made Risks** consist of road closures caused by accidents, fires, fuel spillage, or other errors in judgment made by the driving public and commercial carriers. Historically, these road closures have been relatively short and/or relatively easy to route traffic around. Local emergency response agencies have historically managed such incidents. Man-made events rarely cause significant damage to the transportation infrastructure.

**Project Risk**

The third level is project risk, which pertains to bringing individual projects to contract. Project risk for a pavement marking project refers to the potential challenges or issues that may impact the successful delivery of the project. Weather conditions, pavement conditions, environmental clearances, road closures, funding constraints, and cost increases are some examples of project risks that may prevent a pavement marking project from going to contract as planned. It's important to consider and manage these risks to ensure the successful implementation of the project and minimize its impact on the overall State Transportation Improvement Plan (STIP).

**WYDOT Risk Analysis**

WYDOT is using the PMMP to describe program-level risks and the threats and opportunities that occur at the system level. Available funding is the main driver affecting WYDOT's ability to provide a low-risk transportation experience in Wyoming. Using asset management principles, WYDOT is attempting to optimize the condition of the transportation system using limited available funding.

Using analytical software, like the previously described PMMS, and in-house expertise and inspection processes, WYDOT uses programmatic risk analysis to minimize potential deterioration of the transportation network by emphasizing preventative efforts.

**Risk Management Plan Development Process**

MAP-21 and the FAST Act require states to develop and implement a risk-based asset management plan (23 CFR 515.7(c)) for the NHS to improve or preserve its condition and performance. The PMMP final rule defines risk management as the processes and framework for managing potential risks, including identifying, analyzing, evaluating, and addressing the risks to assets and NHS system performance. WYDOT decided to address this process at the programmatic level.

During the development of WYDOT's risk management plan, it was agreed there are four general types of risk: (1) operational, (2) strategic, (3) environmental, and (4) financial.

**Operational Risks** include asset and maintenance failures, staff turnover, and internal procedural breakdowns.

**Strategic Risks** include public opinion, stakeholder demands, and changing standards and regulations.

**Environmental Risks** include rockslides, landslides, flooding, and seismic events.

**Financial Risks** are not limited to a lack of funding but also include budget uncertainty, price increases, and economic downturns.

During the development of the risk management plan, WYDOT executives, program managers, and planning and administration staff utilized the framework depicted in Figure 55. They employed this framework in a risk management workshop to identify, assess, evaluate, and prioritize program-level risks.

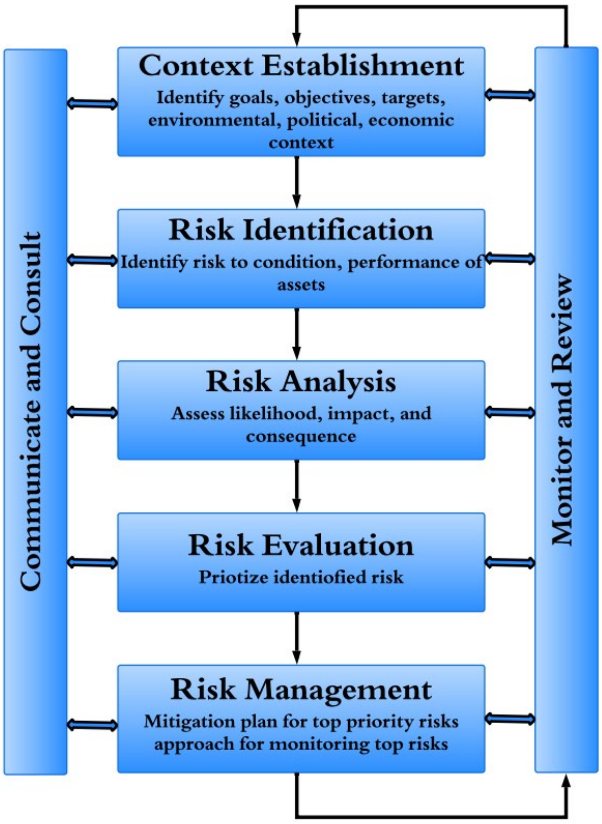


**Figure 55. Flowchart. WYDOT Risk Management Plan Development Framework.**

## X. Maintaining and Preserving Pavement Marking

Policy for pavement marking, maintaining, and preserving is important. Table 47 shows the approach taken by different districts in preserving and maintaining the pavement marking. All districts agreed on having a set schedule based on which preservative maintenance would be carried out. Districts 3 and 4 also reported that they would go for immediate repair as soon as possible when damages were reported. Both districts 3 and 4 also mentioned that they would go for a limited number of repairing those markings which appeared to be in the worst condition. There were also a few markings in District 4, where little or no maintenance was performed annually. Lastly, a corrective approach was also chosen by districts 3 and 5 where repairs were prioritized and scheduled to meet performance targets subject to resource constraints.

**Table 45. Characterization of different districts' approaches to preserving and maintaining pavement marking.**

| District | Preservative maintenance carried out on a set schedule | Immediate-repair carried out as soon as possible after damage reported | Corrective repairs prioritized and scheduled to meet performance targets subject to resource constraints | Worst first - limited number of repairs each year, but backlog exists | Deferred maintenance - little or no work performed annually |
|---|---|---|---|---|---|
| 1 | ✓ | | | | |
| 2 | ✓ | | | | |
| 3 | ✓ | ✓ | ✓ | ✓ | |
| 4 | ✓ | ✓ | | ✓ | ✓ |
| 5 | ✓ | | ✓ | | |

Districts were also asked what the key sources of technical guidance were for the management of pavement marking. Both construction/new installation, as well as maintenance and rehabilitation, were considered. As shown in Table 48, for the management of pavement marking, all districts were willing to follow policies, standard guidelines, and procedures established by WYDOT. Except for District 2, all the districts also wanted to abide by national standards such as the American Association of State Highway and Transportation Officials or Manual on Uniform Traffic Control Devices, etc. Only Districts 3 and 4 mentioned that they explicitly required state or federal law or statewide public policy.

**Table 46. Key sources of technical guidance for the management of pavement striping and marking.**

| For Construction or New Installation, and Maintenance and Rehabilitation | | | | |
|---|---|---|---|---|
| **District** | Explicit requirements in state or federal law | National Standards (e.g., AASHTO, MUCTD) | Explicit requirements of statewide public policy | Policies, standard guidelines & procedures established by WYDOT |
| 1 | | ✓ | | ✓ |
| 2 | | | | ✓ |
| 3 | ✓ | ✓ | ✓ | ✓ |
| 4 | ✓ | ✓ | ✓ | ✓ |
| 5 | | ✓ | | ✓ |

Maintaining pavement striping and markings in good condition is important to several transportation objectives. Finally, districts were asked how they would rank several transportation objectives. The results are shown in Table 19. Public safety, accident, and accident risk reduction were identified as the most important criteria by all the districts. All the districts except District 3 mentioned that preservation of the existing road infrastructure and reduced agency life-cycle costs was the second most important criterion. According to District 3, the comfort and convenience of the traveling public were the second most important criteria. More efficient travel, maintaining intended flow and operating speed, and reducing travel time and cost were identified by Districts 1 and 5 as the third most important criteria, while road aesthetics was considered the third most important criteria by District 4. As shown in Table 49, all the rankings of the criteria were summed up to categorize relative priority. District 2, however, did not respond to this question. When the summary was considered, it can be seen in Table 19 that comfort and convenience of the traveling public were ranked as the fourth most important criterion, while road aesthetics was the fifth most important criterion.

**Table 47. Relative priority to several transportation objectives by different districts (1= most important).**

| District | Preservation of the existing road infrastructure, reduced agency life-cycle costs | More efficient travel, maintain intended flow and operating speed, reduce travel time, costs | Public safety, accident, and accident risk reduction | Comfort and convenience of the traveling public | Road aesthetics |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 1 | 4 | 5 |
| 2 | | | | | |
| 3 | 3 | 4 | 1 | 2 | 5 |
| 4 | 2 | 4 | 1 | 5 | 3 |
| 5 | 2 | 3 | 1 | 5 | 4 |
| **Summary** | 9 (2nd most important) | 14 (3rd most important) | 4 (Most important) | 16 (4th most important) | 17 (5th most important) |

## XI. Pavement Marking Management Process Enhancement

Wyoming inaugurated an enterprise resource program in 2006. One of the primary selection criteria was to facilitate an asset management process. Soon after that, the state planning engineer was appointed the primary asset management program manager. The Planning Program was reorganized to include an asset management coordinator in the Programming Section. WYDOT has made a concerted effort since 2006 to understand and move forward in its goal of optimizing the project selection process by heavily engaging in a transportation asset management plan at the state and national level through training and presentations.

WYDOT spends almost 76 percent of the contract construction budget on three asset categories: (1) pavement, (2) bridge, and (3) safety. Safety infrastructure influences reducing fatalities and serious injuries, another of WYDOT's goals. Recently WYDOT published the Wyoming Strategic Highway Safety Plan (SHSP), which is the guiding document in Wyoming's effort to achieve the national goal of "Towards Zero Deaths." The SHSP considers several actions to improve safety; enhanced pavement marking is one of the essential treatments implemented following the SHSP's guidance. Approximately 32 percentof the motor vehicle crashes in Wyoming in 2020 occurred in the dark. Over three-quarters of these (78 percentage) were in dark conditions with no lighting. Given Wyoming's rural nature, this is not surprising. However, several techniques have proven effective in reducing these numbers. More visible pavement marking can improve roadway safety if implemented correctly.

To create an efficient and budget-friendly pavement marking management plan template, it is essential to adopt various strategies tailored to the functional classification of roads. An example of the pavement marking material selection strategy is shown in Figure 56, which presents a decision tree outlining the selection process for pavement marking materials on different functional classifications of highways.

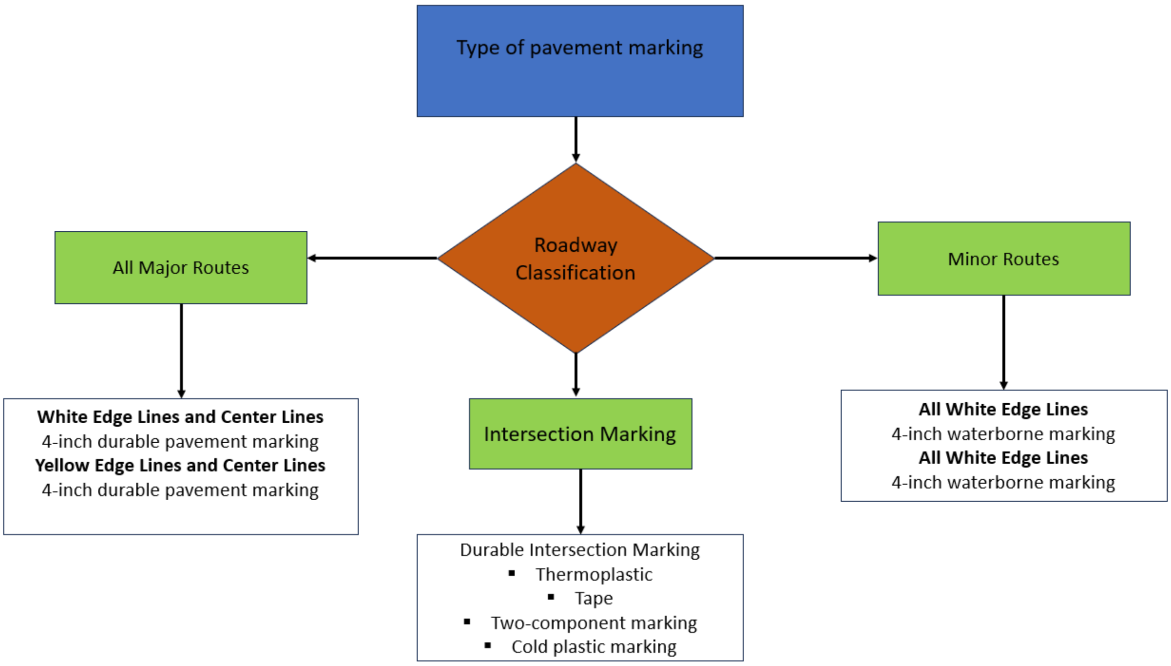


**Figure 56. Flowchart. Decision Tree for the Selection of Pavement Marking Material.**

Figure 57 and Figure 58 provide additional guidance by offering specific strategies for material selection on asphalt and concrete pavements, respectively. These decision trees assist in navigating several options for choosing the most suitable pavement marking materials, ensuring optimal performance and cost-effectiveness for each road type.

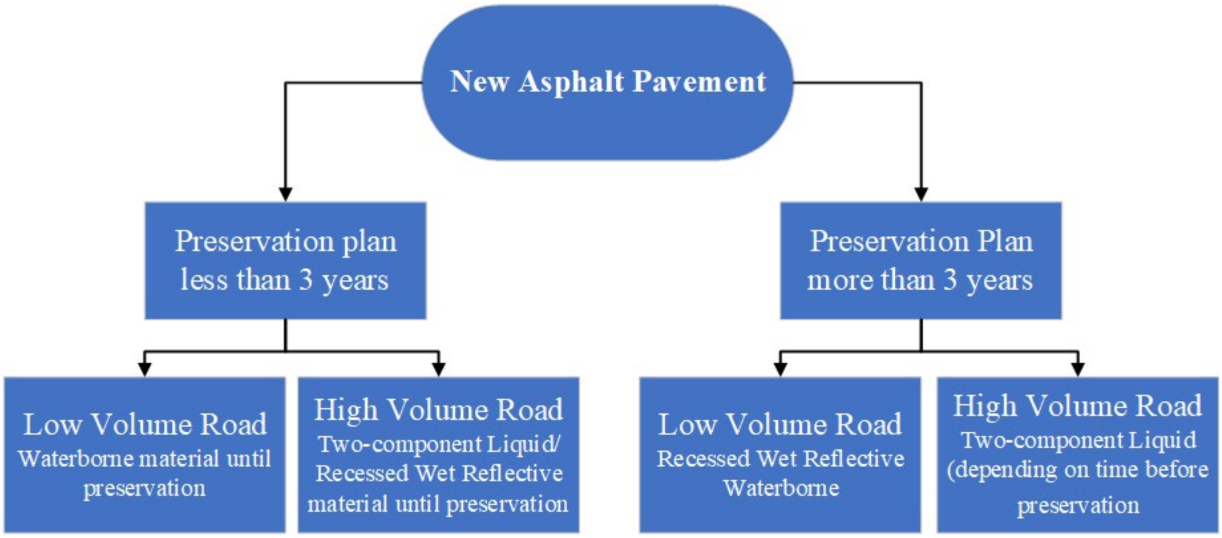


**Figure 57. Flowchart. Pavement Marking Material selection for the Longitudinal Pavement Marking on the New Asphalt Pavement.**

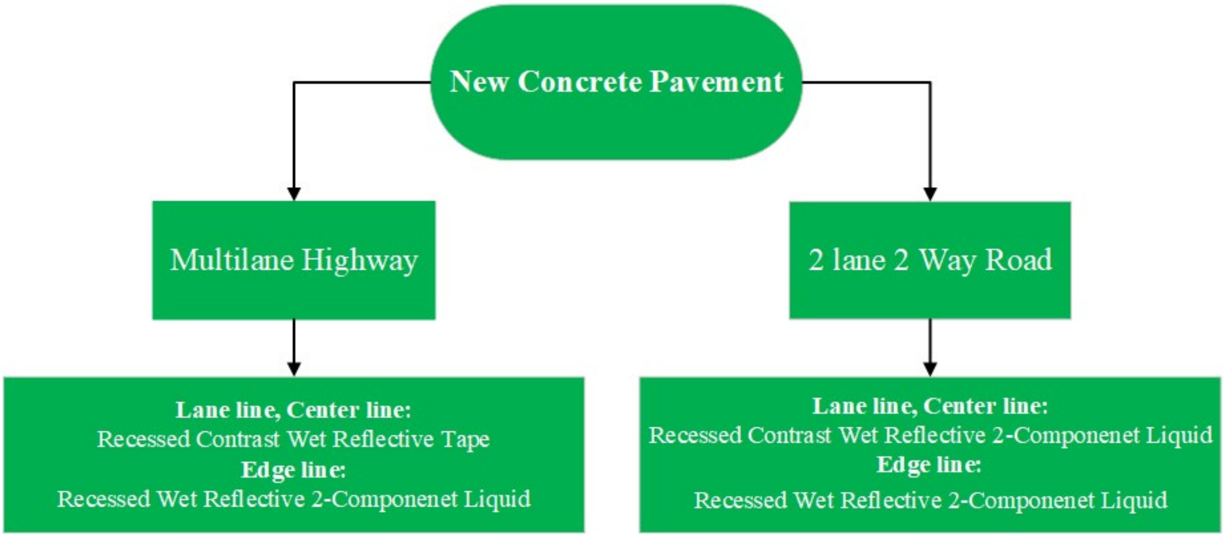


**Figure 58. Flowchart. Pavement Marking Material selection for the Longitudinal Pavement Marking on the New Concrete Pavement.**

WYDOT Pavement marking management plan template was developed based on the WYDOT Transportation Asset Management Plan. This document addresses the pavement marking deterioration and improvement plan for different highways. In addition, this plan is intended to guide the adoption of strategies to increase pavement marking visibility and life-cycle cost analysis of pavement marking.