International Journal of Pavement Research and Technology
https://doi.org/10.1007/s42947-023-00358-z

社團法人中華鋪面工程學會
Chinese Society of Pavement Engineering

ORIGINAL RESEARCH PAPER

Enhancing Pavement Marking Practices in Wyoming: A Roadmap for Comprehensive Management and Statewide Implementation

Uttara Roy[1] · Dima A. Husein Malkawi[2] · Omar Albatayneh[2] · Khaled Ksaibati[1]

Received: 30 March 2023 / Revised: 30 March 2023 / Accepted: 1 July 2023

Abstract

Traditionally, transportation asset management systems focus predominantly on capital asset expenditures (e.g., pavement structure, pavement conditions, bridges, etc.). More recently, there has been a greater focus placed on low-cost assets (e.g., pavement marking). This study aims to critically examine current pavement marking practices, and subsequently formulate a comprehensive pavement marking management plan (PMMP) tailored to the specific needs of Wyoming. The proposed plan will integrate cutting-edge pavement marking standards, which are designed to accommodate advanced machine vision systems. These standards will take into account various critical factors such as contrast markings, pavement surface types, traffic loads, road functional classifications, and land uses, among others. Furthermore, the PMMP will provide essential information pertaining to the minimum required marking retroreflectivity levels, budget allocation for pavement marking, and a detailed pavement marking inventory. Additionally, the plan will address crucial aspects such as maintenance and preservation of pavement markings, the expected service life of the markings, and any other pertinent information. This comprehensive approach aims to enhance the efficacy and sustainability of pavement marking practices in Wyoming, ultimately promoting greater road safety and efficiency for all users. This plan developed for WYDOT will help other DOTs and local agencies to develop their own PMMP considering budgets, labor resources, performance analysis, and newly suggested marking specifications.

Keywords Asset management · Pavement marking · Management plan · Budget for pavement marking · Pavement marking maintenance

1 Introduction

The mechanisms that underpin the management of pavement marking are not fully understood as this topic is still not standardized to be used by all transportation agencies. Investment in transportation infrastructure by the United States is more than $ 1.75 trillion [1]. Yet, US transportation agencies face significant challenges in managing the transportation asset base and funding extensions of the network to meet growing demands at the same time. This situation has led to an emphasis on the development of infrastructure asset management systems [2]. To incorporate pavement markings within the broad framework of infrastructure asset management, US transportation agencies have prepared their specifications, plans, guidelines, and programs [3]. Therefore, a Pavement Marking Management Plan (PMMP) comes into play. A PMMP provides State and district engineers with the ability to manage retroreflectivity, durability, life-cycle cost, budgets, and plan for material selection [4]. However, few

✉ Omar Albatayneh
omar.albatayneh@gju.edu.jo

Uttara Roy
uroy@uwyo.edu

Dima A. Husein Malkawi
dima.malkawi@gju.edu.jo

Khaled Ksaibati
khaled@uwyo.edu

[1] Wyoming Technology Transfer Center, Department of Civil and Architectural Engineering, University of Wyoming, 1000 E. University Ave., Dept. 3295, Laramie, WY 82071, USA

[2] Department of Civil and Environmental Engineering, School of Natural Resources Engineering and Management, German Jordanian University, Madaba, Jordan

Published online: 20 July 2023

State DOTs recognize the importance of developing their PMMP. Several attempts have been made so far to establish and develop PMMP. However, only few published reports and studies addressed pavement marking practices, while others focused on pavement marking strategies. To date, very few studies have assessed the need for comprehensive PMMP frameworks and guidelines that combine both practices and strategies.

In the state of Wyoming, district engineers manage pavement markings based on the existing guidelines that were previously developed, proposed, and recommended by district engineers. Districts and State DOTs have released various documents and reports that address pavement marking strategies and practices throughout the state. Correspondingly, guidelines for managing this asset are tremendously dispersed among the plethora of reports and documents. This study utilizes the WYDOT district engineers' experience to establish and build PMMP frameworks and guidelines. Wyoming allocated $615 million to maintain roads and highways in the 2016 fiscal year. Moreover, $348 million of the total Wyoming budget was allocated for road improvement and contract maintenance [5]. Currently, the Wyoming Department of Transportation (WYDOT) periodically resurfaces its road pavement markings. Yet, their maintenance procedures are not conducted under a fully fledged rigorous management program. This study aims to analyze the existing pavement marking practices and develop a comprehensive PMMP for Wyoming.

Pavement marking management is essential and, with the advent of advanced automobile technologies that run with machine vision systems, marking specifications are currently being updated. Even though WYDOT maintains its road markings regularly, there is a need to develop a fully fledged pavement marking management system that takes into account budget, labor resources, and the newly suggested marking specifications. The significance and contribution of this research study lie in its specific objective to develop and implement a robust pavement marking management plan (PMMP) for the Wyoming Department of Transportation (WYDOT). As a pioneering effort, this study lays the foundation for WYDOT to create and adapt PMMPs for other transportation agencies, consequently promoting a more systematic and coordinated approach to pavement marking management. By establishing a practical and integrated PMMP, the research enables the accurate determination of annual marking requirements and provides valuable guidance on durable pavement marking applications and comprehensive marking strategies at a statewide level. Ultimately, this study not only contributes to the enhancement of road safety and efficiency for all users but also sets a precedent for effective pavement marking management in other jurisdictions, fostering a more unified and informed approach to transportation infrastructure planning and maintenance.

The remainder of this paper is structured as follows. In the next section, a review of existing studies on pavement marking management plans is presented. This section aims to provide a comprehensive understanding of the state-of-the-art approaches in this area. Following this, the study methodology is described, detailing the research design, data collection procedures, and analysis methods employed. Subsequently, the essential components of the pavement marking management plan are discussed in separate sections. Each section provides a detailed description of the specific processes involved in each component, highlighting best practices and potential challenges. Finally, in the last section, conclusions are drawn based on the findings of the study.

2 Literature Review

Very few states in the United States have developed dedicated pavement marking management plans. However, there are a few states that developed transportation asset management plans. The Florida Department of Transportation (FDOT) is considered to be one of the leading state agencies in developing transportation asset management plans [1]. FDOT's asset management approach is based on adopted operational policies that guide the organizational decision-making process. In 2012, FDOT has developed a Pavement Marking Management System (PMMS) to ensure the quality, consistency, repeatability, and accessibility of statewide pavement marking retroreflectivity data [3]. Also, a comprehensive PMMS database was developed to store and display pavement marking data. This PMMS has provided quality data for pavement marking performance evaluation and management to the state of Florida.

Sassani et al. [6] developed a model framework for PMMS, and the building blocks and elements of the framework were discussed based on US transportation agencies' experiences. The primary focus of the study was on modifying the performance models used in the Iowa pavement marking management system. The developed PMMS will help in developing future pavement marking management tools and databases.

Under the NCHRP 371 synthesis study [7], the state of practice for managing transportation infrastructure assets was discussed. Six types of assets were the primary focus of this synthesis study which included pavement markings. A survey of state, provincial, county, and city transportation agencies in the United States and Canada was conducted. Among different agencies that responded to the synthesis study, maintenance of pavement markings was accomplished by the agencies 100% of the time. Survey results regarding budgeting methods used by agencies showed that the majority of agencies chose the previous budget plus adjustments option as best describing their processes. Minimum initial

retroreflectivity values used by DOTs are in the range of 175–700 mcd/m^2/lx for white markings and 100–350 mcd/m^2/lx for yellow markings.

Hawkins et al. [8] reviewed some management tools for pavement markings developed for Iowa DOT. The tools developed for Iowa DOT were used by each district to have short-term and long-term pavement marking plans. The PMMS which was developed in this study also provided Iowa DOT with the opportunity to link pavement marking performance with safety performance.

Hawkins and Smadi [9] developed a web-based pavement marking management system for Minnesota which provided MnDOT staff the ability to map and query pavement marking retroreflectivity information. The research team worked with MnDOT staff to retrieve retroreflectivity measurement data, GIS format, platform information, and paint information. A GIS-based prototype mapping tool was developed using ArcIMS/ArcServer as a platform. Zhang [10] developed a PMMS database for Texas. The overall objective was to improve the performance of PMMS by developing a field performance evaluation program and by identifying field evaluation methods and tools. Under the NCHRP 551 synthesis study [11], asset management and performance measurement were discussed to develop an understanding of what set of performance measures can best serve the principles of good transportation asset management. The study developed a framework that can be used by decision makers to select suitable performance measures and set performance targets. The study comprised a preliminary evaluation of performance measures, a detailed evaluation of the selected performance measures, and finalized the list of promising performance measures.

To provide effective and consistent pavement markings on Iowa's public roadways, Hawkins and Smadi [12] developed a local agency pavement marking plan. The literature review mentioned above suggested that very few states have attempted to develop PMMP, and hence, this study will fill the knowledge gap that exists in pavement marking-related studies.

3 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 Transportation Asset Management Plan (TAMP) in 2018. The Wyoming PMMP was developed in this study on the basis of this asset management plan. Besides, to develop PMMP for Wyoming, a survey was conducted statewide by the Wyoming Technology Transfer (WYT^2) Center. Wyoming's five districts responded to the survey. The survey was intended to ask about Wyoming's five districts' current pavement marking striping and management practices. The survey results were summarized in this study to develop PMMP for WYDOT.

4 Essential Components of PMMP

The use of systematic approaches for pavement marking planning, operations, and maintenance is the core concept of the PMMP. The following section summarizes the core components of the PMMP.

4.1 Enabling Legislation

It is crucial to ensure that the pavement marking management plan (PMMP) encompasses six key elements to guarantee its effectiveness and compliance with established guidelines. These elements include:

a) Inventory and condition of pavement marking on the NHS,
b) Pavement marking management objectives and measures,
c) Performance-gap analysis between goals and conditions,
d) Life-cycle cost and risk-based management analyses,
e) Financial plan for the future, and
f) Investment strategy.

Incorporating these essential components within the PMMP will ensure a holistic and well-rounded approach to pavement marking management, facilitating the achievement of both short-term and long-term objectives in road safety and infrastructure sustainability.

4.2 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:

a) Improve safety on the state transportation system,
b) Serve our customers,
c) Take care of all pavement marking on state-maintained roads in Wyoming,
d) Improve agency efficiency and effectiveness,
e) Develop and care for our people, and
f) Exercise good stewardship of our resources.

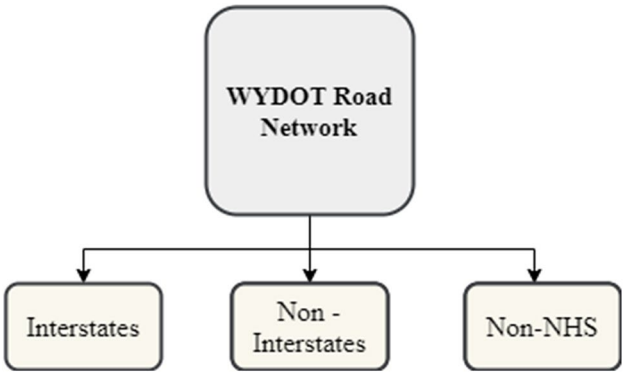

Fig. 1 WYDOT road network classifications

The current research study, which focuses on the development and implementation of a comprehensive pavement marking management plan (PMMP), is strategically aligned with these goals, particularly in the areas of safety improvement and pavement marking maintenance. By integrating the latest pavement marking standards and technologies, the study contributes to the realization of WYDOT's mission by facilitating safer roadways, increased customer satisfaction, and the responsible use of resources.

4.2.1 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.

4.3 Statewide Pavement Marking Inventory, Conditions, and Programs

It is crucial to consider the scope of WYDOT's management responsibilities and the composition of the state-owned highway network to better understand the context in which the PMMP will be developed and implemented. WYDOT oversees 6530 centerline miles (10509.02 centerline Km) of highway, which are categorized into three primary groups, as illustrated in Fig. 1:

Table 1 Approximate quantity and units of different district's inventory

District	White Paint	Yellow Paint	Beads
1	58,500 gallons (221446.6 L)	No Response	468,000 pounds (212281.3 Kg)
2	No response	No response	No response
3	45,000 gallons (170343.53 L)	28,500 gallons (107884.3 L)	No Response
4	No response	No response	No response
5	31,500 gallons 119240.5 L)	28,500 gallons (107884.3 L)	396,000 pounds (179622.6 Kg)

- 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 the state manages.

By taking into account the unique characteristics and needs of each roadway category, this study will contribute to the overarching goals by ensuring that the PMMP is tailored to address the specific requirements and challenges associated with managing pavement markings across the diverse state-owned highway network.

4.3.1 Pavement Marking Management Objectives

For WYDOT or any other State DOT, the following pavement marking management objectives should be 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.

The goal of the pavement marking management program is to maintain existing pavement markings through timely installation and limit the pavement markings reaching "Poor/unacceptable" conditions. Understanding the existing management of pavement marking materials and their distribution across Wyoming's districts is essential for the development of a comprehensive PMMP. In the state, pavement marking materials are annually budgeted by state engineers and supplied to the districts through a statewide contract

Table 2 Annual miles of pavement marking and time taken to do those miles by different districts

District	Miles	Time
1	4000 Passmiles (11,748.3 km)	6 months
2	1537 miles (11,748.3 km)	7–8 months
3	6200–7300 lane miles (9,977.8 – 11,748.3 Lane km)	8 months
4	4000+ Passmiles	8 months
5	4100–4200 miles (6,598.3 – 6,759.3 km)	7 months

orchestrated by the main office. Table 1 presents the inventory of pavement marking materials for various districts, highlighting notable differences in consumption patterns. District 1 consumed 58,500 gallons (221446.6 L) of white paint and 468,000 pounds (212281.3 Kg) of beads. This was the highest amount being spent when compared to other districts. District 3 consumed 45,000 gallons (170343.53 L) of white paint and 28,500 gallons (107884.3 L) of yellow paint. Districts 2 and 4, however, did not respond when asked about their inventory. District 5 mentioned that they have 31,500 gallons (119240.5 L) of white paint, 28,500 gallons (107884.3 L) of yellow paint, and 396,000 pounds (179622.6 Kg) of beads. The data collected on pavement marking material consumption are vital for informing the PMMP, as it allows for the identification of potential areas of improvement in resource allocation, efficiency, and effectiveness. Ultimately, this understanding will enable the development of targeted strategies and best practices for material usage, resulting in enhanced safety, customer satisfaction, and more prudent stewardship of resources.

Investigating the annual miles of pavement marking completed by each district and the duration required to accomplish those miles is crucial for understanding the efficacy and efficiency of current pavement marking practices. It can be seen from Table 2 that Districts 1, 4, and 5 did approximately 4000 miles (6,437.4 Km) annually and it took them around 6–8 months to complete those miles. District 2, on the other hand, did only 1,537 miles (2,473.6 Km) annually in 7–8 months. The highest amount of annual miles was done by District 3 and it was 6,200–7,300 lane miles (9,977.8 – 11,748.3 Lane Km). It took them 8 months to complete those miles. Analyzing the variations in the annual miles of pavement marking and the time taken for completion across districts will significantly contribute to developing a comprehensive PMMP. Identifying potential bottlenecks and inefficiencies can inform targeted strategies and recommendations aimed at optimizing pavement marking operations.

4.3.2 Deterioration Rate

Traffic demand, snowplow operations, and vehicle mix (truck/car ratio) influence the deterioration rate and future condition of pavement marking. Higher traffic volumes, particularly trucks, and/or snowplow operations can dramatically increase pavement marking deterioration rates. Accelerated deterioration caused by increased traffic volumes, and snowplow operation affects the funding level needed to maintain the system and can affect future installation strategy selection. A lack of sufficient funding can cause increased deterioration rates and worsening pavement marking conditions that will have lasting, long-term effects.

4.3.3 Risks to WYDOT Pavement Marking

A secondary risk of the pavement marking management strategy is based on the concept that it is less expensive to keep good pavement marking in "Good" condition. This translates into the accepted risk that some pavement marking in "Poor" condition will technically remain poor and will often continue to deteriorate and become invisible which may result in crashes. All the current funding scenarios use an optimized system that will incorporate a mixture of rehabilitation to maximize the benefit to cost for the pavement marking in interstate, non-interstate NHS, and non-NHS systems.

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.

4.4 Life-Cycle Cost Analysis (LCCA)

Establishing a framework for Life-Cycle Cost Analysis (LCCA) within WYDOT is crucial for optimizing the long-term sustainability of transportation infrastructure. In this regard, the identification and evaluation of the three areas of LCCA, namely Costs, Risks, and Funding, as shown in Fig. 2, are crucial to ensure that the transportation projects undertaken by WYDOT are cost-effective and meet the desired performance criteria over their entire life cycle. The identification of these areas and how WYDOT is addressing them will contribute significantly to the goal of the study, which is to develop a comprehensive framework for LCCA within WYDOT. By analyzing these areas, we can identify the significant factors and challenges associated with LCCA implementation and make recommendations to optimize the decision-making process, reduce project risks, and allocate resources more effectively. Ultimately, this study will help WYDOT to achieve its strategic objectives of delivering

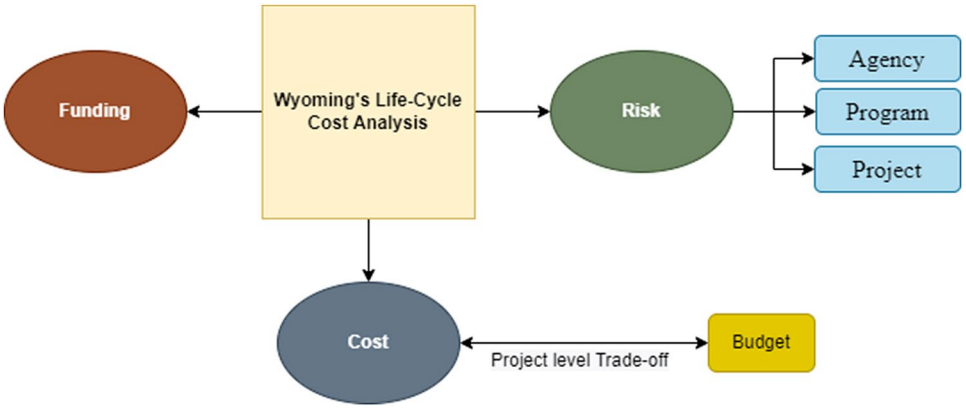

Fig. 2 Required areas for establishing Wyoming's LCCA

safe, sustainable, and efficient transportation infrastructure for the state of Wyoming.

4.4.1 Costs

The inclusion of costs in PMMP is a crucial aspect that requires careful consideration. The PMMP's primary objective is to provide recommendations for pavement marking management that meet the desired performance targets, while remaining within budget constraints. In this context, the recommended budget amounts generated by the PMMP play a critical role in decision-making for pavement marking projects. The mentioned trade-offs between functional classifications help to ensure that resources are allocated optimally across different pavement marking types and levels of service. As a result, the PMMP's cost component provides a mechanism for balancing the cost of maintaining the pavement marking system with the desired level of service, which is essential for effective asset management. The consideration of costs in the PMMP will significantly contribute to the study's overall goal of developing an effective and efficient pavement marking management plan for the transportation network.

4.4.2 Risks

Understanding and mitigating risks is a crucial component of the (PMMP). The identification of risks at three levels as seen from Fig. 2, "agency", "program", and "project", as suggested by the Federal Highway Administration's report, and "Risk-Based Transportation Asset Management: Evaluating Threats, Capitalizing on Opportunities," provides a comprehensive framework for identifying and mitigating potential risks to the pavement marking system. The identification of the Agency Risk, which is the lack of adequate funding to preserve and maintain the existing pavement marking, is critical as it represents the highest risk level and is essential to ensure the long-term sustainability of the pavement marking system. The Program Risk, which is common to clusters of projects, programs, or entire business units, requires careful attention to address potential risks related to natural, environmental, and man-made factors. Finally, the Project Risk, the lowest risk level, is involved in bringing individual projects to contract and requires a focused approach to identify and mitigate risks specific to each project. This will help transportation agencies, such as the Wyoming Department of Transportation, to proactively identify and mitigate potential risks to their pavement marking system, resulting in improved transportation system performance and better asset management.

Table 3 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 4 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%

4.4.3 Funding for Pavement Marking

Table 3 presents the current annual spending on striping and marking by different districts, providing a comprehensive understanding of the current budget allocation. It can be seen from Table 3 that approximately $1.1–$1.4 million was spent annually by different districts. The absence of District 4's response may limit the generalizability of the

Table 5 Effects of increased pricing of pavement marking materials at 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 able to meet minimum reflectivity standards and fewer roads with paint
4	Has not 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

Table 6 Determination of service life of pavement marking by different districts

District	From 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						✓

findings, but the information gathered from the other districts can provide valuable insights. Table 4 shows that all the districts responded that future budgets for pavement marking should be increased. These responses highlight the importance of pavement marking and the need for adequate budget allocation to support effective pavement marking management. District 1's recommendation of a minimum increase of 30–40%, District 3's recommendation of a $1 million increase, and District 5's recommendation of a 50% increase provide valuable insights into the budgetary needs of different districts. Ultimately, this will help transportation agencies, such as the Wyoming Department of Transportation, to allocate resources more effectively and optimize pavement marking system performance.

Table 5 shows the effects of increased pricing of pavement marking materials. It can be seen in Table 5 that increased pricing did not impact Districts 4 and 5 yet, but the other 3 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 inability to meet minimum retroreflectivity standards.

4.5 Performance Analysis

4.5.1 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 6 summarizes the results. It can be seen from Table 6 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 predetermined 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.

Tables 7 and 8 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 7 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

Table 7 District's estimate of the service life of pavement striping and markings in low-volume roads

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

paint was 2 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 8 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 1 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 2 years.

4.6 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 9 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 lines were stripped every two years. District 4 took into account traffic volume, construction projects, and maintenance work in addition to their regular restriping.

Next, the goal of this study is to identify districts' strategies for 5-year and 10-year plans for pavement marking. As shown in Table 10, 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.

Next, districts were asked whether they needed more resources for manpower, material, equipment, or safety/warning devices. Table 11 summarizes the results. All

Table 8 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

Table 9 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 Urban: all striping 2 times/year

Table 10 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.	✓		✓		

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.

4.7 Maintaining and Preserving Pavement Marking

Policy for pavement marking maintaining and preserving is important. Table 12 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 being reported. Both districts 3 and 4 also mentioned that they

Table 11 District's need for more resources

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

Table 12 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	✓		✓		

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.

Districts were also asked what the key sources of technical guidance were for the management of pavement marking. Construction/new installation as well as maintenance and rehabilitation were considered. As shown in Table 13, 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.

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 14. 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, reducing travel time, and cost were identified by Districts 1 and 5 as the third most important criteria, while road esthetics was considered the third most important criteria by District 4. As shown in Table 14, 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 4 that comfort and convenience of the traveling public were ranked as the fourth most important criterion, while road esthetics was the fifth most important criterion.

5 Conclusions

In this study, PMMP was investigated for the state of Wyoming. The investigated PMMP for Wyoming in this study was based on the transportation asset management plan of

Table 13 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		✓		✓

Table 14 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 esthetics
1	2	3	1	4	5
2	NA	NA	NA	NA	NA
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)

Wyoming which was developed in 2018. Besides, to develop a comprehensive PMMP, a survey was conducted statewide where all five districts of Wyoming participated. The objective of the survey was to seek information about districts' current pavement marking striping and management practices. That is, long-term pavement marking management strategies for Wyoming were proposed considering budgets and newly recommended pavement marking specifications that accommodate vehicles with machine vision technologies, such as those with advanced driver assistance systems (ADAS). The important components of this study are summarized in the following paragraph.

The objective of the PMMP developed for Wyoming was to minimize the life-cycle cost of the pavement marking and maximize its value with constrained fiscal funding. The goal of PMMP is to maintain existing pavement markings through timely installation and limit the pavement markings reaching poor/unacceptable conditions. The budget for the pavement marking was done annually by the district and delivered to the district by the vendors via a statewide contract produced by the main office. Approximately, $1.1–$1.4 million was spent annually on pavement marking and striping by different districts. All the districts mentioned that the future budget for pavement markings should be increased. Different districts also identified several effects of increased pricing of pavement marking materials such as fewer lane miles being striped, depreciated markings, a decrease in surface quality reflects in the paint quality and durability, etc. Different districts followed different strategies for planning future restriping. Strategies such as restriping on odd/even years, following pre-determined priority schedules, taking into account traffic volume, construction projects, and maintenance work in addition to regular schedules for striping, etc. were adopted by different districts. When asked about the 5- and 10-year plans for pavement marking, most of the districts mentioned that they wanted to have pavement marking standards that would accommodate machine vision systems. A few districts wanted to have databases that would contain pavement marking management data and additional funding for the pavement marking maintenance program. Also,

all the districts mentioned that they needed more resources for manpower. A few districts mentioned that they needed more resources for material as well. A policy for maintaining and preserving pavement marking was also investigated. All the districts would like to have a set schedule based on which they wanted to do preservative maintenance. For the management of pavement marking, all districts were willing to follow policies, standard guidelines, and procedures established by WYDOT.

The development and implementation of PMMP is important for the efficient management of pavement marking. Very few DOTs were found to have dedicated PMMP. Therefore, the essential components of PMMP which were identified in this study will help DOTs and other agencies to develop their own PMMP considering budget, labor resources, life-cycle cost, performance analysis, and newly suggested marking specifications.

Acknowledgements The authors appreciate the efforts of the Wyoming Department of Transportation (WYDOT) in funding this work through project #RS 06221. All Figures, tables, and equations listed in this paper will be included in a WYDOT final report at the conclusion of this study. A matching fund for this study was secured from the Mountain Plains Consortium. The authors would like to acknowledge all districts of Wyoming that responded to the survey.

Data availability The data that support the findings of this study are available on request from the corresponding author.

Declarations

Conflict of Interest The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

1. Cambridge Systematics and Meyer M.D. (2007) "U. S. domestic scan program: Best practices in transportation asset management" NCHRP project 20–68 domestic scan pilot program report, Federal highway administration (FHWA), Washington, DC.
2. F. Arif, M.E. Bayraktar. (2012) Theoretical framework for transportation infrastructure asset management based on review of best practices. Construction research congress 2012: Construction challenges in a flat world. pp. 2349–2358
3. Choubane, B., Sevearance, J., Holzschuher, C., Fletcher, J., & Wang (Rose), C. (2018). Development and implementation of a pavement marking management system in Florida. *Transportation Research Record, 2672*(12), 209–219. https://doi.org/10.1177/0361198118787081
4. Hawkins, N., Smadi, O., Hans, Z., & Maze, T. H. (2006). Integrated approach to pavement marking management. *Transportation research record, 1948*(1), 98–107.
5. Saha, P., & Ksaibati, K. (2019). Optimization model to determine critical budgets for managing pavement and safety: Case study on statewide county roads. *Journal of Transportation Engineering, Part A: Systems, 145*(2), 04018088.
6. Sassani, A., Smadi, O., & Hawkins, N. (2021). Developing pavement marking management systems: a theoretical model framework based on the experiences of the US transportation agencies. *Infrastructures, 6*(2), 18.
7. Markow, M. J. (2007). *Managing selected transportation assets: signals, lighting, signs, pavement markings, culverts, and sidewalks* (Vol. 371). Transportation Research Board.
8. Hawkins, N. R., Smadi, O. G., & Hans, Z. N. (2006). *Planning, developing, and implementing the iowa pavement marking management system (IPMMS): phases I and II*. Iowa State University.
9. Hawkins, N., & Smadi, O. (2008). *Developing and implementing enhanced pavement marking management tools for the minnesota department of transportation: phase I mapping tool* (No. MN/RC 2008–37). Minnesota. Dept. of Transportation.
10. Zhang, Y. (1999). Pavement marking management system database; 0-5548-P1; Texas transportation institute, The Texas A&M university system: college station, TX, USA
11. NCHRP 551: Performance measures and targets for transportation asset management; The national academies press: Washington, DC, USA, 2006. Available online: https://www.trb.org/publications/nchrp/nchrp_rpt_551.pdf
12. Hawkins, N., & Smadi, O. (2010). *Local Agency Pavement Marking Plan* (No. IHRB Project TR-551). Institute for Transportation, Iowa State University.

Uttara Roy is a postdoc at the University of Wyoming. She had her bachelor's degree from Bangladesh University of Engineering and Technology, her master's from Chalmers University of Technology, Sweden, and her doctoral degree from Lamar University, Texas. Her research interests are road safety, human factors, statistical modeling of big data, etc.

Dima A. Husein Malkawi is an Assistant Professor at German Jordanian University, Amman, Jordan. Her research area is soil-structure interaction, geothermal foundations, and slope stability. She received both her M.Sc. and Ph.D. in geotechnical engineering from the University of Akron.

Omar Albatayneh is currently an Assistant Professor in the Department of Civil and Environmental Engineering at German Jordanian University as well as a Deputy Director for the Road Safety Center of Excellence (RSCE). He holds a Ph.D. in Transportation Engineering from the University of Wyoming. His areas of expertise include Asset Management, Infrastructure Management, Urban Planning, Traffic Analysis, and Transportation Data Science.

Khaled Ksaibati obtained his BS degree from Wayne State University and his MS and Ph.D. degrees from Purdue University. Dr. Ksaibati worked for the Indian Department of Transportation for a couple of years prior to coming to the University of Wyoming in 1990. He was promoted to associate professor in 1997 and full professor in 2002. Dr. Ksaibati has been the director of the Wyoming Technology Transfer Center since 2003.