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Investigating the Necessity and Prioritizing Pavement Markings on Low-Volume Roads

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16. Abstract (Limit: 250 words)

The installation and maintenance of pavement markings represents a significant financial investment for local agencies. Local agencies need a mechanism to better understand the value, cost, and need for markings along their roadways to make the best use of available budgets. This project developed a prioritization approach and spreadsheet tool (link provided in box 15) to assist local agencies in meeting this need. Multicriterion decision analysis using the simple additive weighting method was employed to assess the multiple factors/criteria that affect pavement marking decisions. An Excel spreadsheet tool was developed to implement this approach using different pavement marking alternatives, including centerlines, edgelines, centerlines and edgelines, high-visibility markings, and enhanced-durability markings. The criteria considered by the process include project type, County Roadway Safety Plan (CRSP) rating, functional classification, pavement condition, traffic volume, age of current markings, pavement width, preferences for marking costs, desired marking durability, and crash reduction potential. This tool is posted on the Local Road and Research Board (LRRB) website in the "Resources" section at the following URL: https://lrrb.org/resources/. Factor weights are used to assign a relative importance to each of these criteria for a respective alternative compared to other alternatives. The result is a performance rating score for each marking alternative relative to all model criteria and factors that provide users with information on the relative performance of different marking alternatives in comparison to one another and an estimated project cost for the highest ranking alternative for a site. The highest scoring alternative represents the marking that should be considered for use. Additionally, the tool ranks all sites being evaluated compared to one another based on the highest rating scores from each individual site.

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INVESTIGATING THE NECESSITY AND PRIORITIZING PAVEMENT MARKINGS ON LOW-VOLUME ROADS

FINAL REPORT

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EXECUTIVE SUMMARY

Many miles of local roadways in Minnesota have been enhanced with pavement markings (e.g., yellow centerline and/or white edgelines). The installation and preservation of these markings represent a significant financial investment for the local agencies that maintain them. There is a need to better understand the value, cost, and necessity of pavement markings along roadways in order for local agencies to make the best use of available budgets during the course of decision-making.

The goal of this research was to address this need through the development of a prioritization approach and a tool for determining the use of pavement markings on local roadways. This would help local agencies understand the necessity of, safety and operational benefits from, available materials for, and costs of pavement markings. A multi-step approach was taken by the research team to identify critical information and practices before developing the prioritization approach/tool. This approach included a literature review, a survey of current Minnesota local agency marking practices, and a review of the Minnesota County Road Safety Plans (CRSPs) to identify the extent to which marking recommendations were made. This information was then used to develop the prioritization approach and tool in a way that incorporated both past research results and local state of the practice.

Various literature was reviewed on the safety and operational benefits, costs, maintenance, proposed retroreflectivity requirements, and management/prioritization of pavement markings (traditional and enhanced). The review found that limited research has been completed related to traditional marking use and effectiveness on local roadways. Traditional markings produce safety benefits that include lower crash rates, lower crash frequencies on curves, and general crash reductions but no real impacts on vehicle speeds or lateral placement. Research on enhanced pavement markings found that wider edgelines and wet-reflective markings produce crash reductions but do not appear to alter driver behavior. A review of the proposed retroreflectivity rule for local agencies in the *Manual on Uniform Traffic Control Devices* (MUTCD) determined that the rule's impact on marking practices and maintenance will likely depend on roadway type and speed limit. Finally, a review of marking prioritization and management approaches found that only limited efforts toward the development of such approaches have occurred to date. The approaches identified focus on when marking use is warranted, the condition of markings, available budgets, and general site characteristics.

The survey of pavement marking installation and maintenance activities of local agencies in Minnesota found that most counties replying to the survey used centerlines and/or edgelines on their roadways. This high rate of use appears to be guided, in part, by the MnDOT's State-Aid Operations rules. A number of counties indicated that they chose to apply pavement markings to all of their roadways. Most agencies indicated that they used 4-inch markings, although wider markings were also in use. These markings were typically latex paint or epoxy, with repainting performed based on age, condition, or budgeting.

Minnesota CRSPs incorporate pavement marking recommendations, and it was necessary to understand which pavement marking recommendations are made, how they are incorporated into the plans, and the extent to which such recommendations are made. The marking recommendations made in CRSPs include wider markings (6 inches), alternative materials (epoxy), rumble stripes, and supplemental markings (stop bars, etc.). The review of plans found that pavement markings were recommended, on average, for 109 miles of roadway in each county. Given the extent of these recommendations, they needed to be directly incorporated into the prioritization approach being developed in this project. This was done by including CRSP-recommended sites and treatments among the collective pool of sites being prioritized. In doing so, CRSP sites would be given a greater consideration and priority compared to other sites through the star rating assigned to the particular locations.

Based on the information collected through the previously described activities, an approach and tool to prioritize pavement marking use was developed. The tool is designed to assist local agencies with pavement marking installation and maintenance decision-making by considering the different characteristics of a site, including its CRSP rating, as well as user preferences related to cost, durability, and safety-effectiveness. This tool is posted on the Local Road and Research Board (LRRB) website in the "Resources" section at the following URL: https://lrrb.org/resources/.The approach developed relied on the multicriterion decision-making process to take into consideration the multiple factors and criteria that affect pavement marking decisions. The simple additive weighting method was employed to obtain a weighted sum of performance ratings for each marking alternative (configuration/material) relative to all model criteria/factors.

The pavement marking alternatives considered by this work included centerlines, edgelines, centerlines and edgelines, high-visibility markings, and enhanced-durability markings. The criteria considered by the process included project type, CRSP rating, functional classification, pavement condition, traffic volume, the age of current markings, pavement width, preferences for marking costs, desired marking durability, and crash reduction potential.

The multicriterion decision analysis approach was applied to pavement marking decision-making through the development of an Excel spreadsheet tool. A primary spreadsheet was developed to support user data entry and present marking recommendations for a roadway system on a site-by-site basis. Three additional spreadsheets were developed: the first contains a sorting mechanism for the user to view sites in a ranked order; the second shows subdecision matrices with score values related to each criteria/alternative combination; and the third is a calculation spreadsheet that takes user input and generates marking alternative scores. The tool output consists of information on the relative performance of different marking alternatives compared to the others.

Based on the work completed during this project, the tool that has been developed will provide the user with information on the performance of different pavement marking alternatives based on the set of site characteristics. Use of the tool will allow not only for the prioritization of pavement markings among different sites but also an estimation of the costs associated with each respective alternative. However, the tool itself is intended only to provide assistance in the decision-making process, and engineering judgement must continue to be employed when an agency ultimately selects when and where to apply markings and which materials to use. The tool itself reflects current practices and policies and it should be adapted and modified as needed should these change in the future.

CHAPTER 1: INTRODUCTION

Many miles of Minnesota's local roadways have been enhanced with pavement markings (e.g., yellow centerline and/or white edgelines). The installation and preservation of these markings represents a significant financial investment for the local agencies that maintain these markings. In light of this, there is a need to better understand the value and cost of typical and enhanced (e.g., wider or using alternative materials) pavement markings along the roadways maintained by local agencies. This will allow development of improved guidance to assist local agencies with marking installation and maintenance decisions within the constraints of limited budgets.

The goal of this research was the development of a prioritization approach for the use of pavement markings on local roadways based on their necessity, safety and operational benefits, materials, estimated longevity, and costs. To achieve this goal, the work considered a variety of information to develop an approach to guide decisions regarding pavement marking use along low-volume roads. This was accomplished through a series of tasks:

- A review of existing research on typical and enhanced pavement markings, with a focus on the benefits they produce (e.g., crash reduction or improved lane-keeping), costs, current maintenance practices, and other aspects.
- A survey of Minnesota counties to learn their current practices and management approaches for pavement markings and other information of interest.
- A review of the current County Road Safety Plan (CRSP) methodology to understand the data and approach used to rank at-risk routes and identify improvement strategies to address issues, specifically the use of different types of pavement markings being recommended.
- Development of a decision-making assistance approach and tool to guide pavement marking use decisions and management based on the information identified, collected, and reviewed in the prior tasks.
- Compilation of a final report describing the results of the project tasks and development of a short technical brief explaining the approach and tool and how they can be implemented.

1.1 PROJECT OBJECTIVES

The objectives of this project were to review the existing research on typical and enhanced pavement marking benefits (e.g., reduced crashes), document the characteristics of current pavement marking installation and maintenance practices along local agency roads in Minnesota, review the CRSP site ranking methodology and understand which pavement markings improvements are recommended, and develop an approach and tool based on this collective information to assist local agencies in the state with their pavement marking installation and maintenance decision-making. The approach developed has been designed to aid local agencies that work within a constrained budget and complement the process and recommendations of the CRSP for pavement marking strategies. The end result of this research is a decision-making tool for local agencies (namely counties) to use in determining which routes should receive markings during a given year based on factors such as available budget, age of existing markings, etc.

1.2 REPORT CONTENT

This report includes six chapters. The first chapter includes a general description of the issue addressed by this project, along with its objectives. The second chapter is a summary of the relevant literature and current practices for various aspects of pavement markings, both traditional and enhanced, including safety and operational benefits, costs, maintenance, proposed retroreflectivity requirements, and management/prioritization. Chapter 3 presents the findings of a survey of local agencies in Minnesota regarding their use of pavement markings. The fourth chapter reviews the County Road Safety Plan process, describes how that process produces pavement marking recommendations, and explains what those marking recommendations are. Chapter 5 presents the development of the pavement marking decision-making approach and its implementation through a spreadsheet tool. Chapter 6 includes the conclusions and recommendations developed from the completion of the tasks described in this report.

CHAPTER 2: LITERATURE REVIEW

The starting point in the development of a prioritization approach for pavement markings was a review of previous research and documentation related to the subject. This chapter summarizes existing research on a variety of aspects related to pavement markings, particularly on low-volume and local roadways. It begins with a review of the benefits and costs of typical/traditional and enhanced pavement markings (e.g., crash reduction and improved lane-keeping). Next, the review summarizes existing work on pavement marking maintenance practices. A review of the proposed rule on minimum retroreflectivity for markings in the Manual on Uniform Traffic Control Devices (MUTCD), and the rule's consequences and impacts for agencies if adopted, is then presented. Finally, the chapter concludes with a review of work related to pavement marking prioritization and management approaches and a general summary.

2.1 TRADITIONAL PAVEMENT MARKINGS

Pavement markings can consist of different paint materials. Traditionally used paint materials include latex (for waterborne paint), alkyd or alkyd-modified materials, and chlorinated rubber (these final three materials are used occasionally and appear in literature) (Migletz et al. 1994). The following text discusses the different benefits and costs associated with these traditional paint materials.

2.1.1 Safety Benefits

An extensive review found that the body of literature about the safety effectiveness of traditional pavement markings (particularly on low-volume roadways) is limited. A Texas study summarized crash data from two-lane roadway segments with and without edgelines (Tsyganov et al. 2006). The researchers found that edgelines reduced crashes by up to 26 percent, but the greatest reductions were along roadways with lane widths of 9 to 10 feet (Tsyganov et al. 2006).

Several studies were completed in Louisiana, and the most robust safety analysis found a reduction of 15 percent when edgelines were added on narrow roads (i.e., 22 feet or less). Benefit-cost ratios were calculated ranging from 75.56 to 117.58 (based on contractor versus department installation) (Sun and Das 2012, Sun and Das 2014, Sun et al. 2014).

The Kentucky study considered crash patterns along narrow two-lane rural roadways that had edgelines but no centerline. The analysis revealed that roadways with narrow lanes had approximately twice the percentage of single-vehicle crashes than roadways with wider lanes, while roads with wider lanes had the highest percentages of rear-end, angle, and same-direction crashes. The authors recommended that centerline and edgeline markings be used on roadways with a lane width of 9 feet, centerlines only on roads with a lane width of 8 feet, and edgelines only on roadways narrower than 8 feet (Agent and Green 2008).

The Virginia study examined crash data along two-lane roadways with traffic volumes of 3,000 vehicles per day (vpd) or less and pavement widths of 20 feet or less. Current maintenance demands and limited funds had prompted this investigation of the potential safety benefits of the use of pavement markings along low-volume roads. Models were developed to evaluate four pavement marking conditions: no markings, centerline markings only, edgeline markings only, and the use of both centerline and edgeline markings. For 16-foot pavements, the prediction curves indicated that the expected number of crashes for roadways with no markings was lower than the expected numbers of crashes for roadways with combined pavement markings or centerline markings only (Dougald et al. 2013, Kweon et al. 2015). For 18-foot pavements, the results for roadways with no markings and roadways with a centerline were similar to one another. Finally, for 20-foot pavements, the sites with no markings were predicted to have fewer crashes than roadways with both pavement markings and roadways with centerline markings only at all annual average daily traffic (AADT) levels (Dougald et al. 2013, Kweon et al. 2015).

Knapp et al. (2015) summarized literature on pavement markings and safety on low-volume roadways, and also evaluated the use of pavement markings on low-volume roads in Iowa (Knapp et al. 2015). As part of that work, a basic safety benefit-cost evaluation of pavement markings was conducted along a hypothetical one-mile segment of paved and seal-coated secondary roadway. Using average crash densities per mile from Iowa secondary roadways over a 10-year period, it was determined that the potential percent total crash reduction required to produce a benefit-cost ratio of 1.0 for centerline and no passing zone markings was only 0.42 percent (Knapp et al. 2015). Similarly, along a seal-coated roadway, the reduction needed would be approximately 1.9 percent (Knapp et al. 2015). When considering the use of centerline, no passing zone, and edgeline markings, a total crash percent reduction of 1.1 percent was needed along a paved roadway (Knapp et al. 2015). Similarly, along a seal-coated roadway, the percent reduction needed would be approximately 5.1 percent (Knapp et al. 2015). These estimated percentages were within the range of those reported elsewhere in the literature.

Although not a study focused on evaluating the use of markings, Carlson et al. (2009) synthesized existing research results on the safety benefits of various types of pavement markings (Carlson et al. 2009). Based on the information reviewed, it was concluded that the work completed to date (2009) showed that the addition of edgelines to two-lane rural roadways reduced crashes and fatalities. The crash reduction benefits were achieved even for narrow pavement widths (18 feet or less, as summarized elsewhere in this chapter) and AADT levels as low as 1,000 vehicles per day (Carlson et al. 2009). However, it was noted that crash analyses for state and local roadways were still needed to better understand the safety benefits of markings and develop a correlation between marking retroreflectivity and safety.

2.1.2 Operational Benefits

While the marking materials considered were not specified, van Driel et al. (2004) conducted a meta-analysis (a statistical procedure combining data from multiple studies) to evaluate the effects of edgelines on vehicle speed and lateral placement (van Driel et al. 2004). A total of 65 studies/results from work conducted in the U.S. and the Netherlands between 1958 and 2000 were used in the analysis. The findings of the meta-analysis indicated that the effects of edgelines on speed and lateral placement varied. Increases in speed of up to 6.5 miles per hour (mph) and decreases in speed of 3.1 mph were found (van Driel et al. 2004). Shifts in lateral position ranged from up to 11.8 inches toward the center of the roadway to 13.8 inches toward the edge of the roadway (van Driel et al. 2004). Based on these observations, the researchers concluded that the mean effects of edgelines on speed and position were approximately zero (van Driel et al. 2004).

Further analysis was performed to determine the characteristics that influenced the effects of an edgeline on speed and position (van Driel et al. 2004). The effects of an edgeline on speed were identified to be related to the presence of a centerline. Adding an edgeline to a roadway without a centerline increased vehicle speeds, while replacing a centerline with an edgeline reduced speeds (van Driel et al. 2004). Shoulder width and roadway environment contributed to vehicle placement. Wide shoulders or buildings next to the roadway led to shifts in lateral position toward the roadway edge, while narrow shoulders led to shifts toward the center of the roadway (van Driel et al. 2004).

In a 2009 synthesis, Carlson et al. (2009) drew conclusions on the operational benefits of various types of traditional pavement markings. The researchers found that pavement markings produced no real impacts on vehicle speeds or lateral placement or, at most, produced only small impacts on these aspects (Carlson et al. 2009). These results were consistent between aspects such as day and night and the number and width of lanes. Based on the work they reviewed, the researchers noted that further studies of how drivers use markings during the day and night were needed. Further research was also needed to understand how pavement markings affect driving behaviors during low-visibility conditions, when travelling through curves, and when approaching on-coming traffic at night (Carlson et al. 2009).

A review of material on the operational benefits of pavement markings on low-volume roads was provided by Knapp et al. (2015). Among the materials reviewed were work from Louisiana (Sun and Tekell 2005) and Texas (Tsyganov et al. 2005). This work is summarized below, and more detail can be found in Knapp et al. (2015).

The Louisiana study focused on pavement marking impacts on vehicle position before and after edgeline installation. It was found that on tangent roadway sections, vehicles shifted toward the centerline during the day after edgelines were installed, but fewer vehicles crossed the centerline. At night, vehicles were more centrally located in their lanes after edgeline installation, but the edgelines resulted in vehicles operating further away from the roadway edge. Along curved roadway segments, the researchers' conclusions about vehicle lateral placement after edgeline installation appeared to be mixed, with more centerline encroachments observed (Sun and Tekell 2005). The general conclusions of the researchers were that the addition of edgelines seemed to result in vehicles being more centrally located within their lane at night but that the edgelines resulted in vehicles operating further away from the roadway edge (Sun and Tekell 2005).

In the Texas study, driver behavior and reactions to the addition of edgelines along rural two-lane roadways were examined. Evaluation of field data revealed that drivers increased their speeds after the edgelines were installed (Tsyganov et al. 2005). The addition of edgelines had no significant vehicle positioning impact along the narrowest roadway width (i.e., 18 feet), but an average shift of 1.5 feet toward the edgeline occurred along the wider (i.e., 20- to 22-foot) roadway study sites. It was concluded that edgelines should be used on pavements with a width of at least 21 feet 9 inches and that applications on narrower pavements should be left to engineering judgement (Tsyganov et al. 2005).

2.1.3 Additional Benefits

Miller (1991, 1992) conducted a benefit-cost analysis of traditional painted pavement markings on urban and rural roadways in the U.S. (Miller 1991, Miller 1992). In this work, the benefits of markings were improved safety (reduced crashes) and reduced travel times (higher travel speeds due to lane-keeping). The safety benefits of centerlines were assumed to be a crash reduction of 26.5 percent, based on an average of reported crash reductions from research at the time (Miller 1991, Miller 1992). (Note that the robustness of the methodologies employed in then-current research were not always comparable to today's methods, and this figure should be viewed with caution).

The safety benefits from the addition of edgelines added an 8 percent reduction to that figure (i.e., centerlines and edgelines produced an assumed crash reduction of 34.5 percent). These reductions and Federal Highway Administration (FHWA) crash values were used to calculate the safety benefit produced by pavement markings. This was calculated as the total value of crashes on a segment times the respective crash reduction percentages discussed above. The travel time savings benefit was calculated to be worth the value of a vehicle hour of travel in 1991, which was $8.84 ($15.21 in 2016 dollars) (Miller 1991, Miller 1992). Pavement markings were assumed to raise speeds on roadways by 2 mph during the peak travel period (6:00 a.m. to 7:00 p.m.). The costs of markings included the paint material, equipment, and labor involved in marking operations.

Benefit-cost ratios were developed for different considerations using the benefit and cost values from the prior information and assumptions. The calculated benefit-cost ratios (a ratio exceeding 1.0 indicates at least $1.00 in benefits was achieved for every $1.00 of cost incurred) for single, solid markings are presented in Table 2.1.

Table 2.1. Benefit-cost ratios of traditional pavement markings by roadway classification and location

	Urban		Rural		Combined
Roadway Class*	**VMT**	**B/C Ratio**	**VMT**	**B/C Ratio**	**B/C Ratio**
Interstate	258,662	74.1	181,284	46.3	58.3
Other freeway	116,965	63.4	--	--	63.4
Major arterial	319,286	102.0	160,253	105.2	102.9
Minor arterial	231,786	125.8	151,783	68.9	97.1
Major collector	99,245	52.2	183,507	28.6	34.2
Minor collector	--	--	46,985	20.6	20.6
Total	1,025,944	90.6	723,812	40.1	60.0

Miller 1991, 1992, based on FHWA *Highway Statistics 1988* (published in 1989)

Caution is urged when considering these results because they were developed using several assumptions and because of the shortcoming of calculating crash savings using crash data from the roadway network where pavement markings were largely already present. However, the high benefit-cost ratios presented in Table 2.1 indicate that the use of pavement markings likely produce benefits far in excess of the costs incurred.

Montebello and Schroeder (2000), in a report for the Minnesota Department of Transportation (MnDOT), summarized the general benefits/advantages of painted pavement markings (Montebello and Schroeder 2000). Latex, alkyd, and mid-durable paints all shared the advantages of being inexpensive, quick drying, and long lived on low-volume roads (Montebello and Schroeder 2000). Latex and mid-durable paints also had the advantages of having easy cleanup and disposal of materials and did not generate any hazardous waste products (Montebello and Schroeder 2000). Alkyd paints had the additional advantage of having potential for application in cold weather (Montebello and Schroeder 2000).

2.1.4 Costs of Traditional Markings

A review of material on the costs of painted markings showed a wide range of financial values. Different service life values were also reported. The following text discusses the information that was identified.

Miller (1992) found that in 1988 the average cost of painted markings was \$0.035 per linear foot on rural roadways and \$0.07 per linear foot on urban roadways (\$0.06 and \$0.12 in 2018 dollars) (Miller 1991, Miller 1992). These values reflected the total cost of marking operations, and included the paint material, equipment and labor involved in marking operations.

A 2000 report from the Minnesota Department of Transportation discussed the financial costs and disadvantages of paint markings (Montebello and Schroeder 2000). From a financial cost perspective, latex (waterborne) markings had a cost of \$0.03 to \$0.05 per linear foot (\$0.09 to \$0.11 per linear foot for new construction and \$0.052 per linear foot for maintenance in 2017) (Montebello and Schroeder 2000). Epoxy markings had a cost of \$0.20 to \$0.30 per linear foot (\$0.29 per linear foot for new construction and \$0.156 per linear foot for maintenance in 2017) (Montebello and Schroeder 2000).

National Cooperative Highway Research Program (NCHRP) Synthesis 306 provided average cost data from a national survey of agencies for waterborne paint and solvent-based paints, with both materials reported as costing \$0.05 (\$0.07 in 2018 dollars) per linear foot (Migletz and Graham 2002).

Jiang (2008) surveyed Indiana Department of Transportation (DOT) districts on the cost and service life of markings as part of a larger review of existing marking research. The survey found that waterborne paint costs at districts ranged from \$0.05 to \$0.50 per linear foot (\$0.06 to \$0.56 in 2018 dollars) (Jiang 2008).

Carlson et al. (2009) noted that the costs of traditional pavement markings at the time of their study ranged between \$0.10 and \$0.25 per linear foot (\$0.11 to \$0.28 in 2018 dollars) based on data from 18 states (Carlson et al. 2009). Extrapolating that figure, the researchers estimated that pavement markings on roadways, including local roads, in the entire U.S. represented an annual cost of \$2 billion.

Songchitruksa et al. (2011) presented cost information for traditional pavement markings in Texas (Songchitruksa et al. 2011). That work reported that the mean cost per mile for painted markings was $1,056. This represented an average unit cost of $0.20 per foot ($0.22 in 2018 dollars).

Migletz et al. (1994) listed the targeted service life (at the time, 1994) for painted markings as being 6 to 12 months (Migletz et al. 1994). In high-traffic conditions, a 3-month service life may be more likely.

Montebello and Schroeder (2000) reported that all paint markings in Minnesota at the time of their study had an estimated life of 9 to 36 months (Montebello and Schroeder 2000). The disadvantages of all paint markings included short life on high-volume roads, the potential for being damaged by sands and abrasives, and poor adhesion to concrete (Montebello and Schroeder 2000). Alkyd markings had the additional disadvantages of being flammable and requiring solvents for clean-up activities (Montebello and Schroeder 2000). Finally, latex and mid-durable paints required warm pavements to facilitate adherence (Montebello and Schroeder 2000).

Kopf (2004) developed estimated service lives for painted (waterborne and solvent-based) pavement markings in Washington (Kopf 2004). Yellow markings using waterborne paint had an estimated service life of 12 to 20 months on roadways with 7,500+ AADT. White markings using waterborne paint had an estimated service life of 3 to 18 months on roadways with 7,500+ AADT. Yellow, solvent-based markings had an estimated service life of 10 to 11 months on roadways with 3,500+ AADT. White, solvent-based markings had an estimated service life of 14 to 16 months on roadways with 3,500+ AADT. The researcher noted that all of these figures were dependent on additional factors, including location, climate, etc. (Kopf 2004).

2.2 ENHANCED PAVEMENT MARKINGS

In addition to traditional paint-based markings, enhanced materials and designs are also used by many agencies for a variety of reasons (durability, conspicuity, retroreflectivity, etc.). Enhanced pavement markings can take on a number of different characteristics, including material types, widths, retroreflectivity contrast levels, and so forth. Before proceeding to the findings of past research on enhanced pavement markings, a few definitions are necessary for reader familiarization:

- Thermoplastic: markings made up of a binder, pigment, glass beads, and other filler that are typically applied by spraying and that perform well on asphalt but not as well on concrete pavements (Benz et al. 2009). This material can be applied preformed (a pre-made marking that is applied like a tape), sprayed (applied by spraying to the pavement), or extruded (thermoplastic is heated and applied through an extrusion mold).
- Tape: factory-manufactured markings that are applied in the field as either an inlay (applied in a milled or grooved pavement area, or by pushing the tape into a bituminous pavement) or as an overlay (applied to the top of a pavement following surface preparation with a primer) (Benz et al. 2009). Tapes are a higher cost material, but they have a longer lifespan (4 to 8 years) depending on how and where they are applied (Benz et al. 2009). In Minnesota, only temporary

markings are overlaid, permanent markings are applied to the pavement as either inlays or grooves.

- Epoxy: paint material comprised of a resin, pigment, extender, filler, and catalyst that accelerates set-up and dry time and that can be applied by spraying to asphalt and concrete (Benz et al. 2009). Epoxy markings are durable (lasting 2 to 4 years) and are generally applied in higher traffic volume situations.
- Polyurea: two-component marking material consisting of a mixture of resins, pigment, and fillers as one component and a cross linker (joiner between components) as the second component that can be applied to asphalt and concrete at low temperatures (Bahar et al. 2006).
- Methyl methacrylate: two-component marking material consisting of a pigment containing a methyl methacrylate monomer, pigments, fillers, silica, and glass beads, as well as a liquid or powder catalyst (Bahar et al. 2006). This material has seen limited use in the U.S., but it can be applied in very cool conditions on both asphalt and concrete (Benz et al. 2009).
- Wider markings: markings of widths of 4+ inches.
- Marking contrast: the ratio of luminance from a target to the luminance from the target's surroundings (Migletz et al. 1994).
- Black-outlined or –tagged contrast markings – pavement markings applied over a black background that results in a black outline to the marking. This outline helps increase the visibility of markings in some cases.

2.2.1 Safety Benefits

Hall (1987) evaluated the use of wider (8-inch) edgelines on 176 miles of rural state highways in New Mexico (Hall 1987). The wider edgelines were installed to address run off the road crashes. A simplistic before and after approach was used by this work. Differences between crash counts and crash rates for the treatment and comparison site groups were made. It was found that the run off the road crash rate (all crashes, per 100 million vehicle miles) fell 10 percent versus a drop of 16 percent for the comparison group (Hall 1987). This finding led the researcher to conclude that the observed change in crashes was due to the regression to the mean phenomenon (Hall 1987). It was also observed that run off the road crashes at night and on curves did not significantly change. As a result, it was concluded that the use of edgelines not be continued in the state (Hall 1987). Caution is strongly urged when considering this work, however, because the simple comparison approach that was used does not reflect the current state of the practice for a robust, statistical before and after safety evaluation.

Cottrell (1986) evaluated the use of wide (8-inch) edgelines on 60.7 miles of rural two-lane roadways in Virginia (Cottrell 1986). A total of three sites received the treatment. A before and after study with a comparison group was used to evaluate the impacts of wider edgelines on crashes. Analyses of crash data from run off the road crashes (total), run off the road crashes involving an impaired drivers, run off the road crashes on curves, run off the road crashes at night, run off the road and weather-related crashes, and opposite direction crashes were all performed. The results revealed that reductions in total run off the road crashes had occurred, but the results were not statistically significant. The author concluded that there was no evidence that wider edgelines affected run off the road crash frequencies in general or for any of the subcategories evaluated. As with other work, caution is strongly urged when considering the results of this study. The comparison approach that was used does not reflect the current state of the practice for a robust, statistical before and after safety evaluation.

Although not a specific safety study, the NCHRP Report 500 series outlined (then-current) proven, tried, and experimental strategies and countermeasures for addressing different crash issues in specific emphasis areas (NCHRP 2003). For pavement markings, these included higher contrast and wider markings. Report 500 noted that there was conflicting evidence on the crash related effectiveness of enhanced markings, but that they were compatible with other treatments and should not have adverse impacts (NCHRP 2003).

Potts et al. (2011) conducted an evaluation of the safety effectiveness of the Missouri Department of Transportation's (MoDOT) Smooth Roads Initiative (SRI) (Potts et al. 2011). One of the components of this initiative was different striping and delineation approaches, including the installation of wider and higher visibility lane lines and wider edgelines. These markings were installed on most Interstates, freeways, and multilane divided non-freeways in the state.

The safety evaluation that was performed for the program used the empirical Bayes method to estimate the safety effectiveness of specific marking improvements in combination with other treatments (Potts et al. 2011). Three years of crash data from before and after marking installation was used in the evaluation. The result of the evaluation was that a wide range of crash reduction factors (CRFs) was developed for different treatment combinations, areas, and crash severities. These factors are presented in Table 2.2. They were developed using a sound statistical approach and a large sample size from a diverse set of locations and should be considered highly reliable.

Table 2.2. Crash reduction factors for wider lane and edgelines (Potts et al. 2011)

Treatment	Area Type	Crash Severity(s)	Crash Reduction Factor
Wider lines with center and edgeline rumble strips[1]	Rural	Fatal, serious injury, minor injury	38%
	Rural	Fatal, serious injury	47%
Install wider markings and edgeline rumble strips with resurfacing	Rural	Fatal, serious injury	24% - 25%
	Rural	Fatal, serious injury, minor injury	24% - 26%
	Urban	Fatal, serious injury, minor injury	10% - 14%
Install wider markings and shoulder rumble strips[2] with resurfacing	Rural	Fatal, serious injury	26% - 49%
	Rural	Fatal, serious injury, minor injury	23% - 25%
	Urban	Fatal, serious injury, minor injury	20%
Install wider markings with resurfacing	Rural	Fatal, serious injury	21%-46%
	Rural	Fatal, serious injury, minor injury	9%-25%
	Urban	Fatal, serious injury, minor injury	4% - 8%
	Urban	Fatal, serious injury	38%
Install wider markings without resurfacing	Rural	Fatal, serious injury, minor injury	22%

[1] Centerline rumble strips are rumble strips added to the center of the roadway. Edgeline rumble strips are rumble strips added along the edge of the roadway that may extend partially onto a paved shoulder. Wider markings are those that are 6+ inches.

[2] Shoulder rumble strips are rumble strips added to a paved shoulder beyond the painted edgeline.

As the results in the table indicate, the reported crash reduction factors varied depending on the countermeasure(s) employed and ranged from 4 percent through 49 percent. While many of the countermeasures evaluated included both pavement markings and another infrastructure enhancement (resurfacing, rumbles, etc.), the results themselves are indicative that pavement markings had a role in the observed reductions. This is illustrated by the final countermeasure in the table, which consisted only of the installation of wider makings, which produced a CRF of 22 percent.

The different crash types represented in the countermeasures presented were for more severe crashes and, as a result, were likely to produce higher benefit-cost ratios when employed. This was confirmed through a series of benefit-cost analyses that determined the cost-effectiveness of the treatments. The benefit-cost ratios were developed taking into consideration the annual crash frequency per mile on a particular roadway type (adjusted for traffic volume growth), the proportional reductions in crashes from the striping and other countermeasures used on a particular roadway, and an average crash cost (based on MoDOT values) (Potts et al. 2011). The resulting benefit value was compared to the installation cost per mile for a particular countermeasure package used. The result was a series of benefit-cost ratios generated for the countermeasures used and roadway type, which are presented in Table 2.3.

Table 2.3. Benefit-cost ratios for different durable markings by roadway classification (Potts et al. 2011)

Countermeasure	Roadway Type	Benefit-Cost Ratio
Install wider markings with resurfacing	Rural freeways	9.3
	Rural multilane divided highways	12.0
	Rural multilane undivided highways	145.9
	Urban freeways	5.7
	Urban multilane undivided highways	21.8
	Urban two-lane highways	117.6
Install wider markings and edgeline rumble strips with resurfacing	Rural Freeways	8.3
	Rural multilane divided highways	8.0
	Urban freeways	10.0
	Urban multilane undivided highways	10.4
Install wider markings and shoulder rumble strips with resurfacing	Rural freeways	5.8
	Rural multilane divided highways	7.4
	Urban freeways	17.5
Wider lines with center and edgeline rumble strips with resurfacing	Rural two-lane highways	35.6
	Urban two-lane highways	22.2
Install wider markings without resurfacing	Rural freeways	23.8
	Urban multilane divided highways	28.5

As the benefit-cost ratios illustrate, the various countermeasures considered all produced values in excess of 1.0 (a value of 1.0 representing the point where $1.00 in expenses incurred produced $1.00 in benefits obtained). When considering only the use of wider markings and no other countermeasures, large benefit-cost ratios were produced. These included a ratio of 23.8 on rural freeways and 28.5 on urban multilane divided highways. Each of these ratios indicate that wider markings (and likely also traditional narrow markings) produce a significant benefit to agencies through reduced crashes. They also indicate the significant benefits that this lower cost countermeasure can produce, separate from use in combination with other countermeasures.

Park et al. (2012) evaluated the safety effects of wider edgelines on rural two-lane roadways in Kansas, Michigan, and Illinois (Park et al. 2012). The data used in the work varied from state to state in terms of how, when, and the extent to which wider edgelines were used (Park et al. 2012). For example, in Kansas and Michigan 6-inch-wide edgelines were used, while in Illinois 5-inch edgelines were used. This required the use of three different analysis approaches. For Kansas, an empirical Bayes analysis was performed. For Michigan, generalized linear segmented regression analysis was used. For Illinois, cross-sectional analysis was used.

The analyses produced a number of results. In Kansas, total crashes fell by 17.5 percent following the installation of wider edgelines, while fatal and injury crashes fell by 36.5 percent and PDO crashes fell by 12.3 percent (Park et al. 2012). In Michigan, total crashes fell by 19.4 percent following wider edgeline installation, while fatal and injury crashes fell by 16.1 percent and PDO crashes fell by 19.6 percent (Park et al. 2012). Finally, in Illinois total crashes fell by 30.1 percent following installation of wider edgelines, while fatal and injury crashes fell by 37.7 percent and PDO crashes fell by 23.9 percent (Park et al. 2012). Several other crash types were also evaluated for each state (nighttime, wet, etc.) and the results showed similar reductions. Based on the overall results of the research, it was concluded that wider edgelines on rural two-lane roadways had a positive safety benefit.

Fleming (2013) evaluated the use of wider (6-inch) edgelines installed on the 3,159 miles of county and township roadways in Minnesota between 2010 and 2011 (Fleming 2013). The work used a before and after comparison of treated segments and comparison segments (sites with 4-inch edgelines) to test different hypotheses explaining crash reductions. These included whether reductions had occurred in total crashes, fatal and serious injury crashes, run off the road right crashes, and fatal and serious injury run off the road right crashes. Two years of before and after crash data were used in the evaluation. The comparison sites used in the analysis were employed “in order to control for regression to the mean” (Fleming 2013). The changes in crashes were evaluated using 2 x 2 cross tabulation with a Chi-square test.

The findings indicated that total crashes on treated segments decreased by 24 percent following installation of wider edgelines (these crashes decreased by 8 percent on comparison segments) (Fleming 2013). This was found to be a statistically significant change from the reductions at comparison locations. Fatal and severe injury crashes on treated segments decreased by 5 percent (these crashes increased by 6 percent on comparison segments) (Fleming 2013). This change was not found to be statistically significant.

Run off the road right crashes decreased by 32 percent at treatment sites following installation of wider edgelines (these crashes increased by 3 percent on comparison segments) (Fleming 2013). This crash reduction was found to be statistically significant. Finally, fatal and severe injury run off the road right crashes decreased by 35 percent (these crashes increased by 50 percent on comparison segments) (Fleming 2013). This decrease was not found to be statistically significant.

While these results and the raw reductions in the number of crashes were promising, the analysis methodology employed in this evaluation was not robust or representative of the state of the practice for safety analysis. While the researcher indicated that the approach that was used accounted for the regression to the mean phenomenon, it did not consider other factors that can play a role in changes to the number of crashes in a before and after study, such as AADT. Therefore, the results of this study, while interesting at a basic level, should be viewed with caution and are presented here because of their local nature.

Carlson (2015) completed a synthesis of pavement marking research from the U.S. with a focus on understanding how lane width and retroreflectivity impacted operational performance, visibility, and safety (Carlson 2015). While much of the material covered in the synthesis is discussed elsewhere in this chapter, the more recent date of this work (2015) and the general conclusions it makes with respect to different aspects of pavement markings are worth noting here. This is particularly true of the findings related to marking widths.

The review of pavement marking width found that markings up to 6 inches in width had negligible impacts on vehicle operating speeds and lateral placement on two-lane highways (Carlson 2015). Most recent studies indicated that wider markings could increase marking visibility and reduce driver workload (Carlson 2015). Wider markings had also been shown to improve safety on rural two-lane roadways but did not have a significant safety impact on multilane divided highways (Carlson 2015).

Lyon et al. (2015, 2016) conducted a safety evaluation of wet-reflective pavement markings (Lyon et al. 2015, Lyon et al. 2016). The materials the work considered included paint, tape, and thermoplastic. Data for the analysis, including crashes, geometric features, traffic volumes, and construction/maintenance information, was collected from roadways where wet-reflective markings were applied (Lyon et al. 2015, Lyon et al. 2016). Roadways that were evaluated included freeways (Minnesota, North Carolina, and Wisconsin), rural two-lane roadways (Minnesota), and multilane roadways (Wisconsin). Crash data from before and after installation of the wet-reflective markings were evaluated to determine if the markings reduced crashes. The approach employed was an empirical Bayes analysis. Note that the analysis did not evaluate the impacts of specific materials (e.g., tape versus thermoplastic); rather, the focus of the evaluation was on the impacts of crashes from the use of wet-reflective markings in general.

The results of the analysis showed that a number of statistically significant reductions in crashes occurred following the installation of wet-reflective markings. On freeways, reductions in all states combined for injury (CMF = 0.881) and wet roadway (CMF = 0.861) crashes were found (Lyon et al. 2015, Lyon et al. 2016). On multilane roadways, significant reductions in total crashes (CMF = 0.538) and wet roadway (CMF = 0.751) and night (CMF = 0.696) crashes were found (Lyon et al. 2015, Lyon et al. 2016). No definitive conclusions could be drawn from the analysis of data from two-lane roadways due to a small sample size. However, there were indications that the markings may have had a safety benefit for wet-weather crashes in that category as well (Lyon et al. 2015, Lyon et al. 2016).

A benefit-cost analysis on multilane roads found that the crash reductions from wet-reflective marking use produced a ratio of 5.24. On freeways, the computed benefit-cost ratio was 1.45. In both cases, the results were calculated using conservative assumptions and indicated that wet-reflective markings are a cost-effective treatment (Lyon et al. 2015, Lyon et al. 2016).

2.2.2 Operational Benefits

Cottrell (1986) examined the effects of wider (8-inch) edgelines on vehicle lateral placement and speed in Virginia (Cottrell 1986). Comparisons were made between 4-inch and 8-inch markings along 55.2 miles of rural two-lane roadway. Data were collected using pneumatic tubes laid out in a zee configuration. Analysis of variance was conducted to evaluate placement and speed data. The analyses found that the mean lateral placement of vehicles was significantly lower on roadways with 8-inch edgelines. However, the changes in lateral placement were not significant from a practical standpoint. No other findings of statistical significance were found.

Donnell et al. (2006) conducted a before and after evaluation of the operational effects of wide (8-inch) edgelines installed on rural two-lane horizontal curves in Pennsylvania (Donnell et al. 2006). Eight sites were used in this analysis: four treated with 8-inch edgelines and four using the standard 4-inch edgelines (the comparison sites). Lane widths at the sites ranged between 10.5 feet and 11 feet, while AADTs ranged from 3,000 to 5,700 vehicles per day. Posted speed limits at the sites were not specified, but given the descriptive statistics reported, they were at least 45 mph and more likely 55 mph or higher.

Four piezoelectric sensors were laid out in the travel lanes in a zee pattern designed to collect vehicle speed and lateral position data in the curves (Donnell et al. 2006). Data were collected for a 24-hour period at each study site (treatment and comparison) before and after treatment installation. The performance measures used in the evaluation included mean speed, lateral vehicle position, mean speed differential, mean lateral vehicle position differential, encroachment rate, and location of deceleration approaching the curves (Donnell et al. 2006).

The results of the evaluation found that mean speeds increased by 1.5 mph at one treatment site during the day and 30 mph at night (Donnell et al. 2006). Similarly, speed variance increased at the same location following installation of wider edgelines both during the day and at night. Mean speed and speed variance at the other sites did not change following installation of wider edgelines.

The analysis of lateral vehicle positions produced mixed results. One site experienced a 4-inch shift to the right of the lane at night, while a second site saw a 3-inch shift to the right during the day and a 7.5-inch shift to the right at night (Donnell et al. 2006). Lateral vehicle position variance at these sites also increased at night. The researchers concluded that this showed preliminary evidence that wide edgelines influenced lateral vehicle position, but additional research was still needed (Donnell et al. 2006). Remaining study locations did not see changes to lateral vehicle position or variance during the day or at night.

The encroachment analysis did not indicate any statistically significant changes in centerline or edgeline encroachment rates at the treatment sites. Finally, the results of a subjective evaluation of where vehicle deceleration began prior to a treated curve indicated that there was no evidence that drivers began to slow down further in advance of curves with wide edgelines at night. Based on all of these results, the researchers concluded that wide edgelines on rural two-lane curves did not dramatically alter driver behavior during the day or at night (Donnell et al. 2006).

2.2.3 Additional Benefits

In addition to the safety and operational benefits of enhanced markings, past work has identified other benefits related to materials and width. For example, Miller (1991) estimated the benefits of thermoplastic pavement markings and found an urban benefit-cost ratio of 130.0, a rural ratio of 32.9, and a combined ratio of 58.9. Additional work is summarized below.

Montebello and Schroeder (2000), in a report for the Minnesota Department of Transportation, summarized the benefits/advantages of enhanced pavement markings, including epoxy, thermoplastic, and tape (Montebello and Schroeder 2000). All three of these enhanced markings shared the advantages of having high durability and retroreflectivity. Additional advantages for tape markings included its durability in high-traffic areas where markings were frequently crossed by vehicles, elimination of the need for glass beads to produce retroreflectivity, and reduced worker exposure during installation through longer life/reduced replacement needs. Additional advantages for thermoplastic included elimination of the need for glass beads to produce retroreflectivity and the ability of this material to be installed at any temperature.

Migletz et al. (2001) examined the service life of durable pavement markings (epoxy, polyester, methyl methacrylate, thermoplastic, and tape) in 19 states (Migletz et al. 2001). A total of 85 study sites in 19 states had one of these marking materials installed as part of the work. The sites included freeways, non-freeways with speed limits of 45+ mph, and non-freeways with speed limits of 40 mph or lower (Migletz et al. 2001). Direct measurements of marking retroreflectivity were collected following installation and at six-month intervals thereafter (the total duration of data collection was not specified). Regression models were used to estimate the service life of each material based on retroreflectivity decreases over time and traffic passage. The estimated service lives of the materials by marking color, facility type, and marking material are presented in Table 2.4. Overall, it was concluded that the variations in service lives were attributable to a variety of factors, including roadway type, region, marking material specifications, and quality control and winter maintenance activities (Migletz et al. 2001).

Table 2.4. Service life of durable pavement markings (Migletz et al. 2001)

Roadway Type	Marking Type	Average Life (Months)	Range (Months)
White Markings			
Freeway	Thermoplastic	22.6	7.4 - 49.7
	Polyester	20.8	4.7 - 27.0
	Tape	19.6	11.7 - 27.3
	Methyl Methacrylate	11.9	6.8 - 17.5
	Epoxy	12.8	3.4 - 34.0
Non-freeway (<40 mph)	Thermoplastic	55.7	not specified
	Polyester	45.9	not specified
	Tape	26.9	22.3 - 31.6
	Epoxy	39.4	29.2 - 49.7
Non-freeway (>45 mph)	Thermoplastic	36.6	26.5 - 49.1
	Polyester	27.4	18.8 - 34.1
	Tape	37.3	22.9 - 60.0
	Methyl Methacrylate	34.8	29.9 - 31.2
	Epoxy	38.8	26.1 - 56.0
Yellow Markings			
Freeway	Thermoplastic	24.7	11.0 - 41.6
	Polyester	39.7	not specified
	Tape	25.8	19.6 - 29.8
	Methyl Methacrylate	21.1	18.1 - 24.4
	Epoxy	23.2	12.6 - 47.5
Non-freeway (<40 mph)	Thermoplastic	50.7	not specified
	Polyester	39.6	not specified
	Tape	19.6	not specified
	Epoxy	43.9	34.7 - 53.1
Non-freeway (>45 mph)	Thermoplastic	33.8	26.9 - 39.1
	Polyester	47.9	
	Tape	38.9	25.4 - 53.4
	Methyl Methacrylate	31	29.1 - 32.8
	Epoxy	44.1	35.8 - 57.8

Gibbons (2006) evaluated the performance of pavement markings in wet nighttime conditions to determine driver visibility needs (Gibbons 2006). A total of 54 older drivers (mean age 62.52, ages ranging from 40 to 80) drove a sedan or truck tractor at night through simulated rain conditions on the Virginia Smart Road facility. The speeds driven ranged from 45 to 55 mph. The types of markings evaluated by this work included latex paint with standard glass beads, latex paint with large glass beads, thermoplastic, and wet-reflective tape (Gibbons 2006).

While driving the test course, drivers were instructed to say “start” or “end” when they detected a pavement marking transition (beginning of markings on a segment) (Gibbons 2006). An analysis of variance (ANOVA) analysis was performed to evaluate the relationships between marking materials, vehicle types, lighting, glare, and pavement type. The results of the analysis showed that waterborne paint with regular glass beads had the shortest detection distance for drivers, followed by waterborne paint with large glass beads (82 feet and 120 feet, respectively) (Gibbons 2006). In both cases, the detection distance referred to the distance from the start or end of the marking to the point where a driver first detected the marking. Thermoplastic and tape markings had the longest detection distances for drivers (116 feet and 207 feet, respectively) (Gibbons 2006). Based on these results, and calculations made to establish required limits of visibility, it was recommended that the minimum retroreflectivity value in wet nighttime conditions should be 200 millicandela per meter squared per lux (mcd/m^2/lux) (Gibbons 2006).

Carlson and Wagner (2012) evaluated the effectiveness of wider edgeline markings through a benefit-cost analysis (Carlson and Wagner 2012). The benefits of wider edgelines consisted of the fatal and injury crash reductions produced (calculated as the difference between estimated crashes without the treatment and observed crashes). The crash data and reductions used in this study to estimate the financial value of those benefits were taken from work in Kansas (discussed elsewhere in this chapter) (Park et al. 2012). Two benefit-cost analysis scenarios were considered. The first scenario was developed using a higher percent crash reduction and produced a benefit-cost ratio of 43.96 (Carlson and Wagner 2012). The second scenario, which used a lower percent crash reduction and was considered more conservative, produced a benefit-cost ratio of 21.72 (Carlson and Wagner 2012).

2.2.4 Costs of Enhanced Markings

Miller (1991, 1992) identified the costs of thermoplastic markings as ranging between $0.15 and $0.40 per linear foot in 1991, with an average cost of $0.32 per linear foot. (Miller 1991, Miller 1992). Adjusted for inflation, these figures would be $0.26 and $0.69 per linear foot in 2018 dollars (average of $0.55 per linear foot). Costs varied based on the thickness of the material applied, contractor variability, shipping costs, and fuel-related costs (i.e., amount of propane used during installation). The reader should bear in mind that this is older work when considering the cost figures that were reported.

Montebello and Schroeder (2000) highlighted the financial costs of enhanced pavement markings (tape) in a report for the Minnesota Department of Transportation (Montebello and Schroeder 2000). Tape had a cost of $1.50 to $2.65 per linear foot ($3.29 to $4.05 per linear foot for new construction in 2018) (Montebello and Schroeder 2000).

NCHRP Synthesis 306 (Migletz and Graham 2002) provided average cost data from a national survey of agencies for a variety of enhanced marking materials. These material costs per linear foot were as follows:

- Epoxy - $0.26 ($0.35 in 2018)
- Preformed tapes - $1.41 to $2.33 ($1.89 to $3.13 in 2018)
- Methyl methacrylate - $1.22 to $1.44 ($1.64 to $1.93 in 2018)
- Thermoplastics - $0.14 to $0.35 ($0.19 to $0.47 in 2018) (Migletz and Graham 2002)

Again, the reader should bear in mind that this is older work, and the costs that it reported should be considered with caution. When a life cycle cost that included material and installation costs was considered, the material costs per foot were as follows:

- Epoxy - $0.14 ($0.19 in 2018) for white markings, $0.09 ($0.12 in 2018) for yellow markings
- Preformed tapes - $1.02 ($1.37 in 2018) for white markings, $0.91 ($1.22 in 2018) for yellow markings
- Methyl methacrylate - $1.02 ($1.37 in 2018) for white markings, $0.91 ($1.22 in 2018) for yellow markings
- Thermoplastics - $0.14 to $0.44 ($0.19 to $0.59 in 2018) for white markings, $0.14 to $0.39 ($0.19 to $0.52 in 2018) for yellow markings (Migletz and Graham 2002)

Average service lives (in months) for these markings were 23.0 for epoxy, 27.4 for preformed tapes, 14.4 for methyl methacrylate, and 27.5 for thermoplastics (Migletz and Graham 2002).

Carlson et al. (2007) discussed the costs of different marking materials as part of research on wet-night and wet-contrast pavement markings in Texas (Carlson et al. 2007). Thermoplastic material costs ranged from $0.80 to $1.30 per linear foot (depending on marking width, 4 or 6 inches) ($0.93 to $1.51 in 2018), the costs for tape ranged from $1.04 to $3.76 per linear foot ($1.21 to $4.38 in 2018), and the costs for polyurea ranged from $0.43 to $1.00 per linear foot ($0.50 to $1.16 in 2018).

Benz et al. (2009) provided the costs of different marking materials as part of a project investigating pavement marking retroreflectivity (Benz et al. 2009). Cost information was provided on a linear foot basis and included the costs of both white and yellow markings. That cost information was as follows:

- Epoxy - $0.08 and $0.65 per linear foot ($0.09 and $0.73 in 2018)
- Methyl methacrylate - $0.70 and $1.75 per linear foot ($0.73 and $1.97 in 2018)
- Polyester - $0.05 and $0.30 per linear foot ($0.06 and $0.34 in 2018)
- Tape - $1.50 and $3.10 per linear foot ($1.69 and $3.49 in 2018), and
- Thermoplastic - $0.35 and $1.30 per linear foot ($0.73 and $1.97 in 2018) (Benz et al. 2009)

Fontaine and Gillespie (2009) identified and summarized the material costs of different lane marking materials in Virginia (Fontaine and Gillespie 2009). The reported average costs of the different materials summarized were as follows:

- 4-inch thermoplastic - $0.42 per linear foot ($0.47 in 2018)
- 6-inch thermoplastic - $0.72 per linear foot ($0.81 in 2018)
- 4-inch epoxy - $0.38 per linear foot ($0.43 in 2018)
- 6-inch epoxy - $0.34 per linear foot ($0.38 in 2018)
- 4-inch tape - $2.30 per linear foot ($2.59 in 2018)
- 6-inch tape - $3.17 per linear foot ($3.57 in 2018) (Fontaine and Gillespie 2009)

Potts et al. (2011) reported the costs of pavement marking materials used in striping wider lanes and edgelines in Missouri. The marking materials used were epoxy, polyurea, and tape. The weighted averages of epoxy and polyurea marking materials were reported as $0.57 per foot for 6-inch white markings and $0.55 per foot for 6-inch yellow markings ($0.61 and $0.59 in 2018) (Potts et al. 2011). The tape markings were reported to cost $4.00 per foot ($4.29 in 2018) (Potts et al. 2011).

Songchitruksa et al. (2011) presented cost information for thermoplastic and tape markings in Texas as part of work to develop guidance for the selection of different marking types (Songchitruksa et al. 2011). That authors reported that the mean cost per mile for thermoplastic markings was $1,584 and $3,960 per mile ($1,700 and $4,249 in 2018) for tape markings. This represented an average unit cost of $0.30 per foot for thermoplastic and $0.75 per foot for tape ($0.32 and $0.75 in 2018).

Montebello and Schroeder (2000) highlighted the service lives of epoxy, thermoplastic, and tape markings (Montebello and Schroeder 2000). Epoxy markings had an estimated service life of 4 years. Thermoplastic markings had an estimated service life of 3 to 6 years, while tapes had an estimated service life of 4 to 8 years.

Rasdorf et al. (2009) completed a pavement marking performance analysis for the North Carolina Department of Transportation (Rasdorf et al. 2009). The focus of the work was on thermoplastic markings. Linear regression models found that, for an AADT of 10,000 vehicles per day, thermoplastic markings on asphalt had a lifespan of 5.4 to 8.75 years (Rasdorf et al. 2009). This was dependent on the color of the marking and its lateral location (i.e., centerline or edgeline).

Carlson et al. (2007) summarized information of the service lives of different materials (Carlson et al. 2007). Thermoplastic markings had an expected service life of 2 to 4 years, tape markings had an expected life of 6 years, and polyurea markings had an expected life of 4 years (Carlson et al. 2007).

Fitch (2007) developed an estimation of pavement marking service life for different materials in Vermont (Fitch 2007). This also included an estimate of the cost for each marking material per month based on that service life. The results of these calculations are presented in Table 2.5.

Table 2.5. Estimated service life and cost information from Vermont (Fitch 2007)

Marking Material	Estimated Life (months)	Material Cost (per linear foot) 2007 (2018) dollars	Cost/Month
Thermoplastic	29	$0.46 ($0.54)	$0.02
Epoxy	12	$0.26 ($0.30)	$0.02
Polyurea 1A	10	$0.68 ($0.79)	$0.07
Polyurea 2	17	$0.93 ($1.08)	$0.05
Polyurea 2 recessed	34	$1.34 ($1.56)	$0.04

Notes:

Polyurea 1A used only glass beads for retroreflectivity.

Polyurea 2 used reflective elements and glass beads for retroreflectivity.

Jiang (2008) developed a summary of the service lives and costs for enhanced pavement markings in use by Indiana DOT districts (Jiang 2008). Those costs are presented in Table 2.6.

Table 2.6. Costs and service lives for enhanced markings in Indiana (Jiang 2008)

Marking Material	Service Life (years)	Material Cost (per linear foot) 2007 (2018) dollars
Thermoplastic	2 to 5	\$0.24 - \$0.37 (\$0.27 - \$0.41)
Epoxy	3 to 5	\$0.35 - \$1.16 (\$0.39 - \$1.30)
Polyurea	4 to 5	\$0.75 (\$0.84)
Tape	1 to 8	\$1.16 - \$2.75 (\$1.30 - \$3.08)

Although the researcher did not indicate why there was a wide range in the reported material costs, it was likely the result of factors such as location and contracting quantities.

Fontaine and Gillespie (2009) summarized the expected service life range for different lane marking materials in Virginia (Fontaine and Gillespie 2009). The reported annual cost per mile and service life ranges were as follows:

- 4-inch thermoplastic - \$422 to \$3,249 per mile and 0.65 to 5 years
- 6-inch thermoplastic - \$766 to \$5,889 per mile and 0.65 to 5 years
- 4-inch epoxy - \$604 to \$1,980 per mile and 1 to 3.28 years
- 6-inch epoxy - \$523 to \$1,716 per mile and 1 to 3.28 years
- 4-inch tape - \$1,919 to \$11,739 per mile and 1.03 to 6.3 years
- 6-inch tape - \$2,598 to \$15,891 per mile and 1.03 to 6.3 years (Fontaine and Gillespie 2009)

The work noted that a number of factors should be taken into account when selecting alternative materials versus traditional paints. These include material costs, expected lifespan, marking detection distances and retroreflectivity, traffic volume, location, and installation costs (Fontaine and Gillespie 2009).

Hawkins and Smadi (2010) conducted pavement marking demonstrations of transverse markings (stop bars, crosswalks, large arrows, etc.) on urban and rural roadways in Iowa using preformed thermoplastics (Hawkins and Smadi 2010). The stop bars that were installed were found to last between two and three winter seasons but had lost a majority of their retroreflectivity (falling below mcd/m^2/lux) after one winter (Hawkins and Smadi 2010). Arrow, railroad crossing, and crosswalk markings all performed well and lasted at least two winter seasons. Some markings did suffer snow plow damage, however. Retroreflectivity remained high over two years, with arrows having the least amount of retroreflectivity lost (Hawkins and Smadi 2010). Based on these observations, it was concluded that thermoplastic markings would provide agencies with longer service lives for these types of specialized markings compared to annual repainting.

2.3 PROPOSED MUTCD RETROREFLECTIVITY RULE AND IMPACTS

A critical aspect of pavement marking maintenance and management in the future may be the MUTCD's proposed retroreflectivity rule. This proposed rule was released in April 2010 and may have several potential impacts for agencies (FHWA 2014). The rule itself has not been adopted yet, but the proposed text has been summarized by the Federal Highway Administration (FHWA 2014) and a placeholder is present in the current edition of the MUTCD (Section 3A.03). The entire proposed retroreflectivity text for Section 3A.03 is provided in Appendix A of this report. As with any MUTCD addition or change, there was a rule making review and Federal Register commenting period (this period concluded on May 4, 2017 for marking retroreflectivity) for this proposed material.

To provide a general summary, the proposed minimum levels are divided according to roadway type and speed limit. Roadway type is further divided into two-lane roadways with centerline markings only and all other roadways. Speed limits are further divided into categories of less than 30 mph, 35 to 50 mph, and greater than 55 mph.

No minimum pavement marking retroreflectivity levels are required for any roadways with a speed limit of 30 mph or lower (FHWA 2014). For a speed limit of 35 to 50 mph, two-lane roadway minimum retroreflectivity is 100 mcd/m^2/lux, while all other roadways have a minimum of 50 mcd/m^2/lux (FHWA 2014). Finally, for speed limits of 55 mph and greater, two-lane roadway minimum retroreflectivity is 250 mcd/m^2/lux, while all other roadways have a minimum of 100 mcd/m^2/lux (FHWA 2014).

The primary impact to agencies as a result of maintaining minimum marking retroreflectivity is the identification and/or tracking of retroreflectivity itself. Methods identified by FHWA for maintaining pavement marking retroreflectivity include visual nighttime inspection, measured retroreflectivity, expected service life, blanket replacement, and other methods (Carlson et al. 2014). The details of these approaches are discussed in the proposed MUTCD text presented in Appendix A.

A secondary impact of the proposed rule is the potential for agencies to be more reluctant to mark roadways in an attempt to reduce the extent of mileage where retroreflectivity would need to be maintained. The unintended consequence of this could be an impact on roadway safety through reduced delineation for drivers.

In most cases, there will be a need for agencies to keep an inventory of markings to track age, retroreflectivity levels, etc. This results in a second impact to agencies: those that do not currently maintain a pavement marking inventory will likely need to develop one, whether it is paper-based or electronic. Of course, there are exceptions to this, such as when an agency chooses a blanket replacement of pavement markings at a specified time interval (e.g., annually). Those agencies that already have an inventory in place will need to add a field to track retroreflectivity if such a field is not already present.

Some of the specific required retroreflectivity values for pavement markings may not be practically attainable on a year-round basis. For example, the minimum marking retroreflectivity for county roads with a centerline and edgeline and a speed limit of 55 mph would typically be 100 mcd/m^2/lux.

However, if the retroreflectivity of a marking deteriorates rapidly following snow plowing operations, it is possible that this minimum value will not be met once spring arrives. Impacts such as this may require changes to the timing of marking applications to obtain the longest-lived retroreflectivity values for a particular material in colder climates where snow plowing occurs.

As various sections of this literature review discuss, different marking materials have different service lives, retroreflectivity degradation rates, and costs, and the proposed rule will have an impact on how an agency selects marking materials. For example, will an agency choose to restripe markings annually with paint and accept the budgetary ramifications of that material or switch to a longer life material based on its retroreflectivity performance over time (despite a potentially higher material cost)?

In addition to being required to monitor the retroreflectivity of markings, agencies will be impacted by some of the finer points of the proposed rule itself. For example, some markings in different roadway and speed limit categories in the MUTCD proposed rule are not required to be retroreflective. These include markings where there is ambient illumination present or that are only needed in the daytime (e.g., a park with only daytime access) (FHWA 2014). In other cases, a marking may be required to be retroreflective but is not subject to minimum levels (FHWA 2014). For example, such a case might include a roadway where raised reflective pavement markers have been installed in conjunction with markings.

Finally, when the text of the proposed rule is added to the MUTCD, there will likely be an implementation date associated with it. This will be another impact for agencies because they will need to select and implement a mechanism to manage retroreflectivity by that date.

The purpose of this overview has been to highlight what the proposed rule may require and what some of the more evident impacts to agencies will be. Of course, when minimum marking retroreflectivity is incorporated into a future edition of the MUTCD, there will likely be other impacts to agencies that become apparent. For example, the roles of other factors affecting marking retroreflectivity, such as the presence of dirt, the marking color itself, the color of the pavement (i.e., the marking background), etc., may require agencies to revisit current marking practices and procedures and implement new ones (such as sweeping to clean dirty markings).

2.4 PAVEMENT MARKING MAINTENANCE PRACTICES

The maintenance (mainly repainting) of pavement markings is a critical activity necessary to ensure that they continue to provide drivers with the intended guidance and delineation information. However, there is limited discussion in the literature specifically discussing pavement marking maintenance.

The results of a 2010 survey showed that a majority of agencies in Minnesota (22 counties, 9 cities) used private contractors to apply markings, while others relied on in-house staff (6 counties, 6 cities) (Smadi and Hawkins 2010). The remainder of the respondents used a contract with MnDOT (3 counties) or a multiagency contract (1 county, 3 cities) (Smadi and Hawkins 2010). In addition, 2 cities contracted with a county to apply their markings. The marking materials used were fairly common among agencies. Most agencies used latex paint on new and rehabilitated pavements (18 counties, 7 cities), followed by epoxy

(11 counties, 8 cities) and tape (2 counties, 2 cities) (Smadi and Hawkins 2010). On seal-coated surfaces, latex paint was again widely used (21 counties, 11 cities), followed by epoxy (one county, three cities) and tape (1 city) (Smadi and Hawkins 2010). Finally, latex paint was heavily used in general maintenance striping (24 counties, 11 cities), along with epoxy (2 counties, 2 cities) and tape (1 city) (Smadi and Hawkins 2010). Additional information from participants indicated that either all lines were painted annually or subjective assessments were used to determine repainting needs.

Knapp et al. (2015) surveyed Iowa counties regarding different aspects of their pavement marking usage (Knapp et al. 2015). This survey included obtaining information on the replacement intervals that were used for pavement marking maintenance. On paved (asphalt and concrete) roadways, the survey found that 16 counties replaced their centerline and no passing zone markings every two years, 5 replaced these markings every three years, and 8 replaced them annually (Knapp et al. 2015). For edgeline replacement on paved roadways, 17 counties replaced these markings every two years, 7 replaced them every three years and 3 replaced them every four years (Knapp et al. 2015).

On seal-coated surfaces, one county reported replacing centerline and no passing zone markings annually, one county replaced them every three years, and four reported that they did not use these markings on seal-coated roadways (Knapp et al. 2015). (Note that only a limited number of counties in Iowa have and/or place pavement markings along their seal-coated roadways.) Similarly, for edgelines, two counties reported replacing these markings every two years on seal-coated roadways, while two other counties reported replacing them every three years (Knapp et al. 2015).

2.5 PAVEMENT MARKING PRIORITIZATION AND MANAGEMENT

Limited literature was found that specifically discussed the prioritization of pavement markings, whether in terms of use/application locations, material types, etc. Literature was also found that discussed aspects related to prioritization, such as enhanced marking material performance (discussed in prior sections). However, no specific guidance appears in the literature that highlights when one material might make more sense to apply than another or how marking renewal/replacement should be prioritized. Instead, only general guidance was made under the umbrella of research that focused on other aspects of markings. For example, one study recommended that markings be repainted based on minimum retroreflectivity thresholds (Kentucky) (Fields et al. 2011). The following text summarizes literature that discusses aspects of pavement marking prioritization or management in some manner.

MnDOT provides material selection flowcharts for longitudinal and pavement message markings as part of Technical Memorandum No. 14-11-T-02 (MnDOT 2014). This Technical Memorandum has been provided in Appendix B for reference. The flowchart begins by considering the pavement surface type (asphalt or concrete). For asphalt pavements, the timing of upcoming preservation is the next consideration, followed by traffic volumes. For concrete pavements, the process considers the facility type (multilane or two-lane two-way) to provide guidance on the materials that can be used. The material recommendations are based on research results on marking life expectancy and wet reflectivity.

Hawkins and Smadi (2008) discussed the development of a web-based pavement marking management tool for MnDOT (Hawkins and Smadi 2008). The tool allowed for the viewing/mapping and querying of pavement marking retroreflectivity information. In follow-up work to the development of that tool, Smadi and Hawkins (2012) summarized a proposed retroreflectivity collection approach using a handheld reflectometer (Smadi and Hawkins 2012). That approach would involve the collection of 16 readings using the handheld device over a 400-foot distance within a 4-mile segment of roadway. This approach would provide a representative retroreflectivity value while minimizing collection crew exposure and time.

St. Louis County, Minnesota, developed a pavement marking management plan that determined which longitudinal markings needed to be maintained and when that maintenance was needed (Lund and Cox 2014). The approach that was developed looked at three components: warrants (where markings are placed), the capital improvement program (construction and safety projects involving/affecting markings), and asset condition (marking condition in the field) (Lund and Cox 2014).

The examination of marking warrants initially looked at MUTCD guidance and found that applying that guidance would result in only a small portion of roadways in the county receiving markings. (This was based on the "shall" condition in the warrants which requires use.) Instead, it was decided that the use of markings would consider aspects such as functional classification by mileage in the county system. The type of marking (centerline or edgeline) was also considered. For example, it was decided that centerline markings would be placed on all roadways because this type of marking would be the last one removed if no markings were to be used (Lund and Cox 2014).

Edgeline installation was primarily determined to occur on collectors and arterials based on past findings in the state, which had indicated that roadways with average daily traffic volumes of over 600 vehicles per day were at a higher risk of run off the road crashes. Aside from applying edgelines on these functional classifications, it was also determined that edgeline markings would be placed on local roads where the County Road Safety Plan identified that markings should be used to address a safety issue (Lund and Cox 2014).

Capital improvement project considerations took into account reconstruction, reconditioning, and traffic safety project impacts to pavement markings. When such projects were scheduled to occur, long-lasting marking materials (epoxy) would be used instead of latex paint. This would extend the time between marking maintenance intervals.

The asset condition component accounted for the potential condition of existing markings in the field based on different factors. Through a set of calculations, it was determined that pavements with a surface rating of 3.3 or greater would only need centerline maintenance biannually (Lund and Cox 2014). Those falling below this threshold would have their centerlines maintained annually. For edgelines, a comparison of traffic volumes, marking age, and marking condition index (rating) determined that these markings would need to be maintained at three years of age (Lund and Cox 2014).

A cost analysis of the management plan that was developed showed that it could produce a cost savings when marking centerlines of $100,000 over the traditional approach being used (Lund and Cox 2014).

The traditional approach was to paint all centerlines in the county annually, with the leftover budget then used to renew edgelines. Under the new management plan, these savings could be used to maintain additional edgeline miles, including the installation of wider edgelines (at additional cost), compared to previous years under the traditional approach.

In addition to this approach, St. Louis County is also using a consultant to rate its pavement marking inventory in May, 2018 (Lund, 2018). All roadways will be driven, and current pavement markings measured with a retroreflectometer. Markings will be rated on a 1 to 5 scale, with 1 being a condition where the pavement marking is worn away and 5 being a marking in new condition. The information collected will then be mapped, and the county will only restripe locations where the markings are worn out. This is expected to produce cost savings, even after factoring in the costs of the consultant.

Migletz et al. (1994) discussed general aspects of pavement markings (materials, lifespan, maintenance) as part of the Roadway Delineation Practices Handbook to assist in delineation decision-making (Migletz et al. 1994). Of interest to the present research is the discussion of delineation management. This early document outlined the key aspects of managing pavement marking systems. This included inventorying the condition and performance of existing markings, recording that information to a database, and monitoring the database to determine when and where maintenance is needed. Database monitoring was also cited as being useful in developing a better understanding of what materials are performing effectively and where they are doing so.

Dwyer et al. (2013, 2015) developed a pavement marking selection guide for the Illinois Department of Transportation (IDOT) (Dwyer et al. 2013, Dwyer et al. 2015). The work evaluated the performance of markings on concrete and asphalt pavements over a four-year period to determine marking durability, visibility, and compatibility with pavement materials. The markings that were evaluated include waterborne paint, thermoplastic, tape, epoxy, polyurea, and urethane (Dwyer et al. 2013). A total of 57 sites with different pavement and marking materials were evaluated in this work.

The work employed a marking condition index (discussed elsewhere in this literature review) to characterize marking performance. Based on the condition index value and estimates of marking service life (generated using field data), recommendations were developed for the selection of pavement marking materials (Dwyer et al. 2013). The results of the work were a series of tables that summarized the marking recommendations based on surface type, installation condition (new pavement versus restriping), and traffic volume.

Generally, the recommendations were consistent between pavements, volumes, and materials. For maintenance striping (restriping) on asphalt pavements with 5 years of life remaining, waterborne paint and thermoplastic were recommended for traffic volumes below 7,000 AADT (Dwyer et al. 2013). Waterborne paint, thermoplastic, epoxy, polyurea, and urethane were recommended for those same pavements when traffic volumes were above 7,000 AADT (Dwyer et al. 2013). For similar maintenance on concrete surfaces, epoxy and polyurea were recommended for traffic volumes below 7,000 AADT, regardless of the remaining pavement life (up to 10+ years) (Dwyer et al. 2013). On higher volume concrete pavements, epoxy, polyurea, and urethane were recommended.

On new pavements, the recommendations mirrored those of maintenance restriping. For new asphalt pavements, it was recommended that waterborne paint or thermoplastic be used for traffic volumes below 7,000 AADT and that thermoplastic, epoxy, polyurea, tape, or urethane be used above that volume (Dwyer et al. 2013). For new concrete pavements, it was recommended that epoxy, polyurea, tape, or urethane be applied for volumes below 7,000 AADT and that these same materials be applied in recessed grooves for traffic volumes above that point (Dwyer et al. 2013). The work concluded that the specific selection of materials will always need to account for aspects such as traffic volume, pavement type, application type (on-surface versus recessed), and the costs involved (materials, installation, etc.).

NCHRP Synthesis 306 discussed the process for making pavement marking decisions (Migletz and Graham 2002). This included where markings should be placed, which the text tied back to the MUTCD's warrants. Of more specific interest from a prioritization standpoint was the listing of factors to consider when selecting the type and deciding where to place pavement markings. These included the following:

- Width of traveled way
- Traffic volumes
- Pavement type
- Pavement age, service life, or future reconstruction
- Type of street and highway
- Pavement condition
- Bridges (concrete)
- Snow removal areas
- Brightness benefit factor (Migletz and Graham 2002)

Also of interest is the discussion of when to replace pavement markings (restripe). Three approaches were provided based on a survey of agencies: field inspection, measurement or judgement, and replacement on a set/regular schedule (Migletz and Graham 2002). Factors used in material selection, as identified through an agency survey, included the following:

- Type of line
- Pavement surface material
- Pavement condition
- Traffic volume
- Roadway type
- Remaining pavement surface life
- Location/area
- Snow removal
- Brightness benefit
- Speed
- Project length (for new/rehabilitation projects) (Migletz and Graham 2002)

While specific guidance on the type of materials to use based on these factors was not provided, this list does provide items to take into consideration in any prioritization process under consideration or development.

NCHRP Synthesis 306 highlighted the then-current (2002) MnDOT pavement marking inventory management system (Migletz and Graham 2002). The system tracked the following items:

- Installations (location, date, line type, material type and quantity)
- Inventory
- Retroreflectivity
- Specific action steps
- Costs (employee, equipment, material)
- Suppliers (Migletz and Graham 2002)

The intent of such a system was described as providing a mechanism to track marking service life and allowing agencies to select cost-effective markings with increased service lives. The present MnDOT Excel spreadsheet tool tracks this same information.

Abboud and Bowman (2002a, 2002b) discussed the scheduling of marking (paint and thermoplastic) restriping for Alabama roadways based on service life, cost (material/installation), and user cost (crashes) (Abboud and Bowman 2002a, Abboud and Bowman 2002b). Logarithmic regression analysis from earlier research in Alabama was used to estimate useful life for markings based on average daily traffic (Abboud and Bowman 2002a, Abboud and Bowman 2002b). The ending threshold for the useful life of a marking was identified as a retroreflectivity value of 150 mcd/m^2/lux based on that earlier research. The equivalent annual costs of the markings consisted of the marking/installation cost and crash costs. Crash costs were calculated using 1998 National Safety Council crash values and nighttime run off the road crash data from segments with the paint or thermoplastic materials (Abboud and Bowman 2002a, Abboud and Bowman 2002b). Factoring in the total equivalent costs of markings, the following useful life guidance was developed for paint and thermoplastic markings:

- Paint
    - AADT < 2,500 vpd – 22-month lifespan
    - AADT 2,500 – 5,000 vpd – 7.5-month lifespan
    - AADT 5,000 – 8,000 vpd – 4.5-month lifespan
- Thermoplastic
    - AADT < 2,500 vpd – 53-month lifespan
    - AADT 2,500 – 5,000 vpd – 18-month lifespan
    - AADT 5,000 – 8,000 vpd – 10.5-month lifespan (Abboud and Bowman 2002a, Abboud and Bowman 2002b)

The authors noted that these estimates were made using data for roadways in Alabama and were only applicable to other states with a similar climate (i.e., no snow/plowing such as occurs in Minnesota) (Abboud and Bowman 2002a, Abboud and Bowman 2002b). However, the overall approach used, which accounts for the life of a marking as well as and material and crash costs (or prevented crashes), is summarized here for informational purposes (taking into account climate) when considering approaches to prioritizing markings for the current research.

As part of a synthesis of pavement marking research in the U.S., Carlson (2015) discussed pavement marking selection tools, including a tool under development by FHWA in 2015 (Carlson 2015). That tool took user inputs to perform a service life and cost analysis and then provided recommendations for marking material selection. The process of that tool consisted of the following steps:

1) Site characteristics, cost data, and material choices are entered.
2) The tool selects retroreflectivity models based on the entered site characteristics and estimates retroreflectivity values for the material choices specified.
3) Retroreflectivity decay models that fit the site characteristics are run by the tool to estimate the service life of each material choice.
4) The tool performs a cost analysis of each material to estimate the expected unit cost over the remaining roadway service life.
5) The tool ranks the materials by cost based on the user inputs and provides the top cost-effective materials as the recommended options (Carlson 2015).

While additional investigation has found that the FHWA marking selection tool is not yet completed, the process described above offers a straightforward approach to the comparison and selection of markings based on site-specific needs and characteristics.

2.6 SUMMARY OF FINDINGS

This chapter has presented research results and current practice for various aspects of pavement markings, both traditional and enhanced, including safety and operational benefits, costs, maintenance, retroreflectivity, and management/prioritization. A brief summary of the key findings presented in this chapter are as follows:

- Traditional pavement markings:
  - Limited research has been completed related to marking use on local roadways.
  - Traditional markings produced safety benefits that included lower crash rates when markings were present, lower crash frequencies on curves, and general crash reductions between 3.0 percent and 32.9 percent (depending on the study).
  - Traditional markings operationally produced no real impacts on vehicle speeds or lateral placement or, at most, produced only small impacts.
  - Marking use could produce benefit-cost ratios between 20.6 and 125.8 based on crash cost and travel time savings.
  - Costs reported in the literature ranged from $0.04 to $0.56, depending on the specific paint, location, etc., with a service life of 3 to 36 months.
- Enhanced pavement markings:

    - Use of wider edgelines produced crash reductions between 4 percent and 49 percent, depending on location, crash severity, and use of complimentary treatments.
    - Use of wet-reflective markings produced crash reductions between 12 percent and 30 percent, depending on the type of crash being considered.
    - Wider edgeline use produced benefit-cost ratios between 5.7 and 145.9.
    - Use of wider edgelines does not appear to alter driver behavior.
    - Use of thermoplastic markings produced benefit-cost ratios between 32.9 and 130.0.
    - The costs of enhanced markings varied depending on the material, the location where applied, and other factors.
- The impact of the proposed MUTCD retroreflectivity rule on local agencies will depend on the roadway type and speed limit.
- No agency-specific documentation of pavement marking maintenance practices was discussed in the literature.
- A document summarizing surveys of local agencies in Minnesota indicated that the majority used latex paint for their markings and private contractors or in-house staff for installation/restriping.
- Limited pavement marking prioritization and management approaches have been developed:
    - St. Louis County, Minnesota, has developed an approach that considers different components, including marking warrants, the county's capital improvement program, and marking condition in the field.
    - MnDOT has developed guidance on marking material selection based on basic site characteristics that should be included in the prioritization approach being developed in this research.
    - Additional factors discussed in the literature have included traffic volumes, pavement type, pavement condition, and climate.

Collectively, the information summarized in this chapter was used in developing a pavement marking decision-making process and tool for local agencies in Minnesota. The development of that tool is discussed in Chapter Five.

CHAPTER 3: COUNTY AND LOCAL AGENCY SURVEY

To better understand current pavement marking practices with respect to use, maintenance, and management, a survey was conducted of counties and other local agencies (cities/municipalities) in Minnesota. The questions presented to the respondents sought to obtain information related to the type and extent (mileage) of pavement markings being applied, the materials being used and their cost, the frequency at which markings were repainted, and other management considerations that guide marking prioritization. This information was then used to develop the decision-making approach for pavement marking prioritization.

In order to collect information on agencies' current pavement marking use, maintenance, and management practices, a 21-question survey was developed. The survey asked for both basic information on pavement marking use (e.g., materials used, mileage with markings, etc.) and more detailed information on how marking use is determined, how existing markings are managed and maintained, etc. The full survey instrument used in this task is provided in Appendix C.

The survey was posted online using the website Survey Monkey, and the website link was distributed to local agencies via MnDOT's State Aid for Local Transportation Office email list. The survey link was sent out on February 27, 2017, and the website remained open for data collection until March 10, 2017.

A total of 66 responses to the survey were received. These included 46 responses from counties and 20 responses from cities. Approximately 52 percent of the 87 counties in the state responded to the survey.

3.1 SURVEY RESULTS

The survey began by asking basic information from respondents, including name and contact information, in case there was a need to follow up for response clarification or additional information. After this preliminary information, questions pertaining to different aspects of pavement marking use, maintenance, and management were presented. Survey respondents were instructed that if they did not have exact values available for specific questions (e.g., roadway mileage managed), estimated values were acceptable. The following sections present the results and discussion of the information provided by local agencies.

3.1.1 Miles of Roadway Managed

As a starting point, respondents were asked about the total roadway mileage maintained by their agency. The average mileage reported by all agencies was 361 miles. The minimum reported was 20 miles (by a city), while the maximum mileage reported was 1,350 (by a county). The average mileage managed by counties was 450 miles, while the average for cities was 164 miles. Some agencies reported their figures by paved mileage, while others also included unpaved mileage. This discrepancy does not affect the results or discussions made throughout this chapter, however. The information obtained from this question was intended to provide an overview of the extent of the systems being managed by local agencies, and later questions asked for specific mileage with pavement markings present.

3.1.2 Low-Volume Roadway Mileage

Most local agencies manage a significant number of low-volume roadways. The MUTCD defines a low-volume road as one having an AADT of less than 400 vpd (FHWA 2012). A follow-up question for respondents asked the extent of their roadway system that fell below this 400 vpd threshold. Given the mix of county and city respondents, the full range from 1 percent to 100 percent was reported by respondents as falling into the low volume category. The average percentage of county roads reported as being low volume was 51 percent, while for cities that figure was 54 percent. In short, these figures indicated that the local agencies responding to this survey on average managed a fair amount of low-volume mileage in Minnesota.

It should be noted here that MnDOT collects extensive traffic counts statewide on local roads. These counts are collected on a four years cycle for local roads, meaning that about one quarter of these roadways in the state have traffic counts collected along them each year. Based on this, it is assumed that the agencies completing the survey were aware of the percentage of low volume roads in their network and responded accordingly.

3.1.3 Roadway Mileage with Pavement Markings

The next question asked respondents the percent of paved roadway mileage that their agency had applied pavement markings to (centerline, edgeline, no markings, other). Collectively, counties and cities reported that an average of 78 percent of their paved roadways had centerlines, 73 percent of their paved roadways had edgelines, and 21 percent of their paved roadways had no pavement markings installed. When these figures were separated out by counties and cities, the averages changed substantially. County respondents indicated that an average of 96 percent of paved roadways had a centerline, 95 percent of paved roadways had an edgeline, and 3 percent of paved roadways had no pavement markings. City respondents indicated that an average of 33 percent of paved roadways had a centerline, 18 percent of paved roadways had an edgeline, and 66 percent of paved roadways had no pavement markings. These results plainly illustrate the differences in pavement marking use between county and city roadways. Counties widely use centerlines and edgelines, while cities apply these markings less frequently.

The high percentages of mileage with centerline and edgeline markings reported by counties were initially surprising, but these percentages became clearer from a response provided by a respondent to the subsequent survey question (i.e., How does your agency determine when to use or not use pavement markings?). That response indicated that pavement marking use was guided by MnDOT's State-Aid Operations rules, Chapter 8820.2700, Maintenance Requirements. The particular rule cited by counties as guiding their extensive application of centerlines and edgelines states that "the commissioner shall require a reasonable standard of maintenance on state-aid routes within the county or urban municipality, consistent with available funds, the existing street or road condition, and the traffic being served. This maintenance must be considered to include: […] D) the striping of pavements of 22 feet or more in width, consistent with the current Manual on Uniform Traffic Control Devices, and for which there are no pending improvements" (MnDOT 2013). It appears that based on this this rule, counties are being required to maintain what is marked on their system. However, the language for this rule appears to provide some flexibility for the use of markings on non-state-aid roadways based on available funding, roadway condition, or traffic volumes.

Respondents were also asked whether they had any other marking applications they wanted to specifically mention. Responses to this question included the following:

- Bike lane specific
- Advisory bike lanes
- Bike lane markings
- Crosswalk blocks/directional arrows

All of these responses were provided by cities, which is expected given that bike and pedestrian facilities are more predominant in city environments.

3.1.4 Determining the Use of Pavement Markings

In addition to knowing the percent of roadway mileage that had pavement markings applied, it was also of interest to learn how agencies determined when/where pavement markings would be used. Respondents were asked to briefly describe how their agency determined when to use or not use pavement markings. This was an open-ended question, and the responses provided by counties and cities were generally similar. County respondents indicated that they determined the use of pavement markings based on one or more of the following considerations:

- Use on all roadways (29 responses)
- Traffic volumes and speeds (7 responses)
- Location (4 responses)
- Pavement surface type (3 responses)
- Pavement width (2 responses)
- Visual inspection (2 responses)
- Crash rate (1 response)

As the initial point indicates, many counties have chosen to apply pavement markings to all (or nearly all) of their roadways (state-aid or otherwise). This universal application of pavement markings was not a consideration listed by city respondents, however. City respondents indicated that they determined the use of pavement markings based on one or more of the following considerations:

- Traffic volumes and speeds (9 responses)
- Functional classification (3 responses)
- State-aid routes (3 responses)
- MUTCD recommendations (2 responses)
- Geometrics (2 responses)
- Incorporated areas (1 response)

- Safety concerns (1 response)
- Sight distance (1 response)
- Visual inspection (1 response)
- Initial project engineering (1 response)

Traffic volume and speed were the most frequently cited considerations used to determine pavement marking use. This differs from the approach used by counties, where, in many cases, all roadways received markings. Instead, cities looked at considerations tied to the traffic volumes served, functional classification, design, etc. to determine where markings would be used.

3.1.5 Pavement Marking Management and Prioritization

The next question asked respondents if their agency employed any management or prioritization approach to determine what/when markings would be reapplied/repainted. Collectively, 39 respondents indicated that their agency used a prioritization approach, while 26 respondents indicated that their agency did not use one. When examined separately, 28 counties indicated that they used a prioritization approach, while 11 did not use one. Seventeen cities indicated that they used a prioritization approach, while 9 did not use one. These results indicated that most agencies were using some approach to prioritize when they apply pavement markings and/or the type of markings being applied.

As a follow-up, respondents were asked to provide a general summary/overview of the approach that their agency employed. The complete text of the responses provided by agencies to this question is presented in Appendix D. General approaches listed by respondents, divided by counties and cities, are presented below. Note that in many cases agencies listed multiple approaches or considerations as being used together in managing markings. For example, some agencies considered the type of marking (centerline versus edgeline) and traffic volume to determine where and how frequently a marking would be used and repainted. The approaches and considerations used for management or prioritization by counties included the following:

- Time-based/rotation (annual, biannual replacement) (19 responses)
- Visual inspection/condition (9 responses)
- Traffic volumes (7 responses)
- Marking material type (3 responses)
- Marking type (centerline, edgeline, etc.) (3 responses)
- Available budget (1 response)

For counties that indicated that they are using a time-based approach to marking management or prioritization, a wide range of repainting frequencies was provided. In many cases, a county reported that multiple frequencies were used when repainting markings, dependent on the type of marking (centerline versus edgeline) and/or the material used (latex paint versus epoxy). Keeping this in mind, 16 counties indicated that their management or prioritization approach had an annual repainting component, 15 had a biannual component, and 10 had a three-year or greater component.

The approaches to management and prioritization used by cities were largely the same as those used by counties. This was particularly true in the reliance on time-based management or prioritization for marking repainting. City approaches to management/prioritization included the following:

- Time-based/rotation (annual, biannual replacement) (7 responses)
- Visual inspection/condition (6 responses)
- Traffic volumes (2 responses)
- Available budget (1 response)
- Crash history (1 response)
- Marking location (downtown versus residential) (1 response)

Similar to the counties that relied on time-based management or prioritization, cities also reported different time intervals for the repainting of markings. The difference from counties in this case was that cities did not use multiple time intervals for different locations, marking types, materials, etc. Rather, city respondents indicated that one time interval was used in management or prioritization. Three cities used an annual interval, one used a biannual interval, and one used a three-year or greater interval for marking considerations.

As the responses to this question indicated, agencies are using different approaches, individually or in combination, to manage or prioritize their marking decisions. The most commonly used approach was time-based, with agencies repainting markings on a cycle of some kind, whether annual, biannual, or other. Visual inspections and traffic volumes were also commonly used by agencies. In many cases, agencies indicated that they used a combination of approaches to manage or prioritize their pavement marking decisions.

3.1.6 Pavement Marking Materials

The pavement marking materials used play a role in management and prioritization, particularly in terms of the intervals at which markings are repainted. Therefore, a follow-up question asked respondents the types of materials that their agency used for pavement markings. The responses from all agencies to this question are presented in Figure 3.1. Pavement marking materials used by agencies.. Bear in mind that many agencies use multiple materials for their pavement markings.

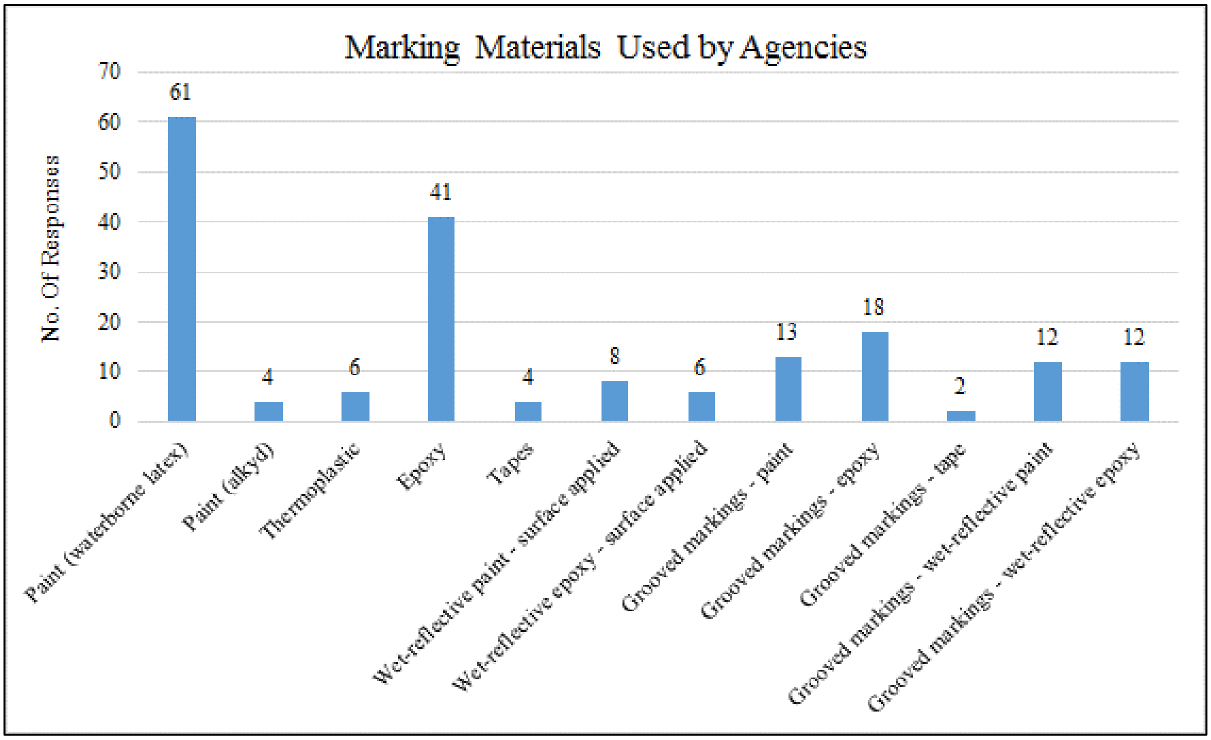

Figure 3.1. Pavement marking materials used by agencies.

As the figure illustrates, latex paint was the most commonly used marking material (61 responses), used by nearly all agencies responding to the survey. This material was followed by epoxy markings (41 responses). The common use of both of these materials was somewhat expected, given that latex paint is low cost and epoxy is durable and longer lived. Other marking materials saw varying levels of use, with paint and epoxy (including wet-reflective) in grooved markings used with some frequency. The remaining materials, such as alkyd paints, thermoplastics, tapes, etc., saw limited use by agencies. Materials such as polyurea, polyester, methyl methacrylate, and milled-in tapes were not reported as being used by agencies.

When separated by county and city respondents, the responses showed that the majority of counties that responded to the survey used latex paint (43 out of 45 counties), while fewer counties used epoxy markings (25 of 45 counties). Cities similarly used latex paint frequently (17 of 19 cities) and reported frequent use of epoxy markings (14 of 19 cities). Counties used other marking materials to varying extents, including grooved paint markings (11 counties), grooved epoxy markings (14 counties), grooved wet-reflective paint (12 counties), and grooved wet-reflective epoxy (11 counties). The use of more wear-resistant grooved markings by counties as opposed to cities was not unexpected, particularly given the ability of these markings to stand up to snow plowing.

Respondents were provided an opportunity to list other materials that their agency might be using for pavement markings. A total of two responses were received for this option. These responses included the use of paint in rumbles to create rumble stripes and the use of glass beads for retroreflectivity.

3.1.7 Marking Materials by Marking Type

A follow-up question asked respondents if different marking materials were used for transverse and word message markings versus longitudinal markings. Twenty-two agencies indicated that they used more durable materials for certain markings, including word messages, wider than normal transverse markings, and markings installed on new pavements. Of those 22 agencies, 18 counties and 4 cities reported using different materials for these markings. These results are generally consistent with what was reported for the pavement marking materials in use. A total of 22 agencies reported that they do not use different materials for transverse and word message markings. Of this total, 16 counties and 6 cities reported that they do not use different materials for different types of markings. In short, it appears that some agencies see a need for more durable markings to be used in certain applications, while others maintain a more uniform use of a single material for their markings.

3.1.8 Centerline Marking Width

Wider pavement markings can be used to increase conspicuity and enhance safety, and a question was asked regarding the width of centerline that agencies used. Choices presented included 4 inches (traditional width), 6 inches, or 8+ inches. A total of 59 respondents indicated that their agency used 4-inch centerlines (40 counties and 17 cities). Three agencies (1 county and 2 cities) indicated that their agency used 6-inch centerlines, at least in some locations. No agencies indicated the use of 8+ inch centerlines. Three respondents provided additional information in relation to this question that indicated that wider markings were used based on traffic volumes (wider on high-volume routes) or when recommended by the County Road Safety Plan.

3.1.9 Edgeline Marking Width

A follow-up question asked respondents whether it was standard practice for their agency to use 6-inch edgelines on all roadways or whether these were only used on County Road Safety Plan projects or routes. A total of 23 agencies (20 counties and 2 cities) reported using 6-inch markings as standard practice. Thirty-eight agencies (24 counties and 14 cities) reported that they did not use 6+ inch edgeline markings or only used these markings in certain instances. Twelve counties indicated that they used 6+ inch markings when recommended by their CRSPs, while one city indicated that it used 6+ inch edgeline markings. If the standard practice and CRSP use of 6+ inch markings for counties are combined, then 32 counties (out of 45 responding to the survey) used some form of wide edgelines in their county. The non-use of wider edgelines by cities is tied to the lack of these types of markings in locations where curb and gutter systems are prevalent.

3.1.10 Pavement Marking Installation

The installation and repainting of markings is a central component to pavement markings. As a result, it was of interest to this work to determine how agencies installed and repainted their markings (i.e., using in-house staff, contractors, MnDOT crews, or another option). In many cases, respondents indicated that they used more than one approach to paint/repaint their pavement markings. For example, some agencies indicated that they hired a contractor to paint longitudinal markings, while in-house staff painted pavement messages (in this context, words or symbols applied to the pavement). This should be kept in mind as the results of this question are discussed.

The use of a contractor was most common among agencies, with a total of 53 (38 counties and 13 cities) using this approach entirely or in part. In-house staff were used for painting markings by 17 agencies (7 counties and 10 cities). Six agencies (5 counties and 1 city) indicated that they have MnDOT painting crews paint/repaint their pavement markings. In addition, 2 cities indicated that they relied on a county's staff to paint/repaint their markings.

The greater use of contractors and MnDOT crews by counties to paint/repaint pavement markings is not surprising, given the extent of roadway mileage that is marked in most counties. The greater use of in-house staff by many cities was tied to the frequency of pavement messages, crosswalks, etc. in these locations. Most cities that used in-house staff to paint markings provided additional details that indicated that they also relied on outside contractors to handle longitudinal markings. Aside from the painting of pavement messages, respondents indicated that their agency also hired contractors if a different material type was going to be applied (e.g., epoxy) or to complete markings on a new or reconstructed roadway.

3.1.11 Pavement Marking Costs

Next, respondents were asked the approximate cost per linear foot that their agency paid for the different marking materials being used. A wide range of costs were provided in response to this question, which was expected given that those agencies with more extensive marking inventories can achieve economies of scale when purchasing materials or services compared to other agencies. Cost information provided by respondents was limited to latex paint, epoxy, grooved wet-reflective epoxy, and grooved latex paint. However, these materials were the ones indicated as being most widely used in earlier survey questions. Cost information for the other types of markings indicated as being used (see the pavement marking materials section of this chapter), such as alkyd paints, thermoplastics, and tapes, cannot be discussed here due to the lack of feedback.

The average cost of latex paint based on the figures provided by respondents was $0.056 (minimum of $0.035, maximum of $0.16) per linear foot. The average latex paint cost for counties was $0.052 (34 counties provided costs) per linear foot, while the average cost for cities was $0.082 (6 cities provided costs). Two counties also reported the cost of their grooved-in latex markings, which averaged $0.375 per linear foot. For reference, MnDOT costs for latex markings were $0.09 to $0.11 per linear foot for new construction and $0.052 per linear foot for maintenance in 2017.

The average cost of epoxy markings was $0.282 (minimum of $0.082, maximum of $0.61) per linear foot. The average cost of epoxy markings per linear foot in counties was $0.306 (12 counties provided costs), while in cities the average cost was $0.233 (6 cities provided costs). For reference, MnDOT costs for epoxy markings were $0.29 per linear foot for new construction and $0.156 per linear foot for maintenance in 2017.

Additionally, 8 counties provided cost information for their grooved epoxy pavement markings. The average cost for grooved epoxy markings was $0.626 (minimum of $0.50, maximum of $0.75) per linear foot. For reference, MnDOT costs for grooved epoxy markings were $0.53 to $0.59 per linear foot for new construction in 2017.

3.1.12 Pavement Marking Program Considerations

Follow-up questions to the cost of pavement markings sought information on what determined an agency's pavement marking program. Respondents were asked to indicate which of the following were taken into consideration as part of their pavement marking program: (1) budget, (2) marking condition, (3) repainting at a set interval, and (4) other considerations. Multiple selections from these items were permitted.

The responses indicated that agencies had multiple considerations that guided their pavement marking programs. A total of 31 agencies (22 counties and 9 cities) indicated that available budget was a consideration for their pavement marking programs. The condition of markings was also a consideration for 36 agencies (27 counties and 9 cities). The repainting of markings at a set interval (annually, biannually, etc.) was indicated as being a consideration by 40 agencies (31 counties and 9 cities). Finally, other considerations provided by respondents included the locations of projects (upcoming or ongoing construction or reconstruction) or the renewal of markings only when they are worn out.

3.1.13 Pavement Marking Program Budget

While the information provided by respondents on the cost of pavement markings offered insights, the total pavement marking budget for agencies was also of interest. The average pavement marking budget, based on the 61 responses provided, was $86,566. The average budget for the 42 counties that provided responses was $111,120 (minimum was $20,000, maximum was $400,000). City pavement marking budgets averaged $32,559 (minimum was $500, maximum was $130,000). Two cities reported a $500 budget, and each of these managed low mileage (20 to 30 miles total). As these figures indicate, the higher mileage systems overseen by agencies require much larger marking budgets.

3.1.14 Pavement Marking Assessment

The condition of pavement markings is a significant factor for many agencies in determining when markings should be repainted. Respondents were asked how their agency assessed the condition of pavement markings. Specifically, were markings inspected visually, with a handheld retroreflectometer, with a vehicle-based retroreflectometer, or based on an estimated service life (e.g., one-year life for latex paint markings), or was no assessment method employed?

The responses to this question indicated that the majority of agencies, 44 in total (30 counties, 14 cities), used visual inspection to determine when pavement markings need to be repainted. Nine agencies (6 counties, 3 cities) indicated that they do not use any assessment method. Six agencies (4 counties, 2 cities) relied on an estimated service life when determining marking condition/replacement. Four agencies indicated that they used a combination of visual inspections and estimated service life to assess marking condition. One county indicated the use of visual inspections combined with direct measurement using a handheld retroreflectometer. Aside from that one county, no other agencies indicated the use of either a handheld or vehicle-based retroreflectometer when assessing pavement markings.

3.1.15 Pavement Marking Repainting Frequency

The frequency with which agencies reapplied/repainted their pavement markings was of interest. Twenty-one agencies (9 counties and 12 cities) indicated that they repainted their markings on an annual basis. Fourteen agencies (12 counties and 2 cities) repainted their markings on a two-year cycle. In comments provided to this question, many respondents indicated that markings were repainted on an alternating basis in such a case (i.e., half of the marking mileage was repainted during one year and the remaining half during the following year). Nine agencies (7 counties and 2 cities) reported painting their markings on a three-year basis (either all markings triennially or, alternatively, one-third of their marking mileage each year).

In many cases, agencies reported repainting their markings on a variable schedule of some type. Some respondents indicated their repainting frequency in the responses outlined above but also included additional information via a comment box. Twenty-five respondents provided feedback that indicated that their agency repainted different markings at different intervals. For example, an agency might repaint latex markings annually and epoxy markings at a four- to five-year interval. The complete feedback from respondents to this question is provided in Appendix D. Briefly, the additional information provided by respondents to this question indicated that counties repainted markings at varying intervals (one to six or more years) based on materials, location/route, the amount of snowplowing that had been done the prior season, and traffic volumes. City respondents providing additional information indicated varying repainting intervals of one to five years but did not elaborate on the factors that contributed to those different intervals.

3.1.16 Pavement Marking Quality Control

The quality of installation for pavement markings has an impact on their effectiveness and longevity, so it was of interest to this work whether agencies performed any quality control procedures after installation/painting. Twenty-two respondents indicated that their agency performed quality control for pavement marking installations (18 counties and 2 cities). However, a greater number of agencies, 43 in total (27 counties and 16 cities), did not perform quality control for pavement markings.

Agencies that indicated that they did perform quality control were asked to describe what was being done. The full details provided by respondents to this follow-up question are provided in Appendix D. In general, counties indicated that they used visual inspections and materials specifications most frequently for their quality control. Additionally, one county used manufacturer certification and another used a retroreflectometer for quality control. City quality control procedures were limited to visual inspections and material specification checks.

3.1.17 Pavement Marking Inventory

It was also of interest whether agencies maintained an inventory of markings by location, the materials used, the date of installation, etc. Respondents were asked whether their agency maintained such an inventory. Thirty-one respondents (24 counties and 9 cities) indicated that their agency maintained a pavement marking inventory. Similarly, 30 respondents (20 counties and 10 cities) indicated that their agency did not maintain a pavement marking inventory. This nearly even split between agencies maintaining or not maintaining an inventory was not unexpected, given the different approaches and frequencies being used to determine when markings were repainted. For instance, agencies that had decided to repaint pavement markings annually because all roadway markings were latex paint likely did not believe they needed to track different material types by location, the age of a marking, etc.

3.1.18 Pavement Marking Retroreflectivity

Because pavement marking retroreflectivity will likely be incorporated into the next edition of the MUTCD, a follow-up question asked whether agencies that maintained a marking inventory included records from the measurement of retroreflectivity values. While over half of respondents indicated that their agency had a pavement marking inventory, only one agency, a county, indicated that its database included a measurement of marking retroreflectivity. (Note that, as part of the responses to the following question, one additional county indicated that it is investigating the use of an inventory program to track marking retroreflectivity.) Fifty-nine other respondents (including agencies that did and did not have an inventory) indicated that their agency/inventory did not record pavement marking retroreflectivity.

3.1.19 Additional Information

The final survey question asked respondents whether they had any additional information related to marking and maintenance activities that may be of interest to this work. Much of the additional information provided in response to this question reiterated what had been provided for earlier questions and was more general in nature. County responses to this question highlighted what was done for markings installed after chip seal operations, the consideration of a marking inventory to track retroreflectivity, the use of milled centerlines and edgelines, the absence of a formal approach to marking management, and experience with marking retroreflectivity deterioration within 2 ½ years of installation. City feedback to this question included one respondent who indicated that his/her agency was in the process of converting its symbol markings to thermoplastic, while another agency discussed participation in a joint powers agreement that incorporated a pavement marking component. The complete text of the responses provided to this question are provided in Appendix D.

3.2 CHAPTER SUMMARY

This chapter has presented the results of a survey of local agencies (counties and cities) in Minnesota regarding their pavement marking practices, maintenance, and management. A total of 66 responses were received from 46 counties and 20 cities throughout the state. The responses and information provided by agencies provided insights into the extent to which markings are used by counties and cities, the materials being employed, the considerations made when deciding where to use markings, budget/cost information, and approaches employed to manage and prioritize marking use. The following is a brief summary of the key findings from the survey:

- Agencies consider, on average, 50 percent to 55 percent of the mileage they maintain to be low volume (less than 400 vpd).
- In counties, an average of 96 percent of paved roadways had a centerline, 95 percent had an edgeline, and 3 percent had no pavement markings.
- The frequent use of pavement markings by counties appears to be guided, in part, by MnDOT's State-Aid Operations rules, Chapter 8820.2700, Maintenance Requirements.
- In cities, an average of 33 percent of paved roadways had a centerline, 18 percent had an edgeline, and 66 percent had no pavement markings.
- Many counties responding to the survey chose to apply pavement markings to all of their roadways.
- The approaches and considerations used for management or prioritization by counties included time-based/rotations (annual, biannual replacement), visual inspection, traffic volumes, marking material type, marking type (centerline, etc.), and budget.
- Latex paint and epoxy were the most commonly used marking materials by agencies, with other materials used to a lesser extent. The average reported cost of these materials was $0.056 and $0.282 per linear foot, respectively
- Most respondents (59) indicated that their agency used 4-inch-wide centerlines.
- Forty-six agencies use 6-inch-wide edgelines to some extent on their system, with 32 counties using these markings based on recommendations from their County Road Safety Plans.
- Repainting markings at a set interval, the condition of markings, and available budget were commonly cited considerations used to determine an agency's marking program.
- Visual inspection is widely used to assess current markings and determine replacement.
- Approximately half of agencies (33) maintained a pavement marking inventory.

The information provided by agencies from the survey summarized in this chapter was subsequently used in the development of the decision-making approach for pavement marking prioritization.

CHAPTER 4: COUNTY ROAD SAFETY PLAN CONSIDERATIONS

The installation of pavement markings, in some cases, has been the result of recommendations made through Minnesota's CRSPs. The CRSPs establish safety emphasis areas in each county and identify at-risk locations that can be addressed through targeted projects and treatments that have been prioritized. The at-risk locations identify and take into account the different features present at a site that increase the risk of crashes, such as the presence of intersections, curves, etc. To address risk at such locations, one of the recommended strategies of the CRSP might be to employ enhanced (wider or wet-reflective) pavement markings to better delineate the roadway. Because pavement markings are typically considered to be lower cost relative to other treatments, they are often a recommended treatment in CRSPs.

This chapter is a review of the methodology employed in the CRSP process. The intent of this review is to develop an understanding of how pavement marking recommendations are incorporated into and prioritized within CRSPs. It also briefly considers how the present research might incorporate those recommendations and priorities into the pavement marking prioritization approach and tool being developed.

4.1 CRSP PROCESS OVERVIEW

In order to understand how the prioritization approach developed in this research might interact with the CRSPs and take those recommendations into consideration, it was necessary to develop a general summary of the overall CRSP process. This was done to identify the points where pavement marking strategies are incorporated within the CRSP process itself.

Between 2009 and 2013, CRSPs were completed for all 87 Minnesota counties (Preston et al. 2016). Minnesota's CRSPs identify high-priority safety projects of a low-cost, systemic nature to address safety proactively. The CRSPs examine the system as a whole and encompass a wide variety of projects that may be addressed with low-cost countermeasures. The development of the CRSP process relied on the NCHRP Report 500 series, which outlined (then-current) proven, tried, and experimental strategies and countermeasures for addressing different crash issues in specific emphasis areas (NCHRP 2003). These are used to guide the identification of the safety strategies pursued in a county. Specific types of pavement marking projects identified through the NCHRP Report 500 series for use in the CRSP process included the following:

- Six-inch wet-reflective epoxy markings in a 20 mm groove used where rumble strips are not feasible due to noise concerns
- Six-inch latex markings along ultra-low-volume roadways based on a consideration of a portion of traffic volume and a portion of risk (i.e., the number of rating stars and average daily traffic [ADT] paired together)
- Rumble stripes using 6-inch or larger grooves milled at the edge of the travel lane with the white edgeline painted directly over the grooves
- Six-inch centerline markings

- Supplemental or improved markings, such as larger stop bars, use of word messages, etc. (only at intersections)

These strategies are recommended for roadway segments and intersections. However, curves, which are also an area addressed in the CRSPs, do not have pavement markings included in the list of potential treatment strategies available for consideration. (Note: This does not mean that enhanced curve delineation through the use of pavement markings is not a viable treatment. Rather, the focus of curve strategies in the Minnesota CRSPs is on delineation using signage and paved shoulders with rumble strips and the Safety Edge. Pavement markings present potential constructability problems at curves, and the benefit-cost ratio from such projects would be lower than the ratios for these other alternatives.)

CRSPs were (and continue to be) developed over multiple steps and include input from local stakeholders from the four E's of safety (Engineering, Enforcement, Education, and Emergency Response). A simplified flowchart of the steps in the CRSP process is outlined in Figure 4-1. The CRSP process has numerous steps/points where the use of pavement markings (primarily enhancements) as a safety treatment could be proposed. Those points where pavement marking strategies can arise are the focus of the following paragraphs.

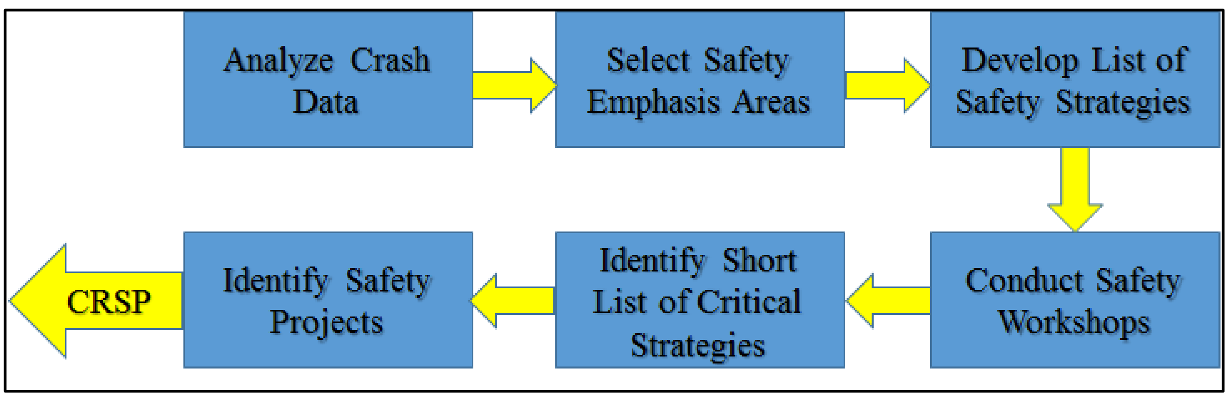

Figure 4.1. Minnesota County Road Safety Plan process (adapted from MnDOT 2010).

In Figure 4.1, the step in which safety emphasis areas are selected is the initial point where the use of pavement markings can arise. The following step, where the list of safety strategies is developed, would be the point where specific pavement marking strategies from the NCHRP Report 500 series would be recognized as potential treatments. Following that, safety workshops with stakeholders would be another potential point where pavement marking strategies could be introduced into the overall CRSP process, depending on the particular emphasis areas selected.

The identification of the short list of critical strategies is where the selection of specific treatments to address crashes in the different emphasis areas occurs. In this step, any pavement marking strategies recommended for use at different locations in a county would be identified through a focus on risk levels. A star-based system is used to characterize risk; a star is assigned to each risk category present at an intersection or along a segment. Intersection sites are rated on a seven-star scale, while segments are rated on a five-star scale. For example, a roadway segment rated with five stars is at a higher crash risk than a segment with zero stars or one star. The establishment of those risk levels for roadway segments is explained in more detail in the following section.

The final step of the CRSP process in which pavement marking use could arise is the identification of safety projects. This is where prioritization of sites based on their star-based level of risk occurs. While the use of pavement markings as a strategy at a site is determined during the prior CRSP step (critical strategies), the actual determination of what locations would receive marking treatments occurs during this final step. Project identification is perhaps the second most important step in the CRSP process when it comes to pavement marking recommendations, because this is the step that transforms a pavement marking strategy from one that is proposed to one that is prioritized for implementation.

As this brief overview has illustrated, pavement marking recommendations and prioritization occur throughout the CRSP process. The primary point at which pavement marking strategies are both recommended and prioritized, however, is during the identification of the short list of critical strategies. In light of this, the remaining discussion in this document will focus on this specific step in the CRSP process and how its outcomes can be incorporated into the pavement marking prioritization process developed in this research.

4.2 RISK LEVELS

The process used to identify risk on a roadway and prioritize the locations that will receive treatments is a central component of the CRSP process. In the context of the research, there was a need to better understand how risk levels are established on routes where pavement marking strategies are recommended by the CRSPs. This could help in determining where in the prioritization process being developed the CRSP pavement marking recommendations should be incorporated.

The development of risk factors is dependent on the type of location being considered. In the Minnesota CRSP process, different risk factors are identified for intersections, roadway segments, and curves. For the purposes of this research, only the approaches used to assign risk to roadway segments will be outlined, because horizontal curve treatment strategies present potential constructability problems for pavement markings and the cost-benefit ratios from such projects would be lower compared to those of the alternatives.

As discussed earlier, the CRSP process uses a star-based rating system in which a star is assigned to each risk category that might be present along a segment. In other words, locations with multiple risk factors present would receive multiple stars to indicate their higher level of risk.

The prioritization process assigns a risk level to a roadway segment based on five factors:

- ADT – Roadway segments within a specified ADT range (varied by county) that experience the highest number of roadway departure crashes are assigned one star. The ADT range could be established by identifying the traffic range that experienced the highest cumulative amount of roadway departure crashes, such as between 500 and 1,500 ADT.

- Roadway departure density – Roadway segments with a higher density of roadway departure crashes per mile compared to that county's average are assigned one star.
- Roadway departure rate – Roadway segments with a roadway departure rate (per million vehicle miles travelled) are assigned one star.
- Critical radius curve density – Roadway segments with a higher than average density of curves per mile compared to that county's average are assigned one star.
- Edge risk assessment – Ratings are assigned to categorize risk to vehicles leaving the travel lane on a specific segment. Roadways with a good pavement edge, a defined shoulder, and good clear zone are assigned a rating of one. Conversely, roadways that lack a shoulder and adequate clear zone receive a rating of three. Roadways that have a rating of two or three are assigned one star.

Based on the cumulative total out of five stars that a roadway segment receives, a general ranking of priority sites is developed. To break ties between segments, the edge risk (based on the rating assigned above) and roadway departure density values are individually taken into consideration.

Once segments and curves are rated, a decision tree is employed to select between the available safety treatments for each site based on different factors (traffic volume, land use, noise sensitivity, presence of paved shoulder, etc.) (CH2M Hill and SRF Consulting Group, Inc. 2010a). This is done in order to make the types of project assignments for each county consistent between one another. For segments, pavement marking strategies include rumble stripes, 6-inch waterborne/latex markings or 6-inch wet-reflective epoxy markings in a longitudinal groove (CH2M Hill and SRF Consulting Group, Inc. 2010a). The CRSPs does not select pavement markings as stand-alone projects.

Based on the selected treatment, an estimated cost for application on the particular segment can be made. These cost estimates do not factor in site prioritization. Instead, the cost estimates are generated to provide a better picture of the potential costs associated with each recommended improvement.

4.3 EXTENT MARKING STRATEGIES EMPLOYED

Earlier results from the local agency questionnaire indicated that many agencies used enhanced markings based on CRSP recommendations. In light of this, another objective of this work was to examine past CRSPs to gauge the extent to which pavement marking strategies were recommended (in terms of mileage). This was accomplished by reviewing various CRSPs (excluding counties in the Twin Cities metropolitan area) (CH2M Hill and SRF Consulting Group, Inc. 2010b, 2010c, 2011a, 2011b, 2012a, 2012b, and 2012c). This review provided general figures of the total paved mileage present in each county, as well as the recommended mileage for that county that was identified as being a candidate to receive some form of pavement marking treatment.

Recall that the pavement marking treatments recommended by the CRSPs include rumble stripes, 6-inch-wide edgelines (latex), 6-inch-wide centerlines (latex), and/or 6-inch wet-reflective epoxy grooved-in markings. Recommendations for marking installation/enhancement at intersections were not considered when quantifying the extent to which pavement marking strategies are recommended by the CRSPs because the continuous markings listed above represent a far greater installation quantity/extent for counties.

As part of this review, data for 79 counties were collected and evaluated. The CRSPs provided summaries on the total paved mileage maintained in each county. This paved mileage could be considered a candidate for some form of enhanced pavement marking treatment in response to a high level of risk being present (based on the risk levels discussed in the prior section). As a result, it was possible to determine the general extent to which pavement marking strategies are recommended on average by the CRSPs.

In reviewing the data from the CRSPs, it was evident that a considerable portion of county-maintained paved mileage received recommendations for one or more enhanced pavement marking treatment. A total of 24,599 paved miles of roadway was managed by the sample of 79 counties reviewed. The average paved mileage maintained by counties was 311 miles, with the minimum being 105 miles and the maximum being 1,158. Of the paved mileage reviewed, 8,637 miles (35.1 percent of total mileage) received one or more recommended pavement marking enhancement projects. On average, this amounted to 109.3 miles of enhanced markings recommended per county. (Note that some of these recommendations may have been in conjunction with one another, such as the use of 6-inch centerlines with 6-inch edgelines.)

The use of rumble stripes was recommended on 3,707 centerline miles of roadway (15.0 percent of total paved, county-maintained mileage). The average rumble stripe mileage recommended for counties was 46.9 miles. The maximum recommendation for one county was 219 miles of rumble stripes

The use of wider 6-inch edgelines was recommended on 1,096 centerline miles of roadway (4.5 percent of total paved, county-maintained mileage). On average, 13.9 miles of county roadways received a recommendation for wider edgelines. The maximum recommendation for one county was 70 miles of 6-inch edgelines.

Wet-reflective epoxy grooved-in markings were recommended on 2,188 centerline miles of roadway (8.9 percent of total paved, county-maintained mileage). On average, 27.7 miles of county roadways received a recommendation for wet-reflective edgelines. The maximum recommendation for one county was 70 miles of wet-reflective markings.

The use of wider 6-inch centerlines was recommended on 1,646 centerline miles of roadway (6.7 percent of total paved, county-maintained mileage). On average, 20.8 miles of county roadways received a recommendation for wider centerlines. The maximum recommendation for one county was 249 miles of 6-inch centerlines.

As these figures illustrate, pavement marking enhancements have been frequently recommended for a portion of each county’s paved roadway network. While the extent of mileage that received enhanced marking recommendations varied by county, all of the data reviewed indicated that each county had at least some mileage recommended to receive one or more of these treatments. Given that the use of enhanced markings is aimed at addressing sites with higher risk for crashes, CRSP recommendations should be considered a critical component of the pavement marking prioritization process being developed. The following section presents initial thoughts on how the results of the CRSPs would be accommodated in the prioritization process.

4.4 INCORPORATION OF CRSP RECOMMENDATIONS

Given the extent to which enhanced pavement markings are recommended by the CRSPs and their targeted objective of addressing higher-risk locations, CRSP recommendations need to be taken into account as a component of the prioritization approach developed in this research. The most straightforward approach is to incorporate CRSP pavement marking recommendations directly into the decision-making process. That is the approach that has been adopted in this work. The prioritization approach has been developed to consider these sites collectively along with the remaining roadway network. CRSP sites, because of their safety focus, are then given a greater consideration compared to the other sites they are being evaluated with. This increased consideration is directly tied to the specific star rating at a particular site.

4.5 CHAPTER SUMMARY

This chapter has presented an overview of the Minnesota County Road Safety Plan process, how enhanced pavement marking recommendations factor into that process, the extent to which enhanced markings were recommended in past CRSPs, and an approach to how these CRSP recommendations can be incorporated into the pavement marking prioritization process developed in this research. The following is a summary of the key findings from this portion of the work:

- Wide pavement markings (6 inches), alternative materials (epoxy), rumble stripes, and supplemental markings (stop bars, etc.) are all strategies recommended by CRSPs.
- Pavement marking recommendations are targeted at roadway segments and intersections within the CRSP process.
- Pavement marking strategy identification and recommendations occur throughout the CRSP process, but the primary point where recommendations are suggested and prioritized is during the identification of the short list of critical strategies.
- Risk levels are used by the CRSPs to prioritize locations that should have different safety strategies implemented.
- Decision trees are used to provide a consistent approach in selecting specific safety treatments, including pavement markings, for locations in a county.
- A review of data from 79 Minnesota counties found that pavement markings were recommended on average for 109 miles of roadway in each county.
- Given the extent to which pavement marking recommendations are made in the CRSPs for each county, CRSP recommendations must be incorporated into the prioritization approach developed in this research.

- The approach to incorporating CRSP recommendations into the pavement marking prioritization approach is to include them as part of the collective pool of sites being prioritized.
- Sites with CRSP recommendations are given a greater consideration and priority compared to other sites in the developed approach given the CRSPs' intent to address safety issues.

The pavement marking recommendations stemming from the CRSPs are important from a safety standpoint in addressing risk. In light of this safety component, as well as the extent to which pavement markings are recommended, CRSP strategies are directly incorporated into the prioritization approach that has been developed. That approach is discussed in the next chapter.

CHAPTER 5: DECISION-MAKING AND PRIORITIZATION PROCESS

This chapter presents the approach to the development of the pavement marking decision-making process and tool. The process and tool do not require extensive data collection or database management/maintenance by local agencies. The process and tool have been developed based on the information collected during previous project tasks and from project panel feedback to provide a mechanism to guide engineers in understanding the sites and conditions where a specific type of marking and/or material may be preferable to another based on different input information.

5.1 IMPORTANT FACTORS IN DECISION-MAKING

The work completed in previous project tasks allowed for the identification of important criteria to consider in decision-making related to pavement markings. Based on those findings, the following items have been incorporated into the decision-making process (note that these are not presented in a prioritized order):

- County Road Safety Plan star rating
- Minnesota MUTCD (MN MUTCD) use warrants
  - Section 3B.1 – Standard – "Center line markings shall be placed on all paved urban arterials and collectors that have a traveled way of 20 feet or more in width and an ADT of 6,000 vehicles per day or greater. Center line markings shall also be placed on all paved two-way streets or highways that have three or more lanes for moving motor vehicle traffic" (MN MUTCD, 2015)
  - Section 3B.7 – "Edge line markings shall be placed on paved streets or highways with the following characteristics:
    - Freeways
    - Expressways
    - Rural arterials with a travelled way of 20 feet or more in width and an ADT of 6,000 vehicles per day or greater" (MN MUTCD, 2015)
  - Section 5E.2: Guidance – "Center line markings should be used on paved low volume roads consistent with the principles of this Manual and with the policies and practices of the road agency and on the basis of either an engineering study or the application of engineering judgement" (MN MUTCD, 2015)
  - Section 5E.3 – Guidance – "Edge line markings should be considered for use on low-volume roads based on engineering judgment or an engineering study" (MN MUTCD, 2015)
  - Future retroreflectivity levels (related to proposed MUTCD rule)
- State requirements for marking use on state-aid routes (County State-Aid Highways [CSAH]) with pavement widths greater than 22 feet (per State-Aid Operations rules, Chapter 8820.2700).
- Marking material
  - Type (i.e., latex paint, epoxy, etc.)
  - Cost

    - Visibility (wider)
    - Milled/grooved for durability
- Marking type (edgeline, centerline, other)
- Available/remaining budget
- Current marking condition
- Pavement condition
- Traffic volumes
- Functional classification

These components are all important ones that need to be taken into account when developing any pavement marking decision-making approach for local agencies.

5.2 DECISION-MAKING PROCESS

The decision-making approach developed in this research takes into account the items cited above to establish which particular markings or enhanced visibility material could be employed on a particular roadway segment. Initially, a hierarchy of considerations was established to assist in developing the overall decision-making process. This hierarchy considered the importance of markings in the context of whether the markings are part of a CRSP safety-related project, their potential for being required as part of State-Aid Operations rules, and MN MUTCD requirements. However, in some cases a county may have a large portion of its system rated as part of the CRSP process, and all of those CRSP-rated segments cannot affordably receive pavement markings every year. Similarly, those state-aid routes that require markings may still total a high enough mileage that they also cannot be repainted each year and therefore require prioritization.

Based on these considerations, the prioritization tool developed in this work considers CRSP-rated sites/segments, state-aid routes, and remaining roadways that were not in these categories (termed “general” throughout this text) collectively. In doing so, the decision-making process considers site characteristics and provides a comparison of the different alternatives to identify the alternative that is most applicable for the site while also prioritizing that site versus others in the user’s roadway system. The overall approach is illustrated in Figure 5.1.

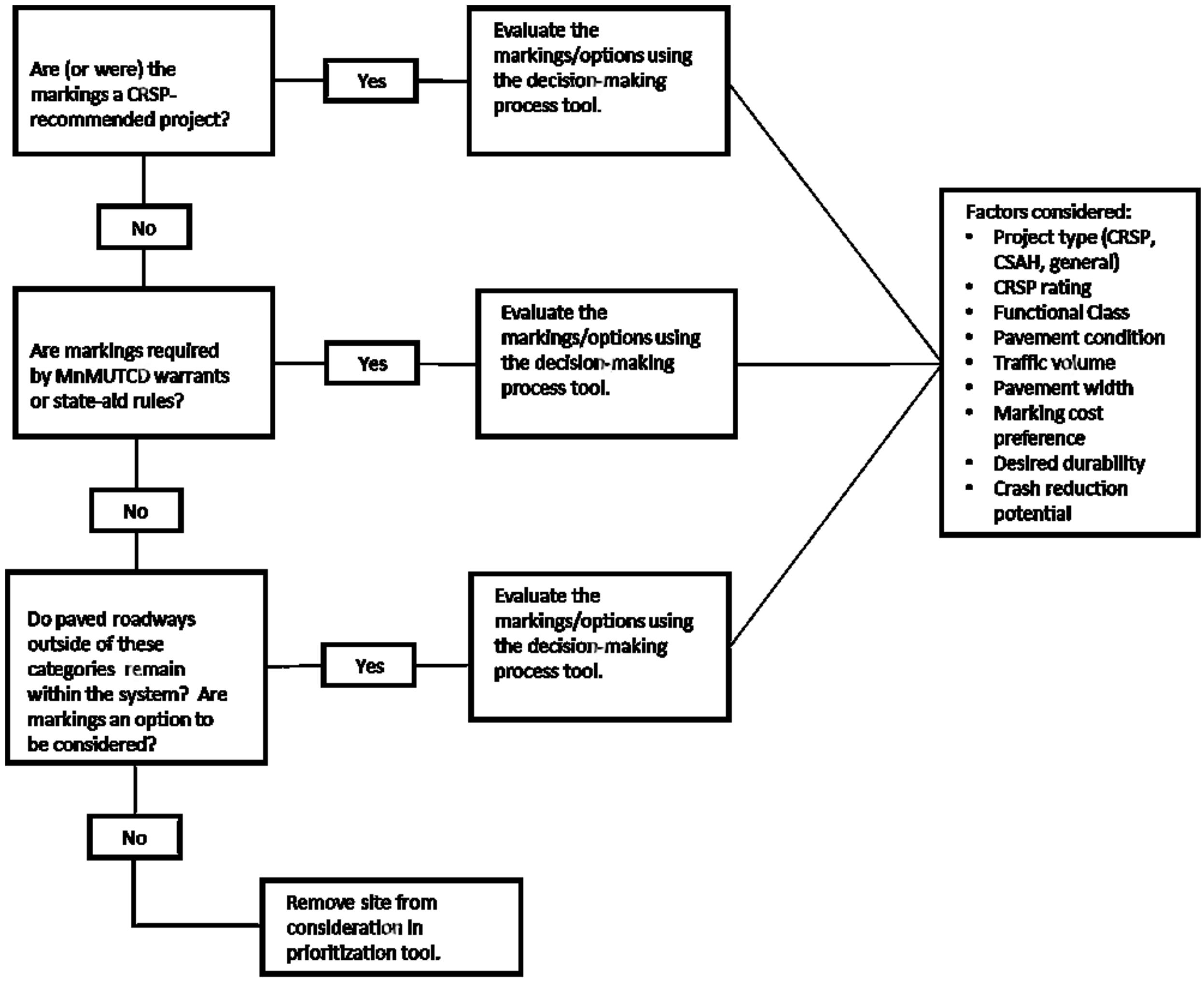

Figure 5.1. Decision-making process flowchart.

The problem presented by the selection of a pavement marking type and prioritization among sites is one of multiple alternatives, factors, and selection criteria. The decision-making process that should be employed in making such a determination requires an approach that provides a balanced consideration of the criteria and factors relevant to pavement markings. The approach identified to address these needs in the case of this project is multicriterion decision analysis.

Multicriterion decision analysis is an analysis technique that handles decision-making when multiple factors and criteria (sometimes conflicting) are involved (Mendoza et al. 1999). This approach has been used to aid in decision-making in different areas of transportation, including traffic engineering (Ozmen et al. 2009), policy (Tsamboulas and Kopsacheili 2003), transit system design (Janarthanan and Schneider 1986), intermodal freight (Kapros et al. 2005), and land use (Venter et al. 2006). The approach itself is straightforward and consists of the following steps:

1) Determine each alternative – In this work, five alternatives were considered, including centerlines only, edgelines only, centerlines and edgelines, enhanced-visibility markings (wider

edgelines), and enhanced-durability markings (alternative material with a longer life). (Note that in the case of the final two alternatives, it is assumed that they include both centerlines and edgelines.)

2) Identify the criteria in the decision-making process – In this work, this includes considerations that impact decision-making related to the type of site/project, safety plan ratings, pavement marking use/type, functional classification, pavement condition, traffic volume, the age of current markings, pavement width, preferences for marking costs, desired marking durability, and crash reduction potential.
3) Generate the subdecision matrices – This is the assignment of score values for each criterion by alternative that indicates the utility of that criterion given a particular site's conditions.
4) Determine and apply factor weights – This assigns a relative importance to each criterion for a respective alternative compared to other alternatives.
5) Calculate the scores of each alternative for a given site given the criteria scores and weights.
6) Rank the alternatives among one another.

The simple additive weighting method is employed in multicriterion decision analysis to obtain a weighted sum of the performance rating for each alternative relative to all model criteria/factors. A numeric value is first assigned for each of the model criteria per alternative. A weight is then assigned to establish the relative importance of each criterion in the model for a given alternative. Finally, a total value is generated by multiplying the weights by the attractiveness of each criterion from the value function.

The end result is a score that is assigned to each pavement marking alternative based on the characteristics for a particular site. The highest alternative score is the marking type/configuration that is best for a site given the features and conditions present. This score can be compared to the scores generated for other sites and ranked to establish a priority list of the order in which pavement marking projects might be considered.

As indicated above, five pavement marking alternatives were considered in this work:

- A_1 = Use of centerlines only on a roadway
- A_2 = Use of edgelines only on a roadway
- A_3 = Use of centerlines and edgelines together on a roadway
- A_4 = Use of enhanced visibility (wider markings, primarily edgelines) on a roadway
- A_5 = Use of a durable marking material and/or grooved/milled markings on a roadway

These alternatives were determined based on feedback obtained during the course of the survey of counties and cities in Minnesota.

A total of 10 criteria were included in the process based on the findings of the literature review, technical advisory panel (TAP) input, and feedback from the county and city survey. These criteria vary between the specific roadway segments being evaluated. The criteria considered include the following:

- C_1 = project type – CRSP, state-aid, or general

- C_2 = CRSP star ranking for site (including zero when applicable)
- C_3 = roadway functional classification
- C_4 = pavement condition
- C_5 = traffic volume
- C_6 = the age of current markings, a proxy for the wear that may be present
- C_7 = pavement width
- C_8 = marking cost preference, i.e., does the engineer wish to employ traditional, low-cost materials, or are higher cost materials an option?
- C_9 = marking durability, i.e., is there a desire to increase the lifespan of the markings being applied?
- C_{10} = crash reduction, i.e., what is the potential for crash reduction for a particular marking alternative?

Expanding on criteria C_8, C_9, and C_{10}, these have been included to capture the user's preferences regarding the cost, durability, and potential crash reduction for pavement markings at a given site. The specific details of these criteria follow:

- Marking cost preference – This criterion is the preferred cost of the markings to be applied. A low cost is weighted by the tool toward traditional materials (i.e., latex paint) as the preferred material. A medium cost is weighted by the tool toward the use of wider markings (typically using latex or other cost-effective materials). A high cost is weighted by the tool toward advanced materials (i.e., epoxy, polyurethane).
- Marking durability – This criterion allows the user to specify the preferred level of durability for pavement markings at a given site. A low-durability selection is weighted by the tool toward the use of traditional marking materials (i.e., latex). A medium-durability selection is weighted toward the use of enhanced-visibility markings (i.e., wider). A high-durability selection is weighted toward the use of alternative materials with enhanced durability characteristics (epoxy, polyurethane, etc.).
- Crash reduction – This criterion allows the user to specify the extent to which a pavement marking alternative could potentially reduce crashes. A low weight indicates that the user is not concerned with the crash reduction potential of a marking. A medium weight indicates that while the user is interested in pavement markings having an impact on reducing crashes, this is not a critical priority. A high weight indicates that the user wants to weight markings that have a potential to reduce crashes more heavily, such as those types that have been shown in past studies to reduce crashes. This can include basic markings, such as centerlines, and enhanced visibility (wider markings). Note that this criterion does not incorporate a specific crash reduction percentage into the calculations being made by the tool, nor does it produce an estimate of reduced crashes.

Agencies will need to have site-specific values associated with the criteria listed above available for entry when using the decision-making tool. They will also need to know the length of the roadway segment. Segment length is used as an input to calculate the estimated cost for a particular project being considered. The tool itself will function and produce calculations regardless of the number of criteria data elements entered, but a lack of criteria will result in a lower set of scores for a site compared to other sites where more complete data are entered.

With the alternative and criteria components established, subdecision matrices were created. The scores assigned to each criterion were based on the level of need, importance, or impact that a marking alternative would have for that criterion. For example, on a pavement with a width of 18 feet or less, a higher score value would be applied to the use of centerlines compared to edgelines based on the effectiveness of centerline markings on narrow roadways compared to edgelines. The score values assigned to the criteria were on a 1 to 5 scale, with 1 indicating that the particular alternative would have a minimal effect. In this manner, an alternative that was not attractive for a particular criterion, such as the use of high-durability markings on a poor pavement, would receive a low score.

Score values for a particular alternative that correspond to a site's features are pulled from each criteria subdecision matrix to create a decision matrix. The decision matrix for ten criteria and five alternatives that results is of the following form:

	A_1 (Centerlines)	A_2 (Edgelines)	A_3 (Centerlines and Edgelines)	A_4 (Visibility)	A_5 (Durability)
C_1 (Project Type)	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
C_2 (CRSP Rating)	X_{21}	X_{22}	X_{23}	X_{24}	X_{25}
C_3 (Functional Classification)	X_{31}	X_{32}	X_{33}	X_{34}	X_{35}
C_4 (Pavement Condition)	X_{41}	X_{42}	X_{43}	X_{44}	X_{45}
C_5 (Traffic Volume)	X_{51}	X_{52}	X_{53}	X_{54}	X_{55}
C_6 (Marking Age)	X_{61}	X_{62}	X_{63}	X_{64}	X_{65}
C_7 (Pavement Width)	X_{71}	X_{72}	X_{73}	X_{74}	X_{75}
C_8 (Marking Cost)	X_{81}	X_{82}	X_{83}	X_{84}	X_{85}
C_9 (Marking Durability)	X_{91}	X_{92}	X_{93}	X_{94}	X_{95}
C_{10} (Crash Reduction)	X_{101}	X_{102}	X_{103}	X_{104}	X_{105}

The performance of the different alternatives for each of the criteria is obtained by multiplying values in the decision matrix by weights assigned to the particular criterion/alternative combination. The performance values of the 5 alternatives and 10 criteria are calculated as follows:

$$V_{CL} = \sum_{i=1}^{n} w_i X_{i1}$$

$$V_{EL} = \sum_{i=1}^{n} w_i X_{i2}$$

$$V_{CL+EL} = \sum_{i=1}^{n} w_i X_{i3}$$

$$V_{Enh\ Viz} = \sum_{i=1}^{n} w_i X_{i4}$$

$$V_{Enh\ Dur} = \sum_{i=1}^{n} w_i X_{i5}$$

where

V_{CL} = overall performance of centerline alternative

V_{EL} = overall performance of edgeline alternative

V_{CL+EL} = overall performance of centerline and edgeline alternative

$V_{Enh\ Viz}$ = overall performance of the enhanced-visibility marking alternative

$V_{Enh\ Dur}$ = overall performance of the enhanced-durability marking alternative

w_i = weight applied to each criterion based on importance

X_{i1} = performance of centerline alternative for each criterion

X_{i2} = performance of edgeline alternative for each criterion

X_{i3} = performance of centerline and edgeline alternative for each criterion

X_{i4} = performance of enhanced-visibility marking alternative for each criterion

X_{i5} = performance of enhanced-durability marking alternative for each criterion

The weights assigned to each of the criteria were determined through consideration of past research results as well as findings from the agency survey summarized in Chapter 4. The weights vary by criteria and alternative. For example, the importance of marking durability receives a low rating for traditional alternatives such as centerlines and/or edgelines but is more highly rated for the enhanced-durability alternative. The result of this is that the particular performance score value for enhanced-durability markings should be higher when a user has indicated that he/she prefers that option compared to low-cost markings. All scores and weights in the subdecision matrices can be adjusted based on professional judgement, future research findings, or other considerations.

An example of how the subdecision score value assignment and weighting process work is illustrated by considering the ADT criteria. Assume that a roadway has an ADT of 1,500. Based on the entry of this volume by the user, the value is matched to the respective input range for criterion C_5 (Traffic Volume). The respective score values for that traffic volume for each of the different marking alternatives are as follows:

- Centerlines = 4
- Edgelines = 4
- Centerlines and edgelines = 5
- Enhanced visibility = 3
- Enhanced durability = 3

More basic marking alternatives are more highly scored for this modest volume because basic delineation is beneficial on what would be characterized as a moderate-traffic roadway. Conversely, traffic volumes are not so high that more durable or higher visibility markings may be needed compared to other, higher volume locations.

The score values for each criterion are multiplied by the weights of each alternative. The alternative weights for the ADT criterion are all 0.10 (on a 1.0 scale across all criteria) because traffic volume is of equal importance to each of the marking alternatives. In the case of other combinations of criteria and alternatives, the weights may be higher or lower, reflecting the importance of the criteria based on user input. For example, if the user specifies that the markings at a site should have high durability, the durable marking alternative is more highly weighted than other alternatives to reflect this preference in the overall scoring. Regardless, the specific weights for an alternative are multiplied by the respective criteria score values to produce a point total for each alternative. The point totals for all criteria and alternatives are then summed and multiplied by 10 to produce normalized point totals for comparison and prioritization.

The result of the multicriterion decision-making process described in the preceding paragraphs is five overall performance scores for the alternatives at each site that can be compared to one another. In the simplest terms, the alternative with the highest score is the one that would be selected in most cases. However, comparisons can be made between the five alternative scores generated for a specific site, and, when scores are close to each other, the respective alternatives could be considered interchangeable. Such decisions are left to engineering judgement in all cases.

5.3 DECISION-MAKING TOOL

The application of the multicriterion decision-making process to pavement marking decision-making was made through the development of a tool using Excel spreadsheets. Four spreadsheets were created to accomplish this task, including prioritization, site sort, subdecision, and calculation engine (calceng) sheets. The prioritization sheet is where the user enters data related to budget, individual pavement marking costs, and site-specific information. This information is used by the tool to produce marking-related outputs that assist in decision-making. The site sort spreadsheet allows the user to perform a sorting of sites by ranking them in ascending or descending order and to sort other fields, if desired. This sorting feature is provided apart from the prioritization spreadsheet because a sort performed in the same sheet where data entry occurs could lead to a rearrangement of cells that are referenced throughout the tool in making calculations. The spreadsheet tool created by this project is posted on the Local Road Research Board website in the "Resources" section at the following URL: https://lrrb.org/resources/.

The subdecision spreadsheet is where the criteria scores and alternative weights are specified. The calculation engine spreadsheet is used for calculating the score values for the sites being analyzed. The subdecision matrices and calculation engine spreadsheets do not require data entry by the user and have been password protected to prevent inadvertent changes from being made. (Note that the password is provided within the spreadsheet should changes need to be intentionally made.)

The prioritization spreadsheet is the location where all site-specific analysis is performed. It requires that an available marking budget be entered as the starting point of the analysis. Additionally, the costs of the different marking alternatives (centerlines, edgelines, centerlines and edgelines, enhanced-visibility markings, and enhanced-durability markings) need to be provided by the user. These costs are entered by the user on a per-foot basis. Later cost calculations completed in the spreadsheet convert these figures to a total cost on a per-mile basis. The user then enters site-specific information, including a description of the project/roadway site, the type of project the roadway falls under (CRSP, CSAH, or general), the star ranking for the site if a CRSP has been completed for the roadway, roadway length, functional classification, pavement condition, traffic volume, current marking age, pavement width, marking cost preference, durability, and crash reduction potential. In the majority of cases, these items are entered via dropdown box selections, although traffic volume and pavement width must be entered by the user as numerical values.

Once all information has been entered for a specific site, the alternative scores are calculated and returned. Scores for all alternatives are presented to the user for comparison purposes. The highest score value from among the alternatives is identified as the recommended marking. The estimated cost of that recommended marking for the site is calculated, and this cost is subtracted from the available budget to produce a remaining budget figure. Finally, each site/project is ranked compared to other sites/projects based on their respective alternative scores. This ranking provides a general prioritization of the different sites based on their score values, which represents the cumulative need for that specific marking compared to other sites using the evaluation criteria.

In the case of the prioritization spreadsheet, the “durable” marking material will need to be specified by the user, including the cost of that material. The results of the Minnesota local agency survey indicated that epoxy is the predominant durable marking material being used, and this is considered the default material for this category. However, the user can exchange the default material with other materials by incorporating information identified through consultation with vendors or using data from the literature review and agency survey tasks.

5.4 CHAPTER SUMMARY

This chapter has presented an overview of the pavement marking decision-making approach developed in this research. The approach that has been developed relies on the multicriterion decision-making process to take into consideration the multiple factors and criteria that affect pavement marking decisions. The following is a summary of the key aspects of the prioritization process and tool that were developed:

- The simple additive weighting method was employed to obtain a weighted sum of the performance rating for each alternative (marking configuration/material) relative to all model criteria/factors.
- The pavement marking alternatives considered in this work include centerlines, edgelines, centerlines and edgelines, high-visibility markings, and enhanced-durability markings.
- The criteria considered by the process in making pavement marking recommendations include project type, CRSP rating, functional classification, pavement condition, traffic volume, the age of current markings, pavement width, preferences for marking costs, desired marking durability, and crash reduction potential.

- The multicriterion decision analysis approach was applied to the problem of pavement marking decision-making through the development of an Excel spreadsheet tool. A primary spreadsheet was developed to support user data entry and present marking recommendations for a roadway system. Three additional spreadsheets were developed to contain a sorting mechanism for the user to view sites in a ranked order, the subdecision matrices with score values related to each criterion/alternative combination, as well as weighting factors for the criterion/alternative combinations. These spreadsheets support the calculations performed to score the respective alternatives based on user input.
- The spreadsheet tool output provides users with information on the relative performance of different marking alternatives in comparison to one another. The highest scoring alternative represents the marking that should be considered for use. Estimated costs of projects using the highest scoring alternative are produced, as is a prioritized ranking of the highest scoring alternatives among the sites evaluated.
- The tool only provides the user with information on the performance of different pavement marking alternatives based on the set of site characteristics, and engineering judgement must still be exercised in the final decision-making.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

The objectives of this project were to review the existing research on typical and enhanced pavement marking benefits (e.g., reduced crashes), document the characteristics of current pavement marking installation and maintenance practices along local agency roadways in Minnesota, and develop a prioritization approach and tool based on this collective information to assist local agencies with their pavement marking installation and maintenance decisions. To that end, the research addressed these objectives through a series of tasks:

- A comprehensive literature review to summarize research results and current practices for various aspects of pavement markings, both traditional and enhanced, including safety and operational benefits, costs, maintenance, retroreflectivity, and management/prioritization.
- A survey of local agencies in Minnesota to obtain information related to the type and extent of pavement markings being applied, the materials being used, their cost, repainting frequency, and other management considerations that guide marking prioritization.
- A review of the Minnesota CRSP process to understand how pavement marking recommendations are made and prioritized within the process itself and how these recommendations might be incorporated into the prioritization process and tool developed by this research.
- Development of a pavement marking decision-making prioritization approach and tool based on the information collected during the previous research tasks.

The efforts of this research were centered on identifying the potential safety, operational, and other benefits of pavement markings on local roadways; their costs; and the current practices regarding the use of markings on Minnesota roadways. This information was then incorporated into the development of a prioritization approach and its implementation within a spreadsheet framework. The spreadsheet tool thus provides agencies with a mechanism to determine pavement marking alternatives for a site, the prospective costs of these alternatives, and a prioritization of the sites compared to one another. The following sections highlight the primary conclusions from the work completed during this project and offer recommendations.

6.1 CONCLUSIONS

The primary conclusions that can be drawn from the work completed during the course of this research include the following:

- Limited research has been completed related to the use of traditional pavement markings (i.e., waterborne paint) on local roadways. The work that has been completed found that traditional markings produce lower crash rates, lower crash frequencies on curves, and general crash reductions between 3.0 percent and 32.9 percent (depending on the study). Operationally, traditional markings produced no real impacts on vehicle speeds or lateral placement or, at most, produced only small impacts. The use of these markings produced benefit-cost ratios between 20.6 and 125.8 based on crash cost and travel time savings. The cost of traditional markings ranged from $0.04 to $0.30, depending on the specific paint (latex or epoxy), location, etc., with a service life of 3 to 36 months.

- The use of wider edgelines produced crash reductions between 4 percent and 49 percent, depending on location, crash severity, and use of complimentary treatments. Use of wider edgelines does not appear to alter driver behavior. Wider edgeline use produced benefit-cost ratios between 5.7 and 145.9. Use of wet-reflective markings produced crash reductions between 12 percent and 30 percent, depending on the type of crash being considered. The use of thermoplastic markings produced benefit-cost ratios between 32.9 and 130.0. The costs of enhanced markings varied depending on the material, the location where applied, and other factors.
- The impact of the proposed MUTCD retroreflectivity rule on local agencies will depend on the roadway type and speed limit.
- No agency-specific documentation of pavement marking maintenance practices has been discussed in the literature. Past work indicated that local agencies in Minnesota heavily used latex paint for their markings and private contractors or in-house staff for installation/restriping.
- Limited pavement marking prioritization and management approaches have been developed. St. Louis County, Minnesota, developed an approach that considered different components, including marking warrants, the county's capital improvement program, and marking condition in the field. Additionally, MnDOT has developed guidance on marking material selection based on basic site characteristics to consider in prioritization.
- The results of a survey of local agencies in Minnesota produced a number of findings that were incorporated into the development of the prioritization approach and tool. The approaches and considerations currently used for management or prioritization by counties included time-based/rotations (annual, biannual replacement), visual inspection, traffic volumes, marking material type, marking type (centerline, etc.), and budget. Repainting markings at a set interval, the condition of markings, and available budget were commonly cited considerations used to determine an agency's marking program. Waterborne latex paint and epoxy were the most commonly used marking materials by agencies, with other materials used to a lesser extent. The average reported cost of latex paint and epoxy was $0.056 and $0.282 per linear foot, respectively. Forty-six agencies used 6-inch-wide edgelines to some extent on their systems, with 32 counties using these markings based on recommendations from their CRSPs.
- The review of the CRSP process also guided the prioritization approach and tool development. Wide pavement markings (6 inches), alternative materials (epoxy), rumble stripes, and supplemental markings (stop bars, etc.) are all strategies recommended by CRSPs. Risk levels are used by the CRSPs to prioritize locations where different safety strategies should be implemented. A review of data from 79 Minnesota counties found that pavement markings were recommended on average for 109 miles of roadway in each county.
- Given the extent to which pavement marking recommendations are made in the CRSPs for each county, these recommendations needed to be incorporated into the prioritization approach and tool developed in this research. CRSP recommendation sites are incorporated into the pavement marking prioritization approach by including them as part of the collective pool of sites being

prioritized. These CRSP recommendations are given a greater consideration and priority compared to other sites in the developed approach through their CRSP star rating.

- The pavement marking prioritization approach developed in this research uses the multicriterion decision-making process to consider the multiple factors and criteria that affect pavement marking decisions. The simple additive weighting method produces a weighted sum of the performance rating for each marking alternative relative to all model criteria/factors.
- The pavement marking alternatives considered include centerlines, edgelines, centerlines and edgelines, high-visibility markings, and enhanced-durability markings.
- The criteria considered by the process include project type, CRSP rating, functional classification, pavement condition, traffic volume, age of current markings, pavement width, preferences for marking costs, desired marking durability, and crash reduction potential.
- An Excel spreadsheet tool was developed to implement the pavement marking prioritization and decision-making process. The spreadsheet tool output provides users with information on the relative performance of different marking alternatives to one another, including an estimate of the project cost for the highest scoring alternative at a site and a ranking of sites that can be sorted by the user.
- The tool provides the user with information on the performance of different pavement marking alternatives based on a set of site characteristics. The prioritization tool is designed to provide assistance in decision-making. Engineering judgement must continue to be employed when making decisions related to what markings to install, the final selection of materials, and so forth.

6.2 RECOMMENDATIONS

The following recommendations are made based on the completion of the tasks in this research:

- The spreadsheet prioritization tool should be employed by local agencies throughout the state to assist in prioritizing different pavement marking alternatives based on site characteristics, CRSP ratings, and user preferences. The use of the tool will allow for not only a prioritization of pavement markings among different sites but also an estimation of the costs associated with a respective alternative.
- A follow-up survey should be performed to determine local agencies' experiences in using the tool and any adaptations/changes that might be needed. The results of this survey will allow the tool to be further modified to meet potential changes in user needs as experience in using the tool grows.
- If a local agency has not already developed a pavement marking database, this should be considered. The information from that database would reduce the level of effort required to characterize a particular site of interest when data are entered into the prioritization tool.
- Based on any future survey or other feedback from agencies, the tool should be adapted and modified as needed. This would address changes in local agency preferences, as well as potential future input factors, should they develop over time. For more basic changes, namely weighting, the spreadsheet has been developed such that the user can make updates with

minimal effort. The user could also make more substantial changes, such as the addition of new factors/criteria, but that will first require a review and understanding of the formulas in use throughout the spreadsheet and the references between sheets and cells before any additions are made.

- While the proposed MUTCD retroreflectivity rule was reviewed during this project to determine its potential impact on local agencies, the rule has not been finalized or implemented. As a result, local agencies will need to evaluate the final MUTCD retroreflectivity rules when the new edition is released. Based on the MUTCD retroreflectivity rule, local agencies may need to make changes to their pavement marking programs as necessary.
- The lack of specific research on the safety and operational effects of pavement markings (both traditional and enhanced) on local roadways should be addressed through future research efforts. That work should employ the state of the practice in statistical evaluations to produce robust results.

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APPENDIX A: PROPOSED MUTCD MINIMUM LONGITUDINAL PAVEMENT MARKING RETROREFLECTIVITY TEXT

The following is the proposed text, verbatim (and following MUTCD format), for the proposed MUTCD retroreflectivity rule (FHWA 2014). It is presented for reader reference with respect to the potential impacts that the proposed rule might have on pavement markings on local roadways.

Section 3A.03 Maintaining Minimum Retroreflectivity of Longitudinal Pavement Markings

Standard:

Public agencies or officials having jurisdiction shall use a method designed to maintain retroreflectivity of the following white and yellow longitudinal pavement markings, at or above the minimum levels in Table 3A-1:

1) **Centerline markings on roads where they are required or recommended by Section 3B.01. This shall include any no-passing zone markings, longitudinal two-way left-turn lane markings, and yellow markings used to form flush medians on such roads.**
2) **Lane line markings on roads where they are required or recommended by Section 3B.04. This shall include any dotted lane lines, lane drop markings, and longitudinal preferential lane markings on such roads.**
3) **Edge line markings on roads where they are required or recommended by Section 3B.07. This shall include any channelizing lines delineating gores, divergences, or obstructions on such roads.**
4) **Any optional edge line markings that are used to qualify for the lower minimum retroreflectivity values in the "All other roads" row of Table 3A-1.**

Support:

Compliance with the above Standard is achieved by having a method in place and using the method to maintain the minimum levels established in Table 3A-1. Provided that a method is being used, an agency or official having jurisdiction would be in compliance with the above Standard even if there are pavement markings that do not meet the minimum retroreflectivity levels at a particular location or at a particular point in time.

There are many factors for agencies to consider in developing a method of maintaining minimum pavement marking retroreflectivity including, but not limited to, winter weather, environmental conditions and pavement resurfacing.

Guidance:

Except for those pavement markings specifically identified in the Option below, one or more of the following methods, as described in the 2010 Edition of FHWA's "Summary of the MUTCD Pavement Marking Retroreflectivity Standard (see Section 1A.11)," should be used to maintain retroreflectivity of longitudinal pavement markings at or above the levels identified in Table 3A-1:

A. *Calibrated Visual Nighttime Inspection – Prior to conducting a nighttime inspection from a moving vehicle and in conditions similar to nighttime field conditions, a trained inspector calibrates his eyes to pavement markings with known retroreflectivity levels at or above those in Table 3A-1. Pavement markings identified by the inspector to have retroreflectivity below the minimum levels are replaced.*
B. *Consistent Parameters Visual Nighttime Inspection – A trained inspector at least 60 years old conducts a nighttime inspection from a moving vehicle under parameters consistent with the supporting research. Pavement markings identified by the inspector to have retroreflectivity below the minimum levels are replaced.*
C. *Measured Retroreflectivity – Pavement marking retroreflectivity is measured using a retroreflectometer. Pavement markings with retroreflectivity levels below the minimums are replaced.*
D. *Service Life Based on Monitored Markings – Markings are replaced based on the monitored performance of similar in-service markings with similar placement characteristics. All pavement markings in a group/area/corridor are replaced when those in the representative monitored control set are near or at minimum retroreflectivity levels. The control set markings are monitored on a regular basis by the visual nighttime inspection method, the measured retroreflectivity method, or both.*
E. *Blanket Replacement – All pavement markings in a group/area/corridor or of a given type are replaced at specific intervals. The replacement interval is based on when the shortest-life material in that group/area/corridor approaches the minimum retroreflectivity level. The interval is also based on historical retroreflectivity data for that group/area/corridor.*
F. *Other Methods – Other methods developed based on engineering studies that determine when markings are to be replaced based on the minimum levels in Table 3A-1.*

Option:

Public agencies or officials having jurisdiction may exclude the following markings from their minimum pavement marking retroreflectivity maintenance method(s) and the minimum maintained pavement marking retroreflectivity levels, but not from any requirements in Section 3A.02 to be retroreflective.

A. Words, symbols, and arrows,
B. Crosswalks and other transverse markings,
C. Black markings used to enhance the contrast of pavement markings on a light colored pavement,
D. Diagonal or chevron markings within a neutral area of a flush median, shoulder, gore, divergence, or approach to an obstruction,
E. Dotted extension lines that extend a longitudinal line through an intersection or interchange area,
F. Curb markings,
G. Parking space markings, and
H. Shared use path markings

Table 3A-1. Minimum Maintained Retroreflectivity Levels[1] for Longitudinal Pavement Markings

	Posted Speed (mph)		
	≤30	**35–50**	**≥55**
Two-lane roads with centerline markings only [2]	n/a	100	250
All other roads [2]	n/a	50	100

1 Measured at standard 30-m geometry in units of mcd/m^2/lux

2 Exceptions:

A. When RRPMs supplement or substitute for a longitudinal line (see Section 3B.13 and 3B.14), minimum pavement marking retroreflectivity levels are not applicable as long as the RRPMs are maintained so that at least 3 are visible from any position along that line during nighttime conditions.

B. When continuous roadway lighting assures that the markings are visible, minimum pavement marking retroreflectivity levels are not applicable.

APPENDIX B: MINNESOTA DOT TECHNICAL MEMORANDUM NO. 14-11-T-02

MINNESOTA DEPARTMENT OF TRANSPORTATION
Engineering Services Division
Technical Memorandum No. 14-11-T-02
October 30, 2014

To: Electronic Distribution Recipients

From: Jon M. Chiglo, P.E.
Division Director, Engineering Services

Subject: MnDOT Provisions for Pavement Marking Operations

Expiration
This technical memorandum will remain in effect until October 22, 2019, unless superseded before that date or incorporated into MnDOT manuals. This technical memorandum supersedes the provisions contained in Technical Memorandum 13-13-T-03, dated July 1, 2013 and Technical Memorandum 08-10-T-02, dated May 20, 2008.

Implementation
This technical memorandum shall be implemented immediately.

Introduction
The FHWA is continuing their efforts for developing minimum retroreflectivity criteria for pavement markings. When this process is completed, striping operations across the state will be responsible for assuring that pavement markings meet or exceed these minimum level criteria. Because of Minnesota's climatic extremes, a systematic approach to pavement markings (District and Statewide striping plans) has been developed and implemented in order to attain MnDOT's mission.

Over the past several years, MnDOT has put emphasis on the efforts to increase the performance of pavement markings throughout the State. These efforts have focused on improving equipment, streamlining maintenance operations, evaluating new materials, retrofitting materials on existing surfaces, and investigating performance based specifications to better deliver MnDOT's goal to:

Provide an appropriate pavement marking on all highways, 365 days per year.

Purpose
The purpose of this technical memorandum is to provide a consistent statewide approach for pavement marking operations on state trunk highways. This includes guidance on material usage for final pavement markings including both longitudinal lines and special markings (i.e. crosswalks, messages, etc.).

The guidance contained in this technical memorandum applies to the pavement marking operations on all pavements that fall under the jurisdiction of the Minnesota Department of Transportation.

Definitions
An appropriate pavement marking is one that meets or exceeds the standards defined in the Minnesota Manual on Uniform Traffic Control Devices (MN MUTCD). During winter weather events, pavement markings should provide presence after pavement is clear of snow and ice.

Performance
Research has shown that the threshold between an acceptable and an unacceptable pavement marking based on nighttime driver visibility needs is between 80 and 120 MCD/m2/lux. MnDOT has adopted the minimum performance of 100 MCD/m2/lux for a white line and 80 MCD/m2/lux for a yellow line. These minimum performance values are used to schedule maintenance or replacement of all pavement marking installations and used to determine when pavement marking materials can be left beyond expected service life. If retroreflectivity data is not available, Districts may use expected life of pavement markings from tables below and a visual nighttime inspection to determine whether maintenance or replacement is necessary.

Pavement markings are an important road asset that needs to be managed effectively and performance measures for pavement markings need to be developed to assess the health of the system. The Office of Traffic, Safety, and Technology, through the Traffic Engineering Organization, will develop these performance measures for pavement markings.

Pavement Marking Life Expectancy
Experience has shown that traffic volumes and resulting snow and ice operations have the greatest impact on the longevity of pavement markings. The following chart outlines the life expectancy of various surface applied materials based on traffic volumes and the minimum retroreflective performance values listed above.

Expected Life of Surface Applied Markings

Material		
Latex Paint	>1 yr.	1 yr.
Epoxy (Plural Component Liquid)	>5 yr.	3-5 yr.
Preformed Polymer Tape or Thermoplastic	>5 yr	>5 yr

Research has shown that recessing pavement marking materials below the pavement surface can significantly increase the life expectancy of the marking. Examples of recessing techniques would be grooving, inlaying, installing in a sinusoidal rumble strip, slightly raising the traveled lanes (while leaving the marking area recessed), etc. The following chart outlines the life expectancy of various materials that have been recessed based on traffic volumes.

Expected Life of Recessed Markings

Material		
Latex Paint	>3 yr.	3 yr.
Epoxy (Plural Component Liquid)	>6 yr.	5-7 yr.
Preformed Polymer Tape or Thermoplastic	>7 yr	>7 yr

Wet Reflectivity/Recoverability
Wet-night visibility is an increasingly important pavement marking issue. Wet reflective and wet recoverable products and processes have been shown to improve the visibility of markings in these adverse conditions. MnDOT considers wet reflective and wet recoverable products to be comparable in wet weather conditions, therefore this guidance will not distinguish between them.

Wet Recoverable Materials and processes are those materials or installation processes that enhance performance of pavement markings during wet weather condition but still lose retroreflective properties when covered with water. Examples of these include larger glass beads, profiled markings and rumble stripes.

Wet Reflective Materials are those materials that enhance performance of pavement marking during wet weather conditions and retain their retroreflective properties when covered by water. Examples of these materials are those that contain specialized elements that are retroreflective when covered by water.

All wet reflective/recoverable materials shall be recessed to insure continued wet weather performance after snow plowing operations. To ensure performance these materials should be installed as recommended by the manufacturer.

Statewide Guidance

To meet the goal of providing an appropriate marking 365 days per year, flowcharts (attached) with recommendations for the application of pavement marking materials have been developed. The materials shown in the flowcharts are the minimum types recommended. Districts may choose to use materials with a longer life expectancy for specific projects or broader applications. All pavement marking materials used shall be on MnDOT's Qualified Products List (QPL). New materials to be investigated shall follow the provisional approval process of the QPL.

When markings have reached the minimum performance levels and are scheduled to be replaced by Maintenance, it is recommended that the materials used are based on remaining life of the pavement surface. The following table lists the recommendations for refreshing markings.

REFRESHING MARKINGS (MAINTENANCE)

Remaining Pavement Surface Life[1] (years)	Surface Applied	Recessed
0-3	Latex	Latex
>3	Epoxy[3,4]	Latex or Epoxy[2]

[1] Anticipated life of existing pavement is based on planned projects and anticipated life of surface is based on preventive maintenance plans. For the purpose of this tech memo, 3 years was chosen based on suggested optimum time until initial preservation project.

[2]Avoid placing Epoxy over Latex unless Latex presence is minimal. Epoxy should be placed on Epoxy if the remaining surface life is anticipated to be 6+ years.

[3]If pavement joint treatment is being used, latex can be used for lines at joints regardless of Remaining Pavement Surface Life.

[4]If the surface condition of the road would require Epoxy to be replaced within 2 years, Latex may be used.

Each year in January, the Office of Maintenance will ask the Districts to submit their annual maintenance striping request. The Districts will fulfill this request by submitting the information requested on the Request for Striping form that can be found at http://www.dot.state.mn.us/trafficeng/pavement/manual.html .

Aside from the material recommendations, it is also recommended that 6" edgelines are installed on rural two-lane two-way roads where there are no additional safety countermeasures for lane departures (such as rumble strips or stripes). Studies have shown a considerable reduction in crashes when wider edgelines are installed. A 2012 study done by the Texas Transportation Institute demonstrated a reduction in total crashes of 15-30% and a reduction of 15-38% in fatal plus injury crashes. An FHWA report released in late 2013 that detailed studies done in Kansas, Michigan and Illinois noted reductions of similar magnitude. The safety benefit determined by these studies makes this an important tool to add to our safety countermeasures.

Alternative Practices and Installations

Statewide goals and plans cannot include all conditions and circumstances. To allow the Pavement Marking Engineer to monitor alternative pavement marking practices, if a District chooses to have an alternative practice or installation that differs from the guidance in this technical memorandum, the District should provide notification to the Pavement Marking Engineer with details and reason(s) for the change. Notification is only requested for large scale differences or district-wide practices, and need not include short segments or intersections. The Pavement Marking Engineer will track alternate practices and installations for the purpose of using the results in future decisions on pavement marking practices and operations.

Questions

Any questions regarding the technical provisions of this Technical Memorandum can be addressed to either of the following:

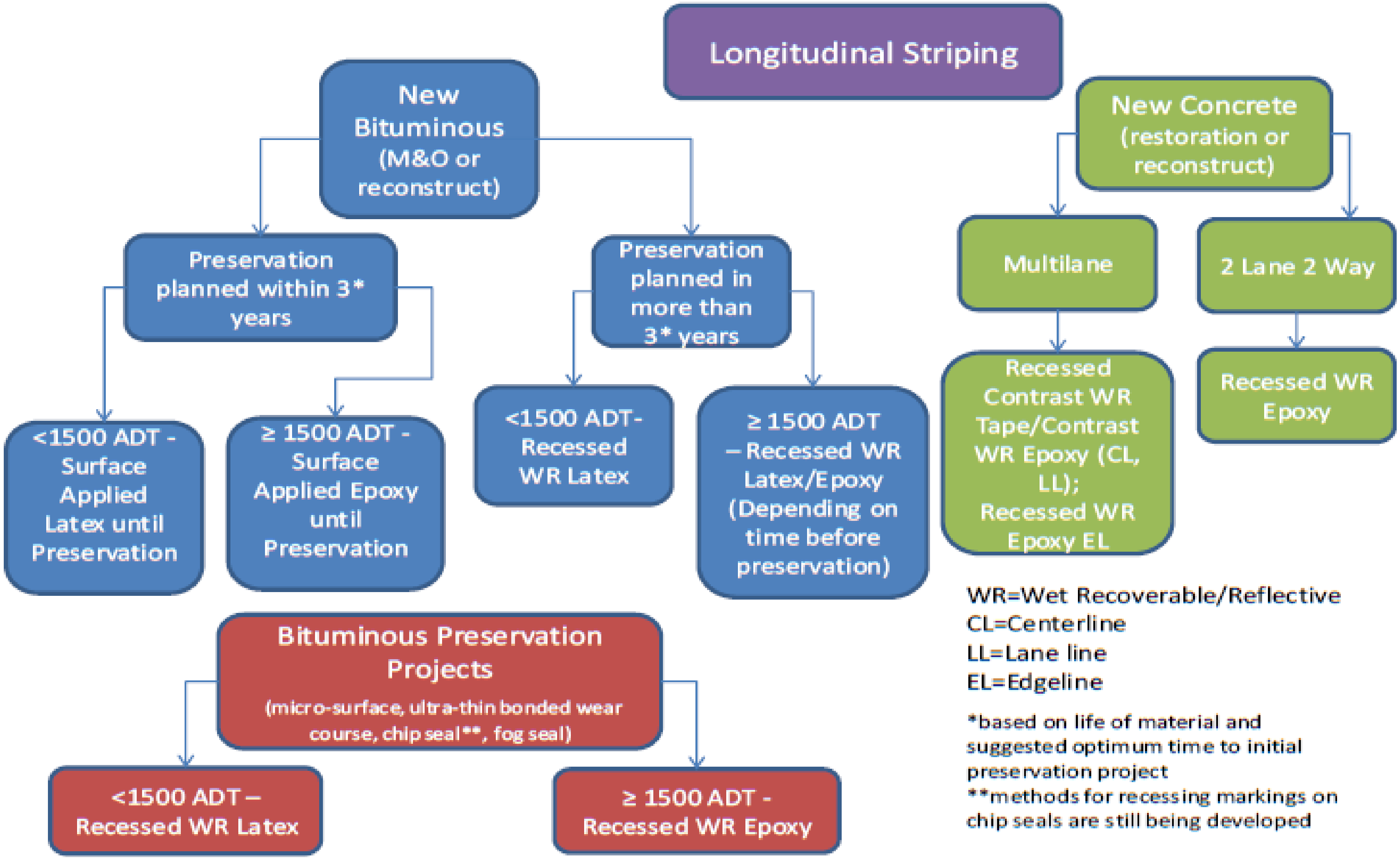
- **Ken Johnson**, Work Zone, Pavement Marking and Traffic Devices Engineer, at **(651) 234-7386**
- **Michelle Moser**, Pavement Marking and Traffic Device Engineer at **(651) 234-7380**

Any questions regarding publication of this Technical Memorandum should be referred to the Design Standards Unit, DesignStandards.DOT@state.mn.us. A link to all active and historical Technical Memoranda can be found at http://techmemos.dot.state.mn.us/techmemo.aspx.

To add, remove, or change your name on the Technical Memoranda mailing list, please visit the web page http://techmemos.dot.state.mn.us/subscribe.aspx

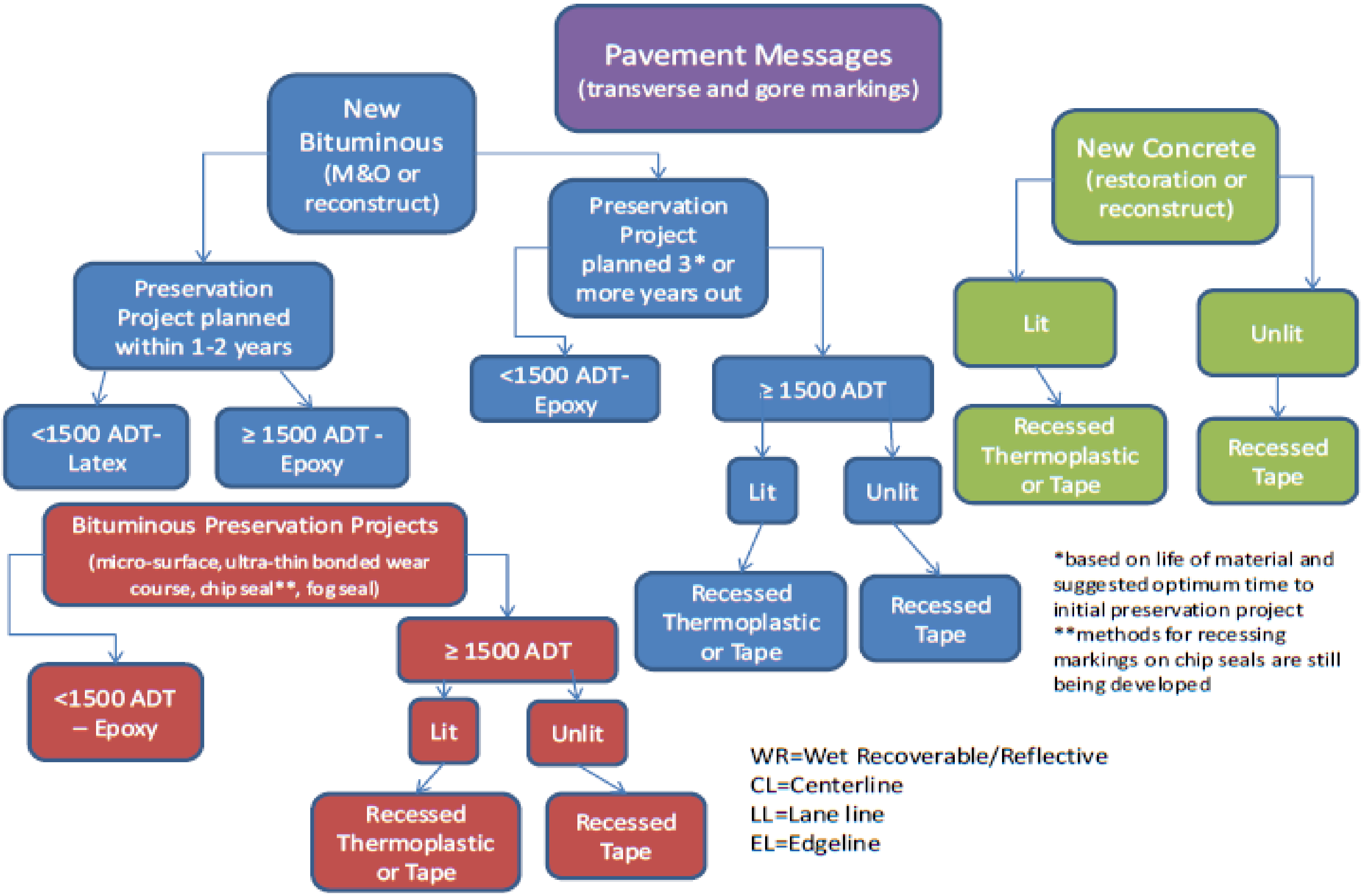
Attachments:

A: Longitudinal Striping
B: Pavement Messages



WR=Wet Recoverable/Reflective
CL=Centerline
LL=Lane line
EL=Edgeline

*based on life of material and suggested optimum time to initial preservation project
**methods for recessing markings on chip seals are still being developed



*based on life of material and suggested optimum time to initial preservation project
**methods for recessing markings on chip seals are still being developed

WR=Wet Recoverable/Reflective
CL=Centerline
LL=Lane line
EL=Edgeline

APPENDIX C: AGENCY SURVEY INSTRUMENT

Local Agency Pavement Marking Use

This questionnaire seeks to obtain information from local agencies (counties, cities) in Minnesota regarding different aspects of their pavement marking use and programs. Please take a few minutes to compete the following questions with as much detail as you can (estimates are acceptable).

If you have any questions or wish to provide additional information, please contact David Veneziano at 515-294-5480 or dvenez@iastate.edu.

Thank you for your participation!

1) Name, Agency and Contact Information

Name____

Agency____

Phone number____

Email____

2) Approximately how many miles of roadway does your agency manage?

____

3) Approximately what percentage of those miles do you consider to be low volume (less than 400 vehicle per day)?

____

4) Approximately what percent of roadway mileage do you use the following pavement markings on:

Centerline____

Edgeline____

No Markings____

Other (please describe) ____

5) How does your agency determine when to use or not use pavement markings? Please briefly describe:

____

6) Does your agency employ a management or prioritization approach to determine what/when markings will be reapplied/repainted?

If yes, please briefly share that management policy or prioritization approach in the text box below. Alternatively, if this approach is documented and can be shared, please send it to dvenez@iastate.edu.

____ Yes

____ No

Summary of approach:

____

7) Which of the following pavement marking materials do you use for longitudinal markings (check all that apply)?

____ Paint (waterborne latex)

____ Paint (alkyd)

____ Thermoplastic

____ Polyurea

____ Epoxy

____ Polyester

____ Methyl Methacrylate

____ Tapes

____ Wet-reflective paint - surface applied

____ Wet-reflective epoxy - surface applied

____ Grooved markings - paint

____ Grooved markings - epoxy

____ Grooved markings - tape

____ Grooved markings - wet-reflective paint

____ Grooved markings - wet-reflective epoxy

____ Grooved markings - wet-reflective tape

____ Other (please specify) ___________________________________

8) Does your agency use different materials for transverse and word message markings? If so, please list what material(s) are used for these below.

____

9) What width do you use for your centerline markings?

____ 4 inches

____ 6 inches

____ 8+ inches

____ Other (multiple widths used, please describe) ___________________________________

10) Is it standard practice to place 6 inch edgelines on all of your roadways, or are these only used on County Road Safety Plan projects or routes?

____ Yes

____ No (please describe)____

11) How does your agency handle the application or reapplication of pavement markings?

____ In-house staff

____ Private contractor

____ State Department of Transportation

____ Other (please specify) ____

12) Approximately what is the cost per linear foot that your agency pays for each of the markings indicated as being used in Question 7?

____

13) What determines your agency's pavement marking program (check all that apply)?

____ Budget

____ Marking condition assessment

____ Markings repainted at set interval

____ Other (please specify) ____

14) Approximately how many dollars is your annual pavement marking budget?

____

15) How does your agency assess its pavement markings?

____ Visual inspection

____ Handheld retroreflectometer

____ Vehicle mounted retroreflectometer

____ Estimated service life

____ No assessment made

____ Other (please describe) ____

16) How frequently does your agency reapply/repaint markings on roadways?

____ Annually

____ Every 2 years

____ Every 3 years

____ Other (please specify) ____

17) What specifications are used when purchasing pavement marking materials?

____ Minnesota DOT

____ In-house/agency-specific

____ Contractor-based

____ Other (please specify) ____

18) Are any quality control procedures performed, either for the marking materials that have been purchased or following installation (regardless of who installed the markings)?

____ Yes

____ No

If yes, please describe: ____

19) Do you currently maintain a pavement marking inventory?

____ Yes

____ No

20) Does that pavement marking inventory record/track retroreflectivity?

____ Yes

____ No

21) If you have any additional information related to marking and maintenance activities that may be of interest to this work, please describe them below.

____

Thank you for your time and participation!

APPENDIX D: TEXT RESPONSES TO SPECIFIC SURVEY QUESTIONS

The following are the textual responses provided by survey respondents to specific survey questions. The number of the respective survey question precedes the question itself. Note that responses are presented verbatim, with no spelling or grammatical corrections made.

6) Does your agency employ a management or prioritization approach to determine what/when markings will be reapplied/repainted? Summary of approach:

County Responses:

- Epoxy and other durable pavement markings are reapplied every 4-5 years. Latex markings are repainted every year.
- General - Highest ADT routes repainted every year, lowest ADT repainted every 5 years, varying terms in between. Routes that are usually damaged by snowplowing with motorgrader get repainted every year. All routes are inspected in the spring and can be added or removed from the summer repainting list.
- Centerline markings and high-volume roadways are the highest priority.
- Just track what is done when with an Excel spreadsheet. Many roads are painted every other year. Priority roads most times are every year, but based on daytime inspection it may be every other year.
- We basically stripe our roads every two years. Alternating half of our roads every year
- Roads with 1500 ADT or greater, striped every year. All other mileage repainted on a 2 year cycle.
- Half the system every year
- Restripe every three years.
- Rotation
- Centerlines every 1-2 years, edgelines every 2-3 years. County Highway paved routes with greater than or equal to 400 ADT will have a 6" wide edgeline and County Highway paved routes with less than 400 ADT will have a 4"wide edgeline.
- We stripe our county roads every year that have and ADT greater than 750. The remaining roads 750 and less will get striped every two years.
- Epoxy pavement marking are prioritized based on condition. Latex markings generally follow the guidelines below:
    - Greater than 1500 ADT - restripe center and edgelines annually
    - 400-1500 ADT - restripe center and edgelines on 2-year frequency
    - Less than 400 ADT - restripe center and edgelines on 3-year frequency.
- We do maintenance painting of one-half the county each year, and its a long standing practice. In addition to the above practice, overlay and seal coat roads are painted under contract.
- Visual inspection. Some routes get remarked every year, every other year, and some every 3rd year.
- Depending upon condition budget usually determines the miles we can address

- We have a rotating cycle on striping and a 3 or 4 year schedule depending on how it is holding up
- Drive highways and determine what is needed each year
- Visual assessment of the marking condition
- We re-stripe annually
- Spreadsheet with centerline on high volume > 400 marked yearly, edgelines marked every two years. On low volume < 400 centerline every 2 years, edgelines every 4 years.
- For latex, the unwritten rule of thumb is the pavement gets either centerline or edgeline every year. If it is a higher quality paint or ground in paint then we evaluate case by case on timing to reapply.
- Repaint everything every two years. Repaint those miles that don't last for two years every year.
- Stripe every other year.
- Annual night pavement marking survey. Rating retroreflectivity.
- Beet roads every year. County split into 3 districts. 1 district per year.
- If striping is worn and road is not scheduled for seal coat, overlay or reconstruction in current year, the road is re-striped.
- We restripe roads on a 2 year interval
- Centerline and edgeline pavement markings determined by ADT. ADT greater than 550/day have centerline and edgelines. ADT less than 550/day have centerline markings only. State Aid Rules 8820.2700 require pavement
- We repaint our entire system annually.
- We restripe all of our markings each year. All pavement markings are reviewed annually and those where the retroreflectivity is deteriorated are restriped.
- Visual inspection as well as last-year striped. GIS helps to track this.
- Based upon need typically every 2 years for latex
- We stripe on a three year cycle
- We restripe every paved road every year.
- The pavement markings become faded/worn off after 2 1/2 years so the County is on a two year rotation for marking replacement. This approached has been developed over time and from local experience.
- On road reconstruction or pavement reconditioning projects, we typically place ground-in wet-reflective pavement markings (centerline and edgeline). Those pavement markings remain in service for 5-7 years or more, until a sealcoat is performed on bituminous roadways. At that time, we generally restripe with a latex paint immediately after the sealcoat and again the following year. After that, we generally restripe the roadway every 2-3 years. On average, we let an annual pavement marking contract that covers approximately 85-100 miles of our system.

City Responses

- Annual review of striping inventory, highest volume roads priority. No written document

- MSAS [Municipal State Aid Street] is striped on a routine basis approximately 3 year rotation. Local streets as the markings fade so as to be nearly unseen.
- Crosswalks and curb lines are painted annually. Everything else is on an as needed basis.
- Re-striping done with sealcoats, reconstruction, and on as needed basis
- Traditionally the Street Division has repainted all pavement markings annually. Starting in 2017 approximately half of the pavement markings will be painted annually with the other half painted the following year. An annual inspection will determine if the pavement markings on higher volume roadways will need to be repainted annually or biannually.
- Management prioritization is not formally documented. However, roads that receive a re-application tend to be roads with the highest traffic volume, highest risk of accidents, and receive the greatest amount of wear and tear.
- We paint the roadways on an annual basis.
- Visual Inspection
- Yearly visual inspection
- We repaint our entire system annually.
- We restripe all of our markings each year.
- Downtown business district & priority snow removal routes first, then all remaining.
- Age of markings is primary determination factor. A visual inspection is secondary.
- Review with staff to prioritize available resources (expense) and use all budget at the most critical areas.

16) How frequently does your agency reapply/repaint markings on roadways?

- County responses:
- 4-5 years for thermoplastics
- varies between 2-3 years based on traffic
- Varies based on marking type, location, and traffic volume. Some locations get markings reapplied annually and other locations may go several years.
- Most are every two years. Some are every 3 years. Centerline every two years. Edgelines try get 3 years but many times its 2 years. Really depends on the winter and how much scrapping we have to do.
- This is general. We do visual inspection on year 2 and occasionally delay repaint until year 3 depending on condition, budget, and traffic volumes
- About 90 miles annually, the remaining mileage divided in two and repaint every 2 years.
- We paint about 150 miles of roads each year. Every road will be painted about once every two years.
- We stripe our county roads every year that have and ADT greater than 750. The remaining roads 750 and less will get striped every two years.
- every 2 years for paint and 7 - 10 for the epoxy
- Latex frequency of 1-3 years based on condition and ADT. Epoxy frequency 6-8 years, based on condition.

- We annually paint one-half the county each year. So, we get a two-year life out of the paint.
- Varies by route
- 3-4 years
- Spreadsheet with centerline on high volume > 400 marked yearly, edgelines marked every two years. On low volume < 400 centerline every 2 years, edgelines every 4 years.
- Latex- annually. Epoxy- 3-5 years.
- ADT > 900/day: CL/EL Annually. ADT 550/day - 899/day: CL/EL Every two years. ADT 300/day - 549/day: CL Every two years. ADT < 300/day: CL Every three years.
- Depends on the roadway. Not more than annually. High-volume roadways can be annual while low-volume roadways can be three years
- Different for each material. Average once per 3 years for latex paint.
- Try to repaint every 2 years but it is budget dependent.
- Every 2-3 years for Paint.... Year 0 and Year 1 following a seal coat.
- Before going to grooved-in markings we were applying on some roads annually. Now we are seeing 3-4 years for reapplying.

City Responses:

- As needed, or with sealcoat work. (Approx. 3-5 yrs)
- Generally every two years. However, a street will receive back to back paintings after a chip seal.
- some streets are completed each year, some are every other year
- Most roads every 3 years but some higher volume more frequently

18) Are any quality control procedures performed, either for the marking materials that have been purchased or following installation (regardless of who installed the markings)? If yes, please describe:

County Responses:

- manufacturers certification
- When local funds are used, we generally we do not perform testing on the marking thickness, paint and beads unless a visual concern is observed during installation. State and/or Federal QC procedures and Mndot Specs are followed when State/Federal funds are utilized.
- Very little just visual inspection and require materials comes from MnDOT approved sources.
- Inspector in the field and check the MN/Dot approved product list
- Work completed is visually inspected and redone if poor workmanship or improper width, etc.
- Follow MnDOT acceptable materials requirements. We accompany the pavement marking contractor during application.
- Comes from approved products list.
- Visual and retroreflectometer
- visual assessment
- Bead + paint checks at time of application; Visual inspections (day + night)
- Inspection.

- Amount of Glass Beads in pavement markings
- Paint/Bead Certifications.
- Following installation, we do visual only.
- approved/qualified source of materials, visual inspection
- visual inspection
- check paint specs and observe placement
- MnDOT Spec- Approved Products List No other QA

City Responses:

- only visual
- Materials check for consistency with MnDOT Approved Products List
- Have a staff person ride with the contractor to inspect installations.
- review life of markings and discuss alternatives

21) If you have any additional information related to marking and maintenance activities that may be of interest to this work, please describe them below.

County Responses:

- If we do a chip sealcoat on a road we will apply the pavement marking and then reapply the next year
- Currently looking into an inventory program that will track the retroreflectivity.
- Started to mill in centerline stripes and edgeline stripes. Looking at using grooved wet-reflective epoxy on edgelines around curves. Will evaluate and determine if all edgelines will have this level of pavement marking
- Our method is basically "old school" and we don't use a formal process or computer program.
- We do not track measured retroreflectivity. However from visual inspections and from experience we know the retroreflectivity after 2 1/2 years is not acceptable, so we replace on a two year schedule.

City Responses:

- We are transitioning all of our symbols to thermoplastic, including crosswalk blocks
- Burnsville operates a 17 community JPA for paving marking, seal coating, fog sealing and crack sealing. Most of these communities restripe over their markings each year.