A REVIEW OF THE PERFORMANCE AND COSTS OF CONTEMPORARY PAVEMENT MARKING SYSTEMS

Final Report

By

Eli Cuelho, Jerry Stephens, and Charles McDonald

of the

Western Transportation Institute
College of Engineering
Montana State University – Bozeman

Prepared for the

State of Montana
Department of Transportation
Research Section

February 2003

TECHNICAL REPORT DOCUMENTATION PAGE

. Report No. FHWA/MT-03-001/8117-17	2. Government Access No.	3. Recipient's Catalog No.
4. Title and Subtitle A Review of the Performance and Costs of Contemporary Pavement Marking Systems		5. Report Date February 2003 6. Performing Organization Code
7. Author(s) Eli Cuelho, Jerry Stephens and Charles McDonald		8. Performing Organization Report Code
9. Performing Organization Name and Address Western Transportation Institute 416 Cobleigh Hall Montana State University PO Box 173910 Bozeman, Montana 59717-3910		10. Work Unit No. (TRAIS) 11. Contract or Grant No. MSU G&C #426425 MDT Project #8117-17
12. Sponsoring Agency Name and Address Research Section Montana Department of Transportation 2701 Prospect Avenue PO Box 201001 Helena, Montana 59620-1001		13. Type of Report and Period Covered Final Report March 2002 – December 2002 14. Sponsoring Agency Code 5401
15. Supplementary Notes Research performed in cooperation with the Montana Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.		
16. Abstract The objective of this study is to provide the Montana Department of Transportation with information that will be useful in selecting cost effective pavement marking systems. This report begins with a description of available pavement marking technologies, including a discussion of performance parameters of importance and the advantages and disadvantages offered by the various technologies. A review of some of the pertinent studies completed by other states on their pavement marking programs is subsequently presented. Based on the summary of the states included in this study, pavement markings such as conventional paints are viable in areas where pavement markings do not experience high levels of wear due to traffic or winter maintenance activities. In areas where more durability is required, such as intersections, highways in snowy areas, etc., durable products like epoxy paints or thermoplastics are justified. Since the Montana Department of Transportation is able to procure epoxy paint markings for a very reasonable cost, greater use of this durable pavement marking is certainly justified, especially considering the level of wear Montana state highways experience from snowplowing and sanding. MDT's investigation of the use of mid-durable paints is warranted due to increased durability and lower cost of these products. In spite of their high cost, extruded thermoplastics and preformed tapes are still viable in areas of high wear, such as intersections and urban streets, according to the results of the studies reviewed in this report.		
17. Key Words Pavement markings, thermoplastics, durability, epoxy, alkyd paints, latex paints, maintenance, life cycle costs		18. Distribution Statement No restrictions. This document is available to the public through NTIS, Springfield, Virginia 22161.
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 25 22. Price

DISCLAIMER

This document is disseminated under the sponsorship of the Montana Department of Transportation and the United States Department of Transportation in the interest of information exchange. The State of Montana and the United States Government assume no liability of its contents or use thereof.

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official policies of the Montana Department of Transportation or the United States Department of Transportation.

The State of Montana and the United States Government do not endorse products of manufacturers. Trademarks or manufacturers' names appear herein only because they are considered essential to the object of this document.

This report does not constitute a standard, specification, or regulation.

ALTERNATIVE FORMAT STATEMENT

The Montana Department of Transportation attempts to provide reasonable accommodations for any known disability that may interfere with a person participating in any service, program, or activity of the Department. Alternative accessible formats of this document will be provided upon request. For further information, call (406) 444-7693 or TTY (406) 444-7696.

NOTICE

The authors, the State of Montana, and the Federal Highway Administration do not endorse products or manufacturers. Trade and manufacturers names appear herein solely because they are considered essential to the object of this report.

ABSTRACT

The objective of this study is to provide the Montana Department of Transportation with information that will be useful in selecting cost effective pavement marking systems. This report begins with a description of available pavement marking technologies, including a discussion of performance parameters of importance and the advantages and disadvantages offered by the various technologies. A review of some of the pertinent studies completed by other states on their pavement marking programs is subsequently presented. Based on the summary of the states included in this study, pavement markings such as conventional paints are viable in areas where pavement markings do not experience high levels of wear due to traffic or winter maintenance activities. In areas where more durability is required, such as intersections, highways in snowy areas, etc., durable products like epoxy paints or thermoplastics are justified. Since the Montana Department of Transportation is able to procure epoxy paint markings for a very reasonable cost, greater use of this durable pavement marking is certainly justified, especially considering the level of wear Montana state highways experience from snowplowing and sanding. MDT's investigation of the use of mid-durable paints is warranted due to increased durability and lower cost of these products. In spite of their high cost, extruded thermoplastics and preformed tapes are still viable in areas of high wear, such as intersections and urban streets, according to the results of the studies reviewed in this report.

TABLE OF CONTENTS

LIST OF TABLES

1. Introduction

Like many states, Montana spends a significant amount of money on pavement markings. Thus, it is important that the state utilize marking systems that offer the best possible performance at the lowest possible cost. With respect to performance, the purpose of the markings is to facilitate safe, efficient and comfortable traffic flow on state highways. Marking configurations and visibility requirements are generally well defined by publications such as the Manual for Uniform Traffic Control Devices. Several choices are available, however, for the materials from which these markings are made. Common systems include thermoplastics, latex and alkyd paints, epoxy paints and preformed tapes. In selecting a system for a particular installation, the characteristics of the marking materials that are of greatest interest include:

1) their ability to perform their intended function, which is generally related to their visibility as quantified in terms of retroreflectivity;
2) their durability, which is affected by the volume of traffic, orientation of the marking, and the climatic conditions to which they are subjected; and
3) their cost.

Naturally, these characteristics tend to be interrelated, with increased durability, for example, being coupled with increased cost. Therefore, in evaluating cost, it is essential to consider life cycle costs as opposed to simply initial installation costs. The life cycle cost analysis is further complicated by the fact that pavement related maintenance activities generally obliterate any pavement markings. The expense of using a system with a long service life may not be justified, if that service life exceeds the time interval before the next pavement maintenance activity is to be performed. A further consideration at some locations may be the relative inconvenience experienced by the motoring public during marking installation. Thus, selecting the most cost effective pavement marking system in any given situation can be a difficult task, given the number of parameters that potentially influence this decision.

The objective of this study is to provide the Montana Department of Transportation (MDT) with information that will be useful in selecting cost effective pavement marking systems. This information was obtained from an in-depth review of the extensive literature available on this subject and direct contact with transportation professionals in other states regarding their practices. At the inception of this project, it was believed that it might be necessary to collect cost and performance data for various pavement marking systems and conduct life cycle cost analyses. However, a review of the literature available on this subject revealed that several states have recently studied their pavement marking programs with the objective of improving their cost effectiveness. Consequently, Montana can benefit from their observations and conclusions.

This report begins with a description of available pavement marking technologies, including a discussion of performance parameters of importance and the advantages and disadvantages offered by the various technologies. A review of some of the pertinent studies completed by other states on their pavement marking programs is subsequently presented. Finally, suggestions are made regarding potential cost effective pavement markings for applications in Montana.

2. Description of Marking Systems

Several pavement marking systems are currently available for commercial use. Table 1 shows nationwide use of various pavement marking materials and the percent of total expenditures for each system. This study focused on the more common systems of pavement markings, which consist of conventional paints (alkyd-based or latex-based paints), epoxy paints, thermoplastics and preformed tape. These marking systems account for approximately 90% of all markings and are used in most applications. The remaining products collectively account for less than 10% overall use and are therefore not discussed in detail in this report.

Table 1: Typical Pavement Marking Material Use in the United States (McGinnis, 2001).

Pavement Marking Material	Percent of Lane Miles	Percent of Expenditures
Conventional Paint	58	17
Thermoplastics	21	34
Epoxy	6	7
Tape	5	26
Polyester	2	2
Profiled Thermoplastics	2	7
Other	6	7

The pavement marking systems considered in this study are classified as either conventional products or durable products. Accordingly, alkyd and latex paints are considered conventional products, and epoxy paints, thermoplastics, and preformed tapes are considered durable. Some products, like mid-durable paints, offer more durability than conventional paints, but less than epoxy and thermoplastics.

In this section of this report, the composition, installation, relative performance, and relative costs of alkyd/latex paints, epoxy paints, thermoplastics, and preformed tapes are generally described. To put this information in perspective, it is necessary to briefly describe some of the performance issues related to marking systems. Independent of type, the intention of the pavement marking system is to provide visible direction to roadway users. This objective is accomplished by including a reflective component in the pavement marking material. The subsequent visibility of a pavement marking is often quantified in terms of retroreflectivity, which is a measure of the light reflected back to the driver (Lee et al, 1999). In evaluating the effectiveness of a marking system, retroreflectivity levels should be considered under a variety of conditions, such as daylight, darkness, wet, dry, etc.

Service life, an important parameter in selecting a marking system, is chiefly determined from the level of retroreflectivity provided by the pavement marking. According to the Kansas Department of Transportation (KDOT), for example, pavement markings should be replaced when retroreflectivity levels fall below 150 millicandelas per square foot per footcandle or millicandelas per square meter per lux (mcd) for white markings and 100 mcd for yellow markings (KDOT, 1999). Note that while loss of retroreflectivity is a dominant mechanism of failure of pavement markings, other conditions that may end the service life of a marking include detachment from the pavement, extensive loss of pigment, and obliteration by pavement maintenance activities. The major factors that affect the performance and service life of a particular type of pavement marking include type of road surface, volume of traffic, orientation with respect to traffic, winter sanding and snow removal practices, and schedule of pavement maintenance activities. While cause and effect relationships between factor and outcome are obvious for several of these factors, additional comment is warranted in some cases. With respect to road surface, some marking systems can be used on both concrete and asphalt surfaces, while others may adhere well only to asphalt surfaces. For either surface and for all marking systems, service lives decrease as traffic volume increases. Marking orientation with respect to traffic also affects service life. Longitudinal markings (markings oriented in the direction of travel) are only occasionally crossed and thus are worn less by vehicles relative to markings oriented transverse to traffic that are crossed and worn by the passage of every vehicle.

Additional factors important in the selection of a pavement marking system include the level of inconvenience experienced by the traveling public during marking installation, and the life cycle cost of the marking. If inconvenience to the highway user during installation were ignored, the marking system with the lowest life cycle costs would be selected in every case. The situation is more uncertain when inconvenience to the highway user during installation is included in the selection process. While methodologies are available to assign costs against user inconvenience associated with construction activities (i.e., delays and increased safety risks), the methodologies are somewhat controversial and the results subject to dispute. Nonetheless, qualitative observations can be made regarding the relative level of interference with normal traffic flow that occurs during installation of each type of marking system. Note that systems with short service lives may inconvenience the motoring public at more frequent intervals than systems with longer service lives. Balancing the reduced inconvenience to the motoring public by using a marking system with a longer service life against the potentially higher cost of such a system is an example of the kind of choice a Department of Transportation may routinely need to make as part of their pavement marking program.

Marking system costs are fundamentally determined by the basic cost of the materials and the equipment, and time required for their installation. Secondary issues that can have a noticeable impact on marking system cost is the volume of markings to be installed and whether or not markings are installed by private firms or public agencies. Typically, the greater volume of markings to be installed, the lower the unit cost of their installation. The reasons for the differential in cost between private and public agency installation are uncertain, although they may be related, in part, to volume of work. The cost values reported herein represent broad averages in these regards, and they are intended to provide the reader with a useful indication of the relative order of magnitude of the cost of each system, rather than the exact cost that would be incurred if a particular system was selected for use.

2.1. Conventional Paints

Two types of conventional paints are commonly used: alkyd- and latex-based. The three main components of these paints are pigment (for color and reflectivity), binder (base material), and solvent (Migletz et al, 1994). In terms of use, latex paints were historically favored over alkyd paints due to environmental and safety concerns with the use of alkyd paints. However, alkyd paints have been reformulated to meet current environmental standards, but are extremely flammable and require the use of harsh solvents to clean the painting equipment (Montebello and Schroeder, 2000). Latex paints offer many advantages relative to alkyd paints, such as their environmental friendliness and their lack of heavy metals and volatile organic compounds, without compromising overall service life (Lee et al, 1999). Nevertheless, both products are relatively inexpensive and easy to cleanup. Installed costs of these products typically range between \$0.03 and \$0.05 per linear foot, based on a four-inch wide longitudinal stripe.

2.1.1 Installation Procedures

Alkyd and latex paints are most commonly installed using large mobile-truck mounted sprayers that apply paint striping at a rate of approximately 12 mph. Glass beads may be premixed with the paint or sprayed immediately on to the top of the paint to achieve a desired level of reflectivity. Paints are normally applied in a thickness ranging between 15 and 20 mils. Alkyd based paints offer slightly more flexibility regarding installation temperatures relative to latex paints. Typical specifications require that the pavement be dry and above 32 degrees Fahrenheit to insure proper adherence. Latex paints are generally more sensitive to temperature and weather conditions than alkyd-based paints. The temperature of the asphalt must be above 50 degrees Fahrenheit and the surface must be dry for proper adherence of latex paints. While neither product adheres well to concrete surfaces, alkyd paints can be used if the concrete surface is warm.

2.1.2 Life Expectancy

The life of alkyd and latex paints are dependent on traffic levels; use of sand, abrasives, and snowplows; and the type of surface upon which they are used (i.e., asphalt or concrete). The life of alkyd and latex paints normally ranges between three and thirty-six months, depending on traffic volume and weather conditions. Painted lines on low volume roads (Average Annual Daily Traffic (AADT) less than 5,000) typically provide about two years of service life, while painted lines on medium volume roads (AADT between 5,000 and 10,000) provide approximately one year of service life. Painted lines on high volume roads (AADT greater than 10,000) provide less than one year of service life according to a study conducted for the Utah Department of Transportation (Martin et al, 1996).

Initial retroreflectivity for alkyd and latex based paints are approximately 275 mcd for white and 180 mcd for yellow (Montebello and Schroeder, 2000). These retroreflectivity levels are achieved when an application rate of eight pounds of glass beads per gallon of paint is utilized.

2.2. Epoxy Paints

Epoxy paints generally consist of two materials: pigment and binder. Typical epoxy paints are comprised of 18 to 25 percent pigment for white or 19 to 29 percent pigment for yellow, and 71 to 82 percent binder. Typically, glass beads are added to the pigment and binder as it is being applied to the road surface. The binder is composed of two materials: resin and a catalyst. When combined, these components chemically react to form a hard material that adheres the color pigments and glass beads to the roadway surface (Migletz et al, 1994)

Epoxy paints are significantly more expensive than alkyd and latex paints, but offer longer life and higher levels of retroreflectivity. Typical installed costs range between $0.20 and $0.30 per linear foot. Cost per linear foot is based on a four-inch wide longitudinal stripe.

2.2.1 Installation Procedures

The installation of epoxy paints is very similar to conventional paints. The epoxy mixture, which contains the color pigments, is mixed with the glass beads as it is sprayed onto the road surface. When heavy applications of glass beads are required to increase retroreflectivity, the road surface may need to be cleaned once painting is complete since excess beads will reduce the frictional properties of the road surface. Epoxy paints are normally sprayed in 15 – 20 mil thicknesses in a single pass. Epoxy paints can be applied at the same rate as conventional paints (approximately 12 mph). Epoxy paints should be applied at temperatures greater than 35 degrees Fahrenheit (Migletz et al, 1994). Epoxy paints are relatively insensitive to most weather conditions during placement; they have the ability bond and set on cold and/or wet roadway surfaces. Placing these materials under these conditions, however, will increase the time for these materials to dry. Nevertheless, longer drying times will not reduce the life expectancy of this pavement marking system. Compared to alkyd and latex paint, epoxy paints require longer time to properly dry, which necessitates the use of coning and flagging during applications. Proper preparation of the pavement surface before application improves service life. Preparations may consist of a light grinding of the roadway surface if old pavement markings exist, and/or using compressed air to remove debris from the area to be painted.

2.2.2 Life Expectancy

Like conventional paints, the life of epoxy paints is dependent on traffic levels and the use of sand, abrasives, or snowplows. Yellow pigmented epoxy paints used on low volume roads provide approximately three to four years of useful service life, while high volume roads have shown a useful service life of two to three years (McGinnis, 2001). White epoxy paints are usually replaced earlier than yellow epoxy paints due to surface discolorations caused by roadway contaminates. This discoloration of the white epoxy paint surface decreases its daytime visibility, which may result in its replacement up to one year earlier.

Initial retroreflectivity levels for epoxy paints are higher than alkyd and latex paints: approximately 300 mcd for white and 180 mcd for yellow. These retroreflectivity levels are achieved when an application rate of 25 pounds of glass beads per gallon of epoxy is utilized (Montebello and Schroeder, 2000).

2.3. Thermoplastic Pavement Markings

Thermoplastics are generally classified by the type of binder used: hydrocarbon-based or alkyd-based. Alkyd-based binders are more widely used because they are resistant to chemical decomposition from motor oil and other hydrocarbon contaminants. This issue is most relevant for transverse markings. Thus, alkyd-based binders are used in transverse and longitudinal applications, while hydrocarbon-based binders are strictly used in longitudinal markings.

Thermoplastics are generally composed of four ingredients: binder, glass beads, titanium dioxide and calcium carbonate. The binder is used to hold the mixture together as a rigid mass, the glass beads are used to provide reflectivity, the titanium dioxide is used for reflectivity enhancement, and calcium carbonate or sand is used as an inert filler material. Typical thermoplastic markings are 15 to 33 percent binder, 14 to 33 percent glass beads, 8 to 12 percent titanium dioxide and 48 to 50 percent filler (Migletz et al, 1994).

Thermoplastics have significantly higher costs when compared to paints. Typical installed costs of thermoplastics range from $4.50 to $6.00 per square foot for inlaid thermoplastic pavement markings and $0.19 to $0.26 per linear foot for sprayed pavement markings. Costs of sprayed thermoplastics are based on a four-inch wide longitudinal stripe.

2.3.1 Installation Procedures

Thermoplastics are applied in a molten state (425º F) by extrusion or by spraying onto the roadway surface. Thermoplastics in a molten state form a chemical bond with the asphalt surface, resulting in a hard, durable product. Because a proper bond depends on this chemical reaction with the asphalt, bonding thermoplastics to concrete surfaces is recommended. Older roads with less asphalt binder may not provide sufficient asphalt material to form a chemical bond. When compared to alkyd, latex and epoxy paints, thermoplastics are the most sensitive to surface preparation and atmospheric conditions during installation. Typically the road surface is lightly ground before thermoplastics are applied, so that a better bond is formed with the surface material. Bond performance is improved by up to 60 percent when this process is used compared to direct surface bonding (Ahmad et al, 2001). In general, the right amount of material must be used at the right temperature and thickness to generate the proper heat transfer between the thermoplastic material and the roadway to produce a good bond. It is suggested that surface and air temperatures be at least 55 degrees Fahrenheit for proper heat transfer to occur (Migletz et al, 1994).

Typical thicknesses of sprayed thermoplastics range between 60 and 90 mils when applied at an average speed of approximately 12 mph. Extruded thermoplastics are generally 90 to 120 mils in thickness when applied at an average speed of approximately three miles per hour.

2.3.2 Life Expectancy

Thermoplastic markings provide excellent performance when applied properly, being the most durable of the commonly used pavement marking system. The life of thermoplastic markings, however, varies widely because of its dependence on installation procedures, volume of traffic, atmospheric conditions when placed, and snowplow activity. Life expectancy typically ranges from four to seven years (KDOT, 1999). This relatively long service life can exceed the interval between pavement maintenance activities.

The life of thermoplastics is typically determined using the following criteria: wear, retroreflectivity levels, and discoloration. In terms of wear, it is assumed that the useful service life of sprayed thermoplastics is reached when only 10 to 15 mils of the marking is remaining. Another form of failure results from deterioration of the surrounding pavement, which can lead to pullout of the material from the pavement structure. Inlaid thermoplastics offer better resistance to physical wear than surface profiled thermoplastics due to the protection afforded by being at or slightly below the pavement surface.

2.4. Preformed Tapes

Preformed tape, or simply – tape, pavement markings are pre-made strips or patterns of durable reflective material that are glued to the pavement surface. These products can be used in urban or rural situations for crosswalks, stop bars, symbols, longitudinal striping, etc. Tapes generally consist of the following ingredients: PVC resin binders, pigment, inert fillers, extender, and glass beads (Martin et al, 1996). These products are manufactured with an adhesive backing to facilitate easy installation.

Reflective tape is generally very expensive, but it is very durable. Prices range between \$1.50 and \$2.65 per linear foot (Montebello and Schroeder, 2000). Initial levels of retroreflectivity can be as high as 1100 mcd and 800 mcd for white and yellow patterned cold plastic marking tapes, respectively (KDOT, 1999).

2.4.1 Installation Procedures

Preformed tapes are relatively easy to install. Installation may be as simple as rolling it into the pavement using compaction equipment during final compaction, when the pavement is still warm (at least 130 degrees Fahrenheit). Applying tapes to preexisting pavements can be done one of two ways. One approach is to simply apply them to the surface of the pavement using the adhesive backing as the bond between the tape and the pavement (Migletz et al, 1994). Another way to install these markings is to recess them into the pavement by milling a groove into the pavement approximately one millimeter deep (KDOT, 1999). This approach reduces general wear and potential damage by snowplow activity. When the useful life of this product is exhausted, it is necessary to remove it from the road before replacement or before an overlay. Removal can be difficult. Heating the material with a torch to break the adhesive bond in conjunction with mechanical scraping is common practice (Migletz et al, 1994).

2.4.2 Life Expectancy

These materials are generally used in areas of high traffic due to their high durability. Service life is roughly four to eight years, which is comparable to thermoplastic markings. Even though the tape materials, themselves, are very durable, they may not provide adequate retroreflectivity throughout their entire life. In urban areas, the useful life of tapes may be extended despite their reduced retroreflectivity, if the streets are well illuminated (Migletz et al, 1994).

2.5. Summary of Pavement Marking Products

The attributes of the four pavement marking materials described above are summarized in Tables 2 and 3. These tables highlight the relative advantages and disadvantages of each material. Generally, conventional paints are the least expensive pavement marking material by a wide margin. While life cycle costs are low for conventional paints, their service life is also relatively short. Thus, the markings need to be refreshed at relatively short intervals (9 to 36 months). Conventional paints (particularly latex-based) can only be installed under particular temperature and moisture conditions. Thus, in some situations, it may be difficult to renew these markings as required to maintain adequate retroreflectivity. These markings are abraded by winter sanding, and weather conditions may not permit their renewal until spring.

Mid-durable, latex paints offer a longer service life than conventional paints, but are more expensive (approximately twice the cost). Epoxy paints offer two to three times the service life of conventional paints (44 months); however, their average cost is approximately two to ten times greater than conventional paints. Epoxy paints offer higher initial and long-term retroreflective levels when compared to conventional paints. While offering better performance than conventional paints, epoxy paints are still degraded by winter maintenance activities. Long curing times for epoxy paints can also result in the need for flagging and/or coning during installation. A benefit of epoxy paints is that they perform better on concrete relative to the other three marking systems being discussed.

Thermoplastics and preformed tapes are the most durable marking systems; offering four to five times the service life of conventional paints and almost twice the service life of epoxy paints. However, these pavement markings are also the most expensive marking system discussed herein. Installed costs can be several orders of magnitude greater than conventional paints and two to four times greater than for epoxy paints. Aside from failure due to excessive wear or discoloration, thermoplastics and preformed tapes will typically last the life of the pavement to which they are bonded. Even though it is prudent to consider the time remaining before the next pavement maintenance activity is scheduled to occur when selecting a pavement marking system, this consideration may be particularly important in the case of thermoplastics and preformed tapes markings due to their long service life and relatively high cost. That is, in many situations, the next pavement maintenance activity may occur before the service life of the pavement marking is reached, thereby increasing its life cycle costs relative to other marking systems. Both thermoplastic and preformed tapes are susceptible to being peeled up from the pavement by snowplows.

Table 2: Summary of Conventional Marking Materials (adapted from Montebello and Schroeder, 2000)

Product	Estimated Installed Cost ($ per linear foot)	Estimated Life of Product (months)	Application Temperature	Initial Retroreflectivity (mcd)	Advantages	Disadvantages
Latex-Based Paint	$0.03 - $0.05	3 – 36	Air and pavement temperature of 50 degrees F, and rising	275 white – 180 yellow with 8 lbs. of beads per gallon of paint	▪ Inexpensive ▪ Quick-drying ▪ Longer Life on low-volume roads ▪ Easy clean-up ▪ No collection of hazardous waste products	▪ Short Life on high-volume roads ▪ Subject to damage from sands/abrasives ▪ Bead application required ▪ Does not adhere well to concrete ▪ Pavement must be warm or it will not adhere to the surface
Alkyd-Based Paint	$0.03 - $0.05	3 – 36	Air and pavement temperature of 32 degrees F	275 white – 180 yellow with 8 lbs. of beads per gallon of paint	▪ Inexpensive ▪ Quick-drying ▪ Longer Life on low-volume roads ▪ Easy clean-up ▪ Works in cold temperatures	▪ Short Life on high-volume roads ▪ Subject to damage from sands/abrasives ▪ Bead application required ▪ Does not adhere well to concrete (surface must be warm) ▪ Is highly flammable and requires the use of solvents for clean-up ▪ Has a bad smell
Mid-Durable Paint	$0.08 - $0.10	9 – 36	Air and pavement temperature of 32 degrees F	275 white – 180 yellow with 8 lbs. of beads per gallon of paint	▪ Inexpensive ▪ Quick-drying ▪ Longer life on low-volume roads ▪ Easy clean-up ▪ No collection of hazardous waste products	▪ Short life on high-volume roads ▪ Subject to damage from sands/abrasives ▪ Bead application required ▪ Does not adhere well to concrete ▪ Pavement must be warm or it will not adhere to the surface

Table 3: Summary of Durable Pavement Marking Materials (adapted from Montebello and Schroeder, 2000)

Product	Estimated Cost ($ per linear foot)	Estimated Life of Product (months)	Application Temperature	Initial Retroreflectivity	Advantages	Disadvantage
Epoxy Paint	$0.20 - $0.30	44	Air and pavement temperature of 50 degrees F, and rising	300 white – 200 yellow with 25 lbs. of beads per gallon of epoxy.	▪ Longer life on low-volume roads ▪ More retroreflectivity	▪ Slow-drying ▪ Requires coning and/or flagging during application ▪ Heavy bead application required- may need to be cleaned off of roadway ▪ High initial expense ▪ Subject to damage from sands/abrasives
Sprayed Thermoplastics	$0.30 - $0.40	72	Air and pavement temperature of 50 degrees F, and rising	275 white – 180 yellow	▪ Longer life on high volume roads ▪ Resistant to sands/abrasives as compared to other markings ▪ Quick set times ▪ Good nighttime visibility ▪ Reduces worker exposure to road hazards because of long life	▪ Sensitive to installation procedures ▪ High initial expense ▪ Subject to damage from snowplows ▪ Cannot be used on concrete
Extruded Thermoplastics	In-laid, $4.50 - $6.00 per square foot, depending on thickness (profiled installations typically are less expensive)	72-108	Pavement temperature of 32 degrees F and dry	275 white – 180 yellow	▪ Longer life on high volume roads ▪ Resistant to sands/abrasives as compared to other markings ▪ Quick set times ▪ Good nighttime visibility ▪ Reduces worker exposure to road hazards because of long life	▪ Installation is more labor intensive ▪ Sensitive to installation procedures ▪ High initial expense ▪ Subject to damage from snowplows ▪ Cannot be used on concrete ▪ Must mill out before overlaying with asphalt
Tapes	$1.50 - 2.65	48 – 96	All temperatures	350 white – 250 yellow.	▪ High retroreflectivity ▪ Longer life on low-volume and high volume roads ▪ Useful in high traffic areas ▪ No beads needed ▪ Reduces worker exposure to road hazards because of long life	▪ Subject to damage from snowplows ▪ High initial expense ▪ Best when used on newly surfaced roads- probably not worth the expense for older roads in poor condition

3. Pavement Marking Practices in Other States and Montana

Many states have performed studies to determine which pavement markings work best under their traffic and climatic conditions. Literature was reviewed in this regard from several rural states that experience traffic and climatic conditions that are to some extent similar to those in Montana, and thus whose practices can reasonably be extrapolated to conditions in Montana. Information is presented on the experiences and/or marking protocols from Pennsylvania, Kansas, Minnesota, Virginia, Wyoming, North Dakota and Idaho. Montana's current pavement marking practices are also described.

3.1. Pennsylvania

Conventional paints comprise approximately 94 percent of the pavement markings used in the state of Pennsylvania (McGinnis, 2001). The remaining pavement markings used include epoxy paints and a small amount of thermoplastics. These products are applied in both rural and urban applications, generally in the longitudinal direction. Of all the states considered in this review, Pennsylvania reported the lowest cost per linear foot (LF) of installed pavement markings, being $0.024 per LF. More recently, Pennsylvania has initiated a study to compare the use of conventional paints with a variety of other marking systems to determine the most appropriate pavement marking based on a life cycle cost analysis.

3.2. Kansas

In recent years, the Kansas Department of Transportation (KDOT) has developed a sophisticated methodology to determine the most economical type of pavement marking to be used under various circumstances. From their analysis, a Brightness Benefit Factor (BBF) is determined; which is described as a benefit/cost ratio based on the material's retroreflectivity, durability, and installed cost. The analysis also includes variables such as traffic, expected life of the pavement and motorist delay. Table 4 shows an example of the output from this algorithm based on <u>two</u> years of service life remaining in the pavement. From this particular analysis, epoxy paint showed the highest BBF, thereby recommending its use in areas having an AADT less than 50,000. Extruded thermoplastics had the highest BBF in areas having greater than 50,000 AADT (KDOT, 1999). Table 5 shows results from the analysis for a pavement having <u>six</u> years of life remaining. When longer service lives are necessary, products like extruded thermoplastics become more beneficial. In areas having lower traffic levels, epoxy paints provide similar performance to thermoplastics (BBF = 814 – epoxy, compared to BBF = 840 – extruded thermoplastics). Typical costs of products used by KDOT are listed in Table 6 (McGinnis, 1999).

Table 4: Results of KDOT Pavement Marking Material Analysis Based on Two Years Service Life Remaining (adapted from KDOT, 1999)

Material Type	Brightness Benefit Factor for AADT of: 5,000	5,000 – 50,000	> 50,000
Patterned Cold Plastic (PCP)	92	112	103
Extruded Thermoplastic	280	300	305
Spray Thermoplastic	406	n/a	n/a
Epoxy	407	393	245
Paint: Contract/KDOT	98/381	51/199	n/a
PCP CL & Thermo EL	237	256	258
PCP CL & Thermo EL	334	328	212

Notes:
CL = center line
EL = edge line

Table 5: Results of KDOT Pavement Marking Material Analysis Based on Six Years Service Life Remaining (adapted from KDOT, 1999)

Material Type	Brightness Benefit Factor for AADT of: 5,000	5,000 – 50,000	> 50,000
Patterned Cold Plastic (PCP)	276	335	257
Extruded Thermoplastic	840	900	762
Spray Thermoplastic	406	n/a	n/a
Epoxy	814	589	245
Paint: Contract/KDOT	98/381	51/199	n/a
PCP CL & Thermo EL	710	769	646
PCP CL & Thermo EL	690	530	248

Notes:
CL = center line
EL = edge line

Table 6: Kansas State Marking Material Cost (McGinnis, 2001)

Material Type	Unit Cost ($/LF)
Conventional Paint	0.05
Epoxy Paint	0.32
Extruded Thermoplastic	0.41
Sprayed Thermoplastics	0.19
Profile Tape	2.12

Kansas DOT has an integrated preventative maintenance program that tracks all pavement markings by the year applied, expected life of pavement, type of material used, and performance guarantees of the pavement markings. Using this information, a prediction of pavement marking life may be made. In the spring, maintenance crews are sent out to visually inspect specific pavement markings at night for retroreflectivity compliance. Information from the inspections is sent to the engineering department to update the list of roads that require new markings and/or warranty repairs. In addition, the list takes into consideration all planned maintenance activities, so that in selecting the optimal marking material to be used, the service life of the marking can be evaluated relative to the interval until the next pavement maintenance activity (KDOT, 1999).

3.3. Minnesota

Minnesota, like Pennsylvania, uses conventional paints for the majority of its striping (90 percent of pavement marking delineations throughout the state). Of the remaining ten percent, approximately eight percent are epoxy paints. Conventional paints are generally used in rural areas. Minnesota, like Pennsylvania, installs approximately 90 percent of the pavement markings statewide. Conventional paints cost approximately $.048/LF, while epoxy paints generally cost around $0.19/LF (McGinnis, 2001).

Minnesota recognizes the need for durable pavement markings due to high wear from snowplow and sanding operations during the winter months, especially in urban areas. Minnesota Department of Transportation (MnDOT) requests that lane marking materials be applied offset from the crown of the road to reduce the direct contact with snow removal equipment (Montebello and Schroeder, 2000).

MnDOT also uses durable products on the roadways it maintains in the Twin Cities metropolitan area due to the large volumes of traffic (Montebello and Schroeder, 2000). In general, traffic levels are considered when choosing an appropriate pavement marking material.

Conventional materials (i.e., conventional paints) can provide up to three years of life on low-volume roads (AADT less than 10,000), however, they provide less than a year of life on high-volume roads (AADT greater than 10,000). In areas having high traffic volumes or in areas that have frequent turning maneuvers, durable materials such as epoxies, tapes and preformed thermoplastics are considered (Montebello and Schroeder, 2000).

The study conducted by Montebello for MnDOT also stated that if a non-conventional marking material is being considered, the condition of the road must first be carefully evaluated to ensure maintenance or other activities will not shorten the life of the pavement marking and compromise the value of the investment. In addition, an investigation of any special mobilization costs for low quantities of specialized materials must be conducted. The cost of applying striping materials is directly related to the quantities, traffic control requirements, material costs, and mobilization to and from the job site. The more work that is planned and coordinated under a single contract, the greater the efficiency, thereby making projects more cost-effective.

3.4. Virginia

Paint, thermoplastics, and waffle tape make up 90 percent of the pavement markings used by the Virginia Department of Transportation (VDOT). The remainder of the pavement markings used includes epoxy paints, polyester paints, and other miscellaneous tapes (Cottrell and Hanson, 2001). Recently, VDOT reviewed their pavement marking activities as a result of implementing a pavement preservation management system that included chip sealing road surfaces on a three-year cycle. The overall conclusion of this study was that conventional paints are the most efficient marking material. Results from the analysis are shown in Table 7, which provides cost estimates of various products with respect to labor and materials. The results compare costs over a six year period for each marking system, where the service life of the individual marking systems were estimated to be 6 months for conventional paints, 3 years for epoxy and thermoplastics, and 6 years for profile tape (Cottrell and Hanson, 2001).

Table 7: Virginia Department of Transportation Pavement Marking Material Costs (adapted from Cottrell and Hanson, 2001)

Material Type	Contract Type	Life Expectancy	Installed Cost ($/LF)
Conventional Paint	Large	6 months	0.09
	Small	6 months	0.67
	Small	1 year	0.34
	VDOT	6 months	0.18
Epoxy Paint	---	3 years	0.30
Thermoplastics	---	3 years	0.26
Waffle Tape	---	6 years	0.67

Note that the costs in Table 7 for conventional paints bear out the observation made earlier that "large" contracts may be less expensive than "small" contracts. In this case, the unit cost of the six-month markings on the large contract ($0.09/LF) are about one sixth as much as the unit cost for the same markings on a small contract cost ($0.67/LF).

3.5. Wyoming

The Wyoming Department of Transportation (WYDOT) predominantly uses alkyd or conventional paints for pavement markings (Gostovich, 2002). WYDOT applies all conventional paint markings on Wyoming state highways. Epoxy markings are used in areas of high wear, and these markings are installed by outside contractors. Even though the cost of epoxy paint is much higher than conventional paint, it is required for safety reasons in areas where pavement markings are unable to withstand wear experienced during the winter season. In addition, it is common for WYDOT to apply paints more than once per year in areas of high wear. It is Gostovich's opinion (2002), that the main factor reducing the life of pavement marking in the state of Wyoming is winter maintenance (sand abrasives and snow plows). Typical material costs and expected service life of pavement markings for Wyoming are shown in Table 8.

Table 8: Wyoming Marking Materials Cost (Gostovich, 2002)

Material Type	Cost ($/ LF)	Service Life AADT <5000
Conventional Paints	0.035 – 0.040	Center lines 1 years Edge lines 2 years
Epoxy Paints	0.40 – 0.45	Center lines 2 years Edge lines 3 - 4 years

3.6. North Dakota

The North Dakota Department of Transportation (NDDOT) bases its selection of pavement markings on several criteria, including: type and condition of the road surface, the level of anticipated traffic, and where on the road the delineation will be used, (e.g., center or edge). The materials it considers for use include conventional paint; inlaid, patterned, preformed plastic; and grooved, patterned, preformed plastic. Table 9 provides an overview of the guide developed by NDDOT to determine best pavement marking practices in any given situation. Referring to Table 9, paints are recommended on lower volume roads or roads that are in poorer condition. Durable products are preferred on roads having higher AADT that are in good condition. NDDOT recommends using their Pavement Management System to determine the condition of the road surface.

Table 9: North Dakota Pavement Marking Selection Matrix (NDDOT, 2000)

Road Characteristics		AADT >10,000			AADT 4,000 – 10,000			AADT 2000 – 4,000			AADT <2,000
Type	**Condition**	**Center/Skip**	**Edge**	**Misc.**	**Center/Skip**	**Edge**	**Misc.**	**Center/Skip**	**Edge**	**Misc.**	**All**
Asphalt	**New**	Inlaid Patterned Pre-formed Plastic	Inlaid Patterned Pre-formed Plastic	Paint	Inlaid Patterned Pre-formed Plastic	Paint	Paint	Paint	Paint	Paint	Paint
	Good*	Inlaid Patterned Pre-formed Plastic	---	---	Inlaid Patterned Pre-formed Plastic	Paint	Paint	Paint	Paint	Paint	Paint
	Fair/Poor*	Paint	Paint	Paint	Paint	Paint	Paint	Paint	Paint	Paint	Paint
Concrete	**New**	Grooved Patterned Pre-formed Plastic	Grooved Patterned Pre-formed Plastic	---	Grooved Patterned Pre-formed Plastic	---	---	Grooved Patterned Pre-formed Plastic	Paint	Paint	Paint
	Good*	Grooved Patterned Pre-formed Plastic	Paint	Paint	Grooved Patterned Pre-formed Plastic	Paint	Paint	Paint	Paint	Paint	Paint
	Fair/Poor*	Paint	Paint	Paint	Paint	Paint	Paint	Paint	Paint	Paint	Paint

* Use the Pavement Management System to determine road surface condition

3.7. Idaho

Conventional paints comprise approximately 98 percent of all pavement markings (by mileage) that are used by the Idaho Transportation Department (ITD). The remainder of the pavement markings in Idaho are epoxy paints. ITD maintenance crews install 60 to 80 percent of the conventional paint markings used in the state. Their installed costs range between \$0.035/LF and \$0.045/LF. Contractors bid for all of the state's interstate work in large contracts that cover multiple districts, which results in lower installation costs. Idaho currently applies paint approximately two times per year in high wear areas. Idaho is investigating the possibility of using epoxy paints in high wear areas to reduce costs (Laragan, 2002).

3.8. Montana

The majority of pavement markings in Montana are conventional products (Stevenson, 2003). MDT has found that the life expectancy and initial retroreflectivity of alkyd based paints and waterborne/latex paints are generally higher than average. Initial values of retroreflectivity for waterborne/latex materials typically exceed 325 mcd for white, and range between 180 and 225 for yellow. Painting contracts where retroreflectivity measurements were made have shown that initial values exceeded 350 mcd and 225, mcd for white and yellow epoxy paint, respectively. Results from other states have shown that white epoxy, in general, is replaced earlier than yellow epoxy due to surface discolorations. In Montana, however, yellow epoxy centerlines undergo considerable damage from snowplows, requiring them to be replaced more frequently.

Like Idaho, Montana practice has been to release large, district-wide pavement marking contracts that utilize mainly one material for delineation. Thus, Montana has been able to realize extremely low prices for epoxy paint. Montana pays approximately one-third as much for epoxy paint as is reported in the various studies cited in this investigation (MDT, 2001). In general, mid-durable latex paints cost almost twice as much as conventional products. However, in a small pilot study completed in 2002, Montana spent only 40 to 50 percent more for mid-durable products relative to conventional products. The opportunity exists for Montana to further reduce the overall cost of this product by utilizing larger contracts, as with epoxy paint.

MDT's philosophy for all striping contracts has been to utilize retroreflectivity as the basis of payment to the contractor (Stevenson, 2003). MDT is in the process of developing warranty-based specifications for pavement marking contracts. Performance measures for these warranties will include reflectivity, durability and color. Contracts with two different warranty periods will be used, namely, a 3-year contract and a 1-year contract. The 3-year contract will give individual contractors the freedom to select a pavement marking product that will meet the specifications set by MDT. The 1-year warranty contract is mainly designed to ensure good workmanship, and initially will be used only for epoxy paints (Stevenson, 2003). For new pavement projects, contractors generally use conventional paints. After 30 to 45 days, lines are refreshed with a more permanent product (Stevenson, 2003).

Montana uses thermoplastics at high-volume intersections due to the high surface wear from traffic at such locations. MDT has tried using spray thermoplastics for longitudinal pavement markings, but difficulties were encountered with the bond between the thermoplastics and the specific chip seal materials used in Montana (Dusek, 2002). The cost of inlaid thermoplastics for longitudinal striping was found to be high when compared to epoxy paint ($1.50/LF for inlaid thermoplastics (Livesay and Livesay, 2002) versus $0.10 – 0.14/LF for epoxy paint). In low volume applications, the benefit of this cost is an increase in service life. However, to realize this benefit, inlaid thermoplastic markings have to be in place for many years. Montana has a pavement management program in which pavements generally are chip sealed every 5 to 6 years with an intervening overlay at ten years and subsequent replacement at twenty years. Under such a program, thermoplastics simply do not appear cost effective. For these reasons, thermoplastic pavement markings are no longer used for longitudinal striping. In addition, the reduction in retroreflectivity of thermoplastics was unacceptable by MDT standards (Stevenson, 2003).

The Pavement Markings Management System (PMMS) under development at MDT will provide a more thorough life cycle cost analysis for pavement markings throughout the state of Montana. The PMMS will help optimize the use of pavement marking products based on retroreflectivity, durability and cost. It will establish a strategy for collecting and storing data from a number of sites having a variety of pavement marking products (Stevenson, 2003).

3.9. Summary and Discussion of State Pavement Marking Practices

In reviewing the information presented above from various states, several trends are apparent with regard to determining the most cost effective marking systems.

1) Conventional paints are the most cost effective system for low-volume roads (below approximately 5,000 AADT) and/or under conditions where only a short service life is needed.
2) In areas where conventional paints are unable to provide adequate retroreflectivity for at least one year, more durable products, such as epoxy paints or thermoplastics, should be considered. Epoxy paints are more cost effective in low volume applications (AADT between 5,000 and 10,000); inlaid thermoplastics become cost effective in high volume applications (AADT greater than 10,000).
3) While the life cycle costs of conventional and epoxy paints are lower than those of thermoplastics in many applications, they may have to be renewed

at more frequent intervals, thereby increasing exposure of maintenance crews to construction zone hazards and potentially increasing delays to traveling public.

4) Thermoplastic pavement markings are heavily used in intersections and other transverse marking applications due to their high resistance to surface wear.
5) "Large" contracts offer significant savings on the unit costs of markings relative to "small" contracts.

Currently, conventional paints are the primary marking system used by the majority of the states considered in this review (Table 10). Notably, the "northern" states of Pennsylvania, Minnesota, Wyoming, and Idaho primarily use conventional paints, where climatic conditions are somewhat similar to Montana and thus they would be expected to engage in similar winter maintenance as well as general pavement maintenance activities as Montana. Table 10 also indicates the party responsible for applying the majority of pavement markings in each of the states considered in this study (public agency or private contractor).

Table 10: Approximate Quantities of Pavement Marking Products Used and Party Responsible for Applying Them (adapted from McGinnis[1], 2001; Gostovich[2], 2002; Laragan[3], 2002; Stevenson[4], 2003)

State	Conventional Products (approximate use)	Durable Products (approximate use)	Party responsible for applying the majority of pavement markings
Pennsylvania[1]	94%	6%	PennDOT
Kansas[1]	21%	79%	Contractor (~79%)
Minnesota[1]	90%	10%	MnDOT
Virginia	Information Not Available		
Wyoming[2]	Majority	Minority	WYDOT
North Dakota	Information Not Available		
Idaho[3]	98%	2%	ITD (60 - 80%)
Montana[4]	60%	40%	MDT/Contractor (50% / 50%)

A variety of approaches are taken with respect to who installs pavement markings, ranging from the DOT installing almost all markings to almost exclusive use of private contractors for this purpose. The relative cost effectiveness of using the DOT versus private contractors for this purpose appears to be uncertain. The more important issue in this regard may be the increased cost effectiveness of "large" versus "small" projects. In using in-house resources to install pavement markings, the DOT may inherently operate in the "large" project mode. Use of a single type of pavement marking may be important in realizing the overall efficiency of large volume contracts. Thus, at some sites, the optimum marking system for that site might not be the best choice from a more global cost perspective, if using the optimum marking system would result in the work at that site falling into the category of "small", and thus higher, cost projects.

Table 11 summarizes the installed costs for various types of pavement markings for the states considered in this study (where such data were available). Ideally, Table 11 would present the life cycle costs found by each state for the various pavement marking systems. Life cycle costs, however, are not simple to quantify due to the myriad of parameters that affect both the costs of installing markings (i.e., small or large contracts, public or private contractor) and their service life (i.e., volume of traffic, type of road surface, orientation of line, winter maintenance activities, and pavement maintenance activities). Thus, the life cycle costs determined by various states are always presented with caveats based on these parameters. Nonetheless, some basic and broad trends are common across all states with respect to the cost effectiveness of various marking systems, and these trends were summarized at the beginning of this section of this report.

Table 11: Cost Summary for Installed Pavement Markings by State

State	Conventional Paint	Epoxy Paint	Thermo-plastic	Sprayed Thermo-plastic	Profile Tape
Pennsylvania	0.02	---	---	---	---
Kansas	0.05	0.32	0.41	0.19	2.12
Minnesota	0.05	0.19	---	---	---
Virginia	0.18	0.30	---	0.26	0.67
Wyoming	0.04	0.40 – 0.45	---	---	---
North Dakota	---	---	---	---	---
Idaho	0.04	---	---	---	---
Montana	---	0.10 – 0.14	1.50	---	---

All prices are reported in $/linear foot
--- Information not available

In reviewing current pavement marking practice in Montana, it appears to be generally consistent with those practices found to be cost effective in other states under similar operating and environmental conditions. Cost effective marking systems for low to moderate volume roads generally appear to be conventional paints. In states where marking practices have been extensively studied, like Minnesota, Pennsylvania, and Virginia, it has been shown that conventional paints are the most cost effective system of highway delineation for these conditions, even when all the above cost factors are applied. Based on their studies, under moderate traffic volumes, and in harsher environments with significant sanding and snow plowing activities, it certainly would be reasonable to use a more durable marker, such as epoxy paints. Use of conventional paints may also require that the markings being renewed more than once a year, which may be possible in some states, but which may be difficult in Montana. MDT is able to procure epoxy paint markings for a very reasonable cost, making their use even more attractive. In spite of their high cost, extruded thermoplastics are still viable in areas of high wear, such as intersections and urban streets, according to the studies reviewed in this report. Again, MDT uses thermoplastics in these types of applications.

4. Conclusions and Recommendations

Selection of the most cost effective pavement marking system in a given situation depends on three main factors: 1) retroreflectivity, 2) durability and 3) cost. Several subordinate factors stem from these three, such as type of road surface, volume of traffic, orientation with respect to traffic, quality control at the time of installation, winter sanding and snow removal practices, schedule of pavement maintenance activities, and inconvenience experienced by the traveling public during marking installation (Migletz, 2001).

Common pavement marking systems include latex and alkyd paints, epoxy paints, and thermoplastics. Selecting the most efficient and effective pavement marking system is difficult due to the variety of factors involved. Many states have researched and developed methodologies for determining the marking systems having the least life cycle cost, based on these factors. In general, conventional paints are used in areas having low traffic volumes and infrequent winter maintenance activities. Conversely, products of higher durability are used in areas having more traffic and more instances of sanding and plowing. These products include epoxy paints, thermoplastics, and preformed tapes.

Currently, the practice of MDT is generally consistent with philosophies developed by other states. While the guidelines in other states indicate that conventional paints may be an appropriate alternative, epoxy paints may be justified due to the specific conditions in Montana and the low contract price for this product. Mid-durable paints also are being researched that may offer better life cycle costs than either epoxy or conventional paints. MDT is actively moving toward improving the cost effectiveness of its pavement marking program. Efforts underway in this regard include collecting and storing retroreflectivity data, developing contracts that include warranty specifications, and investigating ways to develop a pavement marking management system. In moving ahead with these activities, MDT should continue to take full advantage of the considerable work done by other states in this regard.

5. References

Ahmad, Irtishad; Najafi, Fazil; Benham, Joyline; Lancaster, Philip; Sadeghinia, Michael, *Methods of Application and Bonding Strengths of Thermoplastic Pavement Markings: A Comparison Between Concrete and Asphalt Roadway Surfaces*, Department of Civil and Environmental Engineering, Florida International University, 2001.

Cottrell, Benjamin H. and Hanson, Robert A., *Determining the Effectiveness of Pavement Marking Materials*, Virginia Transportation Research Council, Report Number: VTRC 01-R9, February 2001.

Dusek, Don, *Personal Conversation*, Montana Department of Transportation, June 2002.

Gostovich, Mike, *Personal Conversation*, Wyoming Department of Transportation, August 2002.

Kansas Department of Transportation, *Kansas Department of Transportation Pavement Marking Policy*, Kansas Department of Transportation, January 1999.

Laragan, Greg, *Personal Conversation*, Idaho Department of Transportation, August 2002.

Lee, Jung-Taek; Maleck, Thomas L. and Taylor, William C., *Pavement Marking Material Evaluation Study in Michigan*, ITE Journal, Vol. 69, Number 7, July 1999, pp. 44-51.

Livesay, Robert L. and Jan M., *Personal Conversation*, Montana Lines, Inc., 2002.

Martin, Peter T.; Perrin, Joe; Jitprasithsiri; Siriphan; Hansen, Blake, *A Comparative Analysis of the Alternative Pavement Marking Materials for the State of Utah*, Department of Civil and Environmental Engineering, University of Utah, 1996.

McGinnis, R.G., *Pavement Markings Benchmarking*, Commonwealth of Pennsylvania Department of Transportation, October 2001.

Migletz, J.; Fish, J.K. and Graham, J., *Roadway Delineation Practices Handbook*, FHWA-SA-93-001, Federal Highway Administration, U.S. Department of Transportation, August 1994.

Migletz, J.; Graham, J.; Harwood, D. and Bauer, K., *Service Life of Durable Pavement Markings*, Transportation Research Record 1749, Paper No. 01-0447, Journal of the Transportation Research Board, 2001.

Montana Department of Transportation, *Contractor Information, Bid Releases*, MDT Bid Specification STPP-NH-STPS-IM-STPX 0002(621), 2001.

Montebello, D. and Schroeder, J., *Cost of Pavement Marking Materials*, Minnesota Department of Transportation, 2000.

North Dakota Department of Transportation, *NDDOT Design Manual*, North Dakota Department of Transportation, 2000.

Stevenson, James, *Personal Conversation*, Montana Department of Transportation, January 2003.