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MATERIALS ACCEPTANCE RISK ANALYSIS:

PAVEMENT MARKINGS

by

Swarup Dongare

A thesis submitted in partial fulfillment of the requirements for the degree of

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IN

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Committee Approval

To the Graduate Faculty:

The members of the committee appointed to examine the thesis of Swarup Dongare find it satisfactory and recommend that it be accepted.

Dr. James Mahar (Major Advisor)

Dr. Arya Ebrahimpour (Committee Member)

Dr. James Bigelow (Graduate Faculty Representative)

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LIST OF ACRONYMS

ACRONYM	DEFINITION
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ACC	Asphalt Cement Concrete
ASTM	American Society for Testing and Materials
CPT	Cumulative Traffic Passage
FHWA	Federal Highway Administration
MMA	Methyl Methacrylate
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
NTPEP	National Transportation Product Evaluation Program
PRPM	Permanent Raised Pavement Markers
PCC	Portland Cement Concrete
RPM	Raised Pavement Markers
RRPM	Raised Reflective Pavement Markers
TRB	Transportation Research Board
VTI	Virginia Transportation Institute
VOC	Volatile Organic Compound
WSDOT	Washington State Department of Transportation
WSTC	Washington State Transportation Center

ABSTRACT

The first objective of this study was to conduct a comprehensive literature review of various types of pavement markings and markers used by various transportation departments. The second objective was to identify the most cost-effective markings based on their performance and durability. A review of previous studies and investigations revealed that there were no conclusive findings and recommendations for various types of pavement markings. The performance characteristics of pavement markings and their effectiveness in guiding roadway users depend on many factors including, but not limited to: product quality, application process, surface preparation, environmental conditions, annual average daily traffic (AADT), driver's age and visual performance, vehicle type, type of headlights, and pavement type. In addition, the results of field studies conducted by different investigators show that the conclusions were highly dependent upon the method of study, the study models used, the type of measurement devices, and the accuracy of their operation. However, some investigators and transportation departments are in agreement on certain issues including: the performance characteristics, life expectancy, and the associate cost.

The most cost effective pavement marking identified and utilized by different transportation departments on roads with low traffic volumes was paint followed by epoxy. Tape is commonly used on high volume AADT roadways by different agencies. Ninety-eight percent of pavement markings used in Idaho are paint with the other two percent consisting of tape or other types including Methyl Methacrylate (MMA). The Idaho Transportation Department's (ITD) current practice in using pavement markings is the most cost effective. ITD is in line with many other transportation departments throughout the country that deal with similar climate conditions.

CHAPTER 1
INTRODUCTION

Pavement marking technology is continually evolving. There are many types of pavement markings used in the field including, but not limited to, conventional paint, epoxy, preformed tape, thermoplastics, thermosets, Methyl Methacrylate, and Raised Pavement Marker (RPM). Each type of marking has its own unique characteristics related to durability, retroreflectivity, life-cycle, and cost effectiveness. The objective of this study was to identify and compare pavement markings used by different agencies in the U. S. and recommend the most durable and cost effective markings to ITD.

Many studies have been conducted in the last several years to identify the performance characteristics of different types of pavement markings available in the market. The most comprehensive pavement markings study was conducted by the National Transportation Product Evaluation Program (NTPEP).(1) This is an ongoing study jointly conducted by the American Association of State Highway and Transportation Officials (AASHTO) and its member states. The National Cooperative Highway Research Program (NCHRP) has also conducted many feasibility studies on different aspects of pavement markings. These have included the use of all-white markings in the U.S., material and applications affecting serviceability, safety, and environmental issues. The Federal Highway Administration (FHWA) promotes research in pavement markings by funding studies in various agencies and universities. In addition, many state transportation departments have conducted independent research to evaluate the performance characteristic of different types of markings. The goal was to identify the best and most cost effective markings suitable for the condition and climate of their states.

In this study, several pavement markings commonly used in the U.S. were identified and their characteristics including: performance, durability, effectiveness, life-cycle, cost effectiveness, advantages, and disadvantages were studied using the published literature. Based on the findings from this study, recommendations are made on the performance characteristics, life expectancy, and cost-effectiveness of different types of pavement markings.

CHAPTER 2

HISTORY OF PAVEMENT MARKINGS

The use of pavement markings became necessary in the 1920's due to increased automobile traffic. In 1911, the traffic stream in the state of Michigan was divided by white line pavement markings. Initially, white stones were used as centerline to divide the traffic in opposite directions, but later the white stones were replaced with loose, water-bound materials.[2]

In 1921, black-line paints were used as a traffic divider in a one-block length in the middle of University Avenue in Madison, Wisconsin. However, the black-line paints had a short life, and by 1924 they were replaced by white lines. [3] In 1926, Mattimore suggested a need for testing of traffic paints.[4] He listed the most significant factors to be considered in measuring the effectiveness of paints used in pavement markings as: consistency, spreading rate, hiding power or opacity, drying time, resistance to the effects of sunlight, day and nighttime visibility, and resistance to weather and abrasion.

Significant improvements in the performance characteristics of pavement markings have been made since 1920. The use of glass beads in paint to improve the retroreflectivity of paint-based pavement markings was introduced in 1948.[5] The Minnesota Department of Transportation (MnDOT) in collaboration with the H. B. Fuller Company, developed thermosetting epoxy pavement marking materials in 1970s. At the same time, the Ohio Department of Transportation (ODOT) in collaboration with the Glidden Company developed thermosetting polyester. However, the need for a high speed application technique and short drying time prompted the Southwest Research Institute headquartered in San Antonio, Texas to develop Epoxy thermoplastic in 1970s.[5,6] The need to improve the retroreflectivity of pavement marking resulted in development of raised pavement markers in the United States in 1950's. The thermoplastic pavement markings were developed prior to the World War II in Great Britain. Thermoplastic markings consist of glass beads, pigments, and fillers with resin as a binder and the major component. At first, the resin used in thermoplastics was mixture of wool grease and various waxes. Later, alkyd resins and hydrocarbon resins replaced the wool grease and wax as thermoplastics binders.[6]

Solvent-based paints used as pavement markings were developed to meet specific requirements and they are normally cheap and easy to handle. Solvent-based paint contains 50 percent solvent added to paint to improve application characteristics. The solvent used in this type of pavement markers produces atmospheric emission. This has prompted the development of other materials that require little or no solvent. Water-borne pavement markings were developed and put aside due to longer drying time, and solvent-based paints were used predominantly in many states including California. In 1984, the air-quality regulations restricted the use of specific solvents used in producing solvent-based paint due to its harmful emission discharge to the atmosphere. Since then, the water-borne paint have been reformulated and used as an alternative to solvent-based paint in many states.(6) Chatto and Warness in 1985 and Dale in 1988 investigated alternatives for solvent-based traffic paint.(6,7) They reported several advantages of water-borne paint over solvent-based paint including equal or longer service life, no odor, and fewer respiratory complaints.

In 1988, FHWA published a "Manual on Uniform Traffic Control Devices (MUTCD) for Streets and Highways". In 2006, NCHRP published the findings of their multi-year study on safety effect of retroreflectivity of pavement markings as a function of age, safety, color, and marking material type.(3)

Many studies have been conducted on different aspects of the pavement markings by scientists, researchers, and various agencies. Many of these studies involve field inspections, data collection, and surveys of highway users and expert opinions.

CHAPTER 3
TYPES OF PAVEMENT MARKINGS

The pavement markings used for various types of traffic must conform to the *Manual on Uniform Traffic Control Devices for Streets and Highways* as required by Federal regulations.[8] Historically, transportation agencies have used different types of traffic markings including solvent-based paint, water-borne paint, thermoplastic, epoxy, and tape as a primary material for pavement markings. Each type of pavement marking has different application techniques, life expectancy, durability, performance, and costs. The following section provides an overview of the different types of pavement markings including their performance, advantages, and disadvantages.

3.1 Conventional Paint

Paint is the most widely used material in pavement markings due to its performance and cost effectiveness. However, in snow-belt regions, paint markings rarely last throughout the winter due to sanding and snowplow damage. [6] There are two types of paints used for pavement markings: solvent-based paint and water-borne paint. The three main components of these paints are pigment (for color and reflectivity), binder (base material), and solvent or water. Generally, about 25 percent of the total volume is comprised of pigments and fillers, complemented by 25 percent binder and 50 percent solvent. Pigments used for different colors and reflectivity are titanium dioxide for white and lead chromate for yellow. However, with potential health hazards associated with lead chromate, and the regulations dealing with the removal and disposal, it has led to the use of organic, yellow pigments. Early on, there were issues with fading and color changes with organic pigments and they presented some handling hazards.[9] These issues have now been resolved and improved. The binders used in solvent-based paint are alkyd resin and chlorinated rubber modified by alkyd resin. These binders require the use of solvents and thinners to keep the binders in a liquid form for application and were the most cost effective products at the time. The Clean Air Act required a reduction of Volatile Organic Compounds (VOC) and subsequently reduced the amounts of certain organic solvents and thinners to be used in traffic line paint. From this, waterborne paints grew in demand as they used ammonia water in place of organic solvents for keeping the paint in liquid form. This eliminates the hazardous Volatile Organic Compounds (VOC) emissions of solvent material. Water-borne paints are slightly more expensive than solvent-based paints because of the surcharge cost placed on regulated organic solvents. The initial drying time was about 10 minutes on the first generation of waterborne paints, but the drying time has been reduced by using the newer formulations, which not only dry as fast but are more durable than the solvent-based paint.

Chatto and Warness and Dale have concluded that water-borne paints have several advantages over the solvent-based paints.[6,7]

- Service life is equal or better.
- It can be applied hot or cold depending on the weather condition and the availability of the equipment.
- There are no strong odors and fewer respiratory complaints are seen from those who apply the paint.
- Due to non-hazardous nature of water-borne paints, their shipping and handling cost are less than solvent-based paints.

Advantages of Conventional Paint Markings:

- Installation costs are low.
- Alkyd paints are fast drying, and retroreflectivity is high at first but decreases after 6 to 7 months.
- Water-based paints are fast drying and can be formulated for low temperature application. They are more durable than VOC compliant solvent-borne paint systems.
- Conventional paints generally provide equal performance on asphalt and concrete pavement.
- Paints can be applied at a faster rate than most other markings and under non-ideal conditions.

Disadvantages of Conventional Paint Markings:

- Short service life (6 to 7 months).
- The major disadvantage of water-borne paint is its sensitivity to temperature during application. New low temperature formulation on water-borne paint permits application at 35°F, while solvent based paint cannot fully bond onto pavement surfaces at 35°F, and can be fragmented easily.
- During application, latex paint is very sensitive to high humidity, which can drastically increase drying time.
- Conventional paints wear off quickly and lose retroreflectivity after exposure to high traffic volumes and winter-maintenance activities

- After some period of time (1 to 1½ years) in comparison to epoxy and thermoplastics, conventional paints have lower visibility at night.

3.2 Thermoplastics

Thermoplastics are generally composed of four different ingredients: binder, glass beads, titanium dioxide, and carbonate. The binder is used to hold the mixture together as a rigid mass, glass beads provide reflectivity, the titanium dioxide is used for reflectivity enhancement and calcium carbonate or sand are used as inert filler materials. Three types of resins are used for thermoplastics: alkyd, epoxy, and hydrocarbon.[6] Thermoplastics are longer lasting pavement markers. They also have a much higher cost than both solvent- and water-based paints and require special installation equipment. Typical installed costs of thermoplastics range from $0.41 to $1.5/lf. [6,7]

Thermoplastics can be applied by spraying or extrusion. The thickness of sprayed thermoplastics varies between 1.5 and 2.3 mm and the extruded thermoplastics can have a thickness of between 2.3 and 3.0 mm. Thermoplastics adhere best to the pavement in dry conditions. If the pavement surface is wet, it may display blistering and poor bonding to the pavement. There is one additional method called heat fusion (like flint trading). Most often, this method involves the use of a torch to apply the thermoplastics to the pavement.

Advantages of Thermoplastics:

- New materials can be reapplied over old thermoplastic markings.
- When applied on porous surfaces, thermoplastics fill the void spaces, forming a mechanical bond with concrete and a thermal bond with asphalt.
- More durable than conventional paints.
- Service life of thermoplastic is around 3 to 5 years.
- Inlaid thermoplastics offer better wear resistance.

Disadvantages of Thermoplastics:

- Typical installed costs of thermoplastics range from $4.50 to $6.00 per square foot for inlaid thermoplastic pavement marking.
- The cost of sprayed thermoplastic ranges from $0.19 - $0.26/lf for sprayed pavement marking.
- It is less visible during the day because of its grayish color.

3.3 Thermosets

Thermosets are those materials in which two different components react exothermically to produce a hard and durable material. There are three types of thermosetting materials for pavement markings: epoxy, polyester, and polyurea.(10) Thermosets generally consist of two materials: pigment and binder. Typical epoxy is comprised of 18 percent to 25 percent pigment for white or 19 percent to 29 percent pigment for yellow. Binders constitute 71 percent to 82 percent of the mix. The thickness of epoxy is typically 0.6 mm, and some can be applied to wet surfaces. The drying time for epoxy is approximately 15 to 30 minutes, and the typical installed cost ranges from $0.20 to $0.30/lf.

Advantages of Thermosets:

- Epoxy provides exceptional adhesion to both asphalt and concrete pavement.(10)
- Highly durable with better visibility (2 to 3 years) normally and (4 to 6 years) if inlaid.
- Lower maintenance in areas of high traffic volume.
- Glass beads can be applied at higher percentage, normally at 25 lb/gal., on top surface during installation to provide greater reflectivity.

Disadvantages of Thermosets:(11)

- Epoxy materials have longer drying times depending upon ambient and surface temperatures, sometimes up to 60 minutes.
- Thermosets require its own specialized equipment.
- Insensitive to most weather conditions during placement; however, it takes longer to cure if the temperature is colder.
- Cost is slightly more than conventional paints (about $0.10 to $0.45/lf for reference cost).
- It’s difficult to repaint on epoxy without any specific mechanical preparation to abrade the surface.

3.4 Preformed Tapes or Profile Tapes

Preformed tapes or simply tape pavement markings are pre-made strips or patterns of durable material glued to the pavement surface. These products can be used in urban and/or rural situations for crosswalk, stop bars, symbols, longitudinal striping, etc.[3] There are three types of tapes: permanent, temporary, and removable.

- Cold Plastic Tape, generally used for permanent pavement marking, has an adhesive back and can be rolled on manually or mechanically. This type of tape has a high initial cost.
- Foil-Backed Tape is used primarily for temporary pavement marking. The top layer of tape contains a pigmented binder and beads. The bottom layer of tape contains metal foil. Foil-backed tape has high initial brightness, but low durability.
- Removable Tape is often used in construction areas. Removable tape can be manually applied and removed. The reflectivity is high at first, but drops considerably later.

These tapes have pre-applied adhesive backing. During the application, the backing is removed, and the tape is pressed onto the pavement with a roller or truck tire. The pavement surface must be clean and free of oil and debris. The ambient temperature during application must be at least 70°F, and glues are used while installation.

Advantages of Preformed Tapes:

- Preformed tapes are easy to install.
- Service life is roughly 4 to 8 years.
- High resistance to wear and snowplows. Initial level of retroreflectivity can be as high as 1,100 mcd for white and 800 mcd for yellow plastic marking tapes.

Disadvantages of Preformed Tapes:

- The initial cost is higher, with a price range between $0.67 and $2.65/lf. (Contracted costs of material per ft not including removal)
- They may not provide adequate retroreflectivity throughout their entire life.

3.5 Methyl Methacrylate

Methyl Methacrylate (MMA) was initially tested and used in Alaska and Eastern Europe. It is designed for extreme environmental conditions (heavy snowplow areas, mountain passes) and for heavy traffic areas. Its estimated life expectancy is anywhere from 2 to 4 years, depending on the location and traffic volume.[12] MMA can be applied at moderate temperatures and at temperatures as low as 0^{o}F, as long as no frost is present. MMA is a two-part system. The first part contains methyl methacrylate monomer, pigments, fillers, glass beads, and silica. The second part consists of benzyl peroxide dissolved in plasticizer. The two parts are mixed in a 4:1 ratio and then sprayed or coated onto the pavement. Methyl Methacrylate is said to have a no-track time of approximately 20 minutes depending on temperature and the thickness of the applied material. MMA has good visibility in both night and wet conditions. It has been used in both extruded and sprayed applications on Portland cement concrete (PCC) and asphalt cement concrete (ACC) pavements. The extruded version has been shown to last longer, while the sprayed version has the benefit of being less expensive. MMA may not be as effective in areas with high humidity. MMA appears to be well suited for cold climates because it can be applied at such low temperatures and is very resistant to snow plow and chemical damage. MMA are sometimes pre-mixed with beads called Pre-mix formula. The advantage of pre-mix formula is that the beads are directly applied on the pavement marking lines and fewer beads are scattered outside the line.

MMA has been used in Europe for years, but it has had limited use in the U.S. Additionally, it bonds very well to both concrete and asphalt. MMA is similar in cost when compared to other multi component durable types of pavement markings and requires special equipment for installation. On the California DOT's test section after one winter, 95 percent of the MMA markings remained, while only 50 percent of the thermoplastic and paint markings remained in the same area. Oregon has found that the MMA markings generally provide a service life of 6 to 8 years and are applied at a cost of $2.00 - $3.00/lf, depending on whether the markings are recessed and/or profiled.[1]

3.6 Raised Pavement Markers

Raised Pavement Markings (RPM) can be either reflective or non-reflective. The reflective RPMs are normally made of acrylic, tempered-glass, or glass-bead lenses. Non-reflective RPMs are made of ceramic with glazed surface. These pavement markers are normally mounted in plastic, ceramic, or metal base. RPMs have proven to be effective during low-visibility conditions, such as rain and darkness. These markings are more expensive; they have longer installation time, and they are susceptible to destruction by snowplows. The use of raised reflective pavement markings is recommended by FHWA on interstate highways with three or more lanes to simulate lane lines.[6,14]

3.7 Raised, Snow Plowable Marker System (Virginia DOT) [15]

This marker system generally consists of a reflective marker glued in a protective steel or cast-iron casting. The casting is applied with epoxy into a groove that is cut in the pavement surface. The system is designed so that a snowplow blade will ride up and over the reflective marker, leaving it undamaged. The reflective marker can be replaced in the casting. Snow-plowable raised markers and embedded raised markers have been explored with limited success.

CHAPTER 4

LITERATURE REVIEW OF PAVEMENT MARKING PERFORMANCE AND SPECIFICATIONS

This is a summary of the results of the studies conducted by various DOTs, academic institutions, private and public service laboratories, manufacturers, suppliers and NTPEP.

A summary of advantages and disadvantages for different types of pavement markings is provided in Table 1. This study was conducted by Dr. Tarek Zayed, an associate professor of the Building, Civil and Environmental Engineering Department of Concordia University, Canada in 2004.(14)

Table 1. Advantages and Disadvantages of Different Types of Pavement Marking [*sic*]. (5)

Main Category	Application Temperature	Service Life (Months)	Advantages	Disadvantages
Solvent-borne Paint	50°F or higher	3 to 36	Inexpensive Fast drying time Easy cleanup Long life on low volume roads	Highly flammable Does not adhere to concrete well Short life on high volume roads Has bad smell Hazardous Waste Disposal require for spent solvent products.
Water-borne Paint	50°F or higher	3 to 36	Inexpensive Fast drying time Easy cleanup Long life on low volume roads VOC compliant More durable than solvent based paints Reduces or eliminates Hazardous Waste Disposal	Does not adhere to concrete well Short life on high volume roads
Thermoplastic *Sprayed *Extruded	50°F or higher (sprayed) 32°F or higher (extruded)	48 to 84	Quick set time Good night time visibility Excellent durability Long life on high volume roads	High initial cost Sensitive to installation procedure Subject to damage from snow plow

Epoxy Paint	50°F or higher	24 to 48	High retoreflectivity Excellent durability Long life on low volume roads	High initial cost Slow drying time Heavy bead application Subject to damage from snow plow
Tape *Regular or Permanent *Removable	Must be warm enough for the adhesives to adhere	48 to 96	High retoreflectivity Good durability Long life on high volume roads	High initial cost Not suitable for roads in poor condition Subject to damage from snow plow
MMA	0°F or higher	24 to 48	Good durability Long life on high volume roads	High initial cost Subject to damage from snow plow

A list of 16 different types of pavement markings and 4 types of pavement markers used for longitudinal pavement markings is presented in Table 2.[16]

Statistical modeling was used to determine the relationship between decreasing

RL values with time (in months) and cumulative traffic passages (CTP). CTP values were calculated with the reported average daily traffic (ADT). Table 3 list the estimated service lives in terms of roadway type, pavement marking material, and color of line.

Table 2. Various Pavement Markings Used by Transportation Agencies. [16]

Transportation Agencies Reporting Using the Marking Material

Types of Marking	Total		State		Canadian		County		City	
	51[a]	%[b]	37[a]	%[b]	5[a]	%[b]	5[a]	%[b]	4[a]	%[b]
Longitudinal Marking										
Water-borne Paint	40	78	33	89	-	-	5	100	2	50
Thermoplastic	35	69	30	81	-	-	3	60	2	50
Preformed Tape-Flat	22	43	19	51	-	-	2	40	1	25
Preformed Tape-Profiled	21	41	20	54	-	-	-	-	1	25
Epoxy	20	39	19	51	-	-	1	20	-	-
Conventional Solvent Paint	20	39	13	35	5	100	1	20	1	25
Methyl Methacrylate	10	20	9	24	-	-	1	20	-	-
Thermoplastic-Profiled	9	18	9	24	-	-	-	-	-	-
Polyster	5	10	5	14	-	-	-	-	-	-
Polyurea	2	4	2	5	-	-	-	-	-	-
Cold Applied Plastic	1	2	1	3	-	-	-	-	-	-
Experimental	1	2	1	3	-	-	-	-	-	-
Green Lite Powder	1	2	1	3	-	-	-	-	-	-
Polyster-Profiled	1	2	1	3	-	-	-	-	-	-
Tape (Removable)	1	2	1	3	-	-	-	-	-	-
HD-21	1	2	-	-	-	-	1	20	-	-
Pavement Markers										
Raised Retroreflective	16	31	14	38	-	-	-	-	2	50
Recessed Retroreflective	4	8	4	11	-	-	-	-	-	-
Snowplowable Retrorelective	16	31	14	38	-	-	2	40	-	-
Non-Retroreflective	5	10	4	11	-	-	-	-	1	25

Notes:

[a] Number of transportation agencies that respond to survey

[b] Percentage of the responding agencies reporting using the marking material

Table 3. Estimated Service Life by Roadway Type, Pavement Marking Material, Color for Sites Without Roadway Lighting, and Raised Pavement Markers.[16]

Roadway Type	Material	Number of Pavement Marking Lines	Service Life in: CTP (Million Vehicles)	Elapsed Months	
			Average	Average	Range
WHITE LINES					
Freeway	Thermoplastic	14	7.5	22.5	7.4 - 49.7
	Polyester	2	9.6	20.6	14.7 – 27.0
	Profiled Tape	5	6.3	19.6	11.7 – 27.3
	Profiled Thermoplastic	7	6.5	18.4	4.7 – 35.6
	Profiled MMA	6	7.9	14.0	7.8 – 33.5
	Epoxy	11	2.4	12.8	1.0 – 34.0
	MMA	6	3.7	11.9	6.8 – 17.5
	Water-borne Paint	3	3.7	10.4	4.1 – 14.8
Non-Freeway 40 mph	Profiled Thermoplastic	1	25.1	55.7	-
	Profiled Polyester	1	10.9	45.9	-
	Epoxy	2	4.5	39.4	29.2 – 49.7
	Profiled Tape	2	7.6	26.9	22.3 – 31.0
Non-Freeway 45 mph	Epoxy	5	8.8	38.8	25.1 – 56.0
	Profiled Tape	4	5.3	37.3	22.9 – 60.0
	Thermoplastic	5	6.0	36.6	25.5 – 49.1
	Profiled MMA	3	8.8	34.8	29.9 – 43.2
	MMA	1	3.4	29.3	-
	Polyester	3	2.7	27.4	18.8 – 34.1
	Profiled Thermoplastic	6	3.7	24.3	23.8 – 26.2
YELLOW LINES					
Freeway	Polyester	1	11.1	39.7	-
	Profiled Tape	3	6.9	25.8	10.6 – 20.8
	Thermoplastic	7	6.1	24.7	11.0 – 20.8
	Profiled Thermoplastic	4	5.3	23.5	17.8 – 30.3
	Epoxy	7	4.7	23.2	12.6 – 47.5
	Profiled MMA	3	6.2	21.1	18.1 - 24.4
	MMA	3	3.0	15.6	12.6 – 20.3
Non-Freeway 40 mph	Profiled Thermoplastic	1	11.4	50.7	-
	Epoxy	2	3.6	43.9	34.7 – 53.1
	Profiled Polyester	1	4.7	39.6	-
	Profiled Tape	1	3.5	19.6	-
Non-Freeway 45 mph	Polyester	1	9.1	47.9	-
	Epoxy	6	8.9	44.1	35.8 – 57.8
	Profile Tape	3	5.1	38.9	25.4 – 53.4
	Thermoplastic	3	4.5	33.8	26.0 – 30.1
	Profiled MMA	2	6.5	31.0	29.1 – 32.8
	Profiled Thermoplastic	3	3.9	23.0	22.3 – 24.3
	MMA	1	4.8	20.5	-

CHAPTER 5

RETROREFLECTIVITY AND SERVICE LIFE OF PAVEMENT MARKINGS

The Washington State Transportation Center (WSTC) conducted a study to develop retroreflectivity degradation curves for paint pavement markings.[17] In this study, WSTC examined approximately 80 test sections utilizing a vehicle-mounted Laselux Retroreflectometer. This study concluded that the retroreflectivity values varied significantly for roadways with similar AADT and environmental conditions. The report suggests that the potential causes of variability could be attributed to:

- Differences in application methods employed by different crews.
- Depth of glass beads in the paint.
- Roadway differences such as dirt on the markings.
- Background color.
- Variability in the product.
- Environmental conditions during the data collecting trip.
- Calibration of stripping equipment, one of the leading causes of poor stripping results.

According to this report, the statistical precision of the trend lines from the collected data is quiet weak and inconsistent. However, this research found a direct correlation between higher AADT and shorter life expectancy of pavement markers. This is consistent with the findings of other studies. This study did not suggest conclusively that the Washington State Department of Transportation (WSDOT) guidelines outlines in it Maintenance 31 Manual should be changed.[17] According to that schedule, , long line painted pavement markings should be painted at least once per year in low-traffic areas and twice per year in heavy traffic areas.

The American Society for Testing and Materials (ASTM) has developed standards for the testing and measurement of pavement markings retroreflectivity. The unit used for measurement of retroreflectivity is millicandelas per square meter per lux (mcd/m^2/lux). The Idaho Transportation Department sets standard specifications for new pavement markings at a minimum initial retroreflectivity of 250 mcd/m^2/lux for white and 175 mcd/m^2/lux for yellow. Normally, new markings have much higher retroreflectivities. This allows for degradation over time and extends the useful life expectancy.

Many studies have reported a minimum threshold for retroreflectivity of pavement markings. A study conducted in New Jersey in 2003 concluded that the threshold value for an acceptable level of retroreflectivity appeared to be between 80 and 130 mcd/m^2/lux for drivers under the age of 55 and between 120 and 165 mcd/m^2/lux for the drivers over 55.[18]

In 1996, Graham, and his co-authors examined the retroreflectivity of the existing roadway markings and performed a subjective evaluation of their adequacy to determine a threshold.[19] This study reported that for 85 percent of drivers aged 60 years and older, a retroreflectivity level of 100 mcd/m^2/lux was adequate for night conditions.

In 2000, Loetterle, and his co-authors of MnDOT conducted a study to grade the visibility of edge lines and centerlines.[20] This study reported that a threshold level of between 80 and 120 mcd/m^2/lux was adequate for people age 60 and above. As a result of this study, MnDOT uses 120 mcd/m^2/lux as a threshold in its pavement marking management program.

Figures 1 and 2 shows the distribution of marking age effects on retroreflectivity of solvent paint, waterborne paint, epoxy, and thermoplastics for white and yellow colors on asphalt and concrete.[19] This study also provides mixed results for the three pavement markings mentioned above. The results show that the life expectancy of these markings can vary from 6 months for paints to 2 years for thermoplastics for the threshold level of retroreflectivity reported by other investigators.

Data from NTPEP also indicated that the life expectancy of water-borne paints and thermoplastics on asphalt and concrete pavements are about the same, as shown in Figure 3.[21] Table 4 presents the Minimum Pavement Markings Retroreflectivity Specifications adopted by different states.[21]

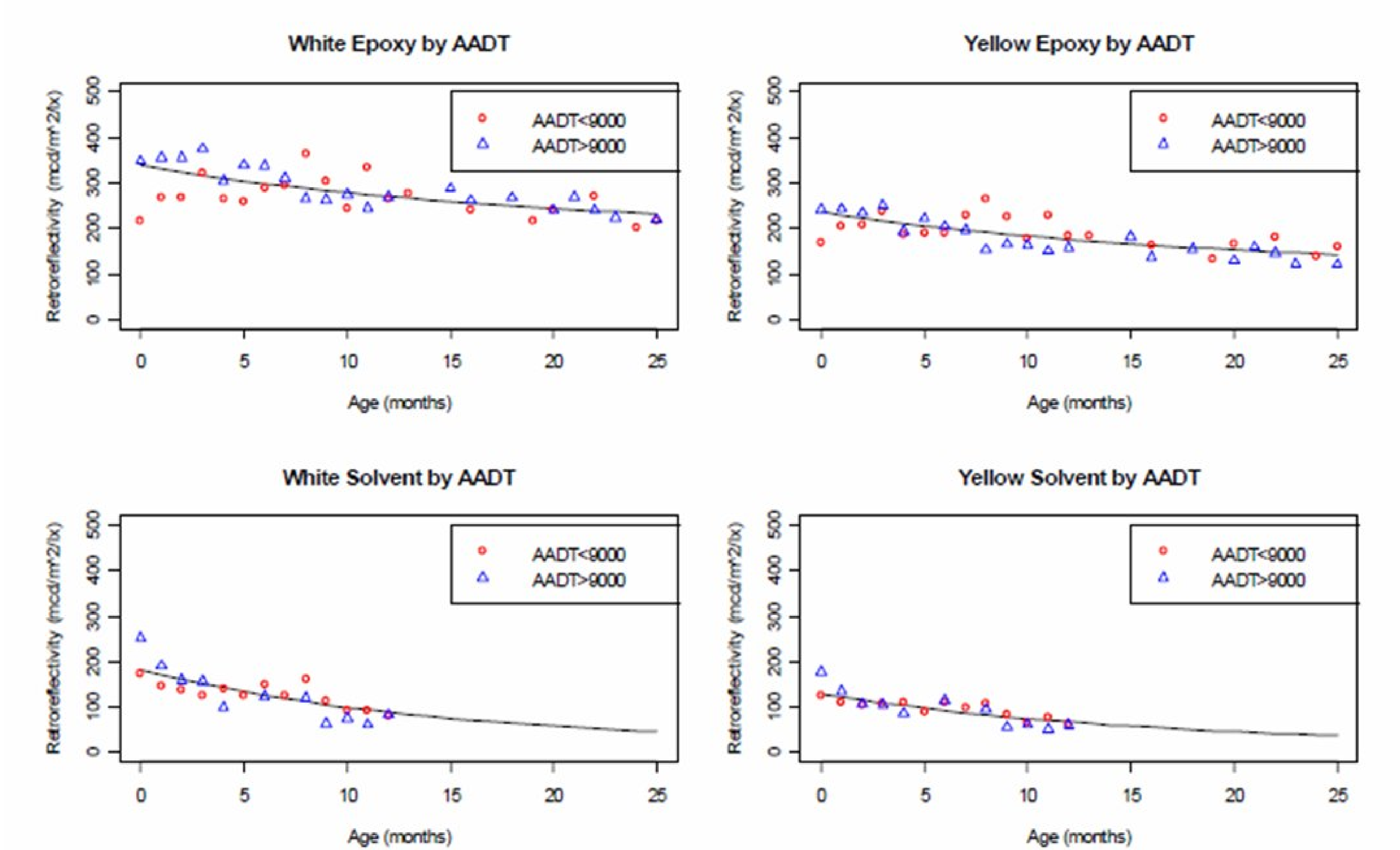

Figure 1. Distribution of AADT for White and Yellow Epoxy and Solvent.[(21)]

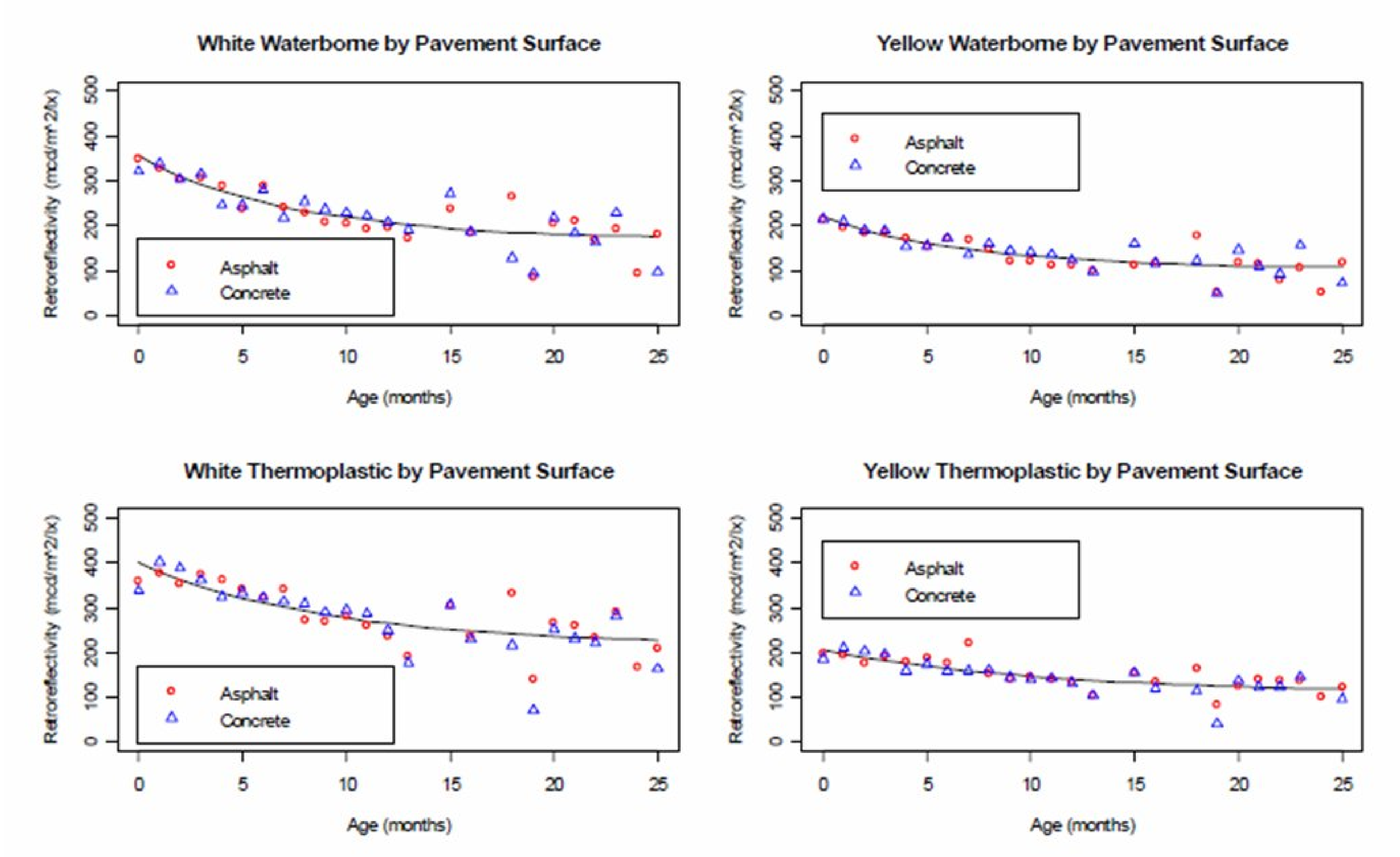

Figure 2. Distribution of AADT for White and Yellow Water-borne and Thermoplastic.[21]

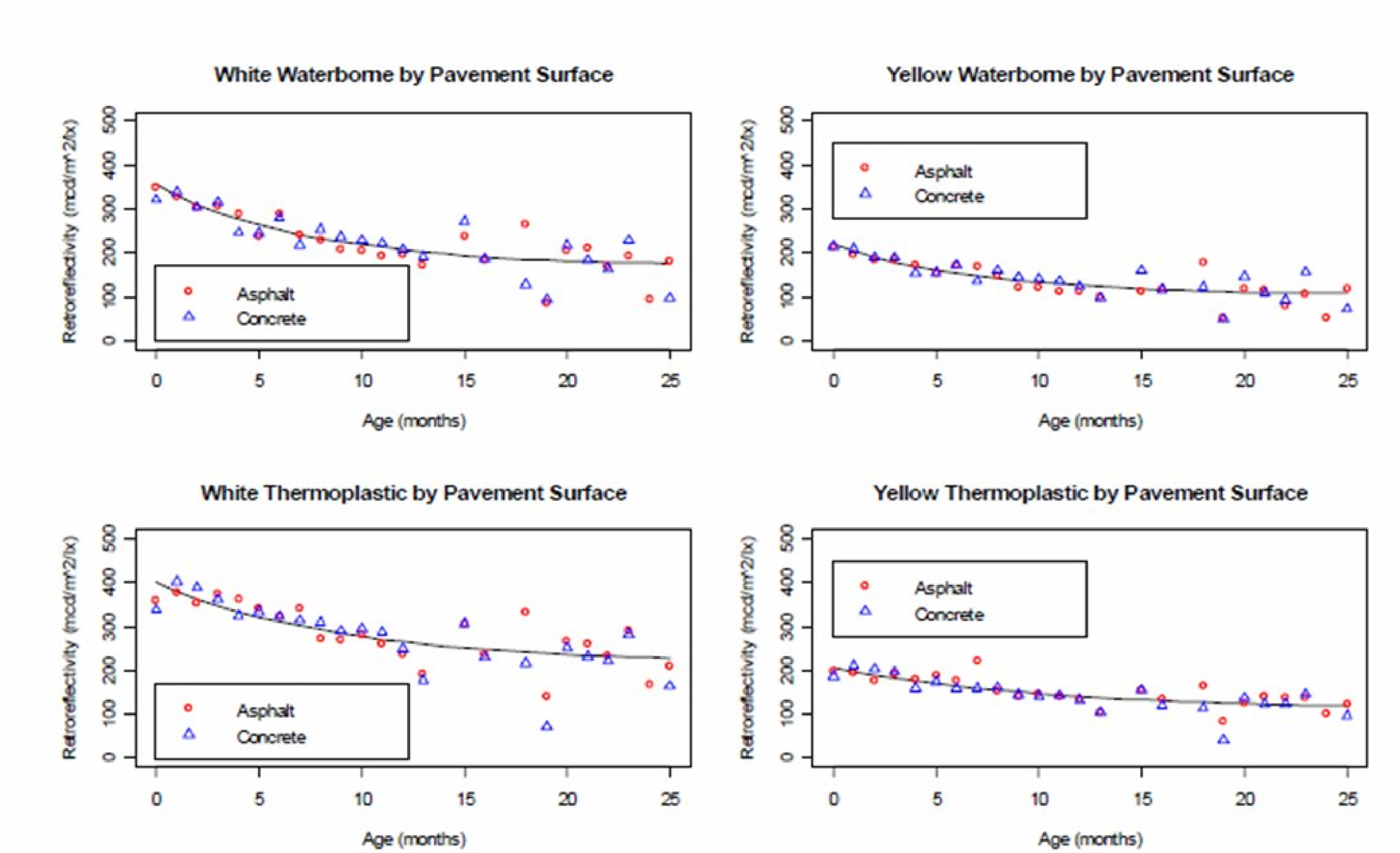

Figure 3. Marking Age by Pavement Surface for White and Yellow Water-borne and Thermoplastic.[(21)]

Table 4. Maximum Retroreflectivity Requirement for Different Types of Pavement Markers.[21]

Type of Line	Standard Color of Line	Material Type	Maximum Retroreflectivity Requirements (mcd/m^2/lux)															
			CA	IA	KA	MD	MI	MN	MO	NV	NJ	NY	NC	OH	OR	PA	TX	UT
Centerline	Yellow	Paint		200 (100)	- (100)	150	- (145)	100 (50)	225	275 (125)	NA	NA	-	NA	-	200 (175)	175	NA
		Thermoplastic	150	-	275 (100)	150	- (145)	500 (50)	225	-	NA	NA	250 (100)	NA	200 (125)	250 (200)	250	NA
		Epoxy	150	-	275 (100)	-	-	300 (50)	225	275 (125)	NA	NA	250	NA	200 (125)	250 (175)	-	NA
Edge Line	Yellow	Paint		200 (100)	- (100)	150	- (230)	100 (50)	225	275 (125)	NA	NA	-	NA	-	200 (175)	175	NA
		Thermoplastic		-	275 (100)	150	- (230)	500 (50)	225	-	NA	NA	250 (100)	NA	200 (125)	250 (200)	125	NA
		Epoxy	150	-	275 (100)		-	200 (50)		275 (125)			250	NA				
	White	Paint	150	300 (150)	- (150)	250	- (220)	100 (50)	300	375 (175)	NA	NA	-	NA	-	250 (175)	-	NA
		Thermoplastic	250	-	- (150)	250	- (220)	100 (50)	300	-	NA	NA	375 (150)	NA	250 (150)	300 (250)	-	NA
Lane/Lane skip	White	Paint		300 (150)	- (150)	250	- (240)	275 (100)	300	375 (175)	NA	NA	-	NA	-	250 (175)	-	NA
		Thermoplastic	250	-	325 (150)	250	- (240)	700 (100)	300	-	NA	NA	375 (100)	NA	200 (125)	300 (250)	-	NA
		Epoxy	250	-	325 (150)		-	300 (100)		375 (175)			375	NA				

The Utah Department of Transportation (UDOT) uses three different types of pavement markings: solvent-based paint, Epoxy resin, and tapes. Currently UDOT uses water-borne paint, epoxy, thermoplastic, tape, and polyurea. UDOT has conducted a study to determine the relationship between the material reflectivity and the traffic volume to determine the lifespan of these three pavement markings. (3) In this study, a Laselux mobile reflectometer was used to measure the reflectivity of the pavement markings in Utah highways. The results were analyzed based on age and AADT traveled. A cost analysis of these three types of pavement markings used in Utah reveals that paint is the most cost-effective pavement marking material. The study also showed that the life expectancy of the tape is twice the useful life of paint and epoxy; however, the long-life of tape does not overcome the installation price advantages of paint and epoxy. Although the water-based paints were not considered in this investigation, the literature review indicates that water-based paint costs slightly more than solvent-based paints, and it does not have the emission problem given off during the drying of solvent-based paint.

In 2004, the Virginia Transportation Institute (VTI) of the Virginia Polytechnic Institute and State University conducted a study on the night visibility of pavement maprkings.(16) This study was sponsored by the Virginia Transportation Research Council. In this study, the visibility distance of several pavement markings including paints with standard and large glass beads, profile thermoplastics, wet reflective tapes, semi-wet reflective tapes, and raised reflective pavement markers (RRPM) were evaluated under dry and wet conditions for sedans and trucks. Figure 4 and Table 5 present summaries of the results of this study in graphical and tabular forms respectively.

Table 6 provides a summary of the results for visibility distance for trucks and sedans. Based on this study, trucks offer greater visibility distance when compared to sedans. This study showed that there was no interaction between vehicle type and line type.

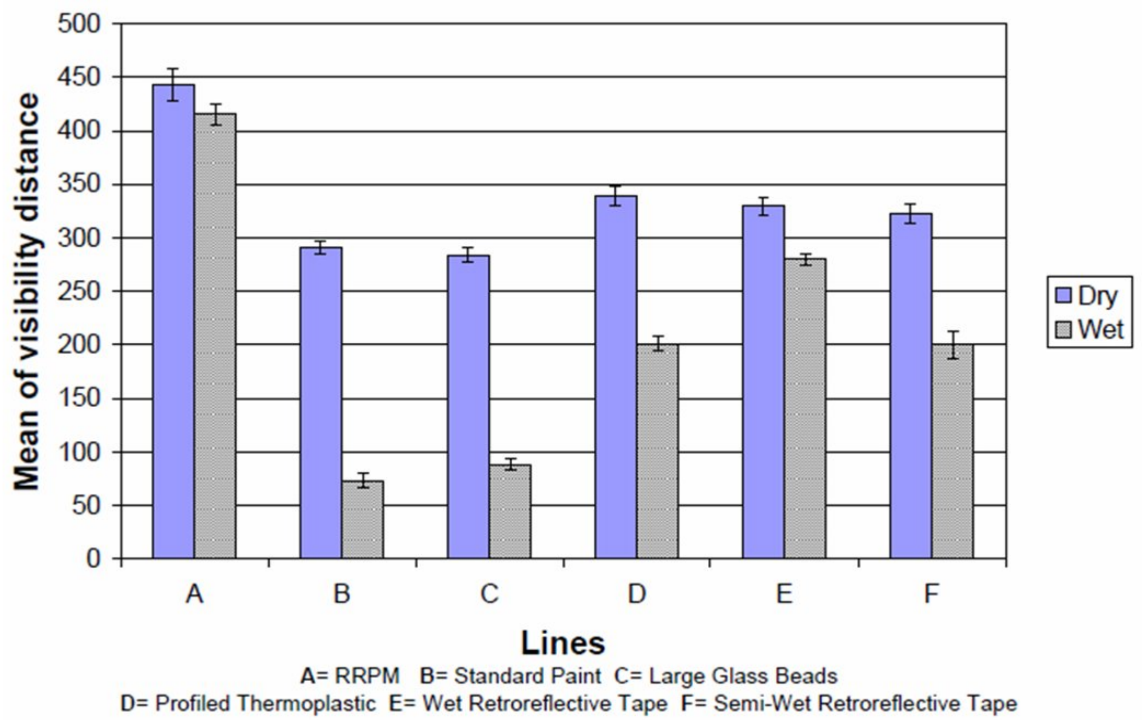

Figure 4. Results of the Visibility Distance for the condition x Line Interaction.[22]

Table 5. Visibility Distance Summary (in feet).[22]

Technology	Dry Condition	Wet Condition
A- RRPM	442	415
B- Standard Paint	291	73
C- Paint and Large Glass Beads	284	88
D- Profiled Thermoplastic	339	201
E- Wet Retroreflective Tape	329	280
F- Semi-Wet Retroreflective Tape	322	200

Table 6. Visibility Distance Summary for Trucks and Sedans[22]

Technology	Truck	Sedan
A – RRPM	428	451
B - Standard Paint	182	94
C – Paint and Large Glass Beads	186	108
D - Profiled Thermoplastic	270	217
E - Wet Retroreflective Tape	304	299
F - Semi-wet Retroreflective Tape	261	208

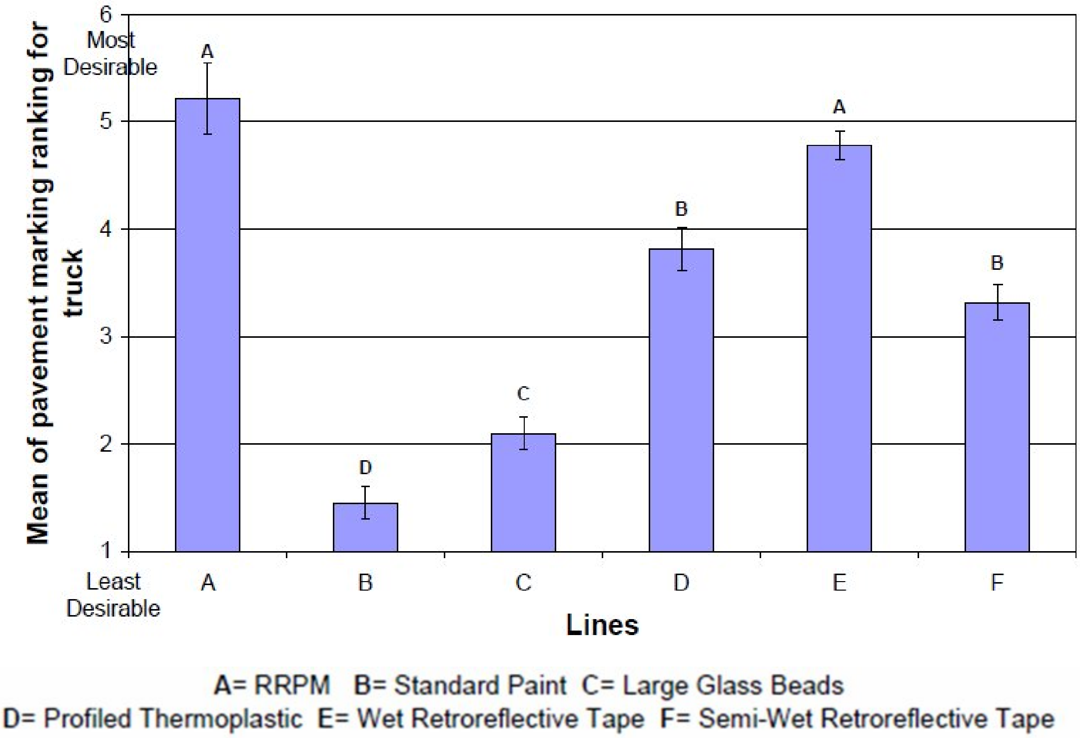

Figure 5. Presents the Results of the Preference Ranking of Pavement Markings by Participants for the Wet Truck Condition.[22]

The conclusions drawn from the VTI study of visibility distance for different pavement markings are as follows:[22]

- The visibility distance measures are correlated most highly with the pavement marking luminance and moderately with the retroreflectivity.
- The wetness of the pavement and the vehicle type affects the visibility distance. The presence of falling rain impacts the visibility distance by attenuation of the light reaching the driver. Also, the angle between a passenger vehicle height and the height of a truck affects the visibility distance.
- The visual performance of the drivers is highly correlated with their comfort level and preference for the pavement marking type.
- The recovery time for visibility distance varies with the pavement material type.
- As the extent of their vision changes, the threshold requirements of the participants change with the luminance of the markings. This, in turn, is related to the visual size of the object at the extent of the vision. This is in part influenced by the vehicle type and the change in the driver's perspective and luminance adaptation.

The safety performance of the snowplowable Permanent Raised Pavement Markers (PRPMs) on 2 and 4-lane freeways is reported in the NCHRP Report 518.[23] The research was sponsored by AASHTO in cooperation with FHWA. The potential cost effectiveness of PRPMs was determined based on an analytical engineering procedure using safety performance functions or crash prediction models for roadways with and without PRPMs.

PRPMs were mounted on centerlines and skip lines as a traffic safety measure to guide the drivers in inclement and low-light conditions. The safety performances of these devices were measured for 2-lane and 4-lane freeways in 6 states: Pennsylvania, Illinois, Missouri, Wisconsin, New Jersey, and New York. The above measurements assessed the impact of PRPMs on non-intersection related crashes only.[23]

The composite analysis of the results indicates that the nonselective installation of PRPMs on 2-lane roads does not significantly affect the total or nighttime crashes. However, the selective implementation policies produced mixed results. Positive effects were found in New York for nighttime and wet weather crashes. The safety effects of these devices for similar conditions were not observed in

Pennsylvania. This study concluded that PRPMs are only effective in reducing nighttime crashes in the roadways with AADT of more than 20,000.(23)

CHAPTER 6

SERVICE LIFE OF PAVEMENT MARKING

FHWA sponsored a Transportation Research Board (TRB) study to evaluate the service life of durable, longer lasting pavement markings. The service life of a pavement marking refers to the time or number of traffic passages required for the retroreflectivity to drop below a minimum threshold value. This indicates that the marking needs to be replaced or restored. Factors that contribute to pavement marking retroreflectivity include the time period, traffic action, weather exposure, and snowplow operations.

The durable pavement markings evaluated consisted of epoxy, methyl methacrylate, polyester, thermoplastic, and preformed tape. In order to measure the service life, threshold retroreflectivity values were used to define the end of a pavement marking service life. The results are summarized in Tables 7 and 8.

Table 7. Estimated Service Life of Yellow Lines by Roadway Type and Pavement Marking Material.[24]

Roadway Type and Material (Freeway)	Number of Pavement Marking Lines	Service Life	
		Average CTP (million vehicles)	Elapsed Months
Polyester	1	11.1	39.7
Profile Tapes	3	6.9	25.8
Thermoplastic	7	6.1	24.7
Epoxy	7	4.7	23.2
Methyl Methacrylate	3	6.2	21.1

Table 8. Estimated Service Life of White Lines by Roadway Type and Pavement Marking Material.[24]

Roadway Type and Material (Freeway)	Number of Pavement Marking Lines	Service Life	
		Average CTP (million vehicles)	Elapsed Months
Polyester	2	9.6	20.8
Profile Tapes	5	6.3	19.6
Thermoplastic	14	7.5	22.6
Epoxy	11	2.4	12.8
Methyl Methacrylate	6	3.7	11.9

CHAPTER 7

PAVEMENT MARKERS USED BY DIFFERENT STATES(11)

A document prepared for the Montana Department of Transportation (MDT) provides a summary of pavement marking practices and current efforts in other states (Cuelho, Stephens, and McDonald 2003). This study sought to provide a background summary of other states' activities regarding pavement marking practices. The summary is given below.

7.1 Pennsylvania: The State of Pennsylvania (PennDot) uses 94 percent conventional paints for pavement markings. The remaining pavement markings used include epoxy paints and small amount of thermoplastic. These products are applied in both rural and urban areas. Among all the states listed in the table below, Pennsylvania has lowest cost per linear foot which is $ 0.024/lf of installed pavement marking.

7.2 Kansas: Kansas Department of Transportation (KsDOT) has developed a methodology to determine most economical type of pavement marking. Brightness Benefit Factor (BBF) is describe as the benefit/cost ratio based on a material's retroreflectivity, durability, and installed cost. The analysis also includes variables such as traffic, expected life of the pavement, and motorist delay. From their analysis, epoxy paint shows higher BBF where average daily traffic is less than 50,000, but extruded thermoplastic display higher BBFs in the areas where the average traffic is more than 50,000. During this study, it was noted that KsDOT uses a high quantity (79 percent) of durable products such as epoxy and thermoplastic pavement markings, when compared to other states. KsDOT Pavement Marking Policy does not provide the reasons for the use of epoxy and thermoplastics in higher quantity; however its specifications are primarily based on the cost effectiveness of the pavement markings.

7.3 Minnesota: Minnesota Department of Transportation (MnDOT) uses conventional paints for the majority (90 percent) of the pavement markings throughout the state. Conventional paints are generally used in rural areas. Of the remaining 10 percent, approximately 8 percent are epoxy paints. Conventional paints cost around $0.048/lf, while epoxy paints cost around $0.19/lf.

7.4 Virginia: Paint, thermoplastics, and waffle tape make up to 90 percent of the pavement markings used by Virginia Department of Transportation (VDOT). The remaining pavement markings used includes epoxy paints, polyurea, polyester paints, and other miscellaneous tapes. VDOT found the service lives are 6 months for conventional paints, 3 years for epoxy and thermoplastics, and 6 years for profile tape.

7.5 Wyoming: The Wyoming Department of Transportation (WYDOT) uses alkyd or conventional paints for pavement markings. Epoxy markings are used in areas of high wear for safety reasons.

7.6 North Dakota: The North Dakota Department of Transportation (NDDOT) bases its selection of pavement markings on a variety of criteria including: type of road, condition of the road surface, and the level of traffic. The materials uses by NDDOT are conventional paints; and inlaid, patterned, preformed tapes. Conventional paints are used on the roads that are in poorer condition or lower volume roads. Durable products are preferred on roads having higher AADT that are in good condition.

7.7 Montana: Most of pavement markings in Montana are conventional products. Montana Transportation Department (MtDOT) also using durable products like epoxy and spread thermoplastics at high volume intersections due to high wear surface from traffic. The cost for epoxy paint per MDT is $0.10/lf to $0.14/lf.

7.8 Idaho: ITD uses conventional paints approximately 98 percent of all the pavement markings. The remaining pavement marking in Idaho are MMA. The installation cost for conventional paints ranges between $0.035/lf to $0.045/lf. ITD currently applies paint approximately 2 times per year in high wear areas. ITD uses water-based paints for most of the highway markings except for highways with high traffic volume. Like Pennsylvania, Idaho uses conventional paint for most of its pavement markings.

Table 9. Approximate Quantities of Pavement Marking Products Used by Different States.[11]

State	Conventional Products (Paints) in Percentage (Approximate)	Durable Products (Epoxy, Thermoplastic etc.)	Party Involve for Applying Majority of Pavement Markings
Pennsylvania	94%	6%	PennDOT
Kansas	21%	79%	Contractor (avg. 79%)
Minnesota	90%	10%	MnDOT
Virginia	90%		VDOT
Wyoming	Majority	Minority	WYDOT
North Dakota	Depends on several criteria: type and condition of road surface		NDDOT
Idaho	98%	2%	ITD (60-80% for maintenance)
Montana	60%	40%	MTDOT/contractor (50%/50%)

Table 10. Cost Summary for Installed Pavement Marking by Different States.[11]

State	Conventional Paint	Epoxy Paint	Thermoplastic	Spread Thermoplastic	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 in $/lf

-- Information not available.

Table 11. Unit Cost of Markings ($/ft for longitudinal marking).[11]

Marking Material	Roadway Delination practices Handbook (1994)[25]	NCHRP Report 392 (1997)[26]	Cottrel and Hanson (2001)[27]	NCHRP Synthesis 306 (2002)[16]	Carlson et al. (2007)[28]
Waterborne paint	0.04 - 0.06	0.06	0.04 - 0.15	0.06	0.08
Thermoplastic	0.32 - 0.60	0.30	0.35	0.32	0.27 - 0.32
Performed tape, profiled	--	1.75	1.80	2.33	2.75 - 3.75
Epoxy	0.40 - 0.45	0.25	0.40	0.26	--
Conventional Solvent paint	--	--	--	0.07	--
Methyl methacrylate	--	0.75	--	1.22	1.50 - 2.10
Thermoplastic	--	--	--	0.87	0.75
Polyester	--	0.10	--	0.13	--
Polyurea	--	--	0.70	0.90	0.85

Table 12. Pavement Marking Cost (Unit Cost /lf).[29]

States		Conventional paint	Thermoplastic	Epoxy	Profiled tape
Utah	Cost (per $/lf)	$0.03- $0.06	$0.30 - $0.40	$0.30	$1.0 - $1.20
	Thickness	15.74mils	59-90mils	23.62mils	59-90mils
Kansas (unit cost)		$0.05	$0.19(sprayed) $0.41(extruded)	$0.32	$2.12

Table 13. Texas Department of Transportation Specification Thermoplastic when Used on Concrete.[1]

Initial Contracted Material Cost ($/lf)	Total Life Cycle Cost ($/lf)	Typical Service Life (years)	Total Cost per Year of Service Life ($/lf/yr)
0.20	0.66	2	0.33

Table 14. Range of Unit Cost for Different Pavement Markings.[30]

Markers		Solvent Based Paint	Epoxy	Thermoplastic	Profiled Tape
Unit Cost		$5 - $10 per gallon	$2,500 per ton	$700-$900 per ton.	$0.50 to $0.80/ft
Installation Cost		$0.03 - $0.06	$0.21	$0.30 to $0.40	$1.10 to $1.20/ft
Life expectancy	Asphalt Pavement	4 to 10 months	2 to 5 years	5 to 9 years	3 to 7 years
	PCC	2 to 7 months	2 to 5 years	3 to 5 years	3 to 7 years

Table 15. Average Unit Cost of Pavement Markers Placed by the Bidders in Different States (Data as of Year 2003).[11]

State	Paint	Epoxy	Profiled Tape
Utah	$ 0.29/lf	$ 0.75/lf	$ 2.39/lf
	43,914 ft(quantity)	3,940 ft	223,993 ft
Virginia	$ 0.55/lf		
	12,000		
Wyoming	$ 0.37/lf	$ 0.30/lf	
	58,205	1,905,700 ft	
Montana	$ 0.10/lf	$ 49.33/gal	
	1,710,958 ft	17,672 ft	
Nevada	$ 0.30 lf	$ 1.00/lf	
Idaho	$ 0.10/lf		$ 1.25/lf
	108,596 ft		1,200 ft

Table 16. Recommended Pavement Marking Materials for Concrete Pavements[1]

Traffic Characteristic[a]	Pavement Remaining Service Life		
	0-2 Years	**2-4 Years**	**> 4 Years**
AADT < 10,000	TxDOT Thermo[b]	Epoxy	Epoxy
10,000 < AADT < 50,000	TxDOT Thermo[b]	Epoxy	Epoxy
AADT > 50,000	Epoxy	Epoxy	Preformed Tape
Commercial Vehicles or Heavy Weaving/Turning	Epoxy	Preformed Tape	Preformed Tape

Notes: Contrast markings or profiled markings may be used to improve visibility and safety as needed.
[a] AADT = Average Annual Daily Traffic.
[b] Primer/sealer required prior to application of current TxDOT spec. thermoplastic on bare concrete.

Table 17. Alternative Pavement Marking Materials for Concrete Pavements [1]

Traffic Characteristic[a]	Pavement Remaining Service Life		
	0-2 Years	2-4 Years	> 4 Years
AADT < 10,000	Epoxy, Water-Based Paint	Thermo[b] (concrete formulation), Modified Urethane, Water-Based Paint, Polyurea, MMA	Thermo[b] (concrete formulation), Modified Urethane, Polyurea, Water-Based Paint, MMA
10,000 < AADT < 50,000	Epoxy, Modified Urethane, Water-Based Paint	Thermo[b] (concrete formulation), Modified Urethane, Polyurea, Water-Based Paint, MMA	Thermo[b] (concrete formulation), Preformed Tape, Polyurea, Modified Urethane, MMA
AADT >50,000	Thermo[b] (concrete formulation), Modified Urethane, Polyurea	Thermo[b] (concrete formulation), Preformed Tape, Polyurea, Modified Urethane, MMA	Epoxy, Thermo[b] (concrete formulation), Polyurea, Modified Urethane, MMA
Commercial Vehicles or Heavy Weaving/Turning	Thermo[b] (concrete formulation), Modified Urethane, Polyurea	Epoxy, Thermo[b] (concrete formulation), Polyurea, Modified Urethane, MMA	Epoxy, Thermo[b] (concrete formulation), Polyurea, Modified Urethane, MMA

Notes: Marking materials listed in order of recommendation, with the highest alternative recommendation listed first.

Contrast markings or profiled markings may be used to improve visibility and safety as needed.

[a] AADT = Average Annual Daily Traffic.

[b] Please see manufacturer's recommendations for use of primer/sealer prior to thermoplastic application.

CHAPTER 8
CONCLUSIONS

A comprehensive literature review was conducted to identify the most cost effective pavement marking material based on their performance, durability, and useful life expectancy. This study revealed that there were no conclusive findings and recommendations by different investigations and field studies for various types of pavement markings. The performance characteristics of pavement markings and their effectiveness in guiding the roadway users depend on many factors including, but not limited to, product quality, application process, surface preparedness, environmental conditions, AADT, driver's age and visual performance, type of vehicle and its headlights, and pavement type. In addition, the results of field studies conducted by different investigators show that the conclusions were highly dependent upon the method of studies, the study models used, the type of measurement devices, and the accuracy of operation.

Some of the findings common to many of the studies are as follow:

- For a given AADT, preformed tapes have longer useful life compared to paint and epoxy pavement markers; however, its initial cost is high and may not provide adequate retroreflectivity throughout their entire life.
- Paint and epoxy pavement markers have longer useful life on Portland cement concrete pavement than asphalt pavement.
- Paint has a little longer life than epoxy thermoplastic on asphalt pavement while epoxy has much longer useful life than paint on Portland cement concrete.
- Epoxy lasts longer on Portland cement concrete than asphalt due to higher coefficient of thermal expansion and contraction of asphalt.
- Paint is the most cost effective pavement marking material for low level AADT.
- Solvent-based markings are not as durable but less expensive than water-borne paint; however their hazardous emissions are an environmental concern.
- Raised pavement markers on 2-lane roadways do not significantly reduce the safety issues, however its use on 4-lane roadways is helpful in reducing crashes in wet weather conditions. The use of RPM in snow belt areas is not cost effectives and many transportation departments avoid using these markers due to frequent maintenance issues caused by snowplow and winter maintenance operations.

- The initial retroreflectivity of white tape pavement markers are always higher than yellow tape markings because of titanium dioxide in white tape pavements.
- The cost results indicate that paints is the most cost effective followed by Epoxy. The tapes are more costly than both paint and Epoxy and should be used in high AADT areas.
- The useful life of paint is about six month on medium to high AADT and approximately a year in low volume traffics.

8.1 Recommendations

Currently, 98 percent of pavement markings used in Idaho are paint with the remaining 2 percent comprising other types of pavement markings including tapes and MMA. Based on the results of this study, it concluded that the current practice of ITD in using pavement markings is the most cost effective method available. As such, continuation of the ITD's current practice is recommended.

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APENDIX

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)