A Comparative Analysis of the Alternative Pavement Marking Materials for The State of Utah

Presented To:

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Executive Summary

Pavement markings provide guidance for traffic and conveys regulations and warnings to drivers, and their effectiveness depends on their visibility. As pavement markings reflective properties diminish, the ability of the pavement marking to provide guidance and safety is reduced. As Utah's population increases, the Utah Department of Transportation (UDOT) has been saddled with increasing traffic levels and the need to re-apply pavement markings more frequently. In order to minimize costs for pavement markings, relationships between pavement marking life expectancy and traffic levels were developed.

Three types of pavement markings are used by UDOT: Solvent Based Paint, Epoflex Epoxy Resin, and Pavement Marking Tape. These materials are referred to as "Paint", "Epoflex", and "Tape". This report provides a relationship between material reflectivity and traffic volume in order to determine useful life span of these three pavement marking materials.

The study used the "Laserlux" mobile reflectometer to measure the reflectivity of pavement markings on Utah State Highways. Paint, Epoflex and Tape reflectivity measurements were analyzed based on age and annual average daily traffic (AADT) traveled. A cost analysis of the three pavement marking materials shows the most cost effective material is Paint. The results indicate that Tape has twice the useful life of Paint and Epoflex. However, the long life of Tape does not overcome the installed price difference between Tape and Paint. Paint remains the least expensive installed pavement marking.

Concerns about the possible elimination of solvent based paints by the Environmental Protection Agency (EPA) due to emissions given off by the drying Paint bring cause to find a suitable replacement for Paint. Although, water-based paints were not analyzed in this study, the literature indicates that water based paints cost only slightly more than solvent based paints with similar useful life times. This indicates that should the EPA restrict the use of solvent based paints, water based paints would be the most cost effective replacement.

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1. INTRODUCTION

Pavement markings provide guidance for traffic, separate opposing lanes of traffic, prohibit passing maneuvers, and delineate roadway edges. Pavement markings convey traffic regulations and warnings to drivers. Effectiveness depends on markings visibility. Most types of pavement markings are retro-reflective. Tiny glass beads are embedded in a white or yellow matrix. Retro-reflectivity is the reflection of light in the direction from which it came. This describes the reflection a driver views when illuminated from the vehicle headlights. An effective pavement marking system facilitates driver guidance, improves traffic flow, contributes to driving comfort, and enhances traffic safety.

Approximately 140,000 m^3 (37,000,000 gallons) of traffic marking paint, 50,000 Mg (55,000 tons) of thermoplastic marking material, 118,000 Mg (130,000 tons) of glass beads, and an unknown quantity of raised, tape, and thermosetting markings are laid annually in the United States.

The following section covers the history, technology, and research of pavement marking materials.

1.1. The History of Pavement Markings

Applications of pavement markings became necessary in the 1920's due to increases in automobile traffic. The earliest use of white line pavement markings to divide traffic streams was in Michigan in 1911 (James, 1964). Initially, white stones were placed in the center of the road for pavement markings. Later the markings were made of loose, water-bound materials. In 1921, black-line paints were used on a one-block length in the middle of University Avenue in Madison, Wisconsin. However, they were fairly short lived and had been replaced with white lines by 1924 (NCHRP 17, 1973, and OECD, 1975).

Mattimore (1926) suggested traffic paints should be tested. He listed the most significant factors affecting the quality of paints used in pavement markings as: consistency, spreading rate, covering power or opacity, drying time, light resistance to deterioration due to the effects of sunlight, visibility in day and night, and durability resistance to weather and abrasion.

Solvent-based paint was developed to meet specific service requirements. Paint is cheap and easy to handle. Normally, fifty percent by volume solvent is added to paint to improve the manufacturing and application characteristics. Solvents contribute nothing to the integrity of the dried paint film, and produce atmospheric emissions. These concerns prompted research to develop other pavement materials that contain no or lesser quantities of solvent.

Thermoplastic marking materials were developed in Great Britain before World War II and contain no solvent. Thermoplastics markings consist of a resin as a binder, glass beads, pigments, and fillers. The resin is the main component of thermoplastic. The first resins mixed into thermoplastics were mixtures of wool grease and various waxes. Later, alkyd resins and hydrocarbon resins were adopted for the binders in the thermoplastics (Dale, 1988).

Many developments regarding pavement marking materials have been carried on to improve their performance characteristic. Glass beads were first mixed with paint to improve the retro-reflectivity of pavement markings in 1948 (Culp, et. al, 1981). Thermosetting epoxy pavement marking materials were developed by the Minnesota Department of Transportation and the H.B. Fuller Company during the 1970s. At the same time, the thermosetting polyester was developed and tested by the Ohio Department of Transportation and the Glidden Company. The need for a short drying time and high speed application techniques resulted in the development of epoxy thermoplastic (Epoflex) by Southwest Research Institute in the late 1970s (Culp, et. al., 1981, and Dale, 1988).

Raised pavement markers became popular in the United States in the 1950s. Raised pavement markers increase retro-reflectivity by raising the glass beads above the road surface. However, raised pavement markers are susceptible to damage in snow-belt regions where snowplows are used.

Waterborne paints were developed and set aside because they cost more than solvent based paints and took longer to dry. In 1984 concerns with harmful emission discharge of solvent paint into the atmosphere caused waterborne paints to be re-evaluated and used as an alternative to solvent based paint in California. It was expected that more than half of the traffic paint used in California by 1987 would be waterborne paint based on the increasingly restrictive air quality regulations (Dale, 1988).

1.2. The Technology Explained

Federal regulations require that pavement markings conform to the "Manual on Uniform Traffic Control Devices for Streets and Highways" (MUTCD, 1988). Pavement markings represent the most common types of traffic marking. They include longitudinal lines, transverse lines, words, and symbols. White and yellow colors are used in pavement markings as defined by the MUTCD (1988). Highway agencies have historically relied upon solvent-based paint, waterborne paint, thermoplastic, epoxy, and tape as the primary materials for pavement markings. These materials have different application techniques, qualities in durability, and costs. This section gives an overview of the types, components, applications, life expectancy, and costs of pavement-markings materials.

1.2.1. Paint

Paint for pavement markings consists of solvent based paint and waterborne paint. Descriptions of each and definitions of glass bead and applications of paint are given here.

Solvent Based Paint

Pigment, extender, and filler combined comprise about 25% of the total volume composite of solvent based paint. These materials are complemented by a 25% by volume binder package and 50% by volume solvent material (Dale, 1988). The inorganic pigments for pavement paints are titanium dioxide for white and lead chromate for yellow. The potential health hazards of lead chromate has led to the use of the organic yellow pigment. However, the organic yellow pigments fade quickly in sunlight, and some of them are hazardous when handling (Campbell and Post, 1978). Inert materials, e.g., calcium carbonate, and various silica products, are normally used for the extenders and fillers, respectively. The most cost effective binders of solvent based paint are the alkyd resin, and alkyd resin modified by chlorinated rubber. Solvents or thinner are used in paint to improve the manufacturing and application characteristics of paint, but add nothing to the dried paint properties. (Dale, 1988).

The terms used for drying time of paints are categorized by Moore (1978) as shown in Table 1.1.

Table 1.1: Terms for Drying Time of Paints

Term	Drying Time
Instant dry	< 30 sec.
Quick dry	30 to 120 sec.
Fast dry	2 to 7 min.
Conventional	> 7 min.

Paint is the most widely used material in pavement markings. It has become the performance and cost standard by which other pavement marking materials are compared and selected. However, performance of paint markings in snow regions rarely last an entire winter due to the abrasive nature of snowplow and sanding damage (Dale, 1988).

A study by Glennon (1979) regarding design and traffic control guidelines for low-volume rural roads reveals that the use of a solvent-based paint center-line costs $200 per mile, with a 1.5 year average life. The average cost of accidents on low-volume rural roads is $9,500. The accident rate was lower with a center-line markings than without. A benefit-cost ratio greater than one was found at an annual average daily traffic (AADT) of 300 vehicles per day. Therefore, center-line markings are warranted on paved low-volume roads when the AADT exceeds 300 (Glennon 1979).

Waterborne Paint

Waterborne paint has water in place of solvents. Waterborne traffic paint is an attractive means of impacting air quality through eliminating solvent discharge. At present, waterborne traffic paints are slightly more expensive and have a much longer drying time than solvent based paints. California has developed a performance specification, and a lead-free yellow pigmentation for waterborne paints. Most of the present formulations are based on acrylic and latex resins, and have a drying time of 10 minutes. Several advantages of the waterborne paints were concluded by Chatto and Warness (1985) and Dale (1988):

1. Waterborne paint is a proven alternative to solvent-based paints.
2. They may be hot or cold applied depending on equipment availability and weather conditions.
3. They provide service life equal to or better than solvent-based paints.
4. They have no strong solvent odor and induce few respiratory complaints from users.

5. They have less shipping and handling hazards owing to reduced flammability.

Using waterborne paints often involves equipment modification. There are several concerns that need to be addressed to convert the equipment for solvent based paint application to use for waterborne paint application (Morton, 1993).

1. Viscosity: Waterborne paints are at a greater viscosity at rest than in motion. This higher viscosity of paint requires larger inside diameter of truck applying plumbing. Waterborne paints may require a larger engine to provide additional pumping power over existing painting system.

2. Plumbing: Waterborne paints require proper grades of stainless steel for plumbing systems.

3. Sheer: Sheer occurs when a mechanical force is applied to the paint and decreases the performance characteristics of the paint. This can be caused by poor plumbing, insufficient agitation, or using the wrong pressure to move the paint. The result of sheer is changes in the paint's characteristics and the agglomeration of the paint. Dry time, durability, early water resistance, etc., may be impacted by degrees of sheer on the paint. It is therefore desired to minimize sheer.

4. Atmospheric-Free System: An atmospheric-free paint holding system is required when retro-fitting a pavement marking vehicle for waterborne paints. Paint tanks with loose fittings that are vented to the atmosphere cause a considerable decrease in the performance of waterborne paint.

5. Atomization: Waterborne paint is a heavier and more viscous material than solvent paint. It therefore takes more pressure to form droplets (atomizing) at the spray tips. Air spray systems provide up to 100 pounds of pressure to atomize the paint. Airless spray systems can generate up to 2000 pounds of pressure for atomization. Therefore, airless spray systems are typically suitable for the more viscous waterborne paint.

6. Transfer Efficiency: Airless spray increases transfer efficiency from 10% to 40% over most atomized air spray systems, which means a reduction in air pollution. If an agency is within air quality management districts, emission taxes for pavement markings could be reduced.

7. Paint Heater: The traditional "high heat" heaters are not required for most formulas of waterborne paints because adequate atomization and spray pattern of waterborne paints need to be heated only to between 90° F and 120° F instead of the 180° F required of most solvent based paints.

8. Waste: Waterborne paints normally produce less hazardous waste than solvent paints. However, residual materials in the paint exist which require proper disposal.

9. Weight Per Gallon: Waterborne paints may require a larger gross vehicle weight (GVW) chassis because of the higher weight per gallon than ordinary solvent paint. Some formulations of waterborne traffic paint weight as much as 16 pounds per gallon while ordinary solvent based paint normally weights between 13 and 14 pounds per gallon.

Glass Beads

Glass beads provide the reflectivity material for paint. However, glass is also used to reflectorize other traffic marking materials such as thermoplastics, Epoflex, epoxy, and tapes. Glass beads are made by projecting crushed glass up into a furnace where they are melted and pulled by gravity and surface tension into spheres. They are then allowed to fall, cool, and are collected. This process produces a wide gradation of bead sizes, with not all beads being spherical. Glass bead sizes between 106 µm to 600 µm are used in pavement marking applications(Dale, 1988). Special bead application is needed in the use of more rapidly drying paints since accelerated drying time reduces the allowable time for bead introduction and distribution (Dale, 1969).

Application of Traffic Paints

Pressurization is the most common force used to deliver the paint from the paint tank to the spray heads and onto the road. An air spray system atomizes liquid paint for application using air pressure. An airless spray system atomizes paint using hydraulic fluid pressure (NCHRP 17, 1973). The airless spraying system provides a higher pressure than the air spray system. The spraying system is usually truck mounted and equipped with a mixer and a compressor (OECD, 1975). Variation in truck speeds, paint temperatures, and the hydraulic head of the paint in the tank results in a different wet-film thickness of the paint (Dale, 1988).

Alternative application methods for traffic marking paint is pumping, such as circulating pumps and positive displacement pumps. The circulating pumps system offers better control in paint film thickness over a spraying system. Only truck speeds vary the paint film thickness. The positive displacement pump is popular in Europe. Its pumping rate directly relates to the truck speed resulting in a constant film thickness being applied to the pavement. (Dale, 1988).

1.2.2. Thermoplastics

Thermoplastics change physical state related to temperature. Thermoplastics are applied as a liquid and dry solid at ambient temperatures, similar to paints. The difference is thermoplastics require a much higher application temperature than paint in order to be applied as a liquid. Another difference is that once paint is applied, the water or solvent evaporates and the paint cannot be transformed back to a liquid. If the temperature of the thermoplastic is raised to it application temperature, the thermoplastic will return to a liquid state. Generally, thermoplastic marking materials consist of resins as a binder, glass beads, pigments, and fillers. Three kinds of resins are currently used for thermoplastics: alkyd resins, hydrocarbon resins, and epoxy resins (Dale, 1988).

Alkyd and Hydrocarbon Thermoplastics

Alkyd and hydrocarbon thermoplastic typically consist of 18 percent by weight resins, 25 percent by weight glass beads, 25 percent by weight fillers, and 32 percent by weight pigment and extender. Alkyd based thermoplastics and alkyd based paints contain similar materials: an alkyd resin binder, glass beads, pigment, extender, and filler. However, the paint is mixed with a solvent or water as a thin film for placement while the thermoplastic is placed as a thick film using heat. Hot-sprayed and hot-extruded thermoplastic striping materials have advantages over water based and solvent based traffic paints. Thermoplastics are faster drying and typically longer lasting but they cost more than paints and require special application equipment. When compared to solvent based paints, thermoplastics typically have a higher viscosity and surface tension, and poorer bonding to pavement surface. (NCHRP Synthesis 17, 1973, and Dale, 1988).

There are two methods of applying (alkyd-based or hydrocarbon-based) thermoplastic markings: spraying and extrusion. Thermoplastics can be sprayed by an atomizing air spray or an airless spray system. The thickness of thermoplastics applied by spraying application are often between 1.5 and 2.3 mm whereas extrusion method thickness' are between 2.3 and 3 mm. The extrusion application has two methods called the Dragging Die (or shoe method), and the Ribbon Extrusion. The applicator drags the die containing the hot material forward and a gate on the die is opened to a preset gap which forms the width and thickness of the marking lines. The ribbon method places a ribbon of molten thermoplastic from a moving application machine down on the pavement. The Dragging Die is the most favorable method for thermoplastic extrusions because it does not require the need for pre-made ribbons.

Thermoplastics cost five to six times more than paints and typically last 3 to 5 years. The application temperature is important in order to obtain optimum bond strength between the thermoplastic and road surface. Most specifications call for an application temperature of 218^{o}C (425^{o}F) for thermoplastic materials.

Successful use of thermoplastic relies on applying the material to a dry and clean pavement. Moisture on the pavement causes blistering and interferes with the bonding mechanism between the thermoplastic and pavement. There are two methods to measure if the pavement is too wet for application of thermoplastics. The first method requires laying a 1m x 2 m (3 ft x 6 ft) tar paper on the pavement surface for approximately 15 to 30 seconds. If after the time the underside of the tar paper has heavy condensation, the thermoplastic should not be used. The second method, introduced in Texas, requires taping a 0.6 m (2 ft) square of clear plastic film onto the pavement. If beads of water form on the underside of the film after 20 minutes, the pavement is considered too wet. Pavement surface temperature should always be considered in the application of thermoplastics.

Thermoplastic Epoxy (Epoflex)

Epoflex is a formulation of thermoplastic marking materials in which the binder is made by plasticizing a solid epoxy resin with a viscous liquid epoxy resin. The chemical name of the epoxy resins is epichlorohydrin-bisphenol A, which is a compound that occurs as thin liquids, viscous liquids, and solids, depending on its molecular weight. A liquid hardening agent is mixed and reacted with the liquid epoxy resin to form a solid adhesive. The compound is a thermoplastic in nature. It is solid at ambient temperatures and liquid at elevated temperatures. Epoflex has the following formulation as shown in Table 1.2 (Chollar and Appleman, 1980):

Table 1.2: Formulation of Epoflex

Materials	Percentage by Weight	
	White	Yellow
Solid epoxy resin	30	30.0
Liquid epoxy resin	20	20.0
Titanium dioxide	10	0.0
Lead chromate	0	9.3
Calcium carbonate	10	10.0
Premix beads	14	14.0
Extender & Filler	16	16.7

Application of Epoflex needs a heated tank with low pressure, 340 to 410 kPa, and air pressure to force the material down a heated line through a valve and out through a fan-spray nozzle. The temperature for heating the Epoflex is 230^{o} C (450^{o} F). The thickness of Epoflex being applied as a thin film is 0.3 to 0.5 mm. Spraying Epoflex is smokeless and the drying time is approximately five seconds from initial contact with the pavement.

1.2.3. Thermosets

Thermosetting materials are those in which two different components react exothermically to produce a hard and durable material. Two kinds of thermosets for pavement markings are epoxy and polyester.

Epoxy

Epoxy is a mixture of two components which react chemically in a heat-releasing (thermosetting) reaction to form a solid adhesive. Typically, the first component contains the epichlorohydrin-bisphenol A epoxy resin, the pigment (titanium dioxide or medium chrome yellow), extenders, and fillers. The second component, which is the catalyst, can be one of a large number of compounds. An amine, a group of organic compounds of nitrogen, is often used. The ratio of the first to the second compound can range from 1:1 to 5:1, depending on the specific chemistry of the system.

Most of the epoxy application systems pump the two components with metering pumps. Both components encounter one another in a power mixer, after which they exit through a spray gun. The thickness of epoxy applied is typically 0.4 mm. Some epoxy formulations can be applied to wet pavements. A water spray gun wets the pavement. Most epoxy formulations in use cure in 15 to 30 minutes and require line protection.

Polyester

Thermosetting polyester pavement marking is comprised of two components. The first component, which is 95 to 99 percent by weight, consists of polyester resin, styrene monomer, wetting agent, adhesion promoter, pigment (titanium dioxide or lead chromate), and calcium carbonate. The second component is a mehyl-ethyl-ketone peroxide catalyst. The actual compositions of polyester marking materials are proprietary to the manufacturers. Both components are mixed together using two separate spray guns. The catalyst is sprayed into the first component after the first component has exited the spray gun but before contacting the pavement. Polyester performs well on aged asphalt concrete. It is applied with a film thickness of approximately 0.4 mm. Drying times normally occur in the range of 10 to 45 minutes and require line protection (Culp, 1981, and Dale, 1988).

1.2.4. Tape

Tapes for pavement markings are of two types:

1. Regular or permanent tapes
2. Removable tapes

Permanent tapes are pre-formed plastic strips fabricated as roll sheet stock or cut-out legends in a factory. Typical composites of tapes are polyvinyl chloride resin binders, pigment, filler, extender, and glass beads. Two types of regular tape marking materials with the following specifications are shown in Table 1.3 (Bryden and Gurney, 1984):

Table 1.3: Specifications of Two Types of Tapes

Composites	Type I (% by weight)	Type II (% by weight)
Resins	40	20
Pigment & Filler	38	30
Glass Beads	14	33
Extender	18	17

Tapes having a pre-applied adhesive backing are normally applied to the road by removing the protective paper backing and pressing the tape onto the pavement with either a roller or truck tire. Adhesive must be applied to the pavement or the tapes at the time of the application if the tapes do not come with pre-applied adhesive backing. A pavement surface to which tapes are to be applied must be clean, free of oil and debris, and applied at a recommended temperature of at least 21° C (70 ° F) (Robertson, 1981). The benefit of tapes for pavement markings is their application takes little or no equipment.

Removable tapes are frequently used as temporary marking materials around construction sites or for special events, such as parade routes. However, the unit cost of tape is high. The evaluation of approximately 200 special markings of pre-formed tapes in North Carolina showed poor reflectivity of pre-formed tapes and problems with pavement adhering (Attaway, 1989).

1.2.5. Raised Pavement Markers (RPM)

Raised pavement markers can be non-reflectorized or reflective. Non-reflectorized raised marker material is made of ceramic with a glazed surface and are preferred to those made with plastics and other materials because of their resistance to scratching. Reflective raised markers most often use cube-cornered acrylic lenses, tempered-glass lenses, or glass-bead lenses. They are mounted in either a plastic, ceramic, or metal base.

Raised reflective markers have proven beneficial to motorists during low visibility conditions such as rain or night. Negative features include initial cost, replacement cost, traffic disruption during placement, and destruction by snowplow blades. Snow-plowable raised markers and embedded raised markers have been explored with limited success. The Federal Highways Administration (FHWA) recommended use of raised reflective markers to simulate lane lines on Interstate highways having three or more lanes in each direction (NCHRP Synthesis 17, 1973 and Hulbert, 1986).

1.3. Life Expectancy and Costs

The life expectancy of pavement marking materials is a function of the type of pavement, traffic volume, type of traffic, and the climate. Most of the pavement marking materials fail more quickly on Portland cement concrete (PCC) than asphalt concrete (AC) pavements except the epoxy and raised pavement markers. In most cases, the failure relates to the loss of adhesion. The volume of traffic directly impacts the life expectancy of pavement markings. The increased speed of traffic and truck load can also reduce the service life of markings (Dale, 1988).

Environmental elements cause deterioration of pavement marking materials. Ultra-violet light causes the chemical bonds of resins and pigment components to break down and loose their original properties. Fluctuations in temperatures cause both the pavement and the marking materials to expand and contract. If the bond strength is greater than the tensile strength of marking materials, cracks will develop in the marking materials. Salt and sand, snowplows, studded tires, and chains are used in the snow-belt areas which deteriorate pavement marking materials through abrasive interaction.

The life expectancy and costs of pavement markings presented here were collected from various field test sites.

Figure 1.1 shows that life expectancy of solvent-based paint on an Asphalt pavement is 4 to 10 months, and 2 to 7 months for a Portland Cement Concrete (PCC) pavement according to Dale (1988) for a range of snowfall conditions. The cost per gallon of paint is $5 to $10 and installation cost of a 4 inch wide by 0.2 mm thick dry line is $0.03 to $0.06 per linear foot.

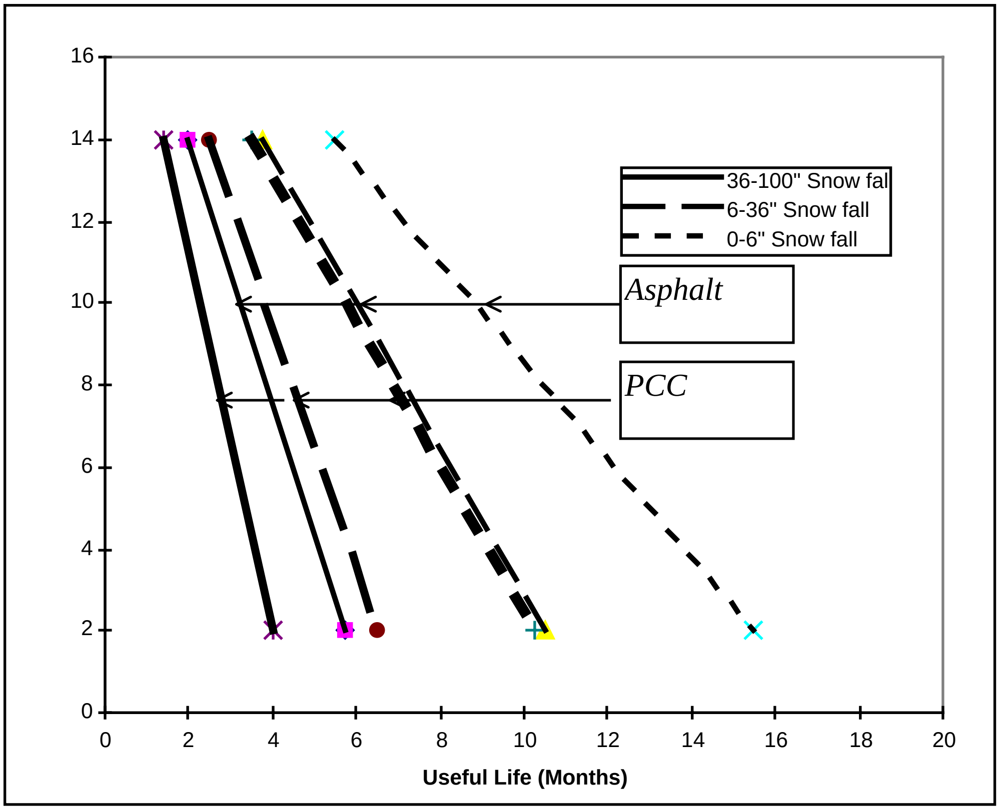

Figure 1.1. Life Expectancy of Solvent-Based Paint on Asphalt and Portland Cement Concrete Pavements.

Source: Adapted from Dale, 1988 (Figure 22 and 23).

The life expectancy of alkyd or hydrocarbon-based thermoplastics is shown in Figure 1.2 according to Dale (1988) for a range of snowfall conditions. Thermoplastics on an Asphalt pavement last 5 to 9 years while only 3 to 5 years on a Portland Cement Concrete. Thermoplastics cost $700 to $900 per ton. Installation of a 4 inch wide and 3 mm thick line costs $0.30 to $0.40 per linear foot.

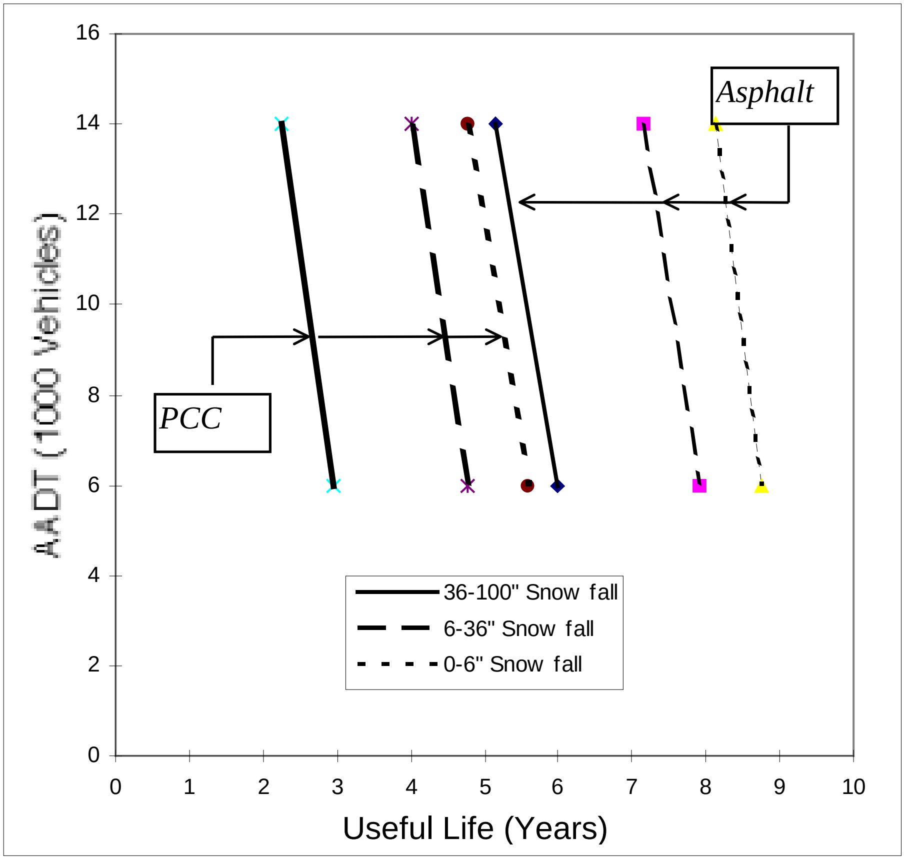

Figure 1.2. Life Expectancy of (Alkyd or Hydrocarbon-Based Thermoplastics)on Asphalt and Portland Cement Concrete Pavements.
Source: Adapted from Dale, 1988 (Figure 24 and 25).

Figure 1.3 illustrates the life expectancy of thermoplastic epoxy (Epoflex) according to Dale (1988) for a range of snow fall conditions. The life span of Epoflex on both Asphalt and Portland Cement Concrete pavements is 2 to 5 years. The cost of Epoflex is $2500 per ton and $0.21 per linear foot installed at 4 inches wide by 0.4 mm thick.

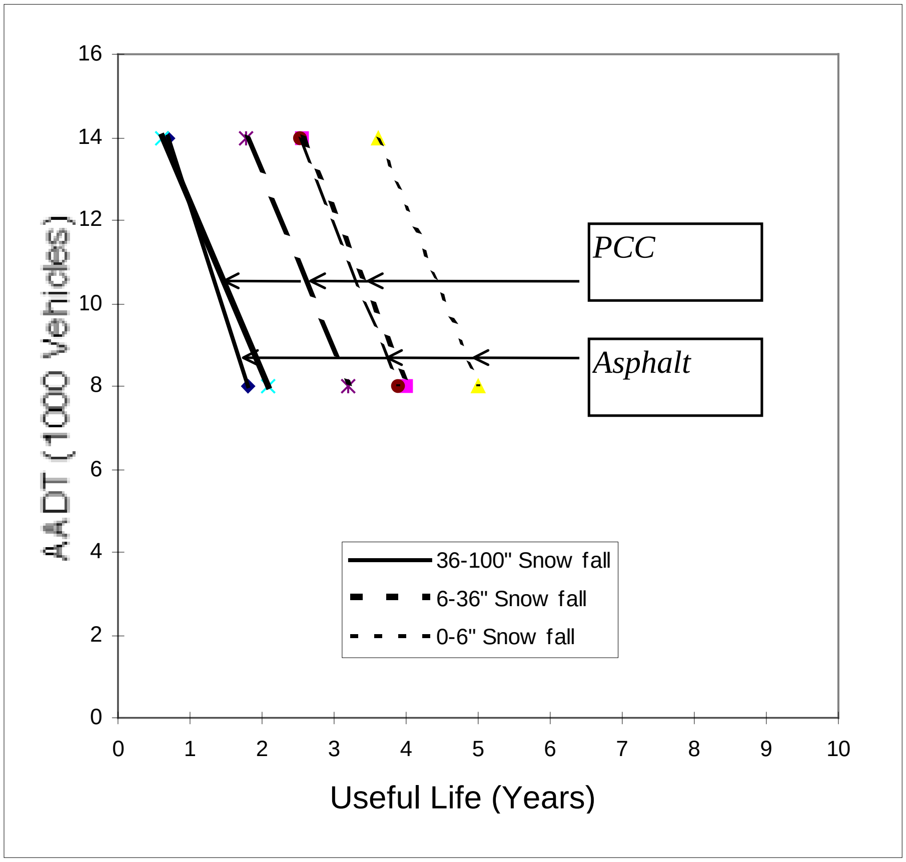

Figure 1.3 Life Expectancy of Thermoplastic Epoxy (Epoflex) on Asphalt and Portland Cement Concrete Pavements.

Source: Adapted from Dale, 1988 (Figure 26 and 27).

Thermoset polyester on an asphalt pavements lasts 2 to 4 years as shown in Figure 1.4 according to Dale (1988) for a range of snowfall conditions. Polyester costs $10 to $15 per gallon and $0.12 to $0.25 per foot installed of 4 in., 0.4 mm line.

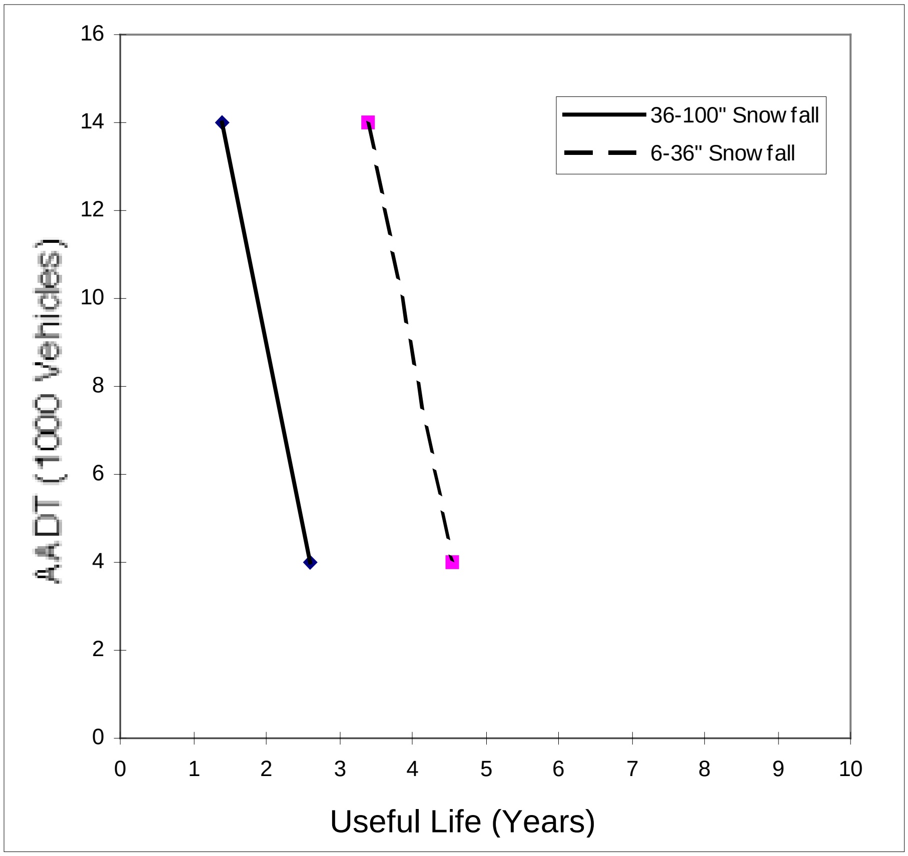

Figure 1.4. Life Expectancy of Polyester on Asphalt Pavements.
Source: Adapted from Dale, 1988 (Figure 28).

The life expectancy of two-component internally mixed epoxy is 2 years for both types of pavements as shown in Figure 1.5 according to Dale (1988) for a range of snow fall conditions. Based on the $20 per gallon of epoxy, installation cost of epoxy is $0.30 per foot of 4 inch wide and 0.4 mm thick line.

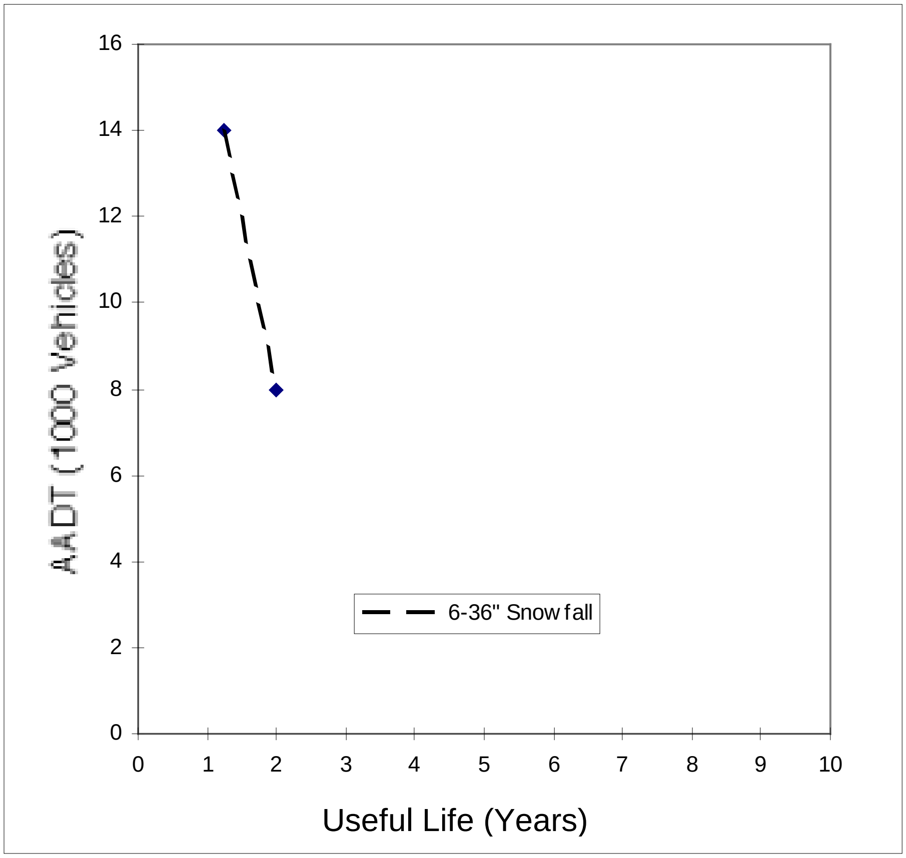

Figure 1.5. Life Expectancy of Two-Component Internally Mixed Epoxy on both Asphalt and Portland Cement Concrete Pavements.

Source: Adapted from Dale, 1988 (Figure 29).

The life expectancy of pre-formed tape on both Asphalt and Portland Cement Concrete pavements is between 3 and 7 years as shown in Figure 1.6 according to Dale (1988) for a range of snow fall conditions. The cost of tape materials is $0.50 to $0.80. The installed cost of tape is $1.00 to $1.20 per linear foot of a 4 inch wide by 2.3 mm thick line.

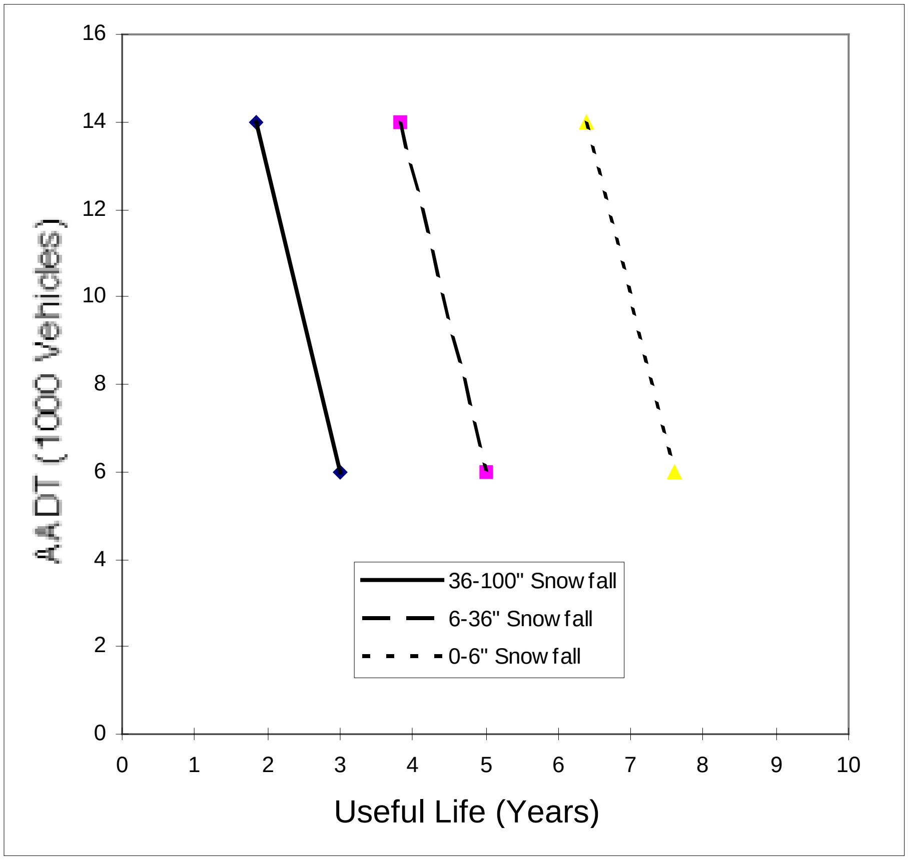

Figure 1.6. Life Expectancy of Pre-formed Tape on both Asphalt and Portland Cement Concrete Pavements.

Source: Adapted from Dale, 1988 (Figure 30).

Figure 1.7 shows the life expectancy of raised pavement markers, snowplow-able, and recessed markers on both cured Asphalt and Portland Cement Concrete pavements according to Dale (1988) for a range of snow fall conditions. Raised markers laid in areas having annual snowfall of up to 6 inches last about 7 years. Snow-plowable and recessed markers used in the heavy snowfall areas (6”-36”) can last 5 years. Installed cost of raised pavement markers is between \$1.00 to \$3.00 per marker. Snow-plowable and recessed markers have an installation cost of \$6.00 to \$10.00 per marker (Dale, 1988).

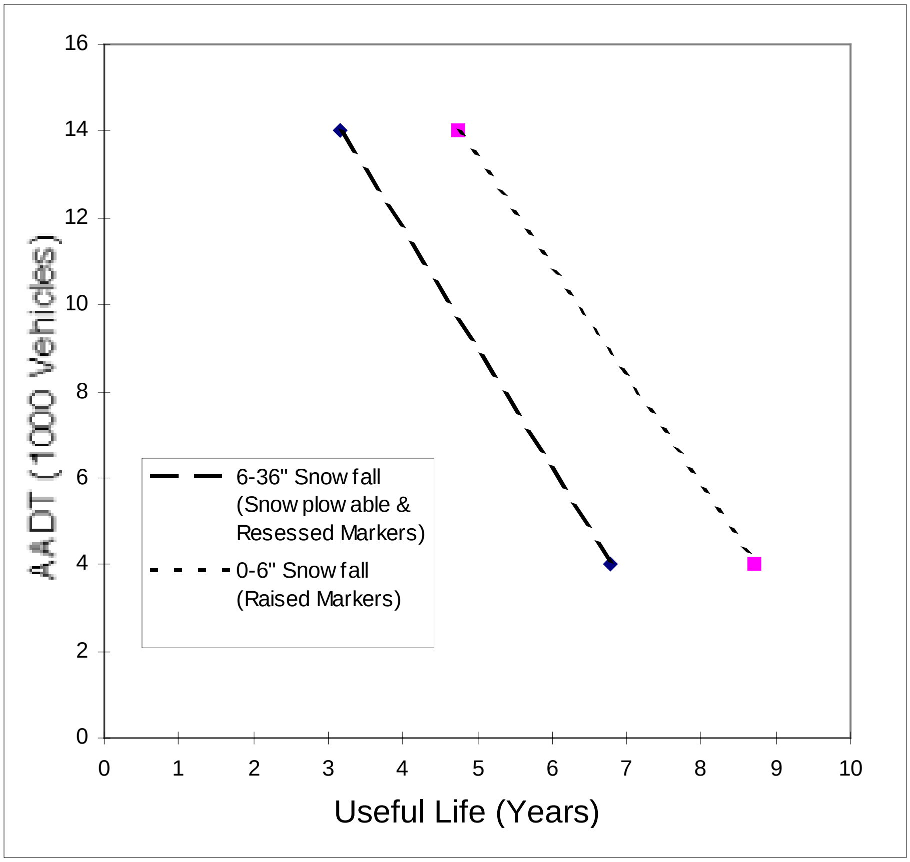

Figure 1.7. Life Expectancy of Raised Pavement Markers, Snow-plowable, and Recessed Markers on both Cured Asphalt and PCC Pavements.
Source: Adapted from Dale, 1988 (Figure 31).

A summary of the performance characteristics of solvent-based paint, waterborne paint, alkyd and hydrocarbon thermoplastics, Epoflex, epoxy, and tape is shown in Table 1.4. The life expectancy estimates shown in Table 1.4 are based on an AADT of 8,000 vehicles per lane.

Table 1.4: Summary of Pavement Markings Characteristics

Materials	Dry/Set Time (minutes)	Typical Thickness (mm)	Life Expectancy (Based on 8,000 AADT/lane)	Cost (per installed linear foot)
Solvent-Based Paint (Moore, 1978, Glennon, 1979, and Dale, 1988)	0.5 - 7	0.2	4 - 10 months on an asphalt concrete, 2 - 7 months on a PCC.	\$0.03 - \$0.06
Waterborne Paint (Chatto and Warness, 1985, and Dale, 1988)	10	0.2	≥ solvent-based paint	\$0.10
Alkyd and Hydrocarbon Thermoplastics (Dale, 1988)	0.01	1.5 - 2.3 spraying, 2.3 - 3 extrusion.	5 - 9 years on an asphalt pavement, 3 - 5 years on a PCC.	\$0.30 - \$0.40
Epoflex (Dale, 1988)	0.08	0.3 - 0.5	2 - 5 years on an asphalt pavement, 2 - 4 years on a PCC pavement.	\$0.21
Epoxy (Gillis, 1981, and Dale, 1988)	15 - 20	0.4	2 years on both types of pavements.	\$0.30
Tape (Bryden and Gurney, 1984, and Dale, 1988)	0	1.5 - 2.3	3 - 7 years on both types of pavements.	\$1 - \$1.20

Figures 1.1 through 1.7 and Table 1.4 from Dale (1988) show the useful life performance for various pavement markings. Dale found that Paint has a life expectancy of less than one year on both Portland cement and Asphalt Concrete. Dale results indicate that Thermoplastics and Tape provide for the longest life expectancy of with between 3 and 9 years. Dale further found that the majority of the pavement marking materials reviewed had longer life expectancies on Asphalt as Portland Cement. Only Epoxy and Tape were found to have the same life expectancies on both Asphalt and Portland Cement Concrete. Dale's results will provide comparison data for this studies results.

1.4. Other Pavement Marking Research

This section contains a review of other research related to pavement markings to provide an overview of the state of technology. Included is recent research on the development of rating systems for classifying pavement markings conditions, how pavement markings have performed in comparison studies of retro-reflectivity and the impacts of reflectivity on driver performance.

1.4.1. A Decision Support System

A decision support system (DSS) was developed for the Connecticut Department of Transportation (ConnDOT) in 1995. The purpose was to aid in selecting pavement marking materials (Davis and Campbell, 1995). The DSS is based on a multi-criteria decision making model using an objective function based on the assignment of weights to measurement values associated with the various criteria. A goal hierarchy was developed based on inputs from the individual and group meetings. Safety, convenience, and availability were the main goals. The goal hierarchy has 12 measures:

1. Initial retro-reflectivity in dry weather condition
2. Initial retro-reflectivity in wet weather condition
3. Final retro-reflectivity in dry weather condition
4. Final retro-reflectivity in wet weather condition
5. Reliability
6. Safety during application
7. Total cost
8. Protection sensitivity during installation
9. In-house capability for application
10. Life cycle prediction
11. Availability of supplier
12. Availability of applicator

A measurement scale was defined for each measure.

- Measures 1 and 3 are both dry-pavement retro-reflectivity, measured in millicandelas per square meter per lux (mcd/m^2/lux). Data collected included published data, measurements on a sample of Connecticut roads, and combinations of sampling and published data.
- Measures 2 and 4 represent pavement marking performance under moderate rainfall conditions. A scale ranging from 1 (barely visible) to 5 (excellent) was developed by ConnDOT.
- Measure 5, reliability, is quantified on a five-point scale ranging from 1 to 5. Level 1 is “ConnDOT has had experience with or strong reason to

suspect premature failure." Level 5 is "There is strong evidence that the material has a high probability of lasting for its specified life."

- Measure 6, the measure for installation safety, remains fixed for a given pavement marking alternative. A quantified five point scale ranging from 1 to 5 is based on ConnDOT's experience with marking types. The higher scores, represented the more desirable states of the marking materials.

Measure 7, the total cost, is designed to incorporate all costs associated with the pavement markings that are expected to be incurred over a 10-year time horizon. The total cost unit is in dollars per linear meter per year.

Measure 7 = [(A x B) + C + (D x E) + F]/10;

where:
A: Cost of Materials and Installation for each Application ($/m),
B: Expect Number of Applications in 10 Years,
C: Maintenance Costs over 10 Years ($/m),
D: Cost of Each Eradication ($/m),
E: Expected Number of Eradications over 10 Years ($/m),
F: Other Costs Incurred over 10 Years ($/m).

- The last five measures (Measure 8 to Measure 12) that relate to convenience are measured using similar ConnDOT-developed scales ranging from 1 to 5 (Davis and Campbell, 1995).

Measurement values for each material are transformed into an overall score for the material using the objective function. This transformation involves two steps. First, each measurement value is converted into a single-measure utility value. Second, single-measure utility values are weighted to obtain multi-measure utility values.

The above discussion may provide a basis from which UDOT may develop its own decision support system similar to ConnDOT. This could be beneficial in determining where on UDOT roadways various pavement marking materials are appropriate.

1.4.2. Evaluating Subjective / Instrumental Reflectivity

A correlation study of subjective and instrumental evaluation of pavement marking retro-reflection was conducted on a two lane, unlit rural highway near West Milford, New Jersey (Niessner, 1987). The roadway was divided into seven test sections. Each section includes a double yellow centerline and a 8-in (203-mm) wide white edge-line. Each line of the centerline had a different bead system. The edge-line was divided into two 4-in (102-mm) widths. Therefore, each test section had four lines composed of different materials. Subjective evaluations were rated at night by 18 raters using a scale from 1 to 10, with 10 as the brightest. The light source was low beam headlights from an automobiles. Each line was rated by the observers three times on three separate drives through the test sections. For instrumental evaluation, fourteen different retro-reflectors were used. Retro-reflectors used in this evaluation were based on high angle, medium angle, and low angle geometry. Some of them were in-house retro-reflectometers designed by highway agencies. Others were introduced by companies, i.e., the Ecolux, the Erickson, and the Optroniks. Each instrument took five measurements on each line in the seven test sections.

Three separate comparisons were performed to compare: one rater with another rater, one retro-reflector with another, and comparing the instrumental data and the subjective ratings. The results show that correlation among subjective ratings was not very strong. The ranges and standard deviations of the correlation coefficients for the instrumental data are much smaller than those of the subjective ratings. In all of the comparisons, the ranges of the correlation coefficients are larger for the yellow lines than for the white lines. It is concluded that retro-reflectors reduce study costs and allow for safer data collection operation. The retro-reflector measurements can be made by one person in the daylight during normal work hours, whereas subjective ratings were made at night with a number of raters (Niessner, 1987).

While objective analysis using instrument measured retro-reflectivity may provide for material type and application guidelines, the purpose of pavement markings are to provide instruction to the driver. A subjective survey performed by UDOT using a sample of drivers may provide insight into pavement marking which can not be quantified by retro-reflectivity measures alone.

1.4.3. Paint Measures of Performance

Parker, Jr. and Shoemaker (1993) provided a better understanding of physical properties of pavement marking paints by predicting the durability of paint pavement markings. Two laboratory tests evaluated the physical properties of pavement marking paints. Tensile tests of free film specimens on paint yielded several properties derived from stress-strain curves. Abrasion tests provided abrasion resistance for both dry and wet conditions.

Ten paint samples representing a variety of volatile and nonvolatile vehicles were tested and evaluated using the laboratory tests developed. The volatile vehicle was either an organic solvent or water. The nonvolatile vehicle was resin, e.g., alkyd resin, and alkyd-chlorinated rubber. For tensile tests, the waterborne paints were considerably more ductile than the organic solvent based paints. However, the waterborne paints performed poorly when submerged in water for the abrasion tests. The alkyd resin paint had the highest abrasion resistance considering both wet and dry test results (Parker, Jr. and Shoemaker, 1993).

The 10 paints were evaluated in the field for 5 years. The performance of the ductile waterborne paint was superior to the more brittle solvent based paints, chlorinated-rubber paints, and alkyd resin paints. Correlation of pavement marking performance with modulus of toughness and dry Taber abrasion wear index showed that paint properties measured by both were necessary and should be considered in paint evaluation (Parker, Jr. and Shoemaker, 1993).

The performance of a pavement marking material should be based on other performance criteria than simply retro-reflectivity. Truck use, snowplows, salt, and tire chains are all factors which influence pavement marking performance.

1.4.4. Marking Patterns and Driver Performance

Harkey, et al. (1993) studied the operational effects of different markings patterns on driver performance. Two non-permanent marking patterns tested were 0.61-m stripes with 11.59-m gaps (2-ft stripes with 38-ft gaps) and 1.22-m stripes with 10.98-m gaps (4-ft stripes with 36-ft gaps). Both patterns were compared with the standard full complement of markings recommended in the MUTCD, i.e., 3.05-m stripes with 9.15-m gaps (10-ft stripes with 30-ft gaps) and edge lines. The marking material for all three patterns was retro-reflective paint. The field data procedure used a van following and videotaping the operations of random cars in the traffic stream along the test segment. Some 436 samples were collected. Data was collected for all three marking patterns during day and night, and under dry and wet weather conditions. Driver performance was evaluated on the video tape based on measures of effectiveness (MOEs).

The MOEs included lateral placement of the vehicle on the roadway, vehicle speed within the test segment, number of edge line and lane line encroachments, and number of erratic maneuvers. The lateral placement measures the distance from the lane line to the center of the vehicle. The speed for the analysis was the average running speed over the test segment. The number of encroachments occurring during each run was the measure used in the analysis. The erratic maneuvers include occurrences of sudden speed or directional changes, and brake applications (Harkey, et.al., 1993).

In conclusion, the 3.05-m (10-ft) marking pattern generally resulted in better performance than either the 0.61-m (2-ft) or 1.22-m (4-ft) pattern. Although there was not a large number of statistical differences in the comparison of operational measures for the two non-permanent marking patterns, certain trends existed with respect to driver performance (Harkey, et.al., 1993):

- The speed at which the drivers traveled decreased as the length of the lane line decreased.
- Drivers positioned their vehicles closer to the center of the lane as the length of the lane line increased.
- The variability of vehicle placement within the lane increased as the length of the lane line decreased.
- The number of encroachments increased as the length of the lane line decreased.
- All operational measures were negatively affected by adverse weather conditions.

The cumulative results of the number of encroachments per run show that drivers performed better with the 1.22-m (4-ft) pattern than with the 0.61-m (2-ft) pattern. Under dry weather conditions, day and night, the number of encroachments is 33 percent higher for the 0.61-m (2-ft) pattern than for the 1.22-m (4-ft) pattern. This value increased to 50 percent for nighttime/wet weather conditions and 77 percent for daytime/wet weather conditions (Harkey, et.al., 1993).

1.4.5. Minimum Nighttime Retro-reflectivity

Ethen and Woltman (1986) performed experiments to find a minimum retro-reflectance for nighttime visibility of pavement markings. The question of minimum retro-reflectance depends on the retro-reflective qualities of the painted line, the quality of head-lamp illumination, the contrast between the line and the adjacent road surface, and the presence or absence of roadway lighting. The tests used 4 inch x 10 foot white tapes with eight separate retro-reflectance levels. The retro-reflectance values are expressed as specific luminance in units of millicandelas per square meter per lux ($mcd/m^2/lx$). Tests involved placing three consecutive stripes for each specific luminance with a 30-ft gap in the center line on an asphalt road. The initial retro-reflectance values included 30, 70, 90, 140, 200 450, 625, and 1,700 $mcd/m^2/lx$. Luminaries were positioned along one side of the test road mounted at a 50-foot height with 250-foot spacing and were provided with 250-watt mercury-vapor lamps.

The tests viewed the tape pavement markings under both dark condition and ambient illumination. One driver and one observer rode together in each car and recorded separate ratings. The subjective ratings used a scale of 1 (very poor) to 7 (superior). The results support a minimum line specific luminance level of 100 mcd/m^2/lx under ideal dark condition. This value is comparatively agreed with in a study by Allen, et.al. (1977) and Serres (1981). The line minimum specific luminance from Allen's study is 90 mcd/m^2/lx, while from Serres's study it is 100 mcd/m^2/lx. For an acceptable line specific luminance, 400 mcd/m^2/lx or higher is indicated for dark roadways, and at least 300 mcd/m^2/lx is accepted for illuminated roadways by Ethen and Woltman (1986).

A minimum acceptable line retro-reflectivity of 100 mcd/m^2/lx as found by Ethen and Woltman (1986) provides a luminance point where pavement marking are considered to end their useful life. For this study, the 100 mcd/m^2/lx will be considered the retro-reflectivity where useful life ends.

1.4.6. Thermoplastic and Tape Comparison

North Carolina performed an in-service evaluation of thermoplastic and tape pavement markings using two hand-held retro-reflectometers, Ecolux and Mirolux 12 (Attaway, 1989). Center lines, edge lines, and special markings, i.e., arrows and symbols were measured by manually place retro-reflectometers on a small section of the pavement markings. The Mirolux 12 unit collected most of the readings because of its ease of operation and speed in data collection. Each tape product was measured 5 to 10 times to determine its retro-reflectivity level. The different readings were averaged to obtain a retro-reflectivity value for each sample.

This paper accepted a minimum retro-reflectivity value of 100 mcd/m^2/lx for comparison of the collected retro-reflectivity readings. The readings were acceptable if the retro-reflectivity value was greater or equal to 100 mcd/m^2/lx, otherwise they are unacceptable. Note that this is not the minimum acceptable standard for pavement markings in the United States. Approximately 350 road miles of thermoplastic on 60 different projects, covering the period from 1979 to 1986, were evaluated. The results showed that nearly all white thermoplastic markings were found to be acceptable regardless of age. More than half of the yellow thermoplastic markings were found failing after less than 6 years of service in both the edge line and center line. For special markings, the evaluation of tape showed that the material was not providing an acceptable retro-reflectivity level after only 2 years. This raised a question of whether tape should be used in special markings except under lighted conditions (Attaway, 1989).

The study by Attaway (1989) showed that Thermoplastic provided for a longer life than Tape. It was concluded that the higher cost of Tape did not provide a longer life or a superior product.

1.5. Review Conclusions

Pavement markings generally used by highway agencies consist of solvent based paint, waterborne paint, thermoplastics, epoxy, Epoflex, tape, and raised pavement markers. The different types of pavement markings have been developed over the last 50 years to provide better performance i.e., durability, reflectivity, and ease of application. The visibility enhancement of pavement marking is achieved by mixing glass beads into the pavement marking materials matrix. The life expectancy and costs of the pavement markings are important elements in considering the best pavement marking choice. Technology for pavement markings is attempting to produce tangible measures of performance using both empirical subjective and objective methods as described in section 1.4.1 through 1.4.6. These measures of performance of pavement marking materials include retro-reflection properties, effects of marking patterns on driver performance, a minimum nighttime retro-reflectance, and development of multi-criteria decision making models in selecting pavement markings.

2. DATA COLLECTION

The objective of this study was to measure the retro-reflectivity of pavement markings for the Department of Transportation State of Utah and develop relationships between age, AADT and useful life of the pavement marking materials in order to develop a cost analysis. In order to produce a relationship between AADT and useful life of pavement markings, data needs included material type, location and date of application, retro-reflectivity, and AADT at the location of the measured marking material. UDOT provided a database of the contract jobs from May 1994 through December 1995. The database shows stripping locations for 23 Epoflex, 12 tape, and 3 thermoplastic installations. A thorough list of contract jobs of tape location and date of application beginning in 1989 through 1995 was also provided. There are only three places with thermoplastic pavement markers which does not provide enough data to draw conclusions regarding Thermoplastic performance. Therefore this study focuses on investigating the performance of Epoflex epoxy, solvent based paint and permanent pavement marking tape. These materials are referred to as “Epoflex”, “Paint”, and “Tape”. The retro-reflectivity of the pavement marking materials is used to determine a useful life based on age, AADT, initial applied retro-reflectivity, and minimum allowed retro-reflectivity.

2.1. Retro-reflectivity Survey Plan

UDOT provided traffic volume maps for Utah through the "Traffic on Utah Highways, 1993" publication. Tape locations were initially marked on the maps with different colors based on year of application from 1989 to 1995. Any location not designated by the tape or in the contact database was assumed to be Epoflex or Paint. Therefore, another set of maps for Salt Lake Urbanized Area was prepared with different colors based on various AADT levels. Based on these two sets of maps, the survey routes were planned to cover the locations of tape, Epoflex, and Paint at different AADT levels. After the collection of retro-reflectivity data, UDOT's Maintenance Management System (MMS) was accessed to determine the date of application of material for each surveyed location.

2.2. Retro-reflectivity Survey

A survey collected retro-reflectivity data from April 18 to 23, 1996 using the new mobile retro-reflectometer developed under the Small Business Innovation Research Program, through the FHWA. The retro-reflectometer system and application software, called Laserlux, was developed by the Roadware Corporation. However, Henderson & Associates is the prime contractor for FHWA to demonstrate nationwide the performance of the system.

The retro-reflectometer device uses the principle of retro-reflection and a scanning laser to measure the retro-reflectivity of pavement markings. The device can be mounted on either the left or right outside of the van. The device mounted on the left side measures the lane division lines or center lines of pavement markings. Edge lines are measured by connection to the right side of the van. The retro-reflectometer has low entrance angle and the measurement is based on a 30-meter observation distance geometry. The 30-meter geometry is shown in Figure 2.1.

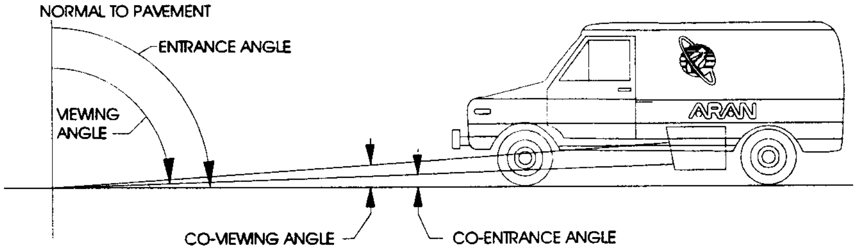

Figure 2.1: 30-Meter Geometry of Laserlux

The laser and receptor are mounted such that it simulates a vehicle's headlights reflecting to a driver's eye. The Laserlux system scales the observed distance by 1/3 such that it is actually measuring at a 10 meter distance. North American geometry standards place the angle between the headlight and the pavement at 1.5°.

The 30-meter observation distance geometry is an optical geometry which more closely resembles that of a typical driver. This geometry was selected under the FHWA's Test and Evaluation Project 29, Retro-reflectivity, because it conforms to the normal passenger automobile's viewing distance at night (Better Roads, 1996). Also, this method satisfies the Congressional requirement that FHWA established for minimum retro-reflectivity values for pavement markings (FHWA pamphlet, undated).

To achieve the 30-meter observation distance geometry and to set a target for laser beam, a piece of marking material is placed on the pavement 10 meters out from the laser lens. The laser device sits 26.2 centimeters above the pavement. A small TV monitor is connected inside the van for displaying the alignment of the marking materials while driving. Application software is run on a PC inside the van to record collected retro-reflectivity data. The van travels along the road at speeds up to 88 km/h (55 mph) measuring the retro-reflectivity of the pavement markings.

The retro-reflectivity values are measured in the units of millicandelas per square meter per lux (mcd/m^2/lx). The outputs are the average retro-reflectivity values for each station interval. Station interval size depends on initial desired distance, i.e., 66 ft., 132 ft., and 264 ft. The laser beam scans 200 sample points each interval. A valid retro-reflectivity value is between 50 and 600 mcd/m^2/lx. Values higher than 600 mcd/m^2/lx are defined as high invalid values. These can be caused by raised pavement markings. The values below 25 mcd/m^2/lx indicate an invalid retro-reflectivity. A total of 58 data files of the retro-reflectivity measurements covering about 500 miles were collected for State of Utah. A list of the survey routes is shown in Appendix A. The locations of the survey routes throughout the State are shown in Figures 2.2 through 2.4.

Figure 2.2: Retro-reflectivity Survey Routes in the Salt Lake City Area

Figure 2.3: Retro-reflectivity Survey Routes in the Ogden Area

Figure 2.4: Retro-reflectivity Survey Routes in the Provo Area

2.3. Material Application Dates

UDOT's MMS provides a record of the dates and type of pavement marking materials applied to the roadways. A review of the MMS on June 20 and June 24, 1996 provided date and marking material type information relevant to the roads surveyed by the Laserlux. The MMS contains only information regarding marking material applied by UDOT personnel. Therefore, the MMS was combined with two private contract databases. Terri Taylor of UDOT provided one database which described the date and marking material type of contract jobs from April 1994. Dal Hawks of UDOT provided the second database containing information where tape had been placed by contract from 1989 through 1995. The collected MMS data and two private contract databases are shown in Appendix B.

2.4. Site Verification of MMS Data

After the collection of the MMS data, a second driving survey over the retro-reflectivity surveyed route provided additional information. It is not known how often the UDOT's MMS database is updated, and the information obtained for both marking material type and age was checked for reasonability. Further, two other useful variables were observed: The road type (Portland Cement Concrete or Asphalt Concrete) and number of lanes. The later information was used to calculate the AADT per lane using the 1993 Traffic on Utah Highways. It was observed that some of the segments had been remarked or resurfaced since the original survey in April, 1996. The total number of sections observed was 60. It was not necessary to travel the entire surveyed route because many of the sections surveyed were not found in the MMS and therefore had to be dismissed due to lack of information regarding date and pavement marking material type.

The majority of the segments verified appeared to match the MMS information. Six segments were removed from the analysis and eleven segments could not to be verified. Those exceptions are as follows:

Six segments were eliminated on the basis of one or more of the following criteria: The material appeared to be much newer than the MMS claimed, the material was different than the MMS recorded, the road appeared to have been resurfaced just before the original retro-reflectivity survey took place and the MMS listed the material as being several years old. These sections are summarized in Table 2.1.

Table 2.1: Data Eliminated from Analysis

Road Name (UDOT Designation)	Segment (by UDOT milepost)
4700 South, Salt Lake City (A266)	3 to 4
3300 South, Salt Lake City (A171)	11.6 to 13.56
1300 South, Salt Lake City (A181)	0 to 2
Redwood Road, Salt Lake City (A68)	56.3 to 59
Harrison Blvd., Ogden (A203)	0.15 to 5.35
I15 N, Salt Lake City (A15)	304.52 to 306

There were eleven locations that could not be visually inspected because the road had either been resurfaced or remarked recently (after the original survey). In these cases, if the retro-reflectivity value measured seemed congruent with the date listed in the MMS, the MMS was trusted and the data segment used in the analysis. Table 2.2 summarizes these locations.

Table 2.2: Un-inspected Data included in the Analysis

Road Name (UDOT Designation)	Segment (by UDOT milepost)
I15, Between Mona and Nephi (A15)	228.09 to 232.19
SR 40, Between Park City and Heber (A40)	13 to 16
State Street, Salt Lake City (A89)	314 to 319
4700 South, Salt Lake City (A266)	0 to 2.81
State Street, Salt Lake City (A89)	320 to 326
State Street, Salt Lake City (A89)	323.6 to 324.4
Redwood Road, Salt Lake City (A68)	62 to 68.85
I15 N, Salt Lake City (A15)	325 to 328
12th Street, Ogden (A39)	4.01 to 5.66
I15 N, Salt Lake City (A15)	312.17 to 314.72
I15 S, Salt Lake City (A15)	316.3 to 318

2.5. AADT per Lane

Using the “Traffic on Utah Highways, 1993” (AADT) was collected for the road segments where marking reflectivity had been measured. The “Traffic on Utah Highways, 1993” does not provide directional split or lane utilization information. Therefore, it was assumed that there is a 50/50 directional split and uniform lane utilization. This means that an equal volume of daily traffic flows in each lane. From the collected number of lanes on each measured roadway, an AADT per lane is determined.

3. RETRO-REFLECTIVITY ANALYSIS

The data analysis involved relating reflectivity information collected by the Laserlux, with the age of striping material collected from the UDOT MMS, and the AADT traffic levels from the “Traffic on Utah Highways, 1993”. This was then developed into relationships between:

- Reflectivity and AADT
- Reflectivity and Age
- Material Deterioration Rate and AADT
- Useful Material Life and AADT
- Cost Comparison of the Materials

The result of the analysis is a set of equations that predict the useful life of a material based on traveled AADT. This can then be further defined into a cost analysis to determine which material provides the most cost effective life span benefit.

The terms used throughout the analysis process are defined below.

1. *Reflectivity Interval* - Small road segment intervals for which the Laserlux collects information. These interval distances are defined by the user and provide average reflectivity information for each small road segment. This analysis used 264 feet or .05 miles as the interval.

2. *Surveyed Section* - A complete segment of roadway measured by the Laserlux, composed of multiple reflectivity intervals.

3. *MMS Segment* - The sections of the roads for which data exists from UDOT on when the material was applied and the type of material.

4. *Analyzed Section* - The overlap sections of the roads where the reflectivity data collected by the Laserlux and the MMS Segment were both available.

Table 3.1 provides the notation used throughout the analysis process.

Table 3.1: Notation Used Throughout the Analysis

Notation	Name	Description
A	Age	Age is defined in months since the pavement marking material was applied to the road
C	Monthly Cost	Installed cost per linear foot per month, based on the Useful Life (U) of a material
C_i	Installed Cost	Installed cost per linear foot
D	Deterioration Rate	The monthly rate at which reflectivity is decreasing measured in (mcd/m^2/lux)/month
I	Initial Retro-reflectivity	The initial Retro-reflectivity when it was first applied at age 0 and AADT of 0.
k	Number of r in R	Number of Reflectivity Intervals per related Analyzed Section for (i^{th}) analyzed sections
M	Minimum Retro-reflectivity	The minimum acceptable retro-reflectivity before the material is considered to be beyond its useful life. This is defined as 100 mcd/m^2/lux
n_i	Acceptable values for a Reflectivity Interval (r_i)	The number of acceptable Retro-reflectivity values in a reflectivity interval (r)
N	Acceptable values from Reflectivity Section $\sum(r_i)$	The sum of n values from all Retro-reflectivity intervals of an Analyzed section.
r_i	Reflectivity Interval	Average Retro-reflectivity of ith 0.05 mile interval of an analyzed section
R	Reflectivity Section	Weighted average Retro-reflectivity of all r_i (0.05 mile intervals) in a continuous analyzed section
U	Useful Life	The life expectancy of a pavement marking material for a given (I), (D) and (M)
V	AADT	The Annual Average Daily Traffic in Vehicles per Lane

3.1. Defining Analyzed Sections

Having completed the retro-reflectivity surveys, the routes were compared with the marking application data supplied by the UDOT MMS database. Many of the surveyed sections were not included in the MMS and the surveyed sections rarely corresponded precisely with the MMS segments. This meant that many of the surveyed sections and MMS segments either overlapped, were incomplete, or had different application dates.

Also, surveyed sections of road that had a different AADT per lane were divided into multiple data segments. Where the AADT per lane for the section of road did not vary greatly, the AADT per lane was averaged for the section. The selection of analyzed sections used the mile post numbers from both the survey section data and the MMS segment data. It was assumed that the information presented in the MMS was bi-directional (on both sides of the street) unless otherwise specified. This resulted in a total of 56 analyzed sections used throughout the analysis. For a list of the surveyed sections, MMS segments and subsequent analyzed sections by milepost, along with the corresponding AADT per lane, road and marking type, average reflectivity, and age, see Appendix C.

3.2. Analyzed Sections Average Retro-reflectivity

Once the analyzed sections were determined, the retro-reflectivity values obtained for each reflectivity interval by the Laserlux reflectometer were averaged for the analyzed section. The Laserlux machine collects values over a 264 foot or 0.05 mile interval and averages the collected reflectivity values over the reflectivity interval. These individual reflectivity mean values were summarized into analyzed section reflectivity values by a weighted average using equation 3.1.

$$R = \frac{\sum_{i=1}^{k} \left(r_i n_i \right)}{N} \qquad \text{EQ 3.1}$$

where:

R = Average reflectivity of an Analyzed Section

r_i = mean retro-reflectivity for the reflectivity interval i

n_i = number of valid data points within the reflectivity interval i

N = total number of valid data points within the analyzed section

$(N = \sum_{i=1}^{k} n_i)$

Appendix C shows the list of the average retro-reflectivity values obtained for each of the 56 analyzed sections.

3.3. Initial Retro-reflectivity Values

UDOT provided information on the initial retro-reflectivity values for 5,208 measurements on newly placed pavement markings. Although the initial values ranged from 200 to 450 mcd/m^2/lux, the 5,208 measurements (3,015 on Epoflex and 2,193 on Tape) provided an average initial value for the retro-reflectivity of each pavement marking material as shown in Table 3.2. The UDOT data did not include any information on Paint. It was therefore assumed that the initial values for the Epoflex and Paint were equal. The justification for this assumption is as follows: Paint, like the Epoflex, is used to provide color and a matrix to hold the small, reflective glass spheres in place, as was discussed in Section 1.2.1. Glass beads are the component of both the Epoflex and the Paint that determines its retro-reflective quality.

Table 3.2: Initial Retro-reflectivity by Material Type

Material Type	Number of Sample Tests	Average Initial Retro-reflectivity (mcd/m^2/lux)
Tape	2,193	370
Epoflex / Paint	3,015	354

Source: UDOT testing data provided by Terri Taylor

The initial retro-reflectivity values from UDOT differentiated between color and marking line type (white solid, yellow solid, white skip, yellow skip). In the survey collection of average retro-reflectivity measure, line type or color was not factored. Therefore, the average initial retro- reflectivity values obtained from the UDOT tests were assumed to be in the same line-type and color proportion as the data collected from the Laserlux analyzed sections. The retro-reflectivity value obtained for each type of mark is therefore a combined average of line-type and color for each marking material.

It is important to note that there is a difference in average initial retro-reflectivity between colors. The UDOT initial retro-reflectivity data shows the average initial value of white tape is 24% greater than yellow tape.

3.4. Retro-reflectivity and Age

Using the age of the material on the road collected from the MMS, the retro-reflectivity measured in April 1996 by the Laserlux, and applying the average initial retro-reflectivity from UDOT testing, a relation between retro-reflectivity and age was developed for each of the marking materials by curve fitting to the empirically collected data. Figure 3.1 shows the measured values which tend to follow an exponential decay curve. The equations for each material is described in Table 3.3.

Table 3.3: Decay Equations for Reflectivity and Age

Material	Decay Equation
Paint	Reflectivity = $354e^{-0.0453(A)}$
Epoflex	Reflectivity = $354e^{-0.0702(A)}$
Pavement Marking Tape	Reflectivity = $370e^{-0.0217(A)}$

Reflectivity is measured in mcd/m^2/lux
Age is measured in months
These equations are based on all the analyzed segments and is insensitive to AADT

These decay curves are insensitive to AADT as they were developed from all of the data collected. They therefore represent a set of general relationships for the entire data and may be applied when an AADT level is unknown.

Figure 3.1: Reflectivity and Age Relationships

3.5. Deterioration Rate by AADT

By re-classifying the data by AADT level, deterioration rates (or decay rates) and AADT relationships were developed.

The deterioration rate was calculated in terms of reflectivity deterioration per month (D) by taking the difference between the initial (I) and measured (R) reflectivity's and dividing by the age in months (A).

$$D = \frac{I - R}{A} \qquad \text{EQ 3.2}$$

This was calculated for each analyzed segment and then plotted against AADT. The data was further segregated into road material type, either Portland Cement Concrete or Asphalt Concrete. It was assumed that the decay would pass through zero deterioration under zero AADT as weather was not factored into the analysis as in itself causing material retro-reflectivity decay. Using linear regression, a best-fit line that passed through zero was developed for each material type. The decay rates were then found from this best-fit line for 5000, 10000, and 15000 AADT per lane. Equations of the decay line were used to find the decay rate for specific AADT per lane values. Figure 3.2 shows an example of the deterioration rate related to AADT for Epoflex using the average initial retro-reflectivity of 354 mcd/m^2/lux.

The wide range of possible initial retro-reflectivity values (200 to 450 mcd/m^2/lux), supplied a range of decay rates and thus the different useful lives of the materials. The above analysis was repeated for initial reflectivity rates in 50 mcd/m^2/lux intervals between 200 and 450 in order to provide decay rates and useful life for the possible range of initial retro-reflectivity values. Plots similar to Figure 3.2 of retro-reflectivity deterioration for each initial retro-reflectivity of each marking material type for each road surface can be found in Appendix D. Table 3.4 shows the deterioration rates based on the plots for Epoflex, Solvent Paint, and Tape on both Asphalt Concrete and Portland Cement Concrete for the range of initial reflectivity values.

Figure 3.2: Deterioration Rates and AADT for Epoflex

Table 3.4: Deterioration Rates by Material, Road Type, and Initial Retro-Reflectivity

3.6. Useful Life and AADT

Using the calculated decay rates (D), initial reflectivity (I) and a minimum acceptable reflectivity (M) of 100 mcd/m^2/lux, equation 3.3 provided a useful life (U) of the material.

$$U = \frac{I - M}{D} \qquad \text{EQ 3.3}$$

A projected reflectivity (R) of the materials at a given age (A) is determined by applying the initial reflectivity (I) and deterioration rate (D) as shown equation 3.4

$$R = I + DA \qquad \text{EQ 3.4}$$

3.7. Costs

These useful life relationships can then be used to compare pavement marking technologies with respect to cost and find the most economically feasible material. From installed material costs (provided by Dale (1988) and UDOT) the monthly cost of each material was determined by dividing the installed cost by the number of projected useful life as shown in Equation 3.5.

$$C = \frac{Ci}{U} \qquad \text{EQ 3.5}$$

The cost is based on a per linear foot for the two different pavement types (Asphalt and Portland Cement) assuming a traffic level of 10000 AADT. This cost comparison analyzed the range of initial retro-reflectivity values.

4. DISCUSSION

Using the deterioration rates from Table 3.4 and applying equations 3.3 and 3.4, the projected useful life (U) of the marking materials by road surface and AADT level are determined. AADT levels of 5000, 10000 and 15000 vehicles per lane on Asphalt and Portland Cement for 6 different initial retro-reflectivity values are shown in Table 4.1. Tape is only shown on an Asphalt Concrete surface as no data was collected for Tape on Portland Cement Concrete.

The results of the analysis show that Tape has a longer useful life for a given AADT than both Epoflex and Paint on both Portland cement and Asphalt. Paint has a longer useful life for a given AADT than Epoflex on Asphalt Concrete. Epoflex has a higher useful life on Portland cement than Paint. Epoflex and Paint typically have longer lives on Portland Cement Concrete than Asphalt Concrete for a given AADT level. Having no data for Tape on Portland Cement prevented a similar comparison by road material type.

The results of the study vary from Dale’s (1988) results regarding Epoflex and Paint. Dale found Epoflex to have a longer useful life than Paint on both Portland Cement and Asphalt. This study found that between Paint and Epoflex, Paint has a longer useful life on Asphalt and Epoflex has the longer life on Portland Cement.

Table 4.1: Useful Life of Marking Materials under Various Initial Retro-Reflectivity Values

The useful life of Epoflex on Asphalt and Portland Cement are shown graphically in Figures 4.1. Epoflex lasts between 100% and 120% longer on Portland Cement than Asphalt.

Figure 4.2 shows the useful life of Paint on Asphalt and Portland Cement. The graph shows that Paint does last longer on Portland Cement than Asphalt similar to Epoflex, but the extension period is influenced by AADT. Paint's life is approximately 80% longer on Portland Cement than Asphalt for AADTs less than 7,500. For AADTs above 7,500, Paint's useful life is approximately 20% longer on Portland Cement. The analysis further shows that Epoflex has a 20% longer expected life on Portland Cement than Paint for a given AADT.

Only Tape on asphalt concrete is shown in Figure 4.3 as data of Tape on Portland Cement Concrete was unavailable. Tape on Asphalt Concrete has a 220% higher useful life than Paint and Epoflex for a given AADT level.

The empirical data graphs provide equations for the useful life of each material. The useful life equations for Epoflex, Paint on both Asphalt Portland Cement Concrete and Tape on Asphalt Concrete are shown in Table 4.2. Unique equations for each pavement marking material on each road surface are shown as a function AADT.

Table 4.2: Useful Life Equations Related to AADT per Lane

Material	Road Surface	Useful Life Equation
Epoflex	Asphalt	$U = \frac{127{,}000}{V}$
Epoflex	Portland Cement	$U = \frac{254{,}000}{V}$
Paint	Asphalt	$U = \frac{133{,}684}{V}$
Paint	Portland Cement	$U = \frac{195{,}385}{V}$
Tape	Asphalt	$U = \frac{385{,}714}{V}$
Tape	Portland Cement	No Data

U = useful life in months
V = AADT per lane
Based on an initial retro-reflectivity of
354 mcd/m^2/lux for Epoflex and Paint and 370 mcd/m^2/lux for Tape

Figure 4.1: Useful Life of Epoflex by AADT

Figure 4.2 Useful Life of Solvent Based Paint by AADT

Figure 4.3 Useful Life of Pavement Marking Tape by AADT

Plotting the useful life of all three materials on one graph and comparing them to the results obtained by Dale (1988), yields similar relationships. However, Dale's relationships of useful life and AADT are linear whereas the method employed in this study found the relationship to be hyperbolic. As a result of the before stated assumption that there was no deterioration at zero AADT, the useful life curve approaches infinity as the AADT approaches zero. This causes the curves then to be valid within the range of AADT data collected, approximately 5000 to 20000 AADT per lane. To be able to obtain results between 0 and 5000 AADT, natural deterioration needs to be considered as causing retro-reflectivity deterioration in addition to that caused by AADT levels. This requires a study which is more controlled than was possible. The study by Dale shows results within the range of 0 and 16000 AADT, depending on the material type. The results of this study encompass the comparison range of 5000 and 16000 AADT.

Figure 4.4 shows the comparison of Dale and this studies results for Asphalt Concrete. The most significant difference between this study and Dale is that he found Epoflex to perform with a longer useful life than Paint. These results indicate that Paint out-performs Epoflex and provides a 6% longer useful life for markings in Utah. This represents a much more similar performance of Epoflex and Paint than that of Dale's results of Epoflex lasting up to 3 times longer than Paint on Asphalt Concrete. Tape is shown to out-perform both Epoflex and Paint in both the study by Dale and this study.

Figure 4.5 shows a similar comparison plots for materials applied on Portland Cement Concrete. Only Epoflex and Paint are shown in Figure 4.5 as there was no data for Tape on Portland Cement. The analysis showed Epoflex to provide a 30% higher useful life than Paint on Portland Cement for a given AADT. Dale also found Epoflex to provide a longer useful life than Paint on Portland Cement Concrete.

Figure 4.4 and 4.5 show that this analysis predicts Paint and Epoflex to perform following the same general trend with relation to AADT. That is for Asphalt Concrete, Paint has an approximately 6% greater useful life than Epoflex and for Portland Cement, Epoflex has an approximate 30% higher useful life than Paint. This percentage increase in useful life is constant regardless of AADT level. Dale's results indicate that while Paint and Epoflex have approximately the same useful life at an AADT level of 16000, Epoflex has up to an 8 times greater life span at 8000 AADT. Dale's resultant curves indicate that small AADT increases have a much greater impact on useful life of Epoflex than Paint.

Figure 4.4: Comparison of Useful Life of materials and AADT on Asphalt Concrete

Figure 4.5 Comparison of Useful Life of materials and AADT on Portland Cement Concrete

A cost analysis based on the useful life determined by this study found that Paint provided the most economical method of providing pavement markings. Paint has a 200 to 400 percent cost benefit over Epoflex and a 700 percent advantage over Tape. The results further show that the initial retro-reflectivity had little influence on the cost of the material. Table 4.3 shows the projected monthly cost of each material based on the initial installation cost and the useful life.

Table 4.3: Monthly Material Installed Cost per linear foot at 10000 AADT per lane

	Epoflex		Solvent Paint		Tape
Road Type	Asphalt	Portland Cement	Asphalt	Portland Cement	Asphalt
Cost per linear foot	$ 0.21	$ 0.21	$ 0.06	$ 0.06	$ 1.00
Initial Retro-reflectivity ($mcd/m^2/lux$)	Average Monthly Cost (in $)				
450	0.0168	0.0084	0.0044	0.0033	0.0314
400	0.0162	0.0084	0.0044	0.0032	0.0314
370[1]	----	----	----	----	0.0314
354[2]	0.0168	0.0083	0.0045	0.0031	----
350	0.0159	0.0084	0.0045	0.0031	0.0314
300	0.0158	0.0084	0.0045	0.0030	0.0314
250	0.0154	0.0084	0.0044	0.0028	0.0314
200	0.0147	0.0084	0.0042	0.0024	0.0314

[1] Tape Average Initial Reflectivity of 370 $mcd/m^2/lux$

[2] Paint and Epoflex Average Initial Reflectivity of 354 $mcd/m^2/lux$

5. CONCLUSIONS

1. Tape has the longest useful life of the three materials on Asphalt Pavement lasting 220% greater than Paint and Epoflex, respectively.

2. Paint and Epoflex have longer useful lives on Portland Cement Concrete than Asphalt Concrete.

3. Paint has approximately 6% longer life than Epoflex on Asphalt Concrete.

4. Epoflex provides a 30% higher useful life than Paint on Portland Cement Concrete.

5. Epoflex lasts between 100% and 120% longer on Portland Cement than Asphalt.

6. Paint's useful life is approximately 80% greater on Portland Cement than Asphalt for AADT levels below 7,500. For AADT levels above 7,500, Paint last approximately 20% longer on Portland Cement than Asphalt.

7. Tape has an average 4.5% (16 mcd/m^2/lux) higher initial retro-reflectivity than Paint or Epoflex.

8. The initial retro-reflectivity of white Tape pavement markings is approximately 24% greater than yellow Tape pavement markings.

9. The cost results indicate that using Paint is 2 to 4 times less expensive as the Epoflex and 7 times less expensive than Tape.

Solvent based paints are the least expensive material considered by this study. Paint is followed by Epoflex in terms of cost effectiveness and finally Tape. These conclusions and relationships are based on the retro-reflectivity data collected, the dates of application as available in the MMS, AADT values from the "1993 Traffic on Utah Highways", and installed costs per linear foot of each material as provided by UDOT.

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7. APPENDICES

1. Appendix A	List of the Retro-reflectivity Survey Routes
2. Appendix B	Collected MMS Data and Private Contract Databases
3. Appendix C	Surveyed sections, MMS segments and Analyzed sections by milepost, along with the corresponding AADT per lane, road and marking type, average reflectivity, and age
4. Appendix D	Deterioration Rate curves for Paint, Epoflex and Tape by initial Retro-reflectivity.
5. Appendix E:	Dale (1988) Reference

Appendix A List of the Retro-reflectivity Survey Routes

File No.	Description (highway number)	From MP	To MP
1	4700S from 5600W to I 15 (1028)	0	6.525
2	4700S from I15 to WASATCH (A00266)	2.84	7.99
3	3900S from WASATCH to 300W (1030)	15.58	9.83
4	3300S from 300W to 2000E (A00171)	10.11	13.56
5	2700S from 2000E to 300W (1034)	3.44	0.04
6	2100S from STATE to 2100E (1038)	0	2.95
7	1700S from 2100E to 300W (1040)	10.25	6.7
8	1300S from 300W to 2100E (1042)	8.56	12.11
9	800S from Ft Hill Blvd. to 300W	10.08	6.76
10	400S from 300W to 2300E (A00186)	4.97	9.77
11	WASATCH from 7000S to 9800S (A00210)	0	3.45
12	1300E from 9400S to 5600S (1047)	7.29	12.19
13	1300S from 5600S to 500S (A00181)	0	7.45
14	1300E from 500S to S TEMPLE (1047)	12.87	13.52
15	100S from 1300E to STATE (1054)	1.79	0.09
16	S TEMPLE from 300W to VIRGINIA (1056)	0	2.45
17	11TH from VIRGINIA to E (1064)	6.95	5.6
18	700E from 400S to 4500S (A00071)	20.04	14.19
19	VAN WINKLE from 900E to 6200S (A00152)	0	2.35
20	HIGHLAND from 6100S to 1700S (1049)	7.51	14.16
21	500E from 1700S to S TEMPLE (1037)	4.07	6.47
22	900E from S TEMPLE to VAN WINKLE (1043)	0	6.47
23	900E from S TEMPLE to VAN WINKLE (1043)	7.13	0.13
24	900E from VAN WINKLE to 9400S (A00071)\	13.32	8.57
25	700E from 9400S to REDWOOD (A00071)	7.33	0.03
26	REDWOOD from SR140 to I15 (A00068)	40	68.85
27	500W in Bountiful from 500S to 2600S (A00089)	333.18	331.73
28	I80 from I15 to 4000W (A00080)	123.14	120.29
29	2100S from 4000W to 8400W (A00201)	13.24	8.24
30	STATE from 400S to Draper I15 (A00089)	324.4	308.8
31	SR89 from I15 AMERICAN FORK to 1600N	0	6.8
32	I15 S from EXIT 276 to UNIVERSITY	0	8.8
33	2700S from 2000E to 300W (1034)	3.44	0.04
34	I15 N from EXIT 228(NEPHI) to MONA	0	4.1
35	89 SOUTH from 143	0	6.6
36	St. George from Bluff to I15	0	1.742
37	I15 from St. George Blvd. to Bluff	0	1.629
38	Bluff from I 15 to St. George Blvd.	0	5.758
39	bluff back to St. George Blvd.	0	3.826
40	I15N from Centerville Interchange to 12th (a00015)	322.33	347.73

Appendix A (Continued)

File No.	Description	From MP	To MP
41	12th from I15 to Wall Ave (a00039)	4.01	5.66
42	Wall Ave from 24th to 2nd (a00204)	2.09	4.565
43	2nd from Wall Ave to Harrison (2042)	0.61	2.135
44	Harrison from 2nd to jct. SR 39 (2033)	1.2	0.025
45	Harrison from 20th to jct. SR89 (a00203)	5.35	0.15
46	SR 89 from Harrison to jct. SR 26 (a00089)	347.12	350.97
47	Riverdale from SR 89 to SR 126 (a00026)	3.75	0.15
48	SR 126 from jct. SR 79 to 12th (a00126)	11.08	15.23
49	SR 126 from SR 39 to I15 (a00126)	14.34	0.49
50	I15 N from 4500s to 2600s SNOW!(a00015)	304.52	317.195
51	I15 SB from SR 273 to I215 (a00015)	331.45	316.3
52	I215 SB from I15 to SR80 (A00215)	28.98	2.18
53	I80 E from EXIT 131 to SILVER CREEK (a00080)	131	147.6
54	SR40 from I80 to SR189 (A00040)	19.18	1.98
55	SR40 from 189 to I80 (A00040)	0	17.3
56	I80 WEST from SILVER CREEK to I215	147.79	130.49
57	I215 from I80 to I15 N of Salt Lake (A00215)	0	26.8
58	I15 SB from EXIT 316 (a00015)	317	305.7

Appendix B Collected MMS Data and Private Contract Databases

Appendix C Surveyed sections, MMS segments and Analyzed sections by milepost, along with the corresponding AADT per lane, road and marking type, average reflectivity, and age

Appendix D Deterioration Rates for Paint, Epoflex and Tape by Initial Retro-reflectivity.

Appendix E: Dale (1988) Reference