Durable, Cost-Effective Pavement Markings
Phase I: Synthesis of Current Research

Final Report

Sponsored by the Iowa Department of Transportation
and the Iowa Highway Research Board
Iowa DOT Project TR-454
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DURABLE, COST-EFFECTIVE PAVEMENT MARKINGS
PHASE I: SYNTHESIS OF CURRENT RESEARCH

FINAL REPORT

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EXECUTIVE SUMMARY

Pavement marking technology is a continually evolving subject. There are numerous types of materials used in the field today, including (but not limited to) paint, epoxy, tape, and thermoplastic. Each material has its own set of unique characteristics related to durability, retroreflectivity, installation cost, and life-cycle cost. The Iowa Highway Research Board was interested in investigating the possibility of developing an ongoing program to evaluate the various products used in pavement marking. This potential program would maintain a database of performance and cost information to assist state and local agencies in determining which materials and placement methods are most appropriate for their use.

The Center for Transportation Research and Education at Iowa State University has completed Phase I of this research: to identify the current practice and experiences from around the United States to recommend a further course of action for the State of Iowa.

There has been a significant amount of research completed in the last several years. Research from Michigan, Pennsylvania, South Dakota, Ohio, and Alaska all had some common findings: white markings are more retroreflective than yellow markings; paint is by-and-large the least expensive material; paint tends to degrade faster than other materials; thermoplastic and tapes had higher retroreflective characteristics.

Perhaps the most significant program going on in the area of pavement markings is the National Transportation Product Evaluation Program (NTPEP). This is an ongoing research program jointly conducted by the American Association of State Highway and Transportation Officials and its member states. Field and lab tests on numerous types of pavement marking materials are being conducted at sites representing four climatological areas. These results are published periodically for use by any jurisdiction interested in pavement marking materials performance.

At this time, it is recommended that the State of Iowa not embark on a test deck evaluation program. Instead, close attention should be paid to the ongoing evaluations of the NTPEP program. Materials that fare well on the NTPEP test decks should be considered for further field studies in Iowa.

INTRODUCTION

The field of pavement marking continuously evolves as new materials and application methods are developed. Jurisdictions at all levels need to stay current with the latest advancements and determine whether their particular operations can benefit from the advancements.

In January 2001, the Iowa Highway Research Board contracted with the Center for Transportation Research and Education at Iowa State University to review pavement marking research completed in the past five to seven years. This report presents the results of that review.

The *Manual on Uniform Traffic Control Devices* (MUTCD) outlines the conditions of when pavement markings are necessary to guide and inform the road user. The Materials Section 3A.03 states that “materials used for marking should provide the specified color throughout their useful life” and that “consideration should be given to selecting pavement marking materials that minimize tripping or loss of traction for pedestrians and bicyclists” (*1*). The MUTCD does not, however, set requirements about the type of material to use. Pavement markings are typically replaced or re-striped many times before the pavement itself is renewed. The typical pavement marking life can range anywhere from three months to several years, while the typical pavement life may be 12 to 20 years (*2*).

The Iowa Department of Transportation (Iowa DOT) has developed their own pavement marking policies. According to the Iowa DOT *Manual on Pavement Marking Program*, a district paint crew determines which roadways will obtain application (or re-application) of marking material. Within certain guidelines, a city can also carry out the marking process and acquire financial reimbursement (*3*).

Pavement marking materials can generally be said to have these desirable characteristics: low cost, long life, high reflectivity, and short drying time (although for some materials, it has been shown that slow-drying paints last longer) (*4*).

The main criteria by which to evaluate pavement marking materials are durability, retroreflectivity, and cost. Other criteria that could be considered include highway lighting, number and skill of workers, installation equipment, environmental effects, and maintenance factors (*2*).

The remainder of this report is divided into four sections. The first section discusses evaluation criteria. The second section reviews the pavement marking process. The various materials used in pavement marking are outlined in the third section. The final section summarizes recent research performed with regard to pavement markings, including details of the National Transportation Product Evaluation Program (NTPEP).

EVALUATION CRITERIA

There are typically three criteria used to evaluate the cost effectiveness of pavement markings: durability, retroreflectivity, and cost.

Durability

Durability is a measure of the staying power of the marking. It includes the strength of the bond between the pavement and the marking material. Durability also is a measure of a marking's resistance to abrasion from traffic and snowplows. Naturally, a more durable material would need to be replaced less frequently and is therefore more cost effective. Durability is dependant on factors such as pavement type, pavement surface texture, weather conditions, surface preparation, traffic volume, snowplow activity, and the application of sand or other abrasives in the works (*2*).

Retroreflectivity

The MUTCD Standardization of Application Section 3A.02 states that "markings that must be visible at night shall be retroreflective unless ambient illumination assures that the markings are adequately visible. All markings on Interstate Highways shall be retroreflective" (*1*).

Retroreflectivity is the portion of incident light from a vehicle's headlights reflected back toward the eye of the driver of the vehicle. Retroreflectivity is provided in pavement marking materials by glass or ceramic beads that are partially embedded in the surface of the material (*5*). For paints and thermoplastics, the beads are usually dropped or sprayed into the material as the road is being marked. The correct bead application rate and consistency of application are significant, since beads can sink to the bottom if not applied properly. The beads must be transparent and round to act like lenses. As light enters a bead, it is refracted or focused down through the bead, and reflected back toward the path of entry (*6*); see Figure 1. Reflectivity refers to the visibility of the material resulting from the retroreflectivity of premixed and dropped-on glass beads in the material (*2*).

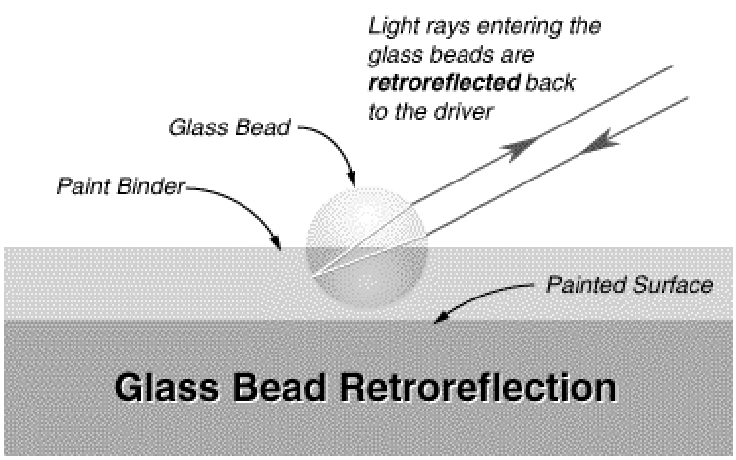

Figure 1 Glass Bead Retroreflection

It is important to clarify a few lighting terms used in describing retroreflectivity. Luminous intensity, measured in candelas (cd), refers to the amount of light from a source in a given direction. Luminous flux is the rate of flow of light over time, measured in lumen (lm). Illuminance, measured in lux (lx), refers to the amount of luminous flux, which travels radially outward from the source, on the surface of the object. The amount of light available for seeing or reflected in a particular direction is called luminance and is measured in candelas per square meter (cd/m^2) (*7*). Retroreflectivity is measured by R_L, the coefficient of retroreflected luminance, in millicandelas per square meter per lux ($mcd/m^2/lux$). R_L is an absolute value and is unaffected by night and day (*2*).

New pavement markings typically have R_L= 250 or greater, but with time and traffic usage, R_L decreases. This rate of the deterioration depends on the material. South Dakota recommends that the lowest accepted value of R_L for white paint is 120 and R_L for yellow paint is 100 (*4*). Different line colors result in different retroreflectivity values since white reflects more light than other colors.

The R_L reading also depends on what type of retroreflectometer is used, since geometry and viewing distance vary by the type of measuring instrument (*5*). Some examples of retroreflectometers include the Mirolux 12, Black Box, or Ecolux devices. These instruments are handheld retroreflectometers that mechanically measure the pavement marking material's reflectivity (*2*). The LTL 2000 retroreflectometer is another portable instrument with a built-in printer that measures the retroreflection properties of pavement markings, both dry and wet, including those with profiled or textured surfaces (*8*). Some of the other latest retroreflectometer devices are the Laserlux, the MP-30, and the MX-30 (*9*). A more detailed evaluation of some of these devices can be found in the fourth section of this report, Recent Pavement Marking Material Research.

Minimum retroreflectivity standards could be difficult to enforce because retroreflectometers have such a high degree of variability and readings are often not repeatable. Retroreflectivity values are constantly changing because of general wear of the marking, moisture on the surface, and particles of soil, dirt, and dried salt on the roadway (*10*).

Cost

Cost can be a critical factor, especially when there is a set amount of available funding. However, a material with a higher initial cost could also have a longer lifetime, which could result in a more cost-effective material.

When evaluating cost, it is important to consider not only the cost of the material, but also the cost of the crew and the application equipment necessary. One should also check for manufacturer guarantees over a specified time. Some manufacturers replace deteriorating materials free of charge if their product does not achieve certain guidelines (*2*).

PAVEMENT MARKING PROCESS

According to the Iowa DOT, surface preparation for the application of waterborne paints involves three basic steps. The first step is the removal of dirt, gravel, debris, vegetation, or other miscellaneous objects from the surface with a broom truck. Next is the removal of overhanging vegetation. The final step is the marking of spot lateral location of lines and terminal points (*3*).

A report produced by Clemson University outlines the following procedure in the pavement marking process (*2*):

Prior to marking:

- Check for proper materials and equipment
- Perform required pavement surface preparation
- Record air and road surface temperatures to assure the value is within the proper range

During marking:

- Check pavement marking alignment and width quality
- Check thickness of material using paint film thickness gauge
- Check uniform curing of material
- Check glass bead distribution and embedment with microscope

After marking:

- Use camera for documentation before roadway is open to traffic
- Check retroreflectivity of material using retroreflectometer
- Inspect markings on a regular basis

Surface preparation for durable markings includes removal of old markings and vacuuming, sweeping, and blowing the surface.

The operating speed of the truck applying the pavement marking should be approximately 12 mph. Speed may be increased with proper equipment. However, at higher speeds there is a greater chance for beads to roll and show through the binder, thereby reducing the initial retroreflectivity. Also at higher speeds it is harder to match existing markings.

The paint tank should be kept relatively full, and the delivery rate should be checked frequently. The paint tanks should be filled to capacity after each day's operation to assure the tank is airtight. This is primarily because of high volatility of paint solvents and their rapid evaporation rate (*3*).

When working with solvent-based paints, toluene is used as a flush solvent to clean the tanks and remove dry paint. Paint tanks should be sealed for 48 hours with 55 gallons of toluene. Toluene costs less than other solvents and is less likely to cause exposure related health problems. However, toluene is highly flammable and its disposal is not allowed in landfills. It must be processed for recycling or stored in sealed drums. Open flames, sparks, and glowing material should be kept away from the equipment and paint truck. Placards must also be shown on the front, rear and each side of the vehicle to identify hazardous materials for emergency response personnel (*3*).

Waterborne paints, on the other hand, can be cleaned up with soap and water. The cleanup can be put into the sanitary sewer.

Many solvent-based paints are no longer available because of recent clean air regulations limiting volatile organic carbons (VOCs). However, acetone is a VOC-exempt solvent, and solvent-based paints have been reformulated using acetone as the main solvent. Solvent based-paints are used in the early spring and late fall when cold weather precludes the use of water-based paints.

MATERIAL TYPES

This section will review the four most commonly used pavement marking materials: preformed tape, paint, thermoplastic, and methyl methacrylate. Most of the material types have several subcategories as well.

Preformed Tape

Preformed tape is typically used as a transverse marking material (e.g., crosswalks, stop bars). It performs well on both portland cement concrete (PCC) and asphalt cement concrete (ACC) pavements. In general, preformed tape has a high initial cost per linear foot. However, it is easy to install and has a high durability. When preformed tape is placed on new ACC pavement sections, the road can be open to traffic as soon as the pavement is ready. This is an advantage in avoiding temporary marking materials. However, it is susceptible to chipping during certain weather conditions (*2*).

Types of preformed tape:

- **Cold Plastic Tape** 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 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 later drops considerably.

Paint

Over 95 percent of roadways in Iowa are marked using fast-drying waterborne paints. As a minimum, centerline and lane lines are repainted each year, and edge lines repainted every other year (*10*).

Drying time (also called “no track” time) of paints is often classified in the following manner:

- Conventional paints: dry in more than seven minutes

- Fast-dry paints: dry in two to seven minutes

- Quick-dry paints: dry in 30 seconds to two minutes

- Instant-dry paints: dry in less than 30 seconds

- There are numerous types of paints. Some of them are discussed below.

Two-Component Epoxy

Two-component epoxy is durable on both PCC and ACC pavements in new or good condition. Because of its long service life, it can be used in areas of high traffic volume. Epoxy can be difficult to install and should be applied at a temperature between 60° and 80°F. The first component consists of resins and pigments. The second part contains hardener that causes the material to change from a liquid to a solid. No track time is 5–60 minutes and may be several hours if the temperature drops below 60˚F

Polyester Paint

Polyester paint consists of a resin and a catalyst. Its no track time is 5–20 minutes (*2*). The service life of polyester paint is two to three years; the paint works in low temperatures and contains no VOCs. In a Michigan study, polyester paint tested with low retroreflectivity values (*11*).

Water-Based Paint

Water-based paints are also referred to as latex paints. Water-based paint is becoming more important as the Environmental Protection Agency (EPA) increases regulations on VOC emissions. Paints that contain VOCs make the paint more workable, but they also contribute to smog. When water-based paints are used instead of solvent-based paint, VOC emissions can be reduced by as much as 80 percent (*9*).

Water-based paints can have higher reflectivity ratings than alkyd solvent-based paint and have a faster drying time. Past research stated that this type of paint has a lower service life, which makes it good for use in a low-traffic volume area (*2*). However, newer formulations of waterborne paints have made them more durable and longer lasting than their predecessors.

The narrow temperature range permitted for application of water-based paint restricts its use in cold weather. It requires stainless steel heated storage tanks in the winter and a heat exchanger (*4*).

Alkyd Paint (Solvent-Based Paint)

Alkyd paints are also referred to as oil-based or solvent-based paints. Alkyds are the most-used class of binder in solvent-borne paints (*12*). Alkyd paint is fast drying and inexpensive. However, durability is poor. Reflectivity is high at first, but drops considerably after one year. No track time is one minute (*2*).

Chlorinated Rubber

Chlorinated rubber has a drying time ranging from 4 to 10 minutes. Chlorinated rubber is said to be more durable and cost effective than other paints (*2*). In New York, chlorinated rubber was found more workable and more durable than alkyd, but was also found to have a higher no track time (*4*). Because of recent VOC regulations, both alkyd and chlorinated rubber materials are required to be packaged in five-gallon containers. Because of this limitation, only small volumes of these paints are used. Typical applications include parking lots and small towns.

Pre-Mix Formulas

Pre-mix formulas are available for latex and alkyd paints. Pre-mix paints are advantageous in that half of the required amount of glass beads is already in the paint. The application is therefore simpler since there are less beads to scatter, and more accurate since beads are on the pavement marking line, not the roadway (*13*).

Paints, both water based and solvent based, are recommended for pavement in poor conditions, since it does not have the proper surface for good adhesion or more durable markings. Also, on poor condition surfaces, the road may likely be resurfaced before the pavement marking reaches the end of its useful life.

Thermoplastic

Thermoplastic is a combination of resins and pigments that become liquid when heated. It is typically intermixed with drop-on glass beads to provide retroreflectivity. The binder is a mixture of plasticizer and resins that holds all of the other ingredients together. When installed on porous surfaces, the hot liquid thermoplastic fills the void spaces, forming a mechanical lock on concrete and a thermal bond on asphalt (*14*). In general, thermoplastic is much more durable on ACC than PCC due to the thermal bond.

The thickness of thermoplastics is usually about 90 mils, which is 6–10 times thicker than paint applications. The material should be heated to between 400° and 450°F. Air and surface temperature is recommended to be at least 55°F. There are two types of thermoplastics: hydrocarbon and alkyd (*2*).

- **Hydrocarbon** is made from petroleum-derived resins and can therefore break down under oily conditions. For this reason it may not last as long in areas of highly congested traffic, or where traffic is stationary for long periods of time.

- **Alkyd** is derived from a naturally occurring resin, which is resistant to oil. Alkyd is heat sensitive, so the temperature needs to be carefully controlled during application. If it is heated for too long, the material becomes thick and makes for an inconsistent application.

There are three ways to apply thermoplastic (*2*):

- **Extrusion method** pushes material through a die onto the pavement. This allows for uniform flow of the material for consistent thickness.

- **Ribbon application** uses a pressurized ribbon gun to apply the material.

- **Spraying** combines air and the thermoplastic together under pressure and applies material directly to the pavement. Thickness is more difficult to control.

Methyl Methacrylate

Methyl Methacrylate (MMA) is a relatively new product that has been 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 two to seven years. MMA can be applied at ambient temperatures and at temperatures as low as 0°F, as long as no frost is present (*15*).

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 sprayed or coated onto the pavement. Methacrylate is said to have a no track time of approximately 20 minutes. It can be applied at varying thickness, ranging from 30 to 120 mil (*16*).

Methyl methacrylate is said to have good visibility for night and wet conditions. It has been used in both extruded and sprayed applications on both PCC and 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. Relatively dry conditions are necessary during installation (*15*).

MMA does not have VOC concerns. However, there may be health hazards present to striping crews due to the minimal volatilization during application of chemicals onto a warm pavement or by aerosols when spraying the material (*15*).

RECENT PAVEMENT MARKING MATERIAL RESEARCH

This section of the report discusses various research projects that have been conducted regarding pavement marking materials.

South Dakota

The research team in this study (*4*) examined epoxy, tape, and waterborne paints in rural test sections. Epoxy and tape were researched in urban test sections. These marking systems were chosen based on the success of these materials in states surrounding South Dakota.

In the rural test sections, alkyd paint was used as the control, since this material was found to be most typical for rural area use. All lane lines were painted around two interchanges 20 miles apart on I-90 with similar climatic and traffic conditions.

The urban test section was located at approaches to an intersection in Sioux Falls, South Dakota. Preformed plastic tape and epoxy paint were used for all symbols, legends, and lane lines within 200 feet of the intersection. Epoxy-painted lines were also used for several blocks past the intersection. Preformed plastic was used as the pavement marking control, as it is the existing standard for urban areas.

In evaluating the cost effectiveness of these marking materials, the factors examined included average daily traffic, surface type, traffic type (percentage trucks), surface preparation type, and climatic conditions.

Reflectivity of all markings at the test sites was measured with a Mirolux 12 retroreflectometer. Based on a study performed by the New York State Department of Transportation, 120 mcd was used as the lowest acceptable value of retroreflectivity for white paint and 100 mcd was used for yellow paint.

The following procedure was outlined to measure the cost effectiveness of pavement markings:

1. Measure reflectivity and the time for the R_L reading to fall below the minimum accepted value.

2. Divide the cost per foot for each marking by the pavement marking lifetime, in days. (use lifetime = 1 year for paints not falling below the minimum value).

3. Result is cost per foot per day (¢/ft/day) for each marking material.

In general, the alkyd paints consistently showed the lowest costs (0.004–0.019 ¢/ft/day). Water based paints were next (0.004–0.040 ¢/ft/day), followed by epoxies (0.03–0.32 ¢/ft/day). Tapes were the most expensive (0.47–4.2 ¢/ft/day).

To measure the total cost of a marking material, labor and equipment costs were based on a percentage of the total cost. Labor and cost data reports from the South Dakota Department of Transportation Operations Support Program were used to determine that in 1992, 69 percent of the total cost of applying a stripe to the road was material, 14 percent was labor, and 16 percent was operation of equipment. Therefore, for centerline operations, the material cost from the manufacturer was divided by 69 percent to estimate the total cost of applying the pavement marking. Edge line operations material costs were 81 percent of the total cost.

As reported in 1993, alkyd is the present pavement marking material in South Dakota. It was found to be cheaper than other markings, but alkyd does not provide year-round traffic delineation and is therefore not as cost effective. Alkyd paints used in 1993 were oil and solvent based and will not meet current VOC regulations. South Dakota also predicted that the federal government would eventually require only environmentally acceptable paints, such as lead-free, water-based paint.

Researchers made the following conclusions from the study:

In **rural** pavement marking test sections:

- Reflectivity with respect to time for epoxy and water-based paint was far superior to alkyd paint.

- Epoxy and waterborne paints behaved similarly on ACC and PCC pavements.

- Water-based paint was concluded to be the most cost effective marking for the rural environment.

In **urban** areas:

- Tape had a higher reflectivity than epoxy or alkyd.

- Tape has a higher initial reflectivity than epoxy or alkyd, but it is more susceptible to peeling, tearing, and deformation due to snowplows or turning vehicles in high traffic intersections.

- Tape was found to be 15 times more expensive than epoxy.

- No pavement marking tested lasted more than two months on the pavement during the winter due to snowplow damage, bonding failures, and traffic wear.

Alaska

A study conducted by the Institute of Northern Engineering at the University of Alaska, Fairbanks, evaluated various traffic marking materials used in Alaska and other northwestern states (*15*). One of the main project objectives was to evaluate methyl methacrylate. This new pavement marking material was presumed to be suitable for the extreme climatic conditions of Alaska. Other pavement marking types examined included traffic paints, thermoplastics, and preformed tapes. The study also set forth to assess pavement markings through retroreflectivity measurements and through a subjective survey given to engineers and employees in the industry.

The subjective field surveys concluded the following:

- MMA supplied good service performance quality and still presented good visibility and appearance during the survey time.

- MMA also maintained the brightest reflectivity on both wet and dry pavements.

- The subjective rating of traffic paints was the lowest.

In the reflectivity evaluation, a four-year time period was used:

- Preformed tapes had the best initial reflectivity performance.

- MMA provided better reflectivity results compared to thermoplastics and traffic paints and performed as well as preformed tapes.

The subjective opinion survey asked questions concerning pavement marking performance, applications, and installation. Sprayed and extruded MMA were found to rank the best in both the performance and the overall categories.

The study concluded that MMA is an appropriate traffic marking in Alaska and the northwestern United States and that field trials and experiments of this product should be continued.

Transportation Research Board

The Transportation Research Board (TRB) has supported numerous studies regarding pavement marking materials. Some of the more recent studies are summarized below.

Study on Pavement Marking Detectability by Retroreflective Brightness

Pavement marking systems have no defined retroreflective brightness required for a road surface marking to provide safe and effective guidance. A study conducted in 1993 shows the relationship between retroreflective brightness and the detectability of pavement markings under both stationary and dynamic conditions (*17*). The selection of test samples represented a wide range of retroreflective performance. For various driver and marking combinations, detection distances were documented.

For the stationery experiment, six pavement marking products were viewed as center skip lines from stationary vehicles in a dark rural setting. Marking samples were 0.1 m wide by 3 m long. Each of these samples was applied to aluminum panels that were observed on top of a viewing table with a matte black surface finish. The tables sat at 3.8 cm above the road surface. Samples were then viewed at distances of 30, 50, 80, 120, 160, 200, and 250 m from the front of the vehicle to the leading edge of the marking. Subjects were allowed to view each sample for two seconds with low-beam headlights and document whether or not the marking was visible.

In the dynamic experiment, seven pavement marking products were viewed from moving vehicles at a speed of 24 kph. Samples were prepared in much the same way as the stationery experiment and placed randomly at centerline locations within a 70 m section of the test roadway. Subjects were asked to drive a vehicle along a straight section of road and inform the passenger in the vehicle when the pavement marking was detected. The passenger would then immediately drop a reflectorized beanbag from the moving vehicle. The distance from the beanbag to the pavement marking at the time of detection was then documented.

It was concluded that brighter markers were detectable at greater distances from observer to marking in both stationary and dynamic viewing experiments. Pavement marking detectability was found to depend on viewing conditions as well as the viewers themselves.

Study on Pavement Marking Retroreflectivity

A TRB study was conducted in 1995 that compared color and type of lines to find differing retroreflectivity values (*5*). The materials were both white and yellow pavement marking lines of six different marking materials (conventional paint, waterborne paint, epoxy, polyester, thermoplastic, and tape). Sites at which the retroreflectivity was measured were identified by 32 state and local highway agencies. Field measurements were taken with a Retrolux Model 1500 retroreflectometer.

White lines were found to have substantially higher retroreflectivity than yellow lines. The type of line (edge line vs. lane line) was found to have no strong effect on retroreflectivity. Roadway type did not yield consistently different retroreflectivity and contrast ratio values. It was also found that markings consisting of durable materials (thermoplastic or tape) had higher R_L values than that of paint.

Study on Lateral Separation between Pavement Markings

Several TRB studies were conducted in Athens, Ohio, pertaining to pavement marking materials. In 1995, one of these studies set to determine the detection distances for new yellow double solid center tape stripes as a function of lateral separation between the stripes under automobile low-beam illumination at night (*18*). The experiment used 48 subjects and was conducted at an old, unused Ohio University runway.

For each run, the subject was told to line up the vehicle in the driving lane and accelerate to a speed of 8–16 kph, then hold the speed and lateral position as constant as possible. When the subject saw the beginning of the center-stripe treatment, the person in the passenger seat dropped a sand bag onto the runway at that location. Measurements were made at the lateral separation distances between the stripes of 0.05, 0.1, 0.15, and 0.2 m.

After the experiment was conducted, the average begin and end detection distances were established, and psychometric curves were plotted. Analysis of variance (ANOVA) tests failed to find consistent statistically significant systematic effects caused by the lateral separation distances. Therefore, it was concluded that increasing the lateral separation between double center stripes from 0.05 m to 0.2 m does not appear to be a useful method of increasing driver visibility.

Study on Pavement Marking Visibility at Night

The TRB research team that conducted the above mentioned study wrote another report about the visibility of new pavement markings at night (*19*). This report included three field studies that evaluated nighttime detection distances of varying widths of markings under low-beam illumination. The site for this experiment was the unused runway in Athens, Ohio.

The first of these field studies investigated the visibility for detecting the beginning and end of a continuous pavement marking line as a function of width (10–25 m), material (paint/tape), color (yellow/white), and lateral position of the line (1.83 m to the right only, left only, or right and left of the longitudinal car axis). Seven subjects were each told to accelerate the car to 8–16 kph and tell the passenger in the car to drop a sand bag as soon as the subject saw the beginning and ending of the straight single pavement marking line. The statistical tests for this experiment found that the average begin and end detection distances are not statistically significantly different based on the previously listed variables.

In much the same manner, the detection of curves was measured. Left and right curves with a radius of 244 m along a tangent section were placed using white tape 3M-5160 with varying widths of 0.05, 0.1, and 0.2 m. Sixteen subjects each reported when they detected the beginning of either a right or left curve by driving the test vehicle and notifying the passenger in the vehicle to drop a sandbag at the time of detection. The results of the test indicated no significant difference between average detection distances for a right curve marked with either a 0.1 m wide or 0.2 m wide line placed on the right side of the car. However, by increasing the marking width from 0.05 to 0.2 m, the average detection distance increased by 21 m for a left curve, and by 22 m for a right curve. The average curve-begin detection distance for a left curve was found to be shorter than that corresponding to a right curve. Psychometric curves were used to interpret the data, showing probability of detection as a function of detection distance. From these curves, it was found that 95 percent of selected drivers could detect the onset of a left curve at a distance of 67 m, and the onset of a right curve at a distance of 81 m.

The third field study in this report measured the begin and end detection distances of five different pavement marking configurations placed in the center of the road with various line widths. This means that all pavement markings appeared on the left side of the vehicle. The configurations varied by double or single lines, solid or dashed lines, and widths of 0.05, 0.1, and 0.2 m. Ten subjects were each asked to use the sandbag method of notifying when the pavement marking was detected. This field study found that configuration type of the pavement marking is critical, and that the double solid line configuration has the longest detection distance.

Some of the conclusions of these three field studies are listed below:

- The average begin and end detection distances of white lines are longer by about 38 and 35 m, respectively. This indicated that color of the pavement marking might have a significant impact on the detection distance.

- The longest average detection distance for the beginning of the pavement marking configuration is 125.61 m, obtained for the 0.2 m double solid centerline configuration used in the third field study.

- The shortest detection distance found was 55.46 m, using the 0.05 m dashed centerline configuration.

- Pavement markings to the right of a car are detected more easily at distances farther away compared to markings on the left side of the car. The reason for this could be due to the fact that automobile low beams point 2° down and 2° to the right.

- White pavement markings had average detection distances slightly longer than yellow pavement markings

Study on Yellow Nighttime Color Pavement Markings

The nighttime reflective color of yellow pavement markings was investigated (*20*). The objective of this study was to compare pavement marking materials that differ in nighttime reflective performance using human observers and lab testing methods for measuring nighttime color of retroreflective materials. Twenty-four different pavement markings materials were tested: five white materials and 19 yellow materials, according to daytime color.

For the field observation portion of this study, seven human observers were used for the viewings, which were located in a parking lot after dark on an overcast night. The markings were applied to aluminum panels and viewed vehicle-to-target distances of 12, 24, and 36 m. First, observers viewed five different samples spanning the range of colors in the experiment to get an idea for the range of colors in the test. After viewing each sample for two to three seconds, the subjects were asked to rate the apparent night color from 1-5, with 1 signifying white and 5 signifying yellow.

In the laboratory portion of this study, the measurement of nighttime color (NTC) was taken, using the direct spectral method, ASTM E-811-936.

At shorter distances, more materials appeared yellow than at longer distances. At longer vehicle-to-target distances, observer ratings showed greater separation of color distinction between materials. It was concluded in this study that daytime color perception is not equivalent to nighttime color. Nighttime performance greatly varies in assorted “yellow” pavement marking products.

Michigan

Highway paint-line performance was studied by the Michigan Department of Transportation along with Michigan State University. The project began in 1993 with three areas of varying degrees of traffic volumes and snowfall. A Mirolux 12 retroreflectometer was used to take retroreflectivity readings.

Field tests were conducted every three months, evaluating the paints, polyester, water-based, and thermoplastic. However, thermoplastics were eventually omitted from the study because of a lack of data. Measurements were taken at each location for the centerline, right-edge line, and one lane line. Measurements were taken late at night on weeknights or during the weekends to avoid heavy traffic. Test sites were located slightly beyond a traffic signal so that readings could be taken during the red phase of the traffic signal.

The study found that yellow paint had less retroreflectivity than white paint, but the decay rate of yellow and white paint was equivalent (*11*).

Michigan State University analyzed the relationship between retroreflectivity levels and traffic variables. The variables measured were average daily traffic, speed limit, and commercial traffic percentage. The study indicated that the decay in retroreflectivity of test materials did not correlate with these traffic variables. However, there was a correlation found between snowfall and the rate of retroreflectivity degradation. This suggests that snowplowing frequency is related to the degradation of retroreflectivity (*21*).

Michigan State University also studied the retroreflectivity level of longitudinal pavement markings and nighttime crashes. This analysis did not suggest evidence that the retroreflectivity levels in the ranges tested in this study affected nighttime crashes (*21*).

The study conducted found that tape materials had the lowest average value of retroreflectivity compared to polyester, thermoplastics, and water-borne paints. Durability was also measured, using a subjective examination based on ASTM D 713. The durability is equal to one-tenth of the percentage of material remaining on the pavement when inspected by the unaided eye. However, for this study, durability was simply reported in percent of the prescribed area of the test stripe in which the substrate was not exposed. Tape showed the highest value for durability at 97.6 percent. Waterborne paints were the lowest (79.5 percent). Polyester and thermoplastics had durabilities of 83.3 percent and 89.9 percent, respectively.

Despite this finding, the study still concluded that waterborne paints are the most cost effective. This was based on the material’s good retroreflectivity (217 mcd/m^2/lux) levels, reasonable durability (80 percent), long average time to failure (445 days), and the fact that they are relatively less costly ($0.05/ft) (*21*).

Pennsylvania

The Pennsylvania Transportation Institute developed a research program whose intent was to provide a balanced approach in determining which pavement marking material is the most cost effective, and to establish typical service lives for the materials (*22*). Service life must be defined by measurable properties that can establish when a marking material is no longer acceptable. These properties may include retroreflectivity, percent loss of material, and contrast between marking material and pavement surface. The centerline portions of the test lines were used as the criteria for service life, so traffic volumes were relatively unimportant.

This study used traffic paints (alkyd, hydrocarbon, and water-based), solvent-borne epoxy, polyester, urethane, epoxy, thermoplastic (alkyd and hydrocarbon), and preformed materials (cold plastic and foil-backed tapes). Three different climates were used for the test deck experiments. In Pennsylvania, dense-graded asphalt (DGAFC) and PCC sites with medium-to-low–density traffic volumes were used. Open-graded asphalt (OGAFC) and DGAFC surfaces were used in Florida on sites with medium to high traffic volumes. In Arizona, OGAFC and PCC pavement types with low traffic volumes were studied.

To evaluate nighttime performance, a panel of 16 drivers was selected to individually evaluate 46 prepared centerlines and edge lines. The panel was asked to rate the lines based on whether or not the line was visible, and the average evaluation was documented for each line. To objectively measure the retroreflectivity, four instruments were chosen, and the instrument that produced the most reliable results, providing the best agreement with the subjective evaluations, was to be further used. The retroreflectometers were the Michigan design, the Erichsen, the Ecolux, and the Mirolux. The Mirolux was selected based on its good results and low cost. However, the Mirolux was not available at the start of this project, so the Michigan design retroreflectometer was used. Later in the project, supplemental readings with the Mirolux were made.

The same set of lines and same project panel were used to evaluate daytime performance. The subjective evaluations were conducted in the same manner. A spot photometer was used to measure the brightness of the lines and the roadway. The contrast ratio between the brightness of the lines and the road was the best technique of predicting the subjective ratings given by the panel. It is noted in the report that the contrast in brightness is independent of the intensity of the light, meaning that sunny days and cloudy days would not be a factor.

Each individual material was placed in six lines at each site of application. The estimated times that the lines reach 100, the established failure level measured with the Mirolux retroreflectometer, resulted in the lifetime of the material.

This study concluded that retroreflectometer data are highly correlated to mean panel ratings, and it is unnecessary to include durability and appearance ratings in the prediction. It was also found in this study that materials that failed the daytime evaluation also failed the nighttime evaluation. This helped reinforce the notion that pavement marking lines could be effectively judged by only their retroreflectometer evaluation. The appendix of the report estimates the lifetimes of pavement marking materials by class, color, test deck location, as well as the material costs (*22*).

Pavement Marking Material Costs

Costs of various pavement marking materials as used in studies conducted by the Pennsylvania Transportation Institute (PTI) (*22*) and Michigan State University (MSU) (*21*) are outlined in Table 1 below.

Table 1 Pavement Marking Material Costs According to the Pennsylvania Transportation Institute and Michigan State University

Pavement Marking Material	PTI Cost per Foot ($/ft)	MSU Cost per Foot ($/ft)
Solvent-borne paint	0.03	0.03
Waterborne paint	0.03	0.05
Polyester paint	0.19	0.09
Epoxy	0.23	0.25–0.35
Thermoplastic	0.31	0.45
Tape	0.89	1.50–2.00

Source: *21*, *22*.
Note: Costs are in 1990 dollars.

Warranty Alternative

A warranty is a guarantee of the reliability of a product and of the responsibility to repair or correct defects for a set amount of time after a project is completed or the product is sold. One reason that warranties are used for pavement marking is to supplement the workforce and reduce the need for inspections. Products that allot decision-making and risk to the contractors are more likely to be warranted. Warranties are appropriate for new products, to bring about innovation and flexibility (*23*).

Researchers at the University of Wisconsin along with the Texas Transportation Institute conducted phone interviews with all 50 state highway agencies to investigate the warranty process as it relates to pavement marking materials.

There are different methods of payment for a warranty contract. In one method, a bonus is paid for performance above a specified level. Another method withholds a percentage of the contract price instead of requiring warranty bond. Then, if the contractor meets specified performance criteria, they are paid a percentage of the money retained each year.

The research found that some states felt warranty specifications can prevent bidders since the warranty programs are a new idea, and contractors are apprehensive about bidding on them. However, the research project also found that most state agencies felt that warranty projects have progressed well and have been constructed with more care than traditional projects. The consensus felt that, on warranted projects, the workmanship on these was enhanced and contractors focused more on quality work.

Service Life

The Federal Highway Administration (FHWA) sponsored TRB to evaluate the service life of durable, longer lasting pavement markings (*24*). 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, which indicated the marking needed 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 in this study consist of epoxy, poly methyl methacrylate, polyester, thermoplastic, and preformed tape. Measurements of the retroreflectivity of the materials were made at six-month intervals during a four-year period with two Laserlux 30 m mobile retroreflectometers provided by the FHWA.

In order to measure the service life, threshold retroreflectivity values were used to define the end of a pavement marking service life. Since there are no established criteria for minimum R_L values, the threshold values shown below in Table 2 were established.

Table 2 Threshold Retroreflectivity Values Used to Define the End of Pavement Marking Service Life

Color of Marking	**Threshold Retroreflectivity Values (mcd/m²/lux)**		
	Non-Freeway ≤ 64 km/hr	**Non-Freeway ≥ 72 km/hr**	**Freeway ≥ 89 km/hr**
White	85	100	150
White with RRPMs and/or lighting	30	35	70
Yellow	55	65	100
Yellow with RRPMs and/or lighting	30	35	70

Source: *24*.
Note: RRPM= raised retroreflective pavement markers.

Statistical modeling was used to determine the relationship between decreasing R_L values with time and traffic passage. One plot was developed to show the relationship between the mean R_L and the cumulative traffic passages (CTP) since the installation of the marking, based on the reported average daily traffic (ADT). A similar plot showed the relationship between mean R_L and the time (elapsed months) since installation. Tables 3 and 4 outline the results of this study, in terms of the estimated service life, based on roadway type, pavement marking material, and color of line, for both CTP and elapsed months.

Table 3 Estimated Service Life of Yellow Lines by Roadway Type and Pavement Marking Material

Roadway Type and Material	Number of Pavement Marking Lines	Service Life	
		Average CTP (million vehicles)	Elapsed Months
Freeway:			
Polyester	1	11.1	39.7
Profiled tape	3	6.9	25.8
Thermoplastic	7	6.1	24.7
Profiled thermoplastic	4	5.3	23.5
Epoxy	7	4.7	23.2
Profiled poly methyl methacrylate	3	6.2	21.1
Poly methyl methacrylate	3	3.0	15.6
Non-Freeway ≤ 64 km/hr:			
Profiled thermoplastic	1	11.4	50.7
Epoxy	2	3.6	43.9
Profiled polyester	1	4.7	39.6
Profiled tape	1	3.5	19.6
Non-Freeway ≥ 72 km/hr:			
Polyester	1	9.1	47.9
Epoxy	6	8.9	44.1
Profiled tape	3	5.1	38.9
Thermoplastic	3	4.5	33.8
Profiled poly methyl methacrylate	2	6.5	31.0
Profiled thermoplastic	3	3.9	23.0
Poly methyl methacrylate	1	4.8	20.5

Source: *24*.

South Carolina: Retroreflectometer Comparisons

It is expected that federal requirements on minimum retroreflectivity will soon order that states monitor their markings on a regular basis. In preparation for this requirement, Clemson University, along with the South Carolina Department of Transportation, evaluated the effectiveness of various types of retroreflectometer devices (*9*). The research compared the Laserlux, the LTL 2000, the MP-30, and the MX-30 instruments. In evaluating these instruments, reproducibility, accuracy, and repeatability were identified as measures of evaluation. Each of these retroreflectometers is handheld, while the Laserlux is vehicle-mounted.

When evaluating the handheld retroreflectometers, the considerations identified for unit comparisons are cost, calibration procedures, effects of temperature and humidity, effects of ambient light, and repeatability and reproducibility of results. The LTL 2000 was found to retail at $17,000, the MX-30 at $12,000, and the MP-30 at $8,000.

Table 4 Estimated Service Life of White Lines by Roadway Type and Pavement Marking Material

Roadway Type and Material	Number of Pavement Marking Lines	Service Life	
		Average CTP (million vehicles)	Elapsed Months
Freeway:			
Thermoplastic	14	7.5	22.6
Polyester	2	9.6	20.8
Profiled tape	5	6.3	19.6
Profiled thermoplastic	7	6.5	18.4
Profiled poly methyl methacrylate	6	7.9	14.0
Epoxy	11	2.4	12.8
Poly methyl methacrylate	6	3.7	11.9
Waterborne paint	3	3.7	10.4
Non-Freeway ≤ 64 km/hr:			
Profiled thermoplastic	1	25.1	55.7
Profiled polyester	1	10.9	45.9
Epoxy	2	4.5	39.4
Profiled tape	2	7.6	26.9
Non-Freeway ≥ 72 km/hr:			
Epoxy	5	8.8	38.8
Profiled tape	4	5.3	37.3
Thermoplastic	5	6.0	36.6
Profiled poly methyl methacrylate	3	8.8	34.8
Poly methyl methacrylate	1	3.4	29.3
Polyester	3	2.7	27.4
Profiled thermoplastic	6	3.7	24.9

Source: *24*.

In terms of calibration, the MP-30 and MX-30 both used an initial retroreflectivity value supplied by the manufacturer. The LTL 2000 manufacturer traces their calibration standard to an internationally recognized lamp standard in Europe. The MP-30 was found to be very sensitive to temperature, which means that a warm-up period can be required before use. The MX-30 and LTL 2000 were not as sensitive to temperature and humidity effects. The MP-30 relies on a thin foam base and a three-piece sunshield to block out ambient light, whereas the MX-30 and LTL 2000 automatically adjust for ambient light. All three devices were found to be adequately repeatable.

The statistical analysis for this research found good correlation between the MX-30 and the LTL 2000. The MP-30's sensitivity to ambient light affected its correlation. When comparing the vehicle-mounted Laserlux to the handheld devices, the correlation is not as good of a fit compared to the handheld devices to one another.

New Approaches to Pavement Marking

Luminark Systems, Inc., has recently developed the Luminark cementitious pavement marking system that in effect combines the tasks of concrete joint cutting and striping (*25*). The system integrates the pavement marking into the concrete, rather than applying the marking to the surface. The marking material is actually polymer-modified cement, claimed to bond to concrete well. Glass beads have also been substituted as the aggregate, so that the beads are mixed throughout the concrete, and can continue to be exposed as the marking wears.

In the Luminark system, an operator first sawcuts a groove into new or existing concrete pavement. After the groove has been cut and washed free of debris, specially designed equipment installs the Luminark material. Although this method incurs higher initial costs compared to paint, epoxy, thermoplastic, and tape, Luminark claims that the lifecycle cost is beneficial, in that striping is not necessary as often as the other methods.

The Luminark system has been placed in Michigan, Colorado, and Kansas. Luminark plans to target northern states where concrete pavement is used and snowplowing often conducted. The company is currently in the approval process with the American Association of State Highway and Transportation Officials (AASHTO) for the Luminark system of pavement marking.

Environmental and Health-Related Performance of Pavement Marking Materials

Growing environmental concerns are causing the pavement marking material industry to look into the environmental and health effects of materials. While it is important to measure the engineering performance of materials, it is also critical to investigate the environmental performance, by assessing the amount of volatile organic compounds and health concerns by evaluating exposure to hazardous air pollutants (HAPs). VOCs and HAPs are a potential hazard to striping crews and other workers exposed to them.

Toxicity is based on the volume of air needed to dilute a unit weight of the marking material to a level where the concentration of volatiles will be at the threshold level. Regular exposure of workers to the HAPs at this concentration is likely to have no severe health effects (*12*).

Solvent-borne paints (alkyd paints) have been found to have the highest potential health hazard as a marking material. Previously, most solvent-borne paints did not comply with maximum VOC regulations. However, new rules by the EPA have changed the formula for alkyd paints so that they no longer contain high levels of VOCs (*13*). The new alkyd is still low in cost ($0.03–$0.05 per linear foot), with a quick drying time. It can be used on both PCC and ACC pavements.

Most waterborne paints are compliant with the maximum VOC requirement, and this type of paint is not flammable. Thermoplastics do not have measurable VOCs and are unlikely to have significant levels of HAPs. However, there are potential hazards in working with thermoplastics, since this material requires handling at high temperatures, and hot aerosols and some fumes during application. Tapes also do not contain high amount of any HAPs or VOCs (*12*).

For epoxy materials, the fully cured epoxy binder shows no hazards, but the reactive chemicals in striping operation can include hazardous chemicals.

National Transportation Product Evaluation Program (NTPEP)

The National Transportation Product Evaluation Program was established in 1994 and is sponsored by AASHTO. It is an ongoing program that conducts evaluation of pavement marking materials through field and laboratory tests. NTPEP combines the professional and physical resources of AASHTO's member departments to test the materials.

The purpose of NTPEP is to bring the users and suppliers of transportation products together into a partnership that works to reduce the cost and complexity of the evaluation process. The program eliminates replication of testing between the state highway departments by presenting the transportation industry with a universal product evaluation. NTPEP evaluates a variety of products in each of its product areas and provides impartial assessment results for state transportation departments (*26*).

NTPEP acts as the administrator of the evaluation program. Each manufacturer pays NTPEP for the cost of testing its paint products. NTPEP maintains a list of approved paint testing facilities with which contracts to perform testing has been executed. NTPEP arranges a test facility to perform the testing for a given manufacturer. Test results are made available to the program. NTPEP then pays the testing facility at the completion of testing. NTPEP maintains records of the test results and distributes those results to participating departments (*27*).

Over a two-year period, four sites are selected for the field evaluations. One site is located in each of the following four areas:

- Northeast, for a cold-humid climate
- Southeast, for a hot-humid climate
- Northwest, for a cold-dry climate
- Southwest, for a hot-dry climate

Materials are placed at two of the sites on an alternating annual basis. Each site is required to have two decks, one located on a concrete roadway and one located on a bituminous roadway (*28*).

The materials are divided into two classifications: paints and durable materials. Paint materials include waterborne and solvent-borne paints. Durable materials refer to thermoplastics, preformed thermoplastics, removable tapes, durable tapes, epoxies, and polyesters (*29*).

NTPEP Field Evaluations

According to the NTPEP "Project Work Plan for Field and Laboratory Evaluation of Pavement Marking Materials," the field testing procedures are based on ASTM D 713, "Standard Practice for Conducting Road Service Tests on Fluid Traffic Marking Materials" (*30*). The field evaluations are performed approximately every 30 days for the first year and every 120 days for the second year on long-life materials. Appearance and durability are monitored and given a weighted rating. For the nighttime visibility evaluation, an LTL 2000 retroreflectometer is used.

The decks for field evaluation are chosen using the procedure of ASTM D 713. This states that sections should be selected where "traffic is heavy (minimum AADT of 5000); free-rolling with no grades, curves, intersections or access points near enough to cause excessive breakage or turning movements; uniform wear with full exposure to daylight hours; and areas with good drainage. Selected surfaces shall be representative of the pavement upon which the traffic marking materials will be applied in practice. Such surfaces include portland cement concrete, sheet asphalt, bituminous concrete, rock asphalt, and bituminous surface treatment" (*30*).

A manufacturer may submit no more than 26 pavement marking materials for evaluation per year. Each supplier supplies five gallons of each material for testing.

Pavement marking materials for the NTPEP field testing procedures may not be applied to wet or damp pavement surfaces. The air temperature must also be within the range of 50° to 95°F.

A study presented at the 2001 annual TRB meeting compared the performance of pavement markings on an NTPEP-type test deck and at intersections. At an NTPEP test deck, stripes are placed in a transverse direction across a travel lane with free-flowing traffic. But for products that are intended for use at intersections with transverse markings, the pavement marking products are exposed to "stop-and-go" and turning traffic that is not accounted for in the NTPEP test deck design. The study evaluated products at six intersections in the Las Vegas area, as well as a control deck with both PCC and ACC pavement surfaces. Paint, thermoplastic, preformed thermoplastic, and tape products were tested for durability, retroreflectivity, and color. The tests found that products with a relatively better performance on the test deck may actually perform worse when installed at intersections. In terms of durability and retroreflectivity, the performance of the materials was more distinct at intersections than at the test deck. The study concluded that problems arise when evaluating intersection markings with an NTPEP test deck. However, it should be noted that intersection test decks are difficult to design so that all the test markings are subject to similar traffic conditions (*31*).

A report for each field evaluation must be completed to include information including the following:

- Site location: ADT, type, age and special treatment of the surface material
- Company information: name, code, class of material, binder, color, primer, and identification of materials containing lead
- Application information: application equipment, thickness, material temperature, relative humidity, no track time, type, and rate of application of beads
- Retroreflectance, by table
- Durability, by table
- Appearance, by table
- Snowplow damage information

Products that perform well on test decks may not perform well in actual long line applications. For instance, thermoplastics, in general, show good durability on the NTPEP test deck for both asphalt and concrete surfaces. However, Iowa has had several experiences with field trials where thermoplastics have had severe debonding problems on PCC surfaces. This may be due to differences in plowing practices. The Iowa DOT uses underbody ice blades on their plow trucks and plow the roads to a bare surface condition. These carbide-tipped ice blades exert tremendous downward pressure and cause significant damage to marking materials. Therefore, the NTPEP test decks should be used as a screening tool for the myriad of pavement marking products available and not as a definitive answer as to a product's actual field performance.

NTPEP Laboratory Evaluations

For the laboratory evaluations, American Society for Testing and Materials (ASTM) and AASHTO tests are used, depending on the material (*30*). Each manufacturer may provide a list of expected laboratory results with their submission. If considerable differences between the laboratory results and the anticipated results are found, the manufacturer is informed. The NTPEP Pavement Marking Materials Project Panel must first accept the list of adequate ranges for each laboratory evaluation procedure.

The following outlines the tests that are conducted for each type of marking material:

Preformed Tapes:

- Tensile Strength (ASTM D 3759)
- Ultimate Elongation (ASTM D 3759)
- Retroreflectivity (ASTM D 4505)
- Whiteness Index (ASTM E 313)
- Adhesion (ASTM D 4505)
- Skid Resistance (ASTM D 4505)
- Wear Index (Fed. Test Method 141 & 6192.1)

Epoxy:

- Drying Time (ASTM D 711)
- Epoxide Number (ASTM D 1652)
- Adhesion to Concrete (ACI Method 503)
- Hardness (ASTM D 2240)
- Abrasion Resistance (ASTM D 501)
- Color (ASTM G 53)
- Yellowness Index (ASTM D 1925)

Waterborne paint:

- Viscosity (ASTM D 562)
- No Track Dry Time (ASTM D 711)
- Total Solids (ASTM D 2369)
- Pigment Content (ASTM D 3723)
- Heat Stability (ASTM D 562)
- Freeze-Thaw Stability (ASTM D 562)
- Water Resistance (ASTM D 562)
- Opacity (Leneta Form 2C Opacity chart)

- Density (ASTM D 1475)
- Settling Properties (ASTM D 869)
- X-Ray Diffraction (Dried Film Scan)

Solvent-borne paint:

- Viscosity (ASTM D 562)
- No Track Dry Time (ASTM D 711)
- Total Solids (ASTM D 2369)
- Pigment Content (ASTM D 2698)
- Opacity (Leneta Form 2C Opacity chart)
- Settling Properties (ASTM D 869)
- I.R. Scan on Vehicle (ASTM D 2621)
- Density (ASTM D 1475)
- X-Ray Diffraction (Dried Film Scan)

Thermoplastic:

- Specific Gravity (ASTM T 250)
- Flowability (ASTM T 250)
- Softening Point, Ring and Ball (ASTM T 250)
- Low Temperature Stress Resistance (ASTM T 250)
- Bead Content and Grading (ASTM T 250)
- Impact Resistance (ASTM T 250)
- Daylight Reflectance (ASTM T 250)
- Yellowness Index (ASTM T 250)

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